Evaluation and Analysis of LTPP Pavement Layer Thickness Data

July 2002

PUBLICATION NO. FHWA-RD-03-041

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-229

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

This report documents a comprehensive review and evaluation of the Long Term Pavement Performance (LTPP) pavement layer thickness data. Pavement layer thickness data are very important for many types of analyses, including backcalculation of pavement moduli, mechanistic analysis of pavement structures, and performance modeling. The accuracy of layer thickness data has a great impact on the outcome of practically all analyses of performance. The report contains an assessment of the LTPP layer thickness data and recommendations for resolution of anomalous data. Results of the statistical analyses documented in this report provide insights into the characteristics of within-section layer thickness variability. The results of the comparison between as-designed and as-constructed layer thickness data provide useful estimates of the expected construction-related variability. These results can serve as a very important input to pavement engineering applications involving the reliability of pavement design and also for quality assurance construction specifications.

This report will be of interest to highway agency engineers involved in pavement analysis, design, construction, and data collection, as well as future researchers who will use LTPP data to improve on the design procedures and standards for constructing pavements.

T. Paul Teng, P.E.
Director, Office of Infrastructure
Research and Development

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-03-041	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle EVALUATION AND ANALYSIS OF LTPP PAVEMENT LAYER THICKNESS DATA		**5. Report Date** July 30, 2002
		6. Performing Organization Code
7. Author(s) Olga I. Selezneva, Y. Jane Jiang, and Goran Mladenovic		**8. Performing Organization Report No.**
9. Performing Organization Name and Address ERES Division of Applied Research Associates, Inc. 9030 Red Branch Road, Suite 210 Columbia, Maryland 21045		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. DTFH61-96-C-00003
12. Sponsoring Agency Name and Address Office of Infrastructure Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative (COTR): Cheryl Allen Richter, HRDI
Work was conducted as part of the LTPP Data Analysis Technical Support Contract.

16. Abstract
In 2001, the Federal Highway Administration sponsored a study to review pavement layer thickness data for Long Term Pavement Performance (LTPP) sites. The main objective of the study was to assess the quality and completeness of pavement layering information and layer thickness data and to provide recommendations for improvement. In the course of the study, layer thickness data available in the LTPP database were examined for quality and completeness using Levels A to E data. Following the data completeness evaluation, pavement layering data were evaluated to determine the consistency of material type and thickness data between different data sources. In addition, layer thickness variability indicators, within-section material type consistency, and material type and thickness reasonableness were evaluated. In the cases where there were inconsistencies in the data, the data were reviewed and reported to the LTPP data managers along with recommendations for data anomaly resolution.

In addition, the layer thickness data from Specific Pavement Studies (SPS) experiments were analyzed to determine characteristics of within-section layer thickness variation. The analysis included layers with different material and functional types. Descriptive statistics such as mean, standard deviation, skewness, and kurtosis were computed for each section. The statistical analysis results for 1,034 SPS layers indicated that 84 percent of all layers thickness variations within LTPP section follow a normal distribution.

The extent of differences between as-designed (inventory) and as-constructed (measured) layer thickness data was also investigated for the SPS sections. The results of analysis indicate that about 60 percent of all section/layers have mean thicknesses within 6.35 mm (0.25 in) of the target thickness. For a tolerance level of 25.4 mm (1 in), this percentage is above 90 for most layer types and target thickness values. For the same layer and material type, the mean constructed layer thicknesses tend to be above the designed value for the thinner layers and below the designed value for the thicker layers.

One important product from this study is the Researcher's Guide to LTPP Layer Thickness Data. The main purpose of this guide is to provide guidance for the selection of layer material type and thickness data from the LTPP database. The guide also contains a discussion about within-section layer thickness variability and comparison between as-designed and as-constructed layer thickness. The guide is available as a separate publication.

17. Key Words Pavements, LTPP, layer thickness, material type, variability, deviations	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.		
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 159	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**	**Symbol**	**When You Know**	**Multiply By**	**To Find**	**Symbol**
	LENGTH					**LENGTH**			
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
	AREA					**AREA**			
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yard	0.836	square meters	m^2	m^2	square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	mi^2
	VOLUME					**VOLUME**			
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: volumes greater than 1000 shall be shown in m^3									
	MASS					**MASS**			
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or metric ton)	Mg (or t)	Mg (or t)	megagrams (or metric ton)	1.103	short tons (2000 lb)	T
	TEMPERATURE (exact degrees)					**TEMPERATURE (exact degrees)**			
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC	^oC	Celsius	1.8C+32	Fahrenheit	^oF
	ILLUMINATION					**ILLUMINATION**			
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
	FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**			
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised September 1993)

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LIST OF ABBREVIATIONS

AC	=	Asphalt concrete (surface course).
AGG	=	Aggregate base (identical to dense-graded aggregate base).
AASHTO	=	American Association of State Highway and Transportation Officials.
ASTM	=	American Society for Testing and Materials.
ATB	=	Asphalt-treated base (dense-graded, generally similar to the AC surface course).
COV	=	Coefficient of variation.
CRCP	=	Continuously reinforced concrete pavement.
CTB	=	Cement-treated base.
DGAB	=	Dense-graded aggregate base (unbound).
DGATB	=	Dense-graded asphalt-treated base (bound).
FHWA	=	Federal Highway Administration.
GB	=	Granular base.
GPR	=	Ground Penetrating Radar.
GPS	=	General Pavement Studies.
HMAC	=	Hot-mix asphalt concrete.
JCP	=	Jointed concrete pavement.
JPCP	=	Jointed plain concrete pavement.
JRCP	=	Jointed reinforced concrete pavement.
LC	=	Lean concrete (base).
LTPP	=	Long Term Pavement Performance (program).
PCC	=	Portland cement concrete.
PATB	=	Permeable asphalt-treated base.
QA	=	Quality assurance.
QC	=	Quality control.
RSC	=	Regional Support Contractor.
SHRP	=	Strategic Highway Research Program.
SB	=	Surface and binder (layer).
SPS	=	Specific Pavement Studies.

1. INTRODUCTION

The mission of the Long-Term Pavement Performance (LTPP) program is to foster increased pavement life through: [1]

- Collection and storage of performance data from a large number of in-service highways in the United States and Canada, over an extended period, to support analysis and product development.
- Analysis of these data to describe how pavements perform and to explain why they perform as they do.
- Translation of these insights into products for pavement design, rehabilitation, maintenance, and management.

Layer structure and thickness information is one of the most important data elements for any type of pavement performance study. Among the studies where layer structure and thickness information is critical are backcalculation of pavement moduli, mechanistic analysis of pavement structures, and performance modeling. In fact, the accuracy of layer thickness data has a strong impact on the outcome of practically all analyses of performance.

Layer Structure and Thickness Information Collected by the LTPP Program

A large amount of data related to layer structure and thickness has been collected as part of the LTPP program. The data have been collected from several sources, including the following:

- Inventory and design records.
- Core measurements from materials sampling and testing.
- Field logs of boreholes.
- Shoulder auger probe logs.
- Test pit logs.
- Field elevation measurements before and after layer placement for Specific Pavement Studies (SPS) sections.
- Ground Penetrating Radar (GPR) measurements (planned to be collected).

The pavement layer thickness data from these sources exist in many different LTPP tables. For example, tables TST_AC01, TST_AC01_LAYER, and TST_PC06 contain core measurement data. The inventory or planned layer thickness data are stored in various other tables (e.g., INV_LAYER and RHB_LAYER). Tables SPS*_LAYER and SPS*_LAYER_THICKNESS contain field elevation data. The design layer thickness data are found in the experimental designs for newly constructed SPS sections.

Please note that the name SPS*_LAYER used herein refers to SPS1_LAYER, SPS2_LAYER, SPS5_LAYER, SPS6_LAYER, SPS7_LAYER, SPS8_LAYER, and SPS9_LAYER tables. The name SPS*_LAYER_THICKNESS used herein refers to SPS1_LAYER_THICKNESS, SPS2_LAYER_THICKNESS, SPS5_LAYER_THICKNESS, SPS6_LAYER_THICKNESS, SPS7_LAYER_THICKNESS, and SPS8_LAYER_THICKNESS tables.

Additionally, material types and depths to strata top and strata bottom are identified or measured in the field from holes, test pits, and probes. Table TST_SAMPLE_LOG stores information about the samples taken from holes, pits, and probes, and is a good raw data source for unbound layers.

Using the above information, the LTPP Regional Support Contractors (RSC's) complete tables TST_L05, TST_L05A, and TST_L05B. Table TST_L05 stores project-level material type information for SPS experiments with multiple sections constructed at the same SPS site. Table TST_L05A summarizes measured layer material type and thickness data at the beginning, within, and at the end of a section, based on the core measurements and field test pit information. The TST_L05B table provides the representative thickness for the section. These representative thicknesses are the recommended analysis level layer thicknesses in the LTPP database.

Following is a list of relevant LTPP tables that contain layer material type or thickness data:

- TST_AC01—Asphalt concrete (AC) core examination and thickness. Contains measured AC core thicknesses.
- TST_AC01_LAYER—AC core examination and thickness information. Contains field layer and real layer number.
- TST_PC06—Portland cement concrete (PCC) core examination and thickness.
- SPS*_LAYER—Summarized layer descriptions and thicknesses for newly constructed SPS layers (Sheet 4).
- SPS*_LAYER_THICKNESS—Field elevation layer thickness measurements (Sheet 12).
- TST_SAMPLE_LOG—Information about the samples taken from holes, pits, and probes.
- INV_LAYER—Layer descriptions and thickness data collected from highway agencies (Data Sheet: Inventory 3).
- RHB_LAYER—Layer descriptions and thickness data collected from highway agencies on rehabilitated layers (Data Sheet: Rehab 2).
- TST_L05—Table containing laboratory material testing data, project level for SPS experiments only.
- TST_L05A—Table containing layer descriptions for all constructions, section level – measured data.
- TST_L05B—Table containing layer descriptions for all constructions, section level – analysis section.

Additional information about the LTPP program, field sampling, materials testing, data collection guidelines, and LTPP database can be found in the following documents:

- *Data Collection Guide for Long-Term Pavement Performance Studies*, Operational Guide No. SHRP-LTPP-OG-001, SHRP, Washington, DC, 1993. [2]
- *SHRP-LTPP Interim Guide for Laboratory Materials Handling and Testing (PCC, Bituminous Materials, Aggregates and Soil)*, Operational Guide No. SHRP-LTPP-OG 004, SHRP, Washington, DC, 1991 (SHRP-LTPP Lab Guide). [3]
- *Field Materials Sampling, Testing, and Handling Guide* No. SHRP-LTPP-OG 006, Version 2.0, SHRP, Washington, DC, 1992. [4]

- *LTPP SPS Pavement Layering Methodology*, FHWA, McLean, Virginia, January 1994. [5]
- Specific Pavement Studies, *LTPP Material Sampling and Testing Requirements for SPS Experiments*. [6-11]
- Specific Pavement Studies, *LTPP Experiment Design and Research Plan for SPS Experiments*. [12-17]
- SHRP-LTPP Protocol P01 for SHRP test designation AC01: *Visual Examination and Thickness of Asphaltic Concrete Cores*. [18]
- SHRP-LTPP Protocol P66 for SHRP test designation PC06: *Visual Examination and Length Measurement of Portland Cement Concrete Cores*. [19]
- *LTPP Information Management System: IMS Quality Control Checks*, Federal Highway Administration, Washington, DC, 2000. [20]
- Specific Pavement Studies, *Data Collection Guidelines for SPS Experiments.* [21-26]

Need for Review of LTPP Pavement Layer Thickness Data

The LTPP database contains a wealth of layer material type and thickness data. However, some discrepancies have been observed in these data, raising some concerns about data quality. For some sections, design thickness or highway agency inventory thickness was reported in the TST_L05B table because of the lack of materials testing data. This is especially true for many rehabilitated sections. In addition, some sections are missing layer thickness information, which severely limits the use of these sections in data analysis studies.

Study Objectives

The goal of this study is to assess and improve the LTPP layer material type and thickness data quality for data that are currently available in the LTPP database. The main objectives for this study are as follows:

- Examine the layer thickness data in the LTPP database to evaluate quality and completeness using data at Levels A through E.
- Evaluate layer material type and thickness data reasonableness and consistency and provide recommendations for layer material types and thicknesses for each LTPP section.
- Characterize the variation in layer thickness data at different locations within sections where data are available (i.e., SPS sections).
- Document the extent of differences in the layer thickness data between as-designed (inventory) and as-constructed (measured) thicknesses (SPS sections).

One important product from this study is a *Researcher's Guide to the LTPP Layer Thickness Data*. The Guide is presented in a separate report.

Report Organization

The report contains seven chapters. Chapter 1 (this chapter) provides an introduction to the issues related to the LTPP layer material type and thickness data, study objectives, and report organization. Chapter 2 summarizes layer structure and thickness data availability and completeness. Chapter 3 discusses the results from evaluation of the LTPP layer material type and thickness data reasonableness and consistency. Chapter 4 provides a summary of layer thickness variability data evaluation. Chapter 5 summarizes characteristics of the within-section thickness data variation for SPS layers with extensive elevation measurements. Chapter 6 discusses evaluation results on comparing designed versus as-constructed or measured thicknesses. Finally, chapter 7 presents a summary, conclusions, and recommendations from this study.

Additional material is included in three appendixes. Appendix A contains a table of material codes used to correlate material type data from inventory and testing tables. This table was developed to enable cross-table comparison of material types specified in several LTPP database tables using different material coding schemes. Statistical formulations used in the skewness-and-kurtosis test are provided in Appendix B. Appendix C contains description of a statistical procedure that was considered for evaluation of within-section layer thickness variability characteristics.

2. ASSESSMENT OF DATA AVAILABILITY AND COMPLETENESS

This chapter summarizes the results of the data availability and completeness assessment for tables related to pavement layer structure. First, the LTPP data source used for this study is presented. Then, LTPP data availability and quality control (QC) are discussed, which explains the QC process of the LTPP data and why some data collected are deemed “unreleasable” to the public. After that, layer structure and thickness data are assessed for their quality level and completeness.

LTPP Data Source Used in This Study

LTPP data release 11.5 version NT3.0, obtained on June 8, 2001, was used for this study. LTPP tables with layer material type and thickness data for individual layers at the section level are evaluated for data availability and completeness for the relevant sections. Tables TST_AC01 and TST_L05 were not included in this study.

Table TST_AC01 was not evaluated in this study because it contains measured core thickness, which may represent thickness from multiple layers. For example, a single AC core identified in the field as AC material and with measured thickness in the TST_AC01 table may contain hot-mix asphalt concrete (HMAC) wearing, binder, and base layers.

Table TST_L05 was not used because it contains information only for SPS projects at the project level. Many SPS projects contain multiple sections at the same site (e.g., SPS-1 and SPS-2). This table is useful for researchers who would like to link material type information from multiple sections at the section level together for a given SPS project.

The following LTPP tables were assessed for data availability and completeness:

- TST_AC01_LAYER—Core examination and thickness information. Contains field layer and real layer number.
- TST_PC06—Core examination and thickness.
- SPS*_LAYER—Layer descriptions (Sheet 4).
- SPS*_LAYER_THICKNESS—Layer thickness measurements (Sheet 12).
- INV_LAYER—Layer descriptions (Data Sheet: Inventory 3).
- RHB_LAYER—Layer descriptions (Data Sheet: Rehab 2).
- TST_L05A—Table containing layer descriptions for all constructions.
- TST_L05B—Table containing layer descriptions for all constructions.

LTPP Data Availability and Quality Control Checks

The quality of the data is the most important factor in any type of pavement performance analysis. From the onset of the LTPP program, data quality has been considered of paramount importance. Procedures for collecting and processing data were defined (and are modified as necessary) to ensure consistency across various reporting contractors, laboratories, and equipment operators. Although these procedures formed the foundation of quality control/quality assurance (QC/QA) and data integrity, many more components of a QC/QA plan were necessary to ensure that the data sent to researchers were as error-free as possible.

LTPP has developed and implemented an extensive QC program that classifies each of the data elements into categories, depending upon the location of the data in this QC process. Several components or steps comprise the overall QC/QA plan used on LTPP data, as discussed in the following paragraphs [20].

1. **Collect Data:** Procedures for collecting data are documented for each module in the LTPP database. These procedures are intended to ensure that data are collected in similar formats, amounts, conditions, and so on. Documentation references include the Data Collection Guide and various module-specific guides.

2. **Review Data:** Regional engineers review essentially all data input into the regional LTPP databases to check for possible errors related to keystroke input, field operations, procedures, equipment operations, and so on. The regional review is intended to catch obvious data collection errors. In addition, some data are preprocessed before they are entered into the LTPP database. For example, PROFCAL software is used on the profilers to provide a system check by comparing measurements taken at different speeds. PROFSCAN is a field QA tool that allows an operator to identify invalid data while still in the field, thus saving costly revisits to the site.

3. **Load Data in LTPP Database:** Some checks are programmed into the LTPP database to identify errors as data are entered. The LTPP database contains mandatory logic, range, data verification, and other miscellaneous checks that are invoked during input.

4. **QC/QA:** Once data are input into the LTPP database and reviewed by regional engineers, formal QC/QA software programs are run on the data.

   - **Level A –** Starting point. When records are first input into the IMS they are assigned a status of A. Records failing the level B or level C checks will have a status of A. At present, data for SPS supplemental test sections, which by policy are not subjected to QC checks, are left at level A in most tables.
   - **Level B –** An old check that is being replaced in some modules. Originally, level B was a dependency check on the availability of certain critical data contained in other tables. In some modules, this check has been phased out and replaced with level E checks and changes to the structure of the EXPERIMENT_SECTION table. There are cases where records with RECORD_STATUS=B exist due to restrictions imposed by the software used to perform manual upgrades.
   - **Level C –** Availability of critical data fields in a record. These are checks to see if certain data fields have non-null values. As an example, test section coordinates are required for all entries in INV_ID and SPS_ID. Some of the level C checks are conditional checks on several fields. Another example, in MON_DEFL_DROP_DATA, of the 7 to 9 possible deflection values, at least 5 must be non-null. These checks are not performed on key fields and fields defined as non-null, since these fields must be populated in order to create a record.

- **Level D –** Range checks on the values contained in single fields. While these are called expanded range checks, they are refined range checks on the reasonableness of the magnitude of a number or code value. When data is entered, its range must match the field format logic, for example, a value of 999 can not be entered in a field defined as NUMBER(2,0). These checks are more stringent than logical range values, but in some instances are set to a rather large range of values to encompass typical conditions. For example, the range of air temperature must accommodate conditions spanning from Arizona to Alaska. In other instances, the range limits are based on traditional practice in order to flag outliers and suspect values. For example, the percent longitudinal reinforcement in PCC pavements is limited to 1% since it is very rare that pavements are built with even this very high level of steel reinforcement.
- **Level E –** Relational checks between data elements in the same record and data elements contained in other records. Although previously described as intra-modular checks, these checks have been expanded to include record level inter-field and inter-modular checks. Some of the types of level E checks include:
    - Logical relationship between related values. For example, a minimum value must be less than or equal to the average, which must be less than or equal to the maximum.
    - Parent-child integrity checks. For example, every record in MON_DEFL_LOC_INFO must have a matching record in MON_DEFL_MASTER.
    - Range checks between related values. For example, the difference between the daily maximum and minimum air temperature must be less than 50° C.
    - Referential cascading parent-child level E relationships. For example, for records in MON_T_PROF_MASTER to reach level E, all matching records in MON_T_PROF_PROFILE must be at level E.
    - Compliance with LTPP rules and test protocols. Many level E-QC checks are based upon LTPP rules for pavement-structure-material layer types, sequence and LTPP test protocols. For example, the surface layer of a GPS-3 test section should consist of portland cement concrete.
    - Computed parameter referential level E checks on records in source tables. For example, for records that contain results of FWD backcalculation computations to reach level E, matching data from the FWD deflection tables must also be at E.

Once the QC/QA programs are completed, the regional engineers review the output and resolve any data errors that they can. Often, the data entered are accurate and legitimate but do not pass a QC/QA check. When this occurs, the regional engineer can document that the data have been confirmed using a Comments table in the database and manually upgrade the record to Level E.

There are many reasons that some important data may not be available from the publicly released LTPP database at the time of analysis. The following are some possible examples:

- Data are yet to be collected or the laboratory tests have not been performed on samples that have been taken.
- Data are under regional office review.
- Data have failed one of the quality checks and are being reviewed.

- Data have failed one of the quality checks and were identified as anomalies.
- Data need to be quality checked.
- The development of the SPS-8 requirements took place over time, and some of the earlier projects may have had different requirements.
- The monitoring requirements for some sites may have changed over time.

As such, the unavailable data identified in this section do not necessarily mean the data were not collected or submitted by the States. There are several instances where data may have gotten held up and did not reach Level E. The LTPP program is continuing on a system-wide effort to resolve all unavailable data so they will be available to future researchers.

Assessment of the LTPP Layer Thickness Data Availability and Completeness

An overview of the available LTPP data, both at all QC levels and at Level E for regular LTPP sections (non-supplemental sections), is provided in table 1.

Table 1. Data availability assessment of the regular sections for layer thickness related tables.

Table Name	Number of Records		Number of Sections Represented		Number of Pavement Structures	
QC Level:	**All QC Levels**	**At Level E only (%)**	**All QC Levels**	**At Level E only (%)**	**All QC Levels**	**At Level E only (%)**
EXPERIMENT_SECTION	3708	3686 (99.4%)	2058	2040 (99.1%)	3476	3457 (99.5%)
INV_LAYER	3928	3918 (99.7%)	882	880 (99.8%)	882	880 (99.8%)
RHB_LAYER	2934	2925 (99.7%)	460	458 (99.6%)	472	470 (99.6%)
TST_L05A	15590	15189 (97.4%)	2044	1939 (94.9%)	3460	3236 (93.5%)
TST_L05B	16600	15298 (92.2%)	2044	1943 (95.1%)	3460	3247 (93.8%)
TST_AC01_LAYER	33984	33749 (99.3%)	1189	1176 (98.9%)	1519	1505 (99.1%)
TST_PC06	4486	4449 (99.2%)	575	573 (99.7%)	583	575 (98.6%)
SPS1_LAYER	1021	1021 (100%)	194	194 (100%)		
SPS1_LAYER_THICKNESS	9220	9220 (100%)	168	168 (100%)		
SPS2_LAYER	634	621 (97.9%)	155	155 (100%)		
SPS2_LAYER_THICKNESS	7282	6960 (95.6%)	142	140 (98.6%)		
SPS5_LAYER	1056	1056 (100%)	155	155 (100%)		
SPS5_LAYER_THICKNESS	5057	5057 (100%)	102	102 (100%)		
SPS6_LAYER	412	402 (97.6%)	86	86 (100%)		
SPS6_LAYER_THICKNESS	1933	1933 (100%)	40	40 (100%)		
SPS7_LAYER	135	135 (100%)	26	26 (100%)		
SPS7_LAYER_THICKNESS	918	918 (100%)	24	24 (100%)		
SPS8_LAYER	157	155 (98.7%)	42	42 (100%)		
SPS8_LAYER_THICKNESS	2175	2175 (100%)	40	40 (100%)		
SPS9_LAYER	475	475 (100%)	83	83 (100%)		

Note: A unique combination of STATE_CODE, SHRP_ID, and CONSTRUCTION_NUMBER comprises a pavement structure.

This overview is presented at three levels to provide a complete picture:

- Record level – Number of records in each of the layer material and thickness tables.
- Section level – Number of sections having data in each of these tables.

- Pavement layer structure level – A unique combination of STATE_CODE, SHRP_ID, and CONSTRUCTION_NO comprises a pavement structure.

Generally, the proportion of records at Level E is good, ranging from 92 to 100 percent. The percentage of records at Level E is especially good for the SPS*_LAYER and SPS*_LAYER_THICKNESS tables, ranging from 96 to 100 percent, with many at 100 percent.

A summary of the data availability assessment for LTPP supplemental sections is presented in table 2. It is the policy of the Federal Highway Administration (FHWA) that records for the supplemental sections should not be at Level E. Therefore, no Level E data availability assessment is given in table 2.

Table 2. Data availability assessment for layer thickness related tables for supplemental sections.

Table Name	Number of Records	Number of Sections Represented	Number of Pavement Structures
EXPERIMENT_SECTION	853	459	853
INV_LAYER	64	12	12
RHB_LAYER	652	98	98
TST_L05A	4021	458	852
TST_L05B	4022	458	852
TST_AC01_LAYER	1868	137	175
TST_PC06	431	78	78
SPS1_LAYER	126	25	
SPS1_LAYER_THICKNESS	550	10	
SPS2_LAYER	137	35	
SPS2_LAYER_THICKNESS	1668	33	
SPS5_LAYER	372	48	
SPS5_LAYER_THICKNESS	1290	29	
SPS6_LAYER	310	58	
SPS6_LAYER_THICKNESS	717	16	
SPS7_LAYER	14	3	
SPS7_LAYER_THICKNESS			
SPS8_LAYER	19	4	
SPS8_LAYER_THICKNESS	132	3	
SPS9_LAYER	327	55	

Note: A unique combination of STATE_CODE, SHRP_ID, and CONSTRUCTION_NUMBER comprises a pavement structure.

Pavement structures that do not have any records in either table TST_L05A or table TST_L05B are listed in table 3. There are 16 regular pavement structures and 1 supplemental pavement structure that currently do not have any data in these tables.

For the Level E data to be used in the subsequent evaluations of the layer thickness data, a more detailed assessment was performed to find out how many pavement layer structures have data in these layer thickness related tables for each LTPP experiment. The results are presented in table 4 for the pavement structure records at Level E in table EXPERIMENT_SECTION. As shown, the experiments contain data in different layer structure related tables, ranging from one table to seven tables, with most experiments having Level E data in four tables.

Table 3. List of pavement structures that do not have any data in either the TST_L05B table or the TST_L05A table at any QC level.

SHRP Region	Supplemental ?	Experiment Type	Experiment Number	State Code	SHRP_ID	CN
S	Yes	S	1	5	0161	1
W		S	2	6	0201	1
W		S	2	6	0202	1
W		S	2	6	0203	1
W		S	2	6	0204	1
W		S	2	6	0205	1
W		S	2	6	0206	1
W		S	2	6	0207	1
W		S	2	6	0208	1
W		S	2	6	0209	1
W		S	2	6	0210	1
W		S	2	6	0211	1
W		S	2	6	0212	1
S		S	3	48	B350	3
S		S	3	48	Q330	2
W		S	8	53	A809	1
W		S	8	53	A810	1

Table 4. Level E data availability for layer thickness-related tables for LTPP experiments.

LTPP Experiment		**Number of Pavement Structures in Table**								**No. Tables with Data for the Experiment**
Type	**No.**	**Experiment _Section**	**TST_L05B**	**TST_L05A**	**INV_Layer**	**TST_AC01 _Layer**	**TST_PC06**	**RHB_Layer**	**SPS*_Layer**	
G	1	***327***	319	317	236	234				**4**
G	2	***202***	202	202	144	142		6		**5**
G	3	***148***	148	146	133	12	124			**5**
G	4	***80***	79	79	69	2	62			**5**
G	5	***96***	96	96	85	19	82	1		**6**
G	6A	***85***	85	85	62	62				**4**
G	6B	***113***	110	109		65		75		**4**
G	6C	***11***	11	11		10		11		**4**
G	6D	***13***	13	13		8		12		**4**
G	6S	***71***	70	68		38		41		**4**
G	7A	***42***	42	42	35	35	35			**5**
G	7B	***45***	45	45		16	6	31		**5**
G	7C	***2***	2	2		1		2		**4**
G	7D	***4***	4	4				1		**3**
G	7R	***2***	2	2				2		**3**
G	7S	***11***	11	11		4		9		**4**
G	9	***28***	28	28	25	19	24	1		**6**
S	1	***238***	232	232		170		6	194	**5**
S	2	***182***	182	182			142		155	**4**
S	3	***750***	746	746		375		58		**4**
S	4	***135***	135	135						**2**
S	5	***347***	291	292	27	210		132	155	**6**
S	6	***282***	206	203	8	26	52	57	86	**7**
S	7	***75***	68	68			31	23	26	**5**
S	8	***45***	27	25		18	2		42	**5**
S	9C	***6***							3	**1**
S	9J	***40***	34	34		4	15	2	20	**6**
S	9N	***40***	31	31		24			40	**4**
S	9O	***37***	21	21		10			20	**4**
Total		**3457**	**3240**	**3229**	**824**	**1504**	**575**	**470**		

Summary

The layer thickness data availability is very good in tables TST_L05B and TST_L05A, which contain the representative layer structure and thickness information for section-level analysis. Only 16 pavement structures from LTPP regular sections and 1 pavement structure from a supplemental section do not have any layer structure information in either TST_L05B or TST_L05A.

Out of 3,457 pavement layer structures at QC Level E in table EXPERIMENT_SECTION, 3,240 layers (93.7 percent) have records in table TST_L05B and 3,229 layers (93.4 percent) have records in table TST_L05A. There are a significant number of records in all the layer structure tables.

A total of 217 pavement layer structures do not contain Level E data in table TST_L05B. Other thickness-related tables contain data for selected experiment or layer types. A more detailed summary of the SPS and General Pavement Studies (GPS) pavement structures that do not contain Level E information in the TST_L05B table is provided below:

- GPS-1 – 8 pavement layer structures.
- GPS-4 – 1 pavement layer structures.
- GPS-6B – 3 pavement layer structures.
- GPS-6S – 1 pavement layer structures.
- SPS-1 – 6 pavement layer structures.
- SPS-3 – 4 pavement layer structures.
- SPS-5 – 56 pavement layer structures.
- SPS-6 – 76 pavement layer structures.
- SPS-7 – 7 pavement layer structures.
- SPS-8 – 18 pavement layer structures.
- SPS-9 – 37 pavement layer structures.

3. EVALUATION OF LAYER STRUCTURE INFORMATION AND THICKNESS DATA REASONABLENESS

Data Evaluation Overview

One of the project objectives was to identify and explain anomalous observations and provide recommendations for layer thickness characterization for each LTPP section. The following potential issues related to layer thickness data were identified during the preliminary data review:

- Unusually high or low thickness values for certain layers.
- Lack of consistency among different data sources.
- Erroneous layer types in materials testing tables.
- Excessive variation in layer thickness or material types among different locations within a layer.

Data Sources

To fulfill this task's objective, the layer thickness data in the following LTPP tables were evaluated for reasonableness and consistency (using cross-table comparison):

- TST_L05B.
- TST_L05A.
- TST_AC01_LAYER.
- TST_ PC06.
- INV_LAYER.
- RHB_LAYER.
- SPS*_LAYER.

Table TST_AC01 and table TST_SAMPLE_LOG in the LTPP database also contain thickness related information. Table TST_AC01 contains AC core thickness measurements from the field. Table TST_SAMPLE_LOG stores information about the samples taken from holes, pits, and probes, and is a good raw data source for unbound layers. However, records in these two tables are not keyed to the layer numbers as stored in TST_L05B and other above listed layer thickness related tables (field LAYER_NO). Therefore, the thickness measurements from these two tables can only be manually matched to the layers established in the TST_L05B table. Furthermore, some measurements span more than one layer, and thus cannot be used for any layer thickness comparison at all. As a result, tables TST_AC01 and TST_SAMPLE_LOG are not included in this evaluation. Nevertheless, these two tables can be used as raw layer thickness related data sources and be consulted for layer thickness measurements on a case-by-case basis.

The main data elements related to pavement layering structure from each of these tables are illustrated in figure 1. Double sided arrows between the table TST_L05B and tables TST_L05A, TST_AC01_LAYER, TST_ PC06, INV_LAYER, RHB_LAYER, and SPS*_LAYER schematically show that the data elements in the later tables were compared against similar data in TST_L05B table.

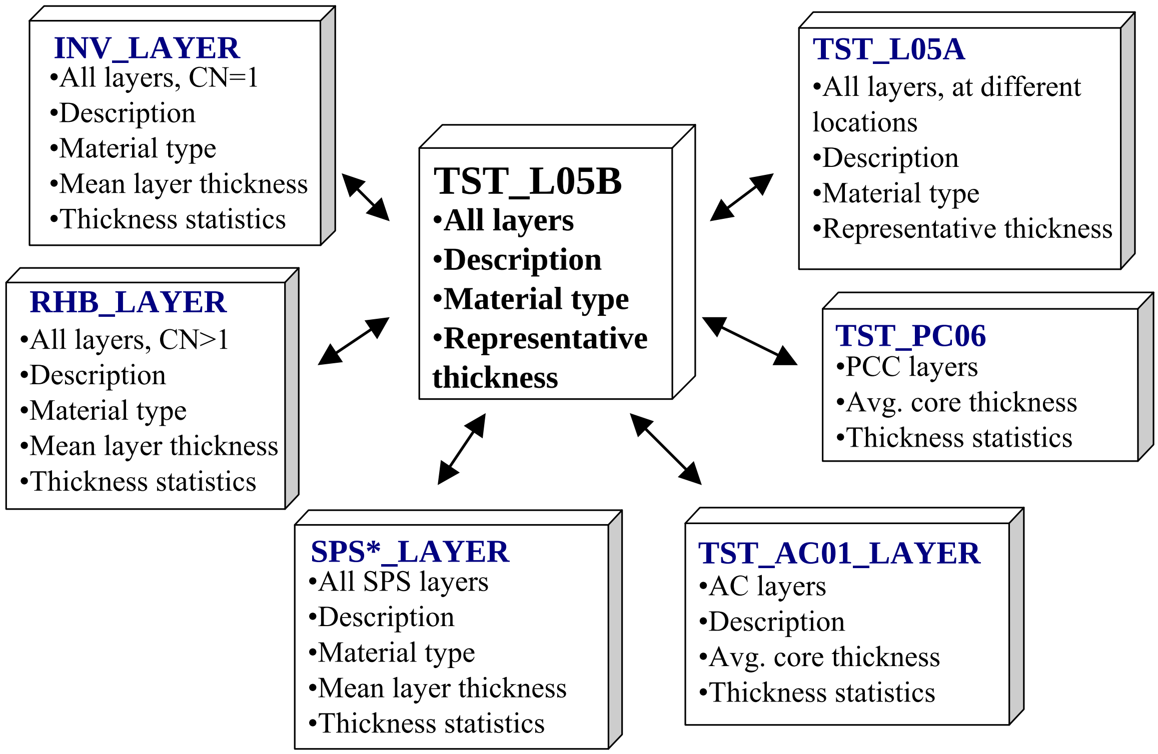


Figure 1: Graph. LTPP data sources containing pavement layering data.

Essential Fields for Data Analysis

Based on the analysis of the fields in the above tables related to pavement layering structure, the following data elements were selected for detailed pavement layering data examination:

1. Layer functional description (e.g., surface, overlay, base, subgrade).
2. Material type description.
3. Representative layer thickness.
4. Layer thickness variability (discussed in the next chapter).

These four essential pavement layering characteristics (schematically identified in figure 2 as question marks and circled numbers 1 through 4) serve as key inputs for many types of pavement analyses. The selected data elements were examined and compared between different data sources (LTPP tables). The comparisons were done individually for each layer and each LTPP section. Additionally, layer thickness variability indicators were examined, as discussed in chapter 4.

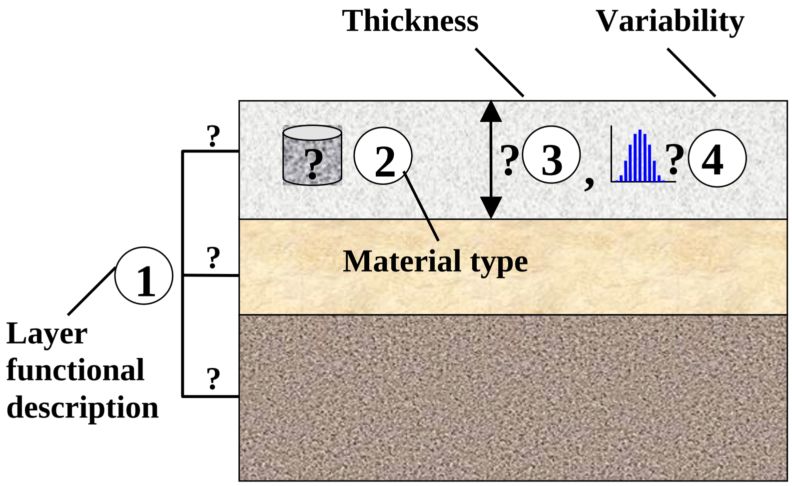


Figure 2: Graph. Four essential pavement layering characteristics.

<u>Analysis Steps</u>

The data review activities carried out in this task included the following:

1. Selection of pavement layering data from different LTPP data sources.
2. Development of a master data analysis table with the layering information from different sources included for each pavement layer.
3. Evaluation of consistency in layer functional description.
4. Evaluation of reasonableness and consistency in material type description.
5. Evaluation of reasonableness of layer thickness data and layer thickness consistency between different sources.
6. Evaluation of layer thickness variability indicators from different data sources (chapter 4).
7. Summarize evaluation outcomes and identify reasons for data inconsistencies.
8. Preparation of feedback reports to help ensure the data issues are resolved.

The flowchart identifying different data analysis and data evaluation activities is shown in figure 3.

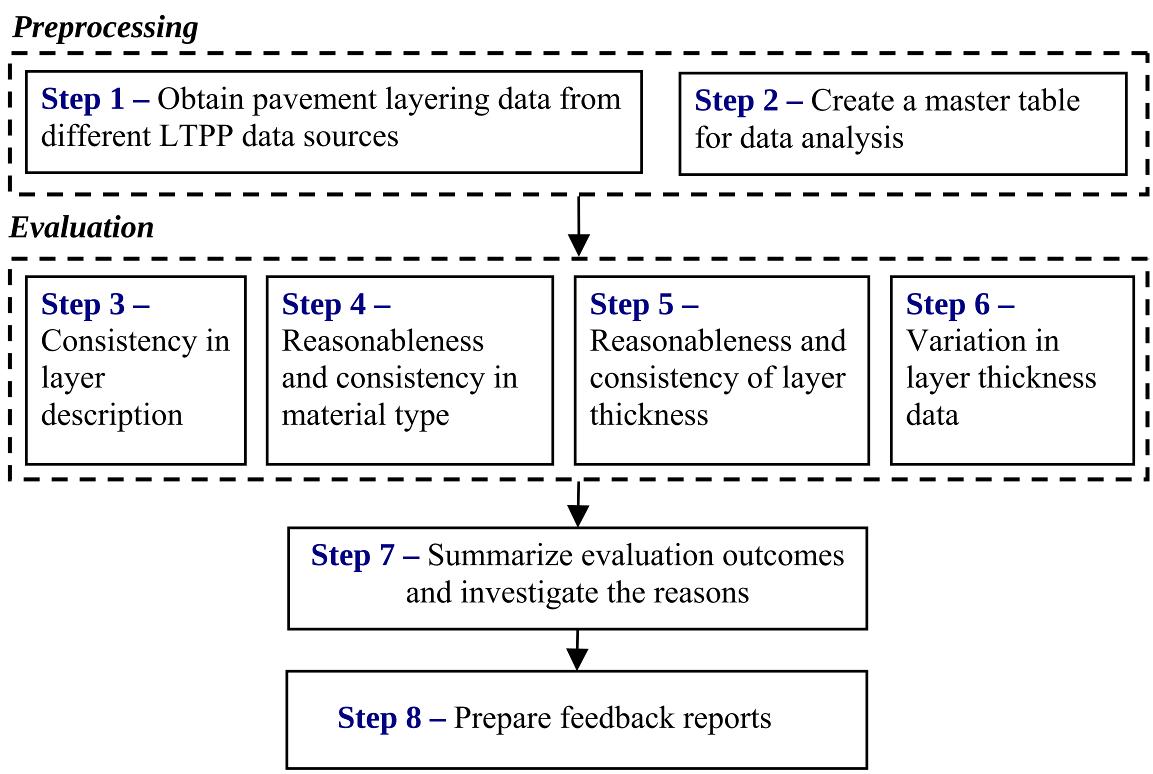


Figure 3: Chart. Flowchart for pavement layering data evaluation.

In steps 1 and 2, all the data elements from different sources were prepared for the layer-by-layer review for each section. Steps 3 through 5 were used to evaluate information for major layer structure data components available in the LTPP database. Results of step 6 are presented separately in chapter 5. Under steps 7 and 8, the anomalies or suspect data in the LTPP layering information were identified, examined, and reported back to the FHWA. These activities are discussed in more detail in the following sections.

Step 2 – Analysis Data Set

Master Table for the Pavement Layering Data Evaluation

To analyze pavement layering information from different sources, a master list of all pavement layers available in the LTPP database was created. The master list contains the maximum number of unique records obtained for each LTPP section, layer number, and construction event. These records were obtained from the INV_LAYER, RHB_LAYER, TST_L05B, TST_L05A, TST_AC01_LAYER, TST_PC06, and SPS*_LAYER tables.

Reference Table Selection

The initial data review indicated that table TST_L05B contains the most recent and most complete LTPP section layering information for each layer. The main attributes of the TST_L05B table are:

- Thickness data based mostly on core measurements
- Representative and most accurate layer thickness
- Most complete layer and material type description
- Highest number of layer records

A total of 96.7 percent of the unique GPS layer records (5,938 records) and 83.8 percent of all SPS layer records (9,360 records) were included in the TST_L05B table at the time of the study. As such, TST_L05B was selected as the target or reference table for the selection of analysis components and cross-table comparison of pavement layering data. Layers not included in the TST_L05B table were not used in the cross-table pavement layering data analysis. These records were examined individually for data reasonableness and identification of anomalous data.

Correspondence in Layer Numbering System between Different Sources

The review of the layer numbering scheme used in different tables indicated that layer numbering is consistent among all the tables except INV_LAYER. Thus, before the layer-related information between different tables could be compared, layers from the INV_LAYER table were aligned with the layers from the other tables.

To align the INV_LAYER records, the TST_L05B table was used as the reference. The TST_L05B table contains two fields (INV_LAYER_NO and INV_LAYER_NO2) that provide information about the corresponding inventory layers. Based on the values in these fields, several different scenarios are possible regarding layer correspondence between the INV_LAYER and TST_L05B tables. The INV_LAYER layer correspondence scenarios and consequent actions are summarized in table 5 below.

Table 5. Evaluation of layer numbering correspondence between the INV_LAYER and TST_L05B tables.

Description	Number of Records (GPS and SPS)	Action
Layer numbers are the same	2803 (72%)	Analyze
Layer numbers are different	488 (12%)	Align and analyze
2 INV_LAYER layers correspond to 1 TST_L05B layer	90 (2%)	Analyze combined thickness
Only part of INV record corresponds to TST layer	69(2%)	Exclude from cross-table analysis
INV_LAYER records exist but not referenced in TST_L05B	468 (12%)	Exclude from cross-table analysis
Total number of records in INV_LAYER	**3918 (100%), with 3381 (86%) analyzed**	

Using the scenarios outlined in table 5, 3,381 records (86 percent) with layer-related information from the INV_LAYER table were aligned with the rest of the data sources.

Data Availability for Consistency Evaluation

Based on the number of data sources available for the analysis of each pavement layer, different data availability codes were assigned to each layer:

- Code 1—layer-related data are available from the TST_LO5B table *and* one or more other tables.
- Code 2—layer-related data are *not* available in the TST_LO5B table but are available in *one or more* of the following tables: TST_L05A, TST_AC01_Layer, TST_ PC06, INV_LAYER, RHB_LAYER, or SPS*_LAYER.

Because the TST_L05B table was selected as a reference table, only records with analysis data availability code 1 were used in the cross-table pavement layering data analysis. Records that did not have a corresponding entry in TST_L05B were reviewed individually for data reasonableness. Table 6 summarizes the number of records used in the analysis for each LTPP experiment.

Table 6. Summary of the number of records used in the cross-table pavement layering analysis.

Experiment		Number of Pavement Layers Analyzed						
Type	**No.**	**TST_L05B**	**TST_L05A**	**TST_AC01_ LAYER**	**TST_ PC06_ LAYER**	**INV_ LAYER**	**RHB_ LAYER**	**SPS*_ LAYER**
G	**1**	1460	1452	526	–	961	–	–
G	**2**	972	971	366	–	648	29	–
G	**3**	516	510	13	126	455	–	–
G	**4**	247	247	1	62	223	–	–
G	**5**	342	342	22	84	292	4	–
G	**6**	1763	1725	636	–	327	877	–
G	**7**	555	553	111	44	171	249	–
G	**9**	146	145	21	48	115	12	–
S	**1**	1214	1162	420	–	–	32	1102
S	**2**	693	656	–	176	–	–	655
S	**3**	3664	3648	1065	–	–	313	–
S	**4**	496	496	–	–	–	–	–
S	**5**	1682	1664	553	–	165	665	1612
S	**6**	779	746	48	55	24	159	654
S	**7**	282	282	–	59	–	105	208
S	**8**	112	104	30	2	–	–	91
S	**9**	416	401	56	34	–	12	409
Total		**15276**	**15041**	**3856**	**690**	**3381**	**2391**	**4731**

Notes: G = GPS experiment.
S = SPS experiment.

Step 3 – Layer Functional Description Evaluation

The pavement layer functional description provides information about the functionality of a given pavement layer, such as overlay, surface, base, or subgrade. LTPP uses a list of codes to describe layer functional description, as shown in table 7.

Table 7. LTPP layer function description codes.

Code	Description
1	Overlay
2	Seal Coat
3	Original Surface Layer
4	AC Layer Below Surface (Binder Course)
5	Base Layer
6	Subbase Layer
7	Subgrade
8	Interlayer
9	Friction Course
10	Surface Treatment
11	Embankment Layer
12	Recycled Layer

In this study, the values from the layer functional description field were compared among the following tables: TST_LO5B, TST_LO5A, INV_LAYER, RHB_LAYER, TST_AC01_ LAYER, and SPS*_LAYER. The description field in the TST_L05B table served as a reference for the functional layer description information, and the description fields from the other tables were compared against it.

The procedure for layer functional description consistency evaluation is shown schematically in figure 4.

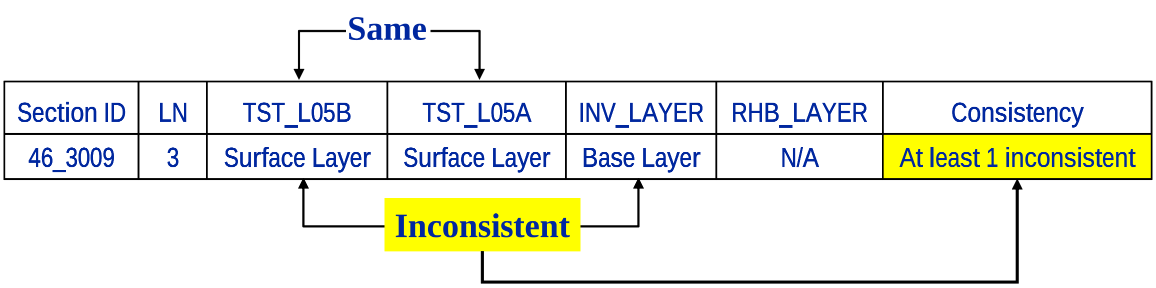


Figure 4: Graph. Example of layer functional description consistency evaluation.

The results of the layer functional description consistency evaluation are summarized in table 8 and are shown in figure 5 separately for the GPS and SPS sections.

Records with a functional layer description field that is inconsistent between different data sources were reported to the LTPP data managers in feedback reports.

Table 8. Summary of the layer functional description consistency evaluation.

Experiment		Percentage of Records with Matching Layer Functional Description				
Type	**No.**	**TST_L05A**	**TST_AC01_ LAYER**	**INV_ LAYER**	**RHB_ LAYER**	**SPS*_LAYER**
G	**1**	100.0%	92.8%	91.9%	–	–
G	**2**	99.9%	95.1%	92.3%	93.1%	–
G	**3**	100.0%	100.0%	95.8%	–	–
G	**4**	100.0%	100.0%	97.3%	–	–
G	**5**	100.0%	100.0%	97.9%	100.0%	–
G	**6**	99.8%	93.3%	91.7%	88.7%	–
G	**7**	100.0%	98.2%	94.7%	83.5%	–
G	**9**	100.0%	90.5%	90.4%	100.0%	–
S	**1**	100.0%	86.7%	–	–	68.8%
S	**2**	100.0%	–	–	–	–
S	**3**	100.0%	87.0%	–	–	79.2%
S	**4**	100.0%	–	–	–	–
S	**5**	100.0%	96.2%	–	90.9%	80.3%
S	**6**	100.0%	89.6%	–	100.0%	74.8%
S	**7**	100.0%	–	–	–	68.6%
S	**8**	100.0%	96.7%	–	–	–
S	**9**	100.0%	75.0%	–	–	16.7%

Notes: G = GPS experiment.
S = SPS experiment.

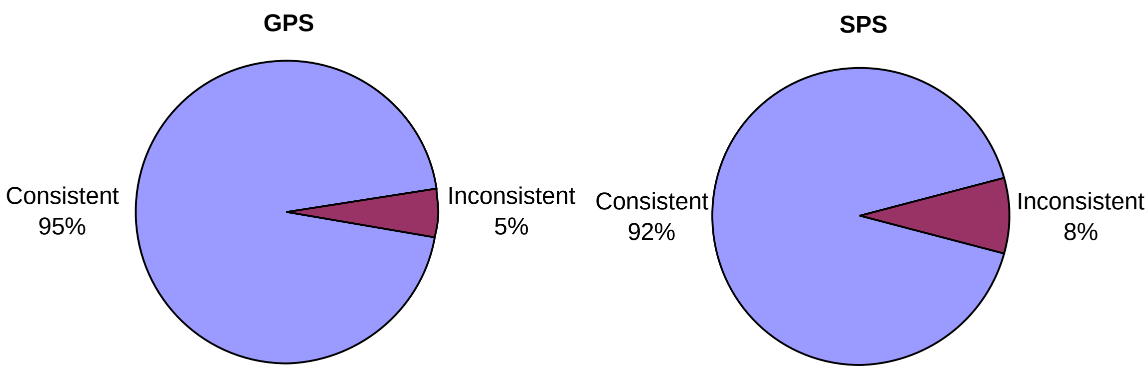


Figure 5: Chart. Results of layer functional description consistency evaluation.

Note that in figure 5, the chart slice labeled “Inconsistent” represents the layers that had at least one of the evaluated tables with data (functional description) inconsistent with the data in the TST_L05B table. Similar statement applies to all other pie charts presented in Chapter 3.

Step 4 – Material Type Reasonableness and Consistency

The material type description is very important pavement layering information. Material type description data are found in tables TST_LO5B, TST_LO5A, INV_LAYER, RHB_LAYER, and SPS*_LAYER. These data were examined to determine:

- Reasonableness or validity of the material type codes in each table.
- Consistency of the material type description from other tables with that in the TST_L05B table.
- Consistency of the material type description available in the TST_L05A table for different locations along the section.

Material Type Reasonableness

The purpose of the reasonableness check was to evaluate whether the material description code for the layer is consistent with the layer functional description. For example, soil material descriptions are not adequate for the paved surface layers. Table 9, based on the SPS Pavement Layering Methodology, Operational Guide [5], was used as a primary reference for evaluating material type reasonableness.

Table 9. Criteria for evaluation of material code validity.

Layer Description Code	Description	Valid Material Code
1	Overlay	01-08, 13, 16-20, 90[1]
2	Seal Coat	71-73, 74-85[2]
3	Original Surface Layer	01-08, 17-20
4	AC Layer Below Surface (Binder Course)	01, 03, 13, 20
5	Base Layer	302-310, 319-350, 21-49[2]
6	Subbase Layer	302-310, 319-350
7	Subgrade	100-178, 200-294, 51-65[2]
8	Interlayer	71-80, 85, 81-84[2]
9	Friction Course	02, 20
10	Surface Treatment	11, 12, 20, 82[3]
11	Embankment Layer	100-178, 200-294, 51-65[2]

Notes: [1] For SPS-7 only.
[2] Based on Appendix A of LTPP Data Collection Guide. [2]
[3] Based on reference. [27]

While most of the records had valid material codes, some records in the evaluated tables had material codes different from those specified in table 9. Table 10 provides a summary of the records with identified erroneous material codes. Additionally, some records were missing material codes. The identified records were reported to the FHWA in the data analysis/operations feedback report.

Table 10. Summary of the records with erroneous material codes.

Table Name	Number of Erroneous Records	Total Number of Records	Percentage of Records with Erroneous Codes
TST_L05B	53	15,298	0.35%
TST_L05A	49	15,189	0.32%
RHB_LAYER	99	2,841	3.48%
INV_LAYER	368	3,918	9.39%
SPS1_LAYER	1	1,021	0.10%
SPS2_LAYER	0	621	0.00%
SPS5_LAYER	18	1,056	1.70%
SPS6_LAYER	13	402	3.23%
SPS7_LAYER	8	135	5.93%
SPS8_LAYER	2	155	1.29%
SPS9_LAYER	31	475	6.53%
Total	**642**	**41,111**	**1.56%**

Material Type Consistency among Different Tables

To evaluate consistency between material types reported in different tables, LTPP material code lists were reviewed first. Two sets of material codes are used in the LTPP database to describe material types in the testing tables (TST_L05A and TST_L05B tables) and in inventory-type tables (including INV_LAYER, RHB_LAYER, and SPS*_LAYER tables) in the LTPP database. As a result, for some layers, material type descriptions in tables TST_L05B and TST_L05A do not have exact corresponding material type descriptions in tables INV_LAYER, RHB_LAYER, and SPS*_LAYER. For these layers, manual reviews of individual layer descriptions and engineering judgment are necessary to identify whether the material descriptions from different tables are consistent (or similar enough).

Correlated material codes need to be formulated to evaluate the consistency in material data from all LTPP tables containing material types. For the material type codes that do not have the exact same descriptions, "similar" material groupings were developed to correlate material codes in the inventory tables and material codes in the testing tables. The reasoning for the assignment of different material categories is summarized below for different material types.

Similar Material Type Grouping for Base and Subgrade Materials

The AASHTO classification system [28] was considered the best way to group "similar" soil or granular materials. For example, clayey materials were grouped as "clayey soils," as per the AASHTO group classification A-6 and A-7. The same criteria were applied to other typical soil types, such as gravels (A-1, A-2), silty soils (A-4, A-5), sand (A-1, A-2), clayey sand (A-2), silty gravel (A-1, A-2), and silty sand (A-2). In addition, the following criteria were applied:

- Stone and rock materials were assigned in two different categories to differentiate between rock that is entrapped and stone or cobbles that are loose unbound aggregate particles no longer intact in their original formation. [29]
- Limerock and caliche were grouped into an individual category because of their specific characteristics (i.e., used only in very specific parts of the country, such as Florida) that differentiate them from typical embedded rock.
- Soils that are treated in some manner were grouped as “stabilized subgrade soil,” and the same criteria were applied to create a group of “stabilized base materials,” which includes soil cement and aggregate mixtures. [30]
- Textiles and geo-grid products cannot be defined as materials in the common sense, but they are part of the pavement system. These materials were grouped as “geomaterials.”
- Processed aggregates such as crushed aggregates and stone should not be grouped with natural-occurring gravelly subgrade soils; therefore, a new group called “processed granular base materials” was defined.
- The “fine soil” and “unbound base/subbase” groups were combined in a new similar group denoted “subgrade soils” that includes fine, unbound/untreated soils. Although some fine-grained soils are grouped as “subgrade soils,” little information about the material properties can be conveyed by the existing definition.

Similar Material Type Grouping for Asphalt Concrete Materials

The basis for grouping “similar” asphalt concrete materials included a decision-tree process. The materials were first aligned by mixture gradation (sand, open- or dense-graded) as a first filtering step. The method of production (hot- or cold-laid) was the second criterion used to distinguish asphalt groupings. Recycled asphalt concrete, maintenance seal coats, and special plant mixes (emulsions, cutbacks) were retained in individual groupings. [27]

The table of new correlated groupings of “similar” materials and corresponding material codes from inventory and testing tables is presented in appendix A.

Material Type Consistency Criteria

To test the consistency of material type data between different tables, the TST_L05B table was used as the reference for material type description information. The material type description data from other tables were compared against it using the criteria outlined in table 11 below.

Table 11. Material type consistency criteria.

Criteria Name	Description	Evaluation Code
Consistent	Material type descriptions are the same.	0
Similar	Material types are similar based on a broad material categories developed for geological materials using the dominant material component(s).	1
Inconsistent	Material type descriptions are different.	2
Not evaluated	Material types cannot be evaluated because no material codes are available in one of the tables that make comparison pair (or if material type is available only at one location for "along the section" consistency test).	3

Figure 6 shows schematically the testing procedure used for evaluation of consistency in the material type description between different tables.

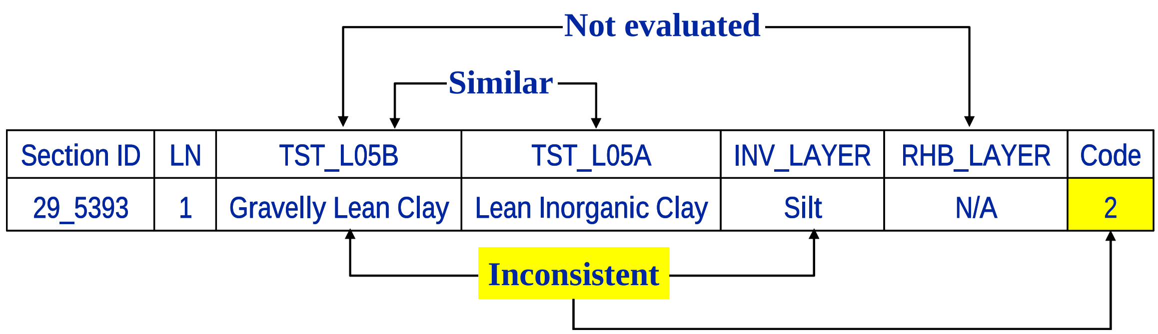


Figure 6: Graph. Example of evaluation of layer material type consistency between different tables.

The results of layer material type consistency evaluation between different data sources are summarized in table 12 and figure 7, separately for GPS and SPS sections.

Table 12. Summary of the layer material type consistency evaluation.

Experiment		Percentage of Layers with Layer Material Type Records Matching with Records in TST_L05B							
Type	No.	TST_L05A		INV_ LAYER		RHB_ LAYER		SPS*_ LAYER	
		Exact	Similar	Exact	Similar	Exact	Similar	Exact	Similar
G	1	98.9	0.6	32.6	39.4	–	–	–	–
G	2	99.0	0.7	41.0	25.8	40.0	20.0	–	–
G	3	98.2	1.0	41.1	24.5	–	–	–	–
G	4	97.6	1.6	37.6	25.3	–	–	–	–
G	5	98.8	0.6	36.6	25.3	–	–	–	–
G	6	99.6	0.2	46.4	26.9	70.3	10.3	–	–
G	7	98.1	1.1	43.8	31.4	61.4	11.4	–	–
G	9	98.6	0.7	45.2	20.9	–	–	–	–
S	1	99.9	0.0	–	–	–	–	35.9	37.4
S	2	99.6	0.0	–	–	–	–	24.0	56.5
S	3	95.6	1.5	–	–	53.0	23.2	–	–
S	4	100.0	0.0	–	–	–	–	–	–
S	5	100.0	0.0	55.2	33.3	73.1	3.4	42.4	29.8
S	6	98.9	0.5	66.7	33.3	64.9	12.2	30.7	31.3
S	7	98.6	1.4	–	–	63.1	33.8	24.0	47.1
S	8	100.0	0.0	–	–	–	–	34.1	38.5
S	9	99.5	0.0	–	–	25.0	0.0	33.0	31.1

Notes: G = GPS experiment.
S = SPS experiment.

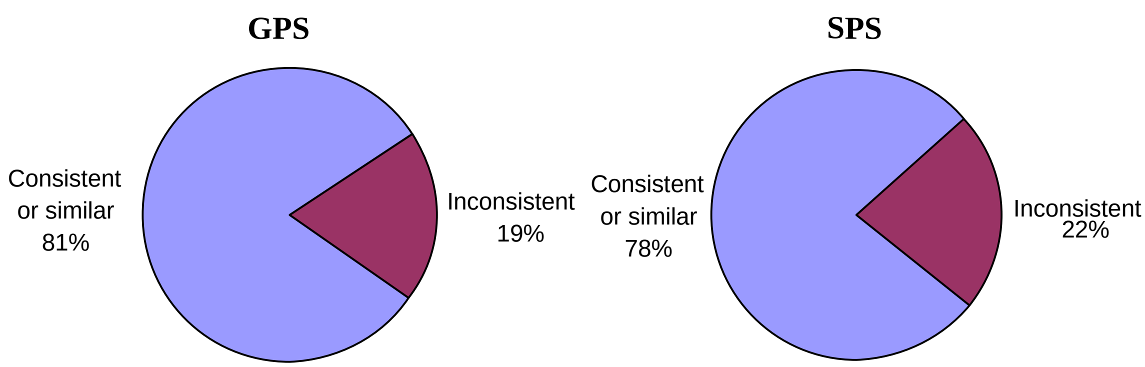


Figure 7: Chart. Results of layer material type consistency evaluation between different data sources.

Records with inconsistent material codes were identified and reported to the FHWA in the form of feedback reports.

Material Type Consistency along the Section

Table TST_LO5A contains information about layer material types evaluated at up to three locations (the beginning, the middle, and the end) along the LTPP section. In this task, the consistency of the material type along the LTPP section was evaluated using the process shown schematically in figure 8.

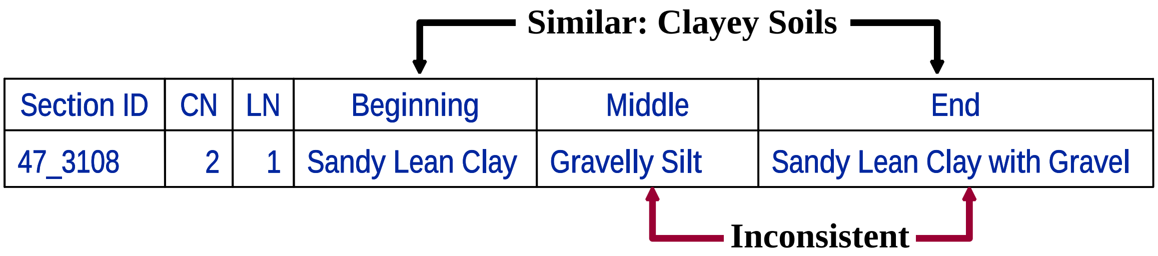


Figure 8: Graph. Example of evaluation of layer material type consistency along the section.

In the TST_L05A table, 5,795 GPS records (97 percent of all GPS records) and 2,581 SPS records (28 percent of all SPS records) had layer material type information for more than one location along the section. The evaluation results of layer material type consistency along the section are summarized for GPS and SPS sections in table 13 and figure 9.

Table 13. Summary of the layer material type consistency evaluation along the LTPP section length (TST_L05A table).

Experiment		**Percentage of TST_L05A Layers with Material Types along the Section**		
Type	**No.**	**Consistent**	**Similar**	**Inconsistent**
G	**1**	87.0	4.8	8.2
G	**2**	89.4	3.0	7.6
G	**3**	88.2	5.1	6.7
G	**4**	84.7	5.6	9.6
G	**5**	87.5	5.2	7.3
G	**6**	89.9	3.7	6.5
G	**7**	91.4	4.0	4.6
G	**9**	88.2	3.5	8.3
S	**1**	99.3	0.0	0.7
S	**2**	96.3	0.5	3.2
S	**3**	99.9	0.0	0.1
S	**4**	–	–	–
S	**5**	99.9	0.1	0.0
S	**6**	98.1	0.9	0.9
S	**7**	95.6	4.4	0.0
S	**8**	96.2	3.8	0.0
S	**9**	85.5	3.4	11.2

Notes: G = GPS experiment.
S = SPS experiment.

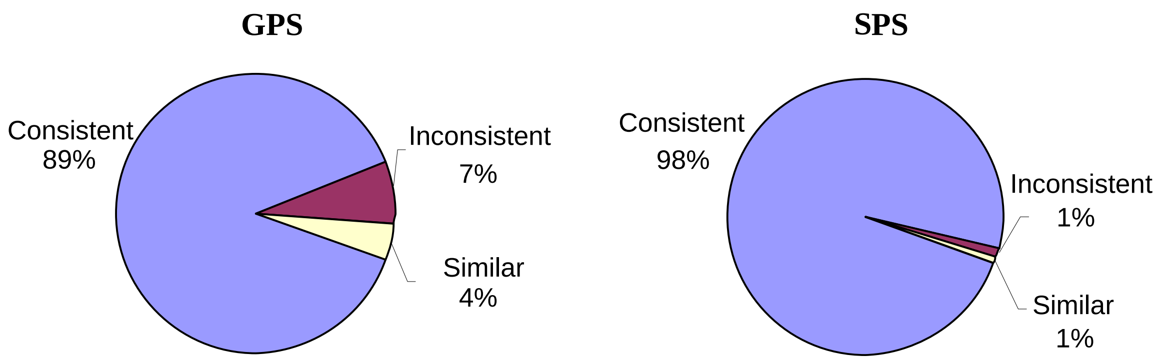


Figure 9: Chart. Results of layer material type consistency evaluation along the section.

Step 5 – Reasonableness and Consistency of Layer Thickness Data

Evaluation of the layer thickness data was one of the most important activities under this project. Layer-specific thickness data are found in the following tables: TST_LO5B, TST_LO5A, TST_AC01_LAYER, TST_PC06, INV_LAYER, and RHB_LAYER, SPS*_LAYER, and SPS*_LAYER_THICKNESS.

The layer thicknesses in the SPS*_LAYER_THICKNESS tables are reported for different locations along the section; these data are grouped by layer type (surface, base, etc.) and material type (AC, PCC, aggregate) categories, rather than using the LTPP consecutive layer numbering scheme. The SPS*_LAYER tables contain the summary information from the SPS*_LAYER_THICKNESS tables.

The TST_LO5A table contains layer thickness measurements obtained at up to three locations (the beginning, the middle, and the end) along the section. These data serve as a source for representative layer thickness values reported in the TST_LO5B table.

The TST_PC06 table contains layer thickness measurements for PCC layers obtained using individual pavement core samples. The TST_AC01_LAYER table contains layer thickness measurements for AC layers obtained using individual pavement core samples.

The layer thickness data from the above tables were analyzed to determine:

- Reasonableness of the thickness data.
- Consistency of the thickness data with the representative thickness data in table TST_L05B.

<u>Reasonableness of the Layer Thickness Data</u>

To evaluate reasonableness of layer thickness data, representative layer thickness ranges were determined for different layer types. The criteria specified in *SHRP-LTPP Interim Guide for*

Laboratory Materials Handling and Testing (PCC, Bituminous Materials, Aggregates and Soil), Operational Guide No. SHRP-LTPP-OG 004 [3] (SHRP-LTPP Lab Guide), were used to set reasonable layer thickness ranges based on the layer description codes, as shown in table 14.

Table 14. Thickness ranges used for reasonableness checks.

Layer Description Code	Description	Range (mm)	Range (inches)
1	Overlay	13 – 229	0.5 – 9
2	Seal Coat	3 – 38	0.1 – 1.5
3	Original Surface Layer	13 – 330	0.5 – 13
4	AC Layer Below Surface (Binder Course)	13 – 254	0.5 – 10
5	Base Layer	25 – 610	1 – 24
6	Subbase Layer	76 – 1217	3 – 47.9
7	Subgrade	N/A	N/A
8	Interlayer	3 – 152	0.1 – 6
9	Friction Course	3 – 64	0.1 – 2.5
10	Surface Treatment	3 – 38	0.1 – 1.5
11	Embankment Layer	76 – 1217	3 – 47.9
12	Recycled Layer	N/A	N/A

The SHRP-LTPP Lab Guide [3] does not provide guidance for the representative thicknesses of the prepared subgrade and recycled layers. Also, only a few records had subgrade thickness data in the LTPP database. Thus, thickness reasonableness was not evaluated for the subgrade and recycled layers. Layer description codes from each table were used as a reference to obtain reasonable thickness ranges for different layers listed in table 14. Based on the representative layer thickness ranges, minimum and maximum thickness values were determined for each layer type.

The TST_PC06 table does not contain a field with layer functional description. To evaluate reasonableness of representative layer thicknesses reported in this table, the layer functional description from the TST_L05B table was used for the corresponding records. Thicknesses for the layers from the TST_PC06 table that did not have matching layer numbers in the TST_L05B table were not evaluated for reasonableness.

The TST_L05A table could contain thickness measurements at different locations. Reasonableness of layer thicknesses at all locations was evaluated in the study. If at least one out of the possible three layer thickness measurement values was outside of the reasonable thickness range for a given layer type, the layer was flagged as one with unreasonable layer thickness.

Table 15 provides the layer thickness reasonableness evaluation results grouped by LTPP table name and experiment type.

Table 15. Summary of the layer thickness reasonableness evaluation results[1].

Experiment		Percentage of Layers with Reasonable1 Layer Thickness						
Type	No.	TST_L05B	TST_L05A	TST_AC01_ LAYER	TST_ PC06	INV_ LAYER	RHB_ LAYER	SPS*_ LAYER
G	1	98.3	97.3	98.8	–	98.9	–	–
G	2	98.2	96.2	99.7	–	99.5	100.0	–
G	3	98.9	96.8	100.0	98.4	98.6	–	–
G	4	100.0	97.6	100.0	100.0	99.4	–	–
G	5	99.6	98.8	100.0	100.0	99.1	–	–
G	6	95.3	93.9	99.1	–	99.1	98.4	100.0
G	7	98.1	97.5	100.0	100.0	100.0	99.3	100.0
G	9	89.1	85.3	100.0	77.1	91.6	–	–
S	1	99.8	99.8	100.0	–	–	100.0	99.7
S	2	99.4	99.4	–	100.0	–	–	99.2
S	3	98.4	98.4	99.3	–	–	97.8	–
S	4	100.0	100.0	–	–	100.0	–	–
S	5	93.2	93.0	98.7	–	98.2	99.0	92.0
S	6	99.1	100.0	100.0	100.0	100.0	97.1	100.0
S	7	100.0	100.0	–	88.1	92.3	100.0	85.2
S	8	97.5	97.5	100.0	100.0	--	–	97.4
S	9	96.7	96.3	–	100.0	100.0	55.6	96.2

Note: [1] Based on the criteria from the SHRP-LTPP Lab Guide. [3]
G = GPS experiment.
S = SPS experiment.

As a result of the layer thickness reasonableness evaluation, all thickness values outside the acceptable thickness ranges were identified and reported to the FHWA for review.

Layer Thickness Data Consistency

One of the objectives of the study was to evaluate the consistency between section-level layer thickness values available from different data sources (tables). Section-level layer thickness values could be found in the following LTPP tables: TST_LO5B, INV_LAYER, RHB_LAYER, and SPS*_LAYER.

In addition, table TST_L05A contains layer thickness values at up to three different locations along the section (beginning, middle, and end) and serves as a source of the representative layer thickness values included in the TST_L05B table. Layer thickness data from the TST_L05A table was considered consistent with the data from the TST_L05B table if at least one of the possible three thickness values in the TST_L05A table passed the consistency test. This criterion is based on the procedure for determination of the representative layer thickness, as explained in the SHRP-LTPP Lab Guide. [3]

Tables TST_AC01_LAYER and TST_PC06 contain layer thickness measurements obtained from the pavement cores taken at different locations along the section. These measurements were used to compute representative layer thicknesses for the records included in the TST_AC01_LAYER and TST_PC06 tables.

To evaluate the consistency of the layer thickness data from different sources, the criteria for allowable differences in layer thickness were developed first. The criteria were based on the layer thickness consistency values utilized in the SHRP-LTPP Lab Guide [3]. The values reported in the guide were developed for evaluating layer thickness consistency between the ends of the LTPP section (i.e., between minimum and maximum values). The comparison carried out in this study is between the representative or "average" thickness values obtained from different data tables. Based on the difference in the data statistics used in the current study compared to the analysis outlined in the operational guide ("range" versus "average" value comparison), the allowable differences used in the current study were reduced by half for the comparison of the average thickness values. The representative thickness data in table TST_L05B were used as a reference for the comparison with the representative thicknesses in the other tables.

Table 16 provides a summary of the allowable differences between representative layer thicknesses that were used in this study to evaluate layer thickness data consistency between different tables. Figure 10 schematically shows the procedure used for evaluation of consistency in layer thickness data between different tables.

Table 16. Criteria used for evaluation of layer thickness consistency between different tables.

Type of Layer Materials	**Layer Type Code from TST_L05B**	**Layer Thickness from TST_L05B (h), mm**	**Allowable Difference in Layer Thickness, mm**
PCC	PC	≤203 >203	38*½ = 19 50.8*½ = 25.4
Bituminous	AC	≤51 >51	0.5*h*½ = 0.25*h 0.3*h*½ = 0.15*h
Bound Base or Subbase	TB, TS	Any	0.3*h*½ = 0.15*h
Unbound Base or Subbase	GB, GS	Any	0.5*h*½ = 0.25*h

Section ID	CN	LN	Layer Type	Thickness			
				from TST_L05B	from RHB_LAYER	Difference	Consistency criterion
17_7937	2	2	GB	8	4	8-4=4	0.25*8=2

Unacceptable

Figure 10: Graph. Example of evaluation of layer thickness consistency between different data tables.

For thin AC layers (less than 51 mm), if the allowable difference computed using formula provided in table 16 was less than 2.5 mm (0.1 inch), the value of 2.5 mm was used as a criterion for evaluation. This decision is based on the fact that layer thickness values are recorded in the IMS database to the nearest one-tenth of an inch.

Layer thickness consistency for the subgrade or engineering fabric layers were not evaluated because no comparison criteria for these layers were established. Additionally, if layer thickness in the TST_L05B table was marked as 999.9, no comparison with the corresponding layer thicknesses from the other tables was carried out. A thickness value of "999.9" indicates that there is a considerable difference in pavement thickness values between section ends, so that no representative thickness value could be established.

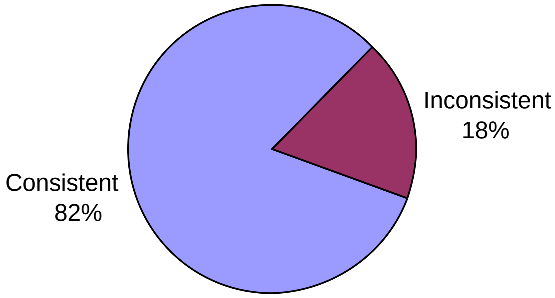
Representative layer thickness values were obtained from different data tables and compared with the representative thickness data in table TST_L05B. The outcome of the thickness data consistency evaluation is summarized in table 17 and figure 11 separately for GPS and SPS sections.

Table 17. Summary of the layer thickness consistency evaluation results[1].

Experiment		Percentage of Layers with Consistent Layer Thickness					
Type	**No.**	**TST_L05A**	**TST_AC01_ LAYER**	**TST_ PC06_ LAYER**	**INV_ LAYER**	**RHB_ LAYER**	**SPS*_ LAYER**
G	1	99.8	97.7	–	73.2	–	–
G	2	100.0	97.0	–	72.7	87.5	–
G	3	100.0	100.0	100.0	79.5	–	–
G	4	100.0	100.0	100.0	83.3	–	–
G	5	100.0	100.0	100.0	81.0	–	–
G	6	99.9	90.6	–	63.2	60.6	–
G	7	99.8	96.4	97.7	73.1	68.9	–
G	9	100.0	94.7	95.8	69.7	–	–
S	1	99.9	80.1	–	–	–	90.8
S	2	99.6	–	90.3	–	–	87.7
S	3	99.5	88.0	–	–	48.8	–
S	4	100.0	–	–	–	–	–
S	5	98.7	91.7	–	74.3	61.8	62.8
S	6	98.7	93.8	100.0	87.5	69.8	82.0
S	7	97.6	–	84.7	–	93.9	63.1
S	8	100.0	93.3	100.0	–	–	93.8
S	9	100.0	76.8	94.7	–	0.0	72.9

Notes: [1] Based on the criteria from the table 16.

G = GPS experiment.
S = SPS experiment.



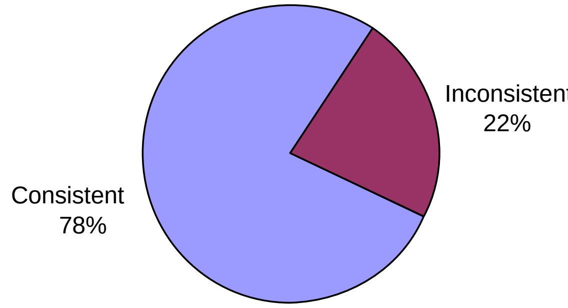


Figure 11: Chart. Results of layer thickness consistency evaluation between different data sources.

Records with layer thickness differences between the tables exceeding the values shown in table 16 were reported to FHWA.

Step 7 – Evaluation Outcome Summary and Resolution

The anomalies, suspect data, and inconsistent information found during the pavement layering data evaluation are described below, along with a discussion of possible causes of their occurrence. Corrective or remedial measures taken to address these data issues are also discussed. Identified layer thickness data issues were reported to the FHWA for data resolution in numerous LTPP Data Analysis and Operations Feedback Reports (feedback reports).

<u>1: Inconsistent Layer Descriptions</u>

A total of 1,067 records had layer functional descriptions different from the description provided in the TST_L05B table—304 records from GPS experiments and 763 from SPS experiments. A feedback report was generated and sent to the FHWA for the data in these records.

<u>2: Erroneous Material Type</u>

Data evaluation of material and layer functional description codes indicated that, in some instances, the material description codes for the layer were inconsistent with the layer functional descriptions. For example, soil material descriptions were used for the base layers. This means that either the material code or the layer functional description code is incorrect. The summary of records with invalid material codes for specified functional layer type is provided below:

- 53 layers out of 15,298 layers in the TST_L05B table.
- 49 layers out of 15,189 layers in the TST_L05A table.
- 99 layers out of 2,841 layers in the RHB_LAYER table.
- 368 out of 3,918 layers in the INV_LAYER table.
- 1 layer out of 1,021 layers in the SPS1_LAYER table.
- 0 layers out of 621 layers in the SPS2_LAYER table.

- 18 layers out of 1,056 layers in the SPS5_LAYER table.
- 13 layers out of 402 layers in the SPS6_LAYER table.
- 8 layers out of 135 layers in the SPS7_LAYER table.
- 2 layers out of 155 layers in the SPS8_LAYER table.
- 31 layers out of 475 layers in the SPS9_LAYER table.

In addition, material or functional layer description codes were missing for some records. A feedback report was generated and sent to the FHWA for the data in these records.

3: Different Material Type Coding Schemes

The review of material type data used to describe different pavement layers showed inconsistencies in the material naming conventions and material codes used in the testing tables and in inventory-type tables (including INV_LAYER, RHB_LAYER, and SPS*_LAYER). As a result, for some layers, material type descriptions in tables TST_L05B and TST_L05A do not have exact corresponding material type descriptions in tables INV_LAYER, RHB_LAYER, and SPS*_LAYER. There are no established reference criteria that could be used to determine whether material types in the above tables are similar or significantly different.

As a remedial action, a materials expert was contacted to develop a methodology for evaluation of material code compatibility. As a result, a table of correlated material codes was created to enable cross-table comparison of the material codes between inventory- and testing-type tables. The results are presented in appendix A.

4: Inconsistent Material Types

A substantial number of records from the SPS*_LAYER, INV_LAYER, and RHB_LAYER tables had material types significantly different from those specified in the TST_L05B and TST_L05A tables, as summarized below.

INV_LAYER Table:

- GPS experiments—31.5 percent (990 of the 3,147 layers with material codes) had inconsistent material types.
- SPS experiments—10 percent (19 of the 189 layers with material codes) had inconsistent material types.

RHB_LAYER Table:

- GPS experiments—22 percent (100 of the 455 layers with material codes) had inconsistent material types.
- SPS experiments—22 percent (147 of the 655 layers with material codes) had inconsistent material types.

SPS*_LAYER Tables:

- SPS-1 experiment—27 percent (294 of the 1,102 layers with material codes) had inconsistent material types.

- SPS-2 experiment—19.5 percent (128 of the 655 layers with material codes) had inconsistent material types.
- SPS-5 experiment—28 percent (449 of the 1,612 layers with material codes) had inconsistent material types.
- SPS-6 experiment—38 percent (248 of the 654 layers with material codes) had inconsistent material types.
- SPS-7 experiment—29 percent (60 of the 208 layers with material codes) had inconsistent material types.
- SPS-8 experiment—27.5 percent (25 of the 91 layers with material codes) had inconsistent material types.
- SPS-9 experiment—36 percent (147 of the 409 layers with material codes) had inconsistent material types.

Some of these inconsistencies could be explained by different material coding lists used in these tables. In some instances, it was difficult to establish material "similarity." In other cases, more than one layer with different material codes in the INV_LAYER table corresponded to a single layer in the TST_L05B table. Identified problems were reported to the FHWA in the form of feedback reports.

5: Unreasonable Thickness Values (Outside the Recommended Range)

The LTTP material testing guide provides typical thickness ranges for most layer types. [3] These values were compared with entries in the TST_L05B, TST_L05A, TST_AC01_ LAYER, TST_ PC06, INV_ LAYER, RHB_ LAYER, and SPS*_LAYER tables. Records that fall outside the recommended range are summarized below for each table.

TST_L05B Table:

- GPS experiments—2.7 percent (125 of the 4,639 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS experiments—2.2 percent (164 of the 7,399 layers with thickness data) had thickness values outside the recommended thickness range.

TST_L05A Table:

- GPS experiments—4.1 percent (192 of the 4,638 layers with thickness data) had thickness values outside the recommended thickness range (least at one location along the section.)
- SPS experiments—2.5 percent (118 of the 4,777 layers with thickness data) had thickness values outside the recommended thickness range (at least one location along the section.)

Computed Representative Values based on the TST_AC01_ LAYER Table:

- GPS experiments—0.7 percent (10 of the 1,364 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS experiments—0.8 percent (12 of the 2,903 layers with thickness data) had thickness values outside the recommended thickness range.

Computed Representative Values based on the TST_ PC06 Table:

- GPS experiments—3.6 percent (13 of the 364 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS experiments—2.3 percent (7 of the 311 layers with thickness data) had thickness values outside the recommended thickness range.

INV_LAYER Table:
- GPS experiments—1.2 percent (32 of the 2,694 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS experiments—1.5 percent (5 of the 344 layers with thickness data) had thickness values outside the recommended thickness range.

RHB_LAYER Table:
- GPS experiments—1.5 percent (7 of the 470 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS experiments—2.0 percent (15 of the 732 layers with thickness data) had thickness values outside the recommended thickness range.

SPS*_LAYER Tables:
- SPS-1 experiment—0.3 percent (3 of the 928 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS-2 experiment—0.8 percent (4 of the 532 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS-5 experiment—8.0 percent (156 of the 1,953 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS-6 experiment—0 percent (0 of the 811 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS-7 experiment—14.8 percent (32 of the 216 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS-8 experiment—2.6 percent (3 of the 114 layers with thickness data) had thickness values outside the recommended thickness range.
- SPS-9 experiment—3.8 percent (24 of the 630 layers with thickness data) had thickness values outside the recommended thickness range.

No remedial action was taken for the identified records. However, comment codes were assigned in the analysis summary table to the records containing such data. A feedback report was submitted to the FHWA for further data review. If the review of data sources would indicate that the reported thickness values are "true" data, we recommend adding a comment field to the relevant layer thickness tables explaining the reason for the unusual layer thickness.

In addition, in the RHB_LAYER table, thickness values of 0.0 are used to identify:

- Thin layers (friction course, surface treatment, seal coat) with a thickness that cannot be established.
- Removed layers.

This creates some confusion because it is unclear whether the layer is removed or whether it is too thin to establish representative thickness. In the future, it is recommended to use a minimum thickness of 3 mm (0.1 in) for thin layers instead of 0.0 to differentiate between "removed" layer and existing thin layers (with thicknesses too small to determine).

<u>6: Inconsistent Thickness Values</u>

Based on the criteria established in table 11 in this report, layer thickness values were compared with the values in the TST_L05B table. Records that had layer thickness values significantly different from those reported in TST_L05B are summarized below.

TST_L05A Table:

- GPS experiments—0.09 percent (4 of the 4,612 layers with thickness data) had thickness values significantly different from those in the TST_L05B table at all locations along the section.
- SPS experiments—0.7 percent (33 of the 4,721 layers with thickness data) had thickness values significantly different from those in the TST_L05B table at all locations along the section.

Computed Representative Values based on the TST_AC01_ LAYER Table:

- GPS experiments—5.2 percent (86 of the 1,670 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS experiments—12.7 percent (272 of the 2,144 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.

Computed Representative Values based on the TST_ PC06 Table:

- GPS experiments—0.8 percent (3 of the 364 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS experiments—8.7 percent (27 of the 311 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.

INV_LAYER Table:

- GPS experiments—26.0 percent (612 of the 2,355 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS experiments—24.4 percent (38 of the 156 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.

RHB_LAYER Table:

- GPS experiments—36.4 percent (147 of the 404 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS experiments—38.5 percent (196 of the 509 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.

SPS*_LAYER Tables:

- SPS-1 experiment—9.2 percent (79 of the 859 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.

- SPS-2 experiment—12.3 percent (61 of the 497 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS-5 experiment—37.2 percent (493 of the 1,325 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS-6 experiment—18.0 percent (88 of the 488 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS-7 experiment—36.9 percent (58 of the 157 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS-8 experiment—6.2 percent (4 of the 65 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.
- SPS-9 experiment—27.1 percent (88 of the 325 layers with thickness data) had thickness values significantly different from those in the TST_L05B table.

No remedial action was taken for the identified records. However, comment codes were assigned in the analysis summary table to the records containing such data. A feedback report was submitted to the FHWA for further data review.

7: Multiple Records in the RHB_LAYER Table

A number of layers in the RHB_LAYER table had multiple records for the same layer and construction number. Only records with the most recent "date complete" were used in the analysis. A feedback report identifying multiple records in the RHB_LAYER table was submitted to the FHWA.

8: Missing Records in the TST_L05B Table

Analysis of the data indicated that the TST_L05B table is the most complete source of layer thickness information. However, there are still 203 (3.3 percent) GPS layers and 1,813 (16.2 percent) SPS layers available in the other tables that are not included in the TST_L05B table. Layers that are available in at least one of the following tables but not available in TST_L05B Level E release 11.5 version NT3.0 were reported to the FHWA: TST_LO5A, TST_AC01_LAYER, TST_PC06, RHB_LAYER, and SPS*_LAYER.

There are 468 (12 percent) records in the INV_LAYER table that are not referenced in the TST_L05B table. These records were reported to the FHWA for data review.

Summary of Pavement Layering Data Evaluation

The results of the pavement layering data evaluation were assessed to determine the consistency of pavement layering information between different sources. In addition, within-section layer material type consistency and material type reasonableness were evaluated using selected tables where these parameters were available.

The consistency of pavement layering data between different sources was evaluated for three data categories:

- Layer functional description
- Material type description
- Representative layer thickness

In this evaluation, data pertinent to the layer functional description, layer thickness, and layer material type were obtained from multiple LTPP data tables for each pavement layer and each LTPP section. The data were reviewed to determine consistency between multiple data sources. A layer was considered to have consistent information between different data sources if all the tables containing pertinent information had the same data for this layer. The only exception to this rule was allowed for evaluation of the layer material types. If material type records from multiple data sources had a "similar" material type, as identified in table 66 of appendix A, these records were considered "consistent." This exception was used to accommodate the comparison between the values from the tables utilizing different material classification codes (i.e., material codes for testing versus material codes for inventory tables.)

If there was inconsistency in data from one or more data sources, a layer was flagged for further review. Inconsistencies in pavement layering data were reviewed and reported to the LTPP data managers in the form of data analysis/operations feedback reports, along with recommendations for data anomaly resolution.

Table 18 contains summary results for the pavement layering data consistency evaluation for each LTPP experiment.

Additionally, reasonableness (or validity) of material type description was evaluated. The purpose of the reasonableness check was to evaluate whether the material description code for the layer is consistent with the layer functional description. While most of the records had valid material codes, 642 records out of 41,111 (1.56 percent) had erroneous material codes, and some records were missing material codes. The identified records were reported to the FHWA in the data analysis/operations feedback report.

Reasonableness of layer thickness data was evaluated using representative layer thickness ranges specified in SHRP-LTPP Lab Guide [3]. As a result of the layer thickness reasonableness evaluation, thickness values outside the representative thickness ranges were identified and reported to the FHWA for the data review.

Table 18. Summary of layering data consistency evaluation for each LTPP experiment.

Experiment		Number (percentage) of Pavement Layers Analyzed					
Type	No.	Layer Functional Description		Material Type Description		Representative Layer Thickness	
		Consistent	Inconsistent	Consistent	Inconsistent	Consistent	Inconsistent
G	1	1410 (96.4%)	53 (3.6%)	1180 (81.6%)	266 (18.4%)	933 (82.1%)	203 (17.9%)
G	2	927 (95.4%)	45 (4.6%)	748 (77.8%)	214 (22.2%)	622 (81.1%)	145 (18.9%)
G	3	496 (96.7%)	17 (3.3%)	354 (69%)	159 (31%)	306 (82.5%)	65 (17.5%)
G	4	243 (98.4%)	4 (1.6%)	165 (66.8%)	82 (33.2%)	143 (85.1%)	25 (14.9%)
G	5	336 (98.2%)	6 (1.8%)	231 (67.5%)	111 (32.5%)	209 (84.3%)	39 (15.7%)
G	6	1583 (92.8%)	122 (7.2%)	1539 (91.2%)	148 (8.8%)	1160 (82.1%)	253 (17.9%)
G	7	490 (91.4%)	46 (8.6%)	452 (84.5%)	83 (15.5%)	352 (82.1%)	77 (17.9%)
G	9	129 (92.1%)	11 (7.9%)	101 (72.1%)	39 (27.9%)	84 (75%)	28 (25%)
S	1	1138 (93.7%)	76 (6.3%)	872 (74.8%)	294 (25.2%)	794 (84.3%)	148 (15.7%)
S	2	633 (91.3%)	60 (8.7%)	559 (81.1%)	130 (18.9%)	457 (85.4%)	78 (14.6%)
S	3	3549 (96.9%)	115 (3.1%)	1353 (94.9%)	73 (5.1%)	1335 (87.3%)	194 (12.7%)
S	4	496 (100%)	0 (0%)	21 (100%)	0 (0%)	14 (100%)	0 (0%)
S	5	1393 (82.8%)	289 (17.2%)	1191 (71.8%)	467 (28.2%)	819 (59.8%)	550 (40.2%)
S	6	698 (89.6%)	81 (10.4%)	488 (66%)	251 (34%)	446 (80.9%)	105 (19.1%)
S	7	233 (82.6%)	49 (17.4%)	219 (78.5%)	60 (21.5%)	144 (67.9%)	68 (32.1%)
S	8	112 (100%)	0 (0%)	87 (77.7%)	25 (22.3%)	75 (92.6%)	6 (7.4%)
S	9	323 (77.6%)	93 (22.4%)	268 (64.4%)	148 (35.6%)	232 (69.9%)	100 (30.1%)
Total		**14189 (93%)**	**1067 (7%)**	**9828 (79.4%)**	**2550 (15.6%)**	**6570 (79.1%)**	**1736 (20.9%)**

Notes: G = GPS experiment.
S = SPS experiment.

<u>Layer Material Type and Thickness Data Status Summary Table</u>

Using the outcome of the data evaluation for the four major parameters related to layer structure and layer thickness (layer functional description, material type, representative thickness, and variation in thickness measurements), the quality assurance codes indicating consistency and reasonableness of pavement layering data from different data sources were assigned to each layer. A data analysis summary table containing QA codes for major layer-related parameters evaluated for each layer was submitted to the FHWA on a CD with the final report. This table includes the following information for each LTPP section on a layer-by-layer basis:

- Layer functional type and material type codes, thickness, and thickness summary statistics indicators extracted from multiple data sources.
- Indicators of functional layer data consistency between sources.
- Indicators of layer material type reasonableness from each source data table.
- Indicators of material type data consistency between sources.
- Indicators of layer thickness data reasonableness from each source data table.
- Indicators of layer thickness data consistency between different sources.
- Within-section layer variability indicators, including excessive variability flags (where available).

- Recommended representative layer thickness for each pavement layer (for layers that satisfied data reasonableness and consistency evaluation criteria).
- List of tables where layer thickness data are available for each pavement layer.

4. EVALUATION OF PAVEMENT LAYER THICKNESS VARIABILITY

This chapter summarizes the results from the evaluation of the thickness data variability indicators based on core thickness measurements and field elevation measurements (SPS only). Typical LTPP layer thickness variability values are summarized by different layer and material types.

The chapter also presents the summary of the comparisons of layer thickness variances and means obtained based on the core and elevation thickness measurements for newly constructed SPS sections for different layer types, material types, and target thicknesses.

Thickness Data Sources

Layer thickness summary statistics such as average, minimum, maximum, standard deviation, and coefficient of variation (COV) serve as indicators of layer thickness variability along the section. For GPS sections, most of these values could be obtained from the LTPP database tables INV_LAYER and RHB_LAYER. These summary statistics were provided by the highway agencies and could be either estimated or computed. No additional information on how summary statistics were derived for these tables is available. For the SPS sections, layer thickness summary statistics could be obtained from the SPS*_LAYER tables. These values were computed from the elevation shots measurements. The SPS*_LAYER tables do not contain summary information on the number of data points used to derive the statistics. No information is available on whether all these data points were used to compute summary statistics or whether some "outlier" points were excluded.

Due to limited information on how the layer thickness summary statistic measures provided in the INV_LAYER, RHB_LAYER, and SPS*_LAYER tables were developed, it was not possible to determine whether statistical indices available in these tables were obtained using similar procedures and whether a comparable number of samples were used to derive the statistical indices. Based on this limitation, no cross-table comparison of layer thickness variability indicators available in these tables was carried out in this study.

Alternatively, layer thickness summary statistics could be computed using LTPP layer thickness data obtained from individual core measurements or from elevation measurements. The following data sources are available in the LTPP database:

- Tables TST_AC01_LAYER and TST_PC06 contain individual core thickness measurements for AC and PCC layers, respectively. The data from these tables were used to compute layer thickness summary statistics in a previous LTPP data analysis study. [31]
- The SPS*_LAYER_THICKNESS tables contain individual elevation thickness measurements along the section and reported for different layer and material type combinations.

Figure 12 shows schematically where core samples and elevation layer thickness measurements were obtained along the LTPP sections. Core data were obtained for both GPS and SPS sections, while elevation measurements were obtained only for the newly constructed SPS sections.

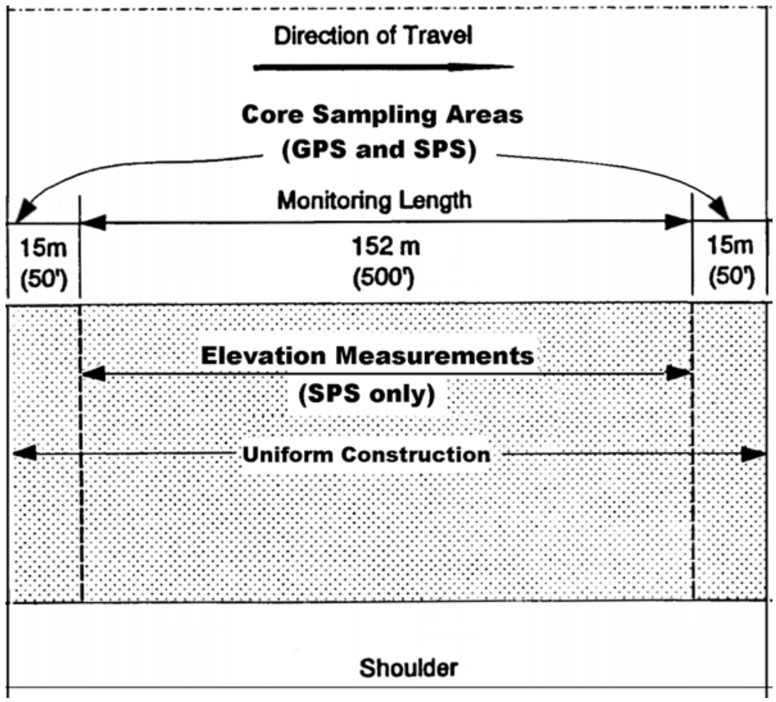


Figure 12: Graph. Location of core sampling and elevation measurement areas along the LTPP section.

Evaluation Methodology for Thickness Variability Reasonableness

Data Assessment and Exclusion of Erroneous Data Points

Two different data sources were used in the analysis of layer thickness variability reasonableness:

- Core thickness measurements for AC and PCC layers from the TST_AC01_LAYER and TST_PC06 tables.
- Elevation thickness measurements along the section from the SPS*_LAYER_THICKNESS tables.

Core elevation measurements are available for both GPS and SPS sections, while elevation measurements are available only for the SPS sections. Analysis of layer thickness variability reasonableness was carried out separately for each data source, and the results of analysis obtained from different sources then were compared.

Prior to the statistical analysis, erroneous layer thicknesses measurements were identified and excluded. Several different error sources were identified in the course of this study. Details of erroneous data evaluation are included in the discussion of analyses carried out using data from each data source.

Thickness Variability Indicators

To compare the thickness information at a layer level in lieu of individual measurement level, the following summary statistics from individual measurements were computed for each pavement layer:

- Average thickness.
- Minimum and maximum thickness.
- Standard deviation.
- COV.

COV provides a good measure of whether the dispersion of layer thickness values around the established mean thickness value is large or small. The COV is computed as a ratio between standard deviation and the mean thickness value.

$$COV = \frac{s}{\bar{x}}$$

Where:

COV = coefficient of variation of layer thickness.
s = standard deviation of layer thickness.
$\bar{x}$ = mean layer thickness.

Figure 13: Equation. Definition of coefficient of variation.

Thickness Variability Reasonableness Criteria

Criteria established under an LTPP material study [31] were adopted to evaluate the reasonableness of the thickness variability measures, as following:

- For asphalt bound layers, a COV of 20 percent was used as the cut-off value.
- For PCC surface and lean concrete base layers, a standard deviation of 8 mm was used as the cut-off value.

Evaluation of the Layer Thickness Variation Reasonableness Using Core Data

The analysis is based on evaluation of the layer thickness variation reasonableness for individual LTPP sections and individual layers within the section. Under the LTPP material study [31], the core thickness data for individual layers from the LTPP tables TST_AC01_LAYER and TST_PC06 were evaluated to exclude erroneous data points and to compute summary statistics. These summary statistics were used in this study to evaluate reasonableness of the layer thickness variability indicators for individual layers.

Prior to the analysis, LTPP sections and individual layers with computed summary statistics were correlated with data elements in the TST_L05B table describing experiment, layer, and material types.

The criteria established in the referenced study [31] were used to evaluate the reasonableness of layer thickness variability indicators for each layer that had data in either the TST_AC01_LAYER or TST_PC06 table and in the TST_L05B table. The results of the layer thickness variability evaluation are presented in table 19 for different LTPP experiments, layers, and material types.

Table 19. Summary of project-level layer thickness variability evaluation using core data.

Layer Type	Experiment	Number of Sections			Percentage of Sections with Acceptable Layer Thickness Variations
		With Data	With COV > 20 %	With SD > 8 mm	
PCC Overlay	GPS-9	24		7	70.8
	SPS-7	29		10	65.5
PCC Original Surface	GPS-3	126		22	82.5
	GPS-4	61		12	80.3
	GPS-5	84		9	89.3
	GPS-7	43		6	86.0
	GPS-9	24		5	79.2
	SPS-2	139		40	71.2
	SPS-6	50		1	98.0
	SPS-7	30		5	83.3
	SPS-8	2		0	100.0
	SPS-9	18		1	94.4
LC	SPS-2	35		7	80.0
AC Original Surface	GPS-1	229	13		94.3
	GPS-2	139	9		93.5
	GPS-6	143	21		85.3
	SPS-1	134	2		98.5
	SPS-3	252	39		84.5
	SPS-5	133	14		89.5
	SPS-8	18	0		100.0
	SPS-9	25	1		96.0

Table 19. Summary of project-level layer thickness variability evaluation using core data, continued.

Layer Type	Experiment	Number of Sections			Percentage of Sections with Acceptable Layer Thickness Variations
		With Data	With COV > 20 %	With SD > 8 mm	
AC Binder	GPS-1	147	3		98.0
	GPS-2	83	6		92.8
	GPS-3	2	0		100.0
	GPS-6	125	20		84.0
	GPS-7	41	8		80.5
	GPS-9	2	1		50.0
	SPS-1	110	8		92.7
	SPS-3	118	16		86.4
	SPS-5	150	22		85.3
	SPS-6	11	1		90.9
	SPS-8	11	0		100.0
	SPS-9	19	1		94.7
AC Overlay	GPS-6	204	25		87.7
	GPS-7	57	4		93.0
	SPS-1	6	1		83.3
	SPS-3	51	11		78.4
	SPS-5	96	6		93.8
	SPS-6	20	3		85.0
	SPS-8	7	0		100.0
ATB	GPS-1	2	0		100.0
	GPS-2	52	1		98.1
	GPS-3	7	1		85.7
	GPS-4	1	0		100.0
	GPS-5	20	1		95.0
	GPS6	8	1		87.5
	SPS-1	102	15		85.3
	SPS-3	24	3		87.5
	SPS-5	13	0		100.0
Total		**3227**	**257**	**125**	**88.2**

Core Thickness Data Availability and Assessment for Newly Constructed SPS Layers

For the newly constructed SPS layers with a documented target thickness, thickness measurements are available from both core examination and elevation measurements. Layer thickness summary statistics computed for the newly constructed SPS layers were compared to the elevation measurements data, as discussed later in this chapter.

To reflect the most recent LTPP data upload status for the newly constructed SPS layers with a specified target thickness, the core thickness data were evaluated again with erroneous data points excluded and summary statistics computed for each layer and each analysis cell. A summary of the available core thickness data for SPS experimental sections is presented in table 20.

Table 20. Core data availability in tables TST_AC01_LAYER and TST-PC06.

Layer Type	Experiment	Number of Records (measurements)	Number of Sections with Data
DGATB	SPS-1	323	78
PATB	SPS-1	142	32
	SPS-2	0	0
LC	SPS-2	182	36
PCC	SPS-2	894	140
	SPS-7	235	22
	SPS-8	16	2
SB	SPS-1	759	170
	SPS-5	455	92
	SPS-6	99	26
	SPS-8	137	18
Total		**3242**	**616**

Using the three-standard deviation criterion, one core thickness record was identified as erroneous (Section 22-0708, PCC layer) and was eliminated from the analysis at the project level. The measured core thicknesses for this layer are between 140 mm (5.5 in) and 149 mm (5.85 in), except for the excluded core measurement that was 198 mm (7.8 in).

Evaluation of the Layer Thickness Variation Reasonableness Using Elevation Data

For SPS newly constructed layers, elevation measurements were taken throughout the section of the final finished surface. The measurements normally are made at five offset points at 152-m (500-ft) spacing along the section.

This big number of elevation thickness measurements available at each layer level makes them a good candidate for thickness variability evaluation. One additional advantage of these thickness measurements is that their layer design or target thickness is known to the research team. As a result, the thickness variability values can be compared and summarized for different target values.

<u>Elevation Data Availability</u>

The availability of elevation data in SPS*_LAYER_THICKNESS tables by layer type and number of sections are presented in table 21.

Table 21. Summary of the elevation thickness measurements in the SPS*_LAYER_THICKNESS tables.

Layer Type	Experiment	Number of Records (measurements)	Number of Sections with Data
DGAB	SPS-1	5295	97
	SPS-2	4050	85
	SPS-8	1863	38
DGATB	SPS-1	5250	97
PATB	SPS-1	4496	83
	SPS-2	2242	47
LC	SPS-2	2458	48
PCC	SPS-2	6955	140
	SPS-7	918	24
	SPS-8	763	14
SB	SPS-1	9138	167
	SPS-5	4856	93
	SPS-6	1933	40
	SPS-8	1202	24
Total		**51419**	**997**

The total number of records at Level E in the SPS*_LAYER_THICKNESS tables was 51,419 at the time of the study.

Exclusion of the Erroneous Data Points

Prior to the data analysis, 78 erroneous data points were excluded before the analysis because of data inconsistency. The following list summarizes data inconsistencies found during review of the data from the SPS*_LAYER_THICKNESS tables:

- Fifty-five records for section 35-0501 are excluded from the analysis because these data were collected for the control section that was overlaid.
- A total of 10 records for sections 46-0603, 46-0604, 46-0606 and 46-0607 are excluded because of a very small number of measurements per section (two or three). In addition, core stations did not match for binder and surface layer for all cores except one. The stations of most of the cores are within the section (not in the sampling area) and the offset for all measurements is 21.95 m (72 ft).
- Section 55-0224 has only one layer thickness record available for each of the three different layer types (DGAB, PATB, and PCC). These layers were also excluded from the analysis.
- Ten records (six records for section 08-0506, two records for section 08-0505 and one record for sections 48-A808 and 08-0508 are excluded because of zero values in the thickness field).

These erroneous thickness values were reported to the FHWA for further investigation.

Additionally, data points that deviated by more than three standard deviations from the mean were considered as potentially erroneous and were excluded from the analysis data set. Analysis of sections with outliers revealed that most of these sections had one outlier per section; some had two outliers, and a few three or four outliers. In all, 202 data points were excluded from further analysis. The summary of outlier analysis is presented in the table 22. A total of 51,139 records were used in the statistical analysis.

Table 22. The distribution of the elevation thickness records not used in the analysis.

Number of Outliers per Layer	Number of Layers		Total
	With Outliers	With Other Excluded Points	
1	162	5	167
2	15	3	18
3	2	2	4
4	1		1
6		1	1
55		1	1
Total number of layers	**180**	**12**	**192**
Total number of outlier records	**202**	**78**	**280**

The number of outliers summarized by different layer types is presented in table 23.

Table 23. Distribution of the outliers by layer type.

Layer Type	Number of Records (Measurements)	Total Number of Records (Measurements)	Percent of Records (Measurements)
DGAB	46	11208	0.41
DGATB	18	5250	0.34
PATB	23	6738	0.34
LC	8	2458	0.33
PCC	35	8636	0.41
SB	72	17129	0.42
Total	**202**	**51419**	**0.39**

The highest percentage of the sections with outliers is for AC and PCC surface layers and unbound base, while the lowest percentage is for LC base, PATB, and DGATB.

Analysis of Layer Thickness Variation

Elevation measurements obtained after each layer construction were used to conduct analysis of layer variation reasonableness. Table 24 provides summary of the layer thickness variation reasonableness evaluation results for all SPS sections.

Table 24. Summary of project-level layer thickness variability evaluation using elevation grid data.

Layer Type	Experiment	Number of Sections			Percentage of Sections with Acceptable Layer Thickness Variations
		With Data	With COV > 20 %	With SD > 8 mm	
DGAB	SPS-1	97	5		94.8
	SPS-2	84	2		97.6
	SPS-8	38	3		92.1
DGATB	SPS-1	97	0		100.0
PATB	SPS-1	83	1		98.8
	SPS-2	46	0		100.0
LC	SPS-2	48		26	45.8
PCC	SPS-2	139		61	56.1
	SPS-7	24		14	41.7
	SPS-8	14		12	14.3
SB	SPS-1	167	2		98.8
	SPS-5	92	12		87.0
	SPS-6	36	0		100.0
	SPS-8	24	1		95.8

For all material types except for PCC and LC the percentage of acceptable data is very close to or above 90 percent. For PCC and LC material types this percentage is below 60.

Typical LTPP Layer Thickness Variability Values

To estimate typical values for layer thickness variability indicators, layer thickness data for SPS experimental sections were obtained from TST_AC01_LAYER and TST_PC06 tables (core thickness), and from SPS*_LAYER_THICKNESS tables (elevation thickness). The analyses were done separately for the thickness data obtained from core measurements and for the data from elevation measurements. Table 25 summarizes layer thickness COV and standard deviations by layer and material types obtained for PCC and AC layers from GPS and SPS sections based on the analysis of core thickness data. Table 26 summarizes layer thickness COV and standard deviations by layer and material types obtained for the newly constructed SPS sections based on analysis of elevation measurements. The COV and standard deviation values from the tables 25 and 26 could be used as approximate estimates of the expected layer thickness variability along the project for a given material and layer type.

Table 25. Summary of layer thickness COV and standard deviations based on core measurements.

Experiment Type	Description	Number of Analysis Layers	Mean COV, %	Min COV, %	Max COV, %	Mean St. dev., mm	Min St. dev., mm	Max St. dev., mm
GPS	AC Binder	396	10.10	0.78	83.19	7.46	0.87	110.28
	DGATB	88	6.83	1.02	46.92	8.34	1.30	61.38
	AC Surface	506	9.76	0.70	93.24	5.44	0.52	107.46
	AC Overlay	259	10.68	1.48	59.92	5.44	0.87	44.90
SPS	AC Binder	382	10.41	0.62	71.38	7.89	1.27	95.19
	ATB	139	12.66	0.85	184.88	14.79	1.47	135.97
	AC Surface	488	10.21	0.69	64.28	5.34	1.14	45.58
	AC Overlay	160	10.70	0.72	70.71	4.90	1.14	25.85
GPS	PCC	336	2.36	0.40	10.92	5.44	1.04	31.14
	PCC Overlay	24	2.92	0.55	13.10	6.22	1.04	20.74
SPS	LC	34	4.62	1.12	23.38	7.37	1.80	38.80
	PCC	233	2.66	0.51	27.97	6.31	1.14	65.21
	PCC Overlay	29	5.19	1.61	12.59	7.22	2.19	14.63

Table 26. Summary of layer thickness COV and standard deviations based on SPS elevation measurements.

Material Type	Number of Analysis Layers	Mean COV, %	Min COV, %	Max COV, %	Mean St. Dev., mm	Min St. Dev., mm	Max St. Dev., mm
DGAB	219	8.78	1.90	37.44	13.00	3.20	55.76
DGATB	97	5.31	1.79	15.10	9.50	3.87	24.48
LC	48	5.69	2.55	20.33	8.96	3.81	32.38
PATB	129	8.74	3.45	21.21	8.91	3.59	20.41
PCC	177	4.18	0.98	17.98	8.61	2.88	22.96
SB	319	8.32	2.01	35.80	8.41	2.47	21.10

Comparison between Elevation and Core Thickness Measurements

For the newly constructed SPS layers (layers that were constructed during the LTPP program and were monitored by the LTPP team), both elevation and core thickness measurements are available in the LTPP database. These two measurement methods employ different measuring techniques. The objective of this section is to evaluate if the means and the variances derived from these two methods are significantly different from each other at the project-level. Thus, the analysis is based on evaluation of statistical indicators derived for each layer of each SPS section. Only newly constructed SPS layers were used in the analysis.

Analysis Methodology

The normality of distribution of elevation data was tested and it was concluded that for a majority of sections and for all material types the distribution is normal. The detailed results are presented in chapter 5. In this analysis it was assumed that core thickness measurements have also normal distribution, because they represent different sort of the measurements for the same kind of data.

The variances and means of layer thickness data were obtained for each newly constructed layer from each SPS section from two different data sources, elevation and core thickness measurements, were compared to determine the level of agreement.

Two statistical procedures were utilized to perform the comparison of elevation and core thickness measurements:

- **Comparison of the Variances—**The F-test for inference of variances. The F-test is highly influenced by non-normality; therefore, a 99 percent confidence level was used. The null hypothesis is that variances of two populations are equal, i.e.:

$$H_O : \sigma^2_{elev.} = \sigma^2_{core} \text{ versus } H_{alt} : \sigma^2_{elev.} \neq \sigma^2_{core}$$

Figure 14: Equation. The null and alternative hypotheses for the F-test.

- **Comparison of the Means—**t-test (95 percent confidence level) for inference of means, assuming equal or unequal variance, based on results of the F-test. The null hypothesis is that means of two population are equal, i.e.:

$$H_O : \mu_{elev.average} - \mu_{core.average} = 0 \text{ versus } H_{alt} : \mu_{elev.average} - \mu_{core.average} \neq 0$$

Figure 15: Equation. The null and alternative hypotheses for the t-test.

Analysis Data Set

Elevation data for bound asphalt and concrete layers were available for 770 individual layers, while core data were available for only 616 layers. However, both elevation and core thickness data were available for only 498 asphalt and concrete layers. For 118 layers, only core data were available and for 272 layers only elevation data were available. Additionally, for 15 layers only one core measurement per layer was available. Therefore, the total number of asphalt and concrete layers used in the analysis was 483. Table 27 presents the summary of data availability.

Table 27. Summary of layers with both elevation and core data available.

Layer Type	Experiment	Number of Layers with both Elevation and Core Data
DGATB	SPS-1	59
PATB	SPS-1	30
	SPS-2	-
LC	SPS-2	31
PCC	SPS-2	123
	SPS-7	15
	SPS-8	2
SB	SPS-1	134
	SPS-5	60
	SPS-6	15
	SPS-8	14
Total		**483**

Comparison of the Standard Deviation and COV Values

Figure 16 provides a comparison of the standard deviations computed from core thickness measurements versus standard deviations computed from elevation thickness for all the layers. For the standard deviation values below 10 mm, the standard deviations computed from the core thickness data are lower than the standard deviations computed from the elevation measurements in most cases. However, for standard deviations above 10 mm, the standard deviations from the core data are higher than the standard deviations computed from the elevation measurements for a significant number of cases. For the majority of the elevation data, the standard deviation is below 20 mm.

Overall, 321 layers (66.5 percent) had a standard deviation computed from the elevation measurements higher than the standard deviation computed from the core measurements. Figure 16 indicates that, for a few sections, the variation of core thickness was very high as compared to the elevation-determined thickness. However, the differences between the standard deviations were not statistically significant (99 percent confidence level) for a large majority of the sections.

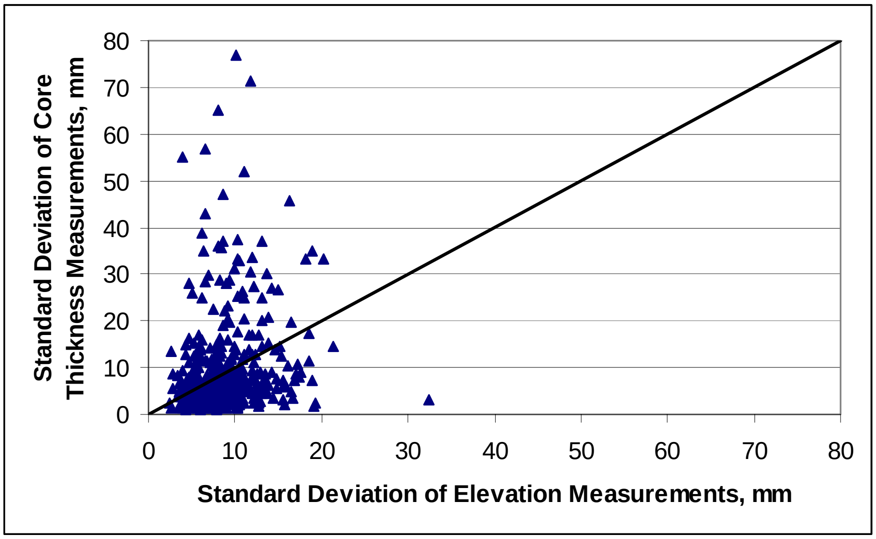


Figure 16: Chart. Comparison of the standard deviation for core thickness and elevation measurements.

Figure 17 provides a comparison between the COV values computed from the elevation and core thickness data sets. Over 80 percent of the COV values computed using each data set are below 10 percent. However, a small percentage of sections show low COV computed from one data source and high COV computed using the other data source, i.e. high COVs for elevation measurements and low COVs for core thickness measurements for the same section, or vice versa.

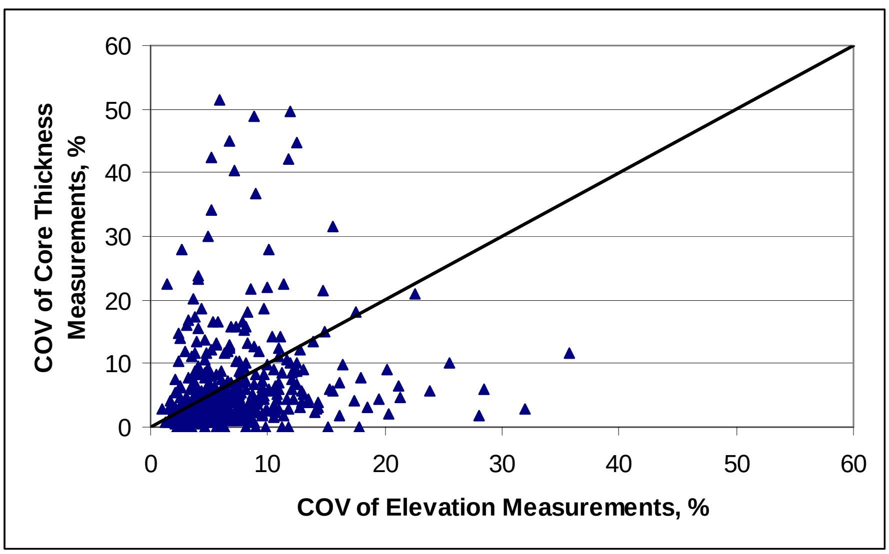


Figure 17: Chart. Comparison of the COV for core thickness and elevation measurements.

Comparison of the Variances

Table 28 presents the results of the comparison of variances. Sections were grouped by material type, experiment number, target thickness, and subbase type. For more than 80 percent of the sections, the differences between variances obtained from elevation and core thickness measurements were not statistically significant (99 percent confidence level). This percentage is even higher for DGATB and LC layers (about 90 percent).

The greatest differences of variance values were observed for PATB and some analysis cells with PCC and SB layers, and the lowest differences were observed for DGATB and LC layers.

Table 28. Comparison of variances (F-test, 99 percent confidence level) obtained from elevation and core thickness measurements.

Material Type	EXP.	Target Thickness		Subbase	Variance				Total Number of Sections
					Equal		Unequal		
		mm	in		Number of Sections	Percent of Sections	Number of Sections	Percent of Section	
DGATB	SPS-1	102	4		12	80.0	3	20.0	15
		203	8		25	92.6	2	7.4	27
		305	12		16	94.1	1	5.9	17
PATB	SPS-1	102	4		22	73.3	8	26.7	30
LC	SPS-2	152	6		28	90.3	3	9.7	31
PCC	SPS-2	203	8	S[1]	17	77.3	5	22.7	22
				W[2]	35	89.7	4	10.3	39
		279	11	S	15	68.2	7	31.8	22
				W	35	87.5	5	12.5	40
	SPS-7	76	3	S	6	85.7	1	14.3	7
		127	5	S	4	50.0	4	50.0	8
	SPS-8	203	8	W	1	100.0	0	0.0	1
		279	11	W	1	100.0	0	0.0	1
SB	SPS-1	102	4	S	33	82.5	7	17.5	40
				W	25	86.2	4	13.8	29
		178	7	S	32	86.5	5	13.5	37
				W	20	71.4	8	28.6	28
	SPS-5	51	2	S	24	85.7	4	14.3	28
		127	5	S	23	71.9	9	38.1	32
	SPS-6	102	4	S	12	100.0	0	0.0	12
		203	8	S	1	33.3	2	66.7	3
	SPS-8	102	4	W	5	71.4	2	28.6	7
		178	7	W	5	71.4	2	28.6	7
Total					**397**	**82.2**	**86**	**17.8**	**483**

Notes: S – "Strong" subbase (DGATB, LC).
W – "Weak" subbase (DGAB, PATB).

Comparison of the Means

The mean layer thicknesses computed from elevations and those computed from core samples were compared using the t-test at a 95 percent confidence level and assuming either equal or unequal variances, based on the F-test results, presented in table 28. The results of the t-tests are presented in table 29.

Table 29. Results of the comparison of means (t-test, 95 % confidence level) for elevation and core thickness measurements.

Material Type	**Exp.**	**Target Thicknesses**		**Subbase**	**No Significant Difference between Elevation and Core Thickness**		**Significant Difference between Elevation and Core Thickness**		**Total Number of Sections**
		mm	in		Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGATB	SPS-1	102	4		9	60.0	6	40.0	15
	SPS-1	203	8		20	74.1	7	25.9	27
	SPS-1	305	12		8	47.1	9	52.9	17
LC	SPS-2	152	6		20	64.5	11	35.5	31
PATB	SPS-1	102	4		12	40.0	18	60.0	30
PCC	SPS-2	203	8	S	14	63.6	8	36.4	22
	SPS-2			W	16	41.0	23	59.0	39
	SPS-2	279	11	S	10	45.5	12	54.5	22
	SPS-2			W	16	40.0	24	60.0	40
	SPS-7	76	3	S	3	42.9	4	57.1	7
	SPS-7	127	5	S	5	62.5	3	37.5	8
	SPS-8	203	8	W	0	0.0	1	100.0	1
	SPS-8	279	11	W	1	100.0	0	0.0	1
SB	SPS-1	102	4	S	19	47.5	21	52.5	40
	SPS-1			W	10	34.5	19	65.5	29
	SPS-1	178	7	S	11	29.7	26	70.3	37
	SPS-1			W	13	46.4	15	53.6	28
	SPS-5	51	2	S	10	35.7	18	64.3	28
	SPS-5	127	5	S	12	37.5	20	62.5	32
	SPS-6	102	4	S	9	75.0	3	25.0	12
	SPS-6	203	8	S	2	66.7	1	33.3	3
	SPS-8	102	4	W	3	42.9	4	57.1	7
	SPS-8	178	7	W	4	57.1	3	42.9	7
Total					**227**	**47.0**	**256**	**53.0**	**483**

Notes: S – "Strong" subbase (DGATB, LC).
W – "Weak" subbase (DGAB, PATB).

Based on the t-test results, the mean thicknesses computed from the core measurements are not different from those computed from the elevation measurements at a 95 percent confidence level for 227 (47 percent) of all layers analyzed. The opposite is true for the remaining 256 layers analyzed (53 percent).

Figure 18 presents aggregated results of the statistical analysis of the differences between elevation and core thickness measurements. More than 60 percent of the layers with DGATB and LC had no significant difference between elevation and core thickness data. This percentage is about 40 for PATB, PCC, and SB layers.

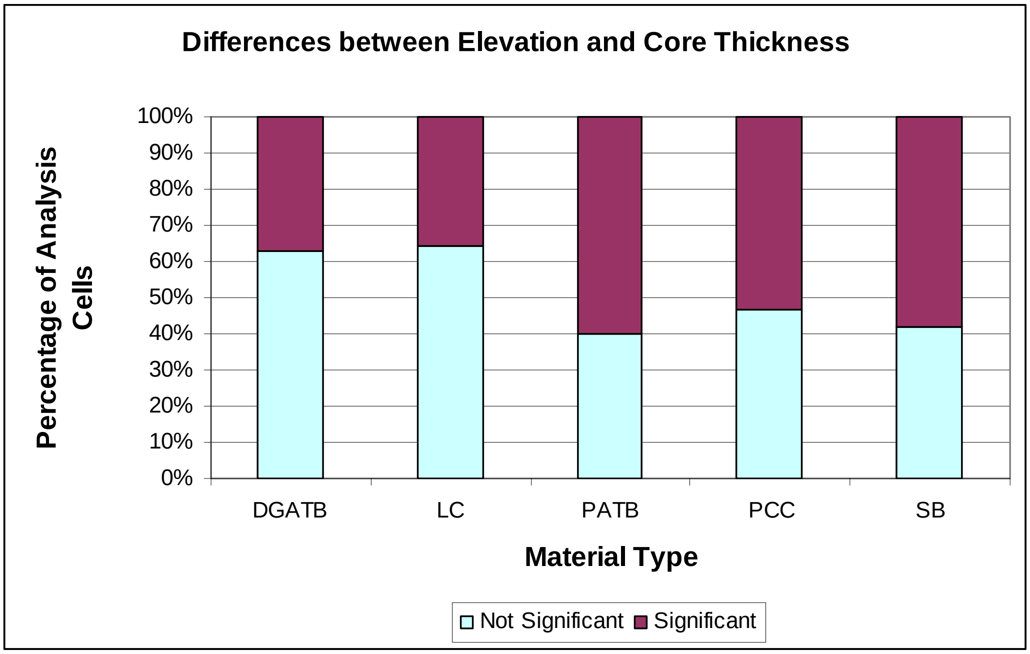


Figure 18: Chart. Results of the statistical analysis of differences between elevation and core thickness measurements.

Summary

In this chapter, the layer thickness variability indicators available in the LTPP database were reviewed. A discussion about the limitations of the available data was provided. In addition, new layer thickness variability indicators (mean, range, standard deviation, COV, and variance) were developed based on the core thickness measurements and field elevation measurements (SPS only) from the most recent LTPP database upload (release 11.5 version NT3.0, obtained on June 8, 2001).

Evaluation of Layer Thickness Variability Reasonableness

Using layer thickness summary statistics, reasonableness of the layer thickness variability data was evaluated. The purpose of the analysis was to compare layer thickness variation for each section and each layer with the benchmark layer thickness variability values. The analysis results indicated that over 88 percent of layers have layer thickness variability indicators below the benchmark values.

Additionally, typical values and ranges of layer thickness variability indicators for different layer and material types were computed. These typical values could serve as approximate estimates of the expected layer thickness variability for the project-level analysis and design.

Excessive Variability in Layer Thickness

For the layer thickness data obtained from the core measurements, 257 layers (10.0 percent) from the TST_AC01_LAYER table and 125 layers (18.8 percent) from the TST_PC06 table had excessive variability in the layer thickness data even after outliers were removed.

For the layer thickness data obtained from the elevation measurements, 139 layers (14.1 percent) from the SPS*_LAYER tables had excessive variability in the layer thickness data even after outliers were removed.

No remedial action was taken for the identified records. However, comment codes were assigned in the analysis summary table to the records containing such data. To determine the reasons for excessive variability, individual core samples should be reviewed.

Comparison of Layer Thickness Variability Indicators from Different Data Sources

Statistical comparisons were made between the layer thickness variances and means obtained from the core and elevation thickness measurements. Only data for newly constructed SPS sections were utilized. The results of the analysis are as follows:

- Overall, 321 layers (66.5 percent) had a standard deviation computed from the elevation measurements higher than the standard deviation computed from the core measurements. However, for 25 layers (5.2 percent) that had very high standard deviations (above 30 mm), the opposite trend was observed.
- The differences between the standard deviations were not statistically significant (99 percent confidence level) for most of the sections.
- Over 80 percent of the COV values computed using each data set are below 10 percent.
- A small percentage of sections show low COV computed from one data source and high COV computed using the other data source. This observation applies to both elevation and core thickness data sets.
- For more than 80 percent of layers, the variances between core and elevation measurements at a 99 percent confidence level could be assumed “equal.” This percentage is even higher for DGATB and LC layers (about 90 percent).
- The mean thicknesses computed from the core measurements are not different from those computed from the elevation measurements at a 95 percent confidence level for 227 (47 percent) analysis cells. The opposite is true for the remaining 256 analysis cells (53 percent).
- More than 60 percent of the sections with DGATB and LC had no significant difference (95 percent confidence level) between elevation and core thickness data. This percentage is about 40 for PATB, PCC, and SB layers.

5. CHARACTERIZATION OF LTPP THICKNESS WITHIN-SECTION VARIABILITY

This chapter contains the results of an evaluation of within-section variation in layer thickness values. Characteristics of within-section layer thickness variability are very important inputs in reliability-based pavement engineering applications. This chapter contains the discussion of data sources used for the analysis of within-section variation in layer thickness values, the methodology used to assess characteristics of within-section layer thickness distribution, testing procedures used to evaluate goodness-of-fit between theoretical models and observed layer thickness data, and the results of the within-section layer thickness variability evaluation.

Data Sources

Data from the elevation measurements were used to evaluate the extent of within-section variation in layer thicknesses. Elevation measurements for each pavement layer were taken along the LTPP section length during the construction phase of the SPS experiments. These data are available in the SPS*_LAYER_THICKNESS tables. Unlike other LTPP layer thickness tables, the data in the SPS*_LAYER_THICKNESS tables are stored not by the layer number but by layer and material type identifiers. Table 30 provides an overview of which identifiers are available in the SPS*_LAYER_THICKNESS tables.

Table 30. Pavement layer and material type identifiers available in the SPS*_LAYER_THICKNESS tables.

Layer and Material Type	LTPP Field Name (layer identifier)	LTPP Table Name
AC surface course	SURFACE_COURSE	SPS5_LAYER_THICKNESS, SPS6_LAYER_THICKNESS
AC binder course	BINDER_COURSE	SPS5_LAYER_THICKNESS, SPS6_LAYER_THICKNESS
AC surface and binder course	SURFACE_AND_BINDER	SPS1_LAYER_THICKNESS
	ASPH_SURFACE_AND_BINDER	SPS8_LAYER_THICKNESS
AC surface friction course	SURFACE_FRICTION	SPS1_LAYER_THICKNESS, SPS5_LAYER_THICKNESS, SPS6_LAYER_THICKNESS, SPS8_LAYER_THICKNESS
DGAB	DENSE_GRADE_AGG_BASE	SPS1_LAYER_THICKNESS, SPS2_LAYER_THICKNESS, SPS8_LAYER_THICKNESS
DGATB	DENSE_GRD_ASPH_TREAT_BASE	SPS1_LAYER_THICKNESS
PATB	PERM_ASPH_TREAT_BASE	SPS1_LAYER_THICKNESS, SPS2_LAYER_THICKNESS
LC base	LEAN_CONCRETE	SPS2_LAYER_THICKNESS
PCC surface layer	PCC_SURFACE	SPS2_LAYER_THICKNESS
	PORT_CEMENT_CONCRETE_SURFACE	SPS8_LAYER_THICKNESS
PCC overlay layer	SURFACE_COURSE	SPS7_LAYER_THICKNESS
Rut level-up layer	RUT_LEVEL_UP	SPS5_LAYER_THICKNESS, SPS6_LAYER_THICKNESS
Mill replacement layer	MILL_REPLACE	SPS5_LAYER_THICKNESS, SPS6_LAYER_THICKNESS

SPS Layer Thickness Characteristics

Design Thickness

For a particular SPS experiment, several design thickness values were used as a target design layer thickness. For a given SPS section, only one design thickness value was used along the section length. The design thicknesses for different layers were reviewed for each SPS experiment. Table 31 provides an overview of the material and layer types used in different SPS experiments, the design thicknesses, and the number of layers with the along-the-section thickness measurements available in the LTPP database, Level E version released on June 29, 2001.

Descriptive Layer Thickness Statistics

Using layer thickness measurements along the section, an exploratory data analysis was conducted, and descriptive statistical measures such as mean, standard deviation, kurtosis, skewness, and number of thickness measurements per layer were computed for each structural layer (surface and base courses) that had layer thickness information available in the SPS*_LAYER_THICKNESS tables. These descriptive statistics were then used to evaluate characteristics of layer thickness distribution along the LTPP section.

The following description of the statistical variables provides background information to facilitate the understanding of the procedures used to evaluate within-project layer thickness variability.

The mean is a property of the distribution that describes the location of the distribution. The mean layer thickness is computed as the average of the individual thicknesses obtained from elevation measurements taken along the LTPP section.

The standard deviation is a property of the distribution that describes the spread of the distribution. The standard deviation is based on the second moment of the measurement distribution.

The skewness is a property of the distribution that is used to evaluate how skew the distribution is. The skewness is 0 for a symmetric distribution, positive if the distribution has a long tail to the right, and negative if the distribution has a long tail to the left. The skewness is based on the third moment of the measurement distribution.

The kurtosis is another property of the distribution that provides a mean to evaluate how heavy (or light) the tails of the distribution are. For a normal distribution, the kurtosis is 0. For a distribution with long or fat tails, the kurtosis is positive. For a distribution with short or slim tails, relative to a normal distribution, the kurtosis is negative (but always > -3). The adjusted fourth moment of the measurement distribution is one way to measure the kurtosis of the distribution.

Table 31. Design thicknesses for different SPS experiments sorted by layer and material type.

Layer and Material Type	Experiment Type	Design Layer Thickness, mm (in)	Total Number of Layers used in the Analysis
AC surface course	SPS-5	0	93
		51 (2)	
		127 (5)	
	SPS-6	0	40
		102 (4)	
		203 (8)	
AC surface and binder course	SPS-1	102 (4)	167
		178 (7)	
	SPS-8	102 (4)	24
		178 (7)	
AC binder course	SPS-5	Varies	33
	SPS-6	Varies	17
DGAB	SPS-1	102 (4)	97
		203 (8)	
		305 (12)	
	SPS-2	102 (4)	85
		152 (6)	
	SPS-8	152 (6)	38
		203 (8)	
		305 (12)	
DGATB	SPS-1	102 (4)	97
		203 (8)	
		305 (12)	
PATB	SPS-1	102 (4)	83
	SPS-2	102 (4)	47
LC base	SPS-2	152 (6)	48
PCC surface layer	SPS-2	203 (8)	140
		279 (11)	
	SPS-8	203 (8)	14
		279 (11)	
PCC overlay layer	SPS-7	76 (3)	24
		127 (5)	

The skewness and kurtosis are two main properties of a distribution that together describe the shape of the distribution, while the mean describes the location and the standard deviation the spread of the distribution. These statistical measures were used then to determine the extent to which the variation of layer thickness along the section follows normal distribution.

Identification of Suspect Layer Thickness Data

Before the analysis of the within-section layer thickness variability, layer thickness data were reviewed to identify any anomalous thickness measurements along the section. The purpose was to identify outliers – the data points that appear not to belong with the rest of the data. Figure 19 shows an obvious example.

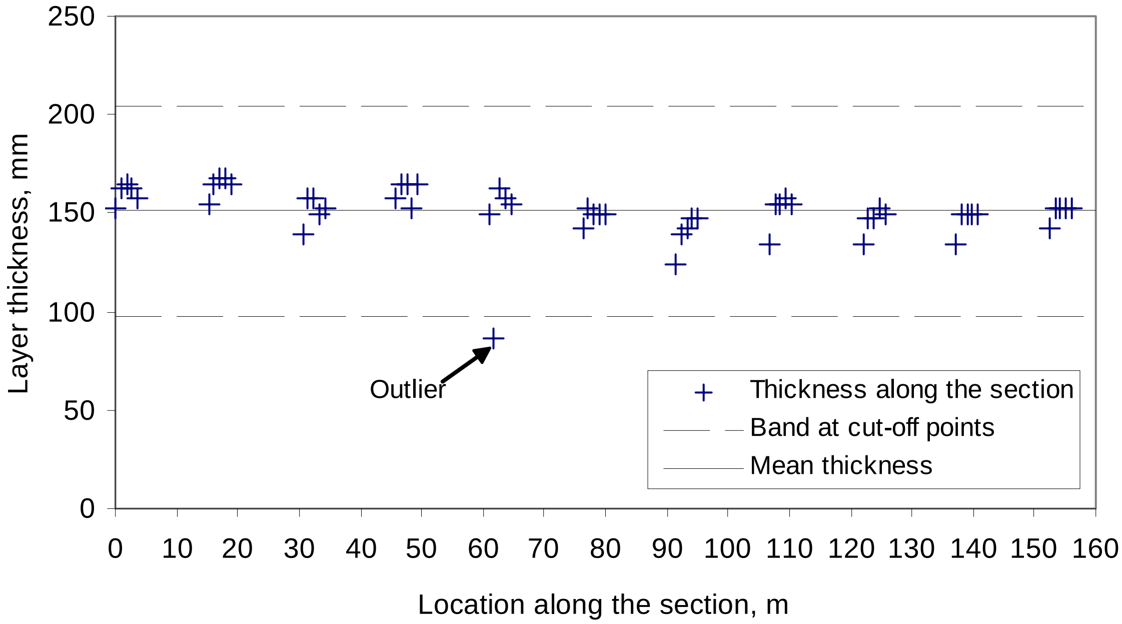


Figure 19: Chart. Example of the binder course thickness measurements along SPS-6 Section 40_0608 with an apparent outlier.

Methodology to Identify Outliers

Because outliers can have a strong influence on both the skewness and kurtosis calculated for a data sample, the presence of a few outliers in a sample from a normal distribution may cause the sample to fail a normality test. Therefore, it is important to determine whether the apparent non-normality might be due to the presence of outliers. A data point was considered an outlier and removed from the analysis if the following is true:

- The absolute difference between an individual layer thickness measurement and the mean layer thickness, standardized (divided by) by the standard deviation, is greater than the 99.995 percentile (0.001 percent level of significance, two-sided test) of the t-distribution with n-1 degrees of freedom (df), where n is the number of data points in the sample.

The criterion is shown in equation format in figure 20.

$$\frac{|x_i - \bar{x}|}{s} > t_{0.00005\ (n-1)}$$

Where:

x_i	= individual layer thickness measurement along the section
$\bar{x}$	= mean layer thickness
s	= standard deviation of layer thickness
$t_{0.00005\ (n-1)}$	= the 99.995 percentile of the t distribution with df=n-1, where
n	= number of layer thickness measurements for the layer

Figure 20: Equation. Outlier definition criterion.

The t-values at the 99.995 percentile correspond to a level of significance of 0.01 percent for the two-sided t-test. The choice of a significance level of 0.01 percent is very conservative and was based on the fact that only "true" outliers (i.e., those that clearly do not belong in the same population with the other data points) should be excluded. If the distribution in reality is skewed, it is not desirable to cut out values based on a higher significance level, since the cut-off points are based on the (symmetric) normal distribution.

Note that the commonly used criterion (mean +/- 2 standard deviations) for identification of outliers was not used in this study. That criterion is based on a 5 percent significance level and the assumption that the distribution of the sample is normal. Because the standard deviation for LTPP sections is not known but estimated, the assumption of normality leads to the use of the t-distribution to create the 95 percent confidence interval. Based on the sample size, the t-distribution will provide a different number that the standard deviation is multiplied by to determine the cut-off points for outliers, as the examples in table 32 show.

Table 32. Multiplier for the standard deviation used in the outlier criterion based on t-distribution.

Sample Size	Degrees of Freedom	Multiplier for the Standard Deviation
11	10	2.23
21	20	2.09
29	28	2.045
121	120	1.98
∞	∞	1.96

The following example using data from SPS-6 Section 40_0608 demonstrates the methodology and rationale used to determine the outlier points. The descriptive statistics for the binder course layer used in this example are provided in table 33. A scatter plot of all the thickness measurements is shown in figure 19.

Table 33. Descriptive statistics for the binder course layer, SPS-6 section 40_0608.

Section ID	Layer Type	Number of Layer Thickness Measurements	Mean Layer Thickness, mm (in)	Standard Deviation of Layer Thickness, mm (in)
40_0608	binder course	55	151 (5.951)	13 (0.501)

The data point identified as "Outlier" in figure 19 was evaluated to identify whether this point is a true outlier. The layer thickness value for this point is 86 mm (3.4 in), while the mean value for the sample is 151 mm (5.951 in). Using the criterion shown in figure 20, for the left side of the expression, we obtain the t-statistic value of 5.1. For the right side of the expression, the t-value of 4.2 was obtained at the 99.995 percentile of the t distribution with 54 (df = 55-1) degrees of freedom. Since the t-statistic of 5.1 is greater than the t-value of 4.2, this point was found to be an outlier using a cut-off point based on the t-distribution at a significance level of 0.01 percent with n-1degrees of freedom.

For the data in figure 19, the outlier point at 86 mm (3.4 in) could have been as large as 97 mm (3.8 in) and still would have been removed. In this particular data set, it may be desirable to remove points even greater than 97 mm (3.8 in) because the data otherwise do not appear skewed. However, in the data sets where some skewness is present, removal of the data points on the outskirts of the distribution could bias the reliability of the distribution evaluation results. The following example is used to demonstrate this concern.

Three different layer thickness frequency distributions are presented in figures 21, 22, and 23. The distribution in figure 21 shows an example of the clear outlier point on the left side of the distribution. Here the layer thickness value of the outlying point is <20 mm, while layer thicknesses for the rest of the points range from 82 to 142 mm. However, for the figures 22 and 23, the question whether the leftmost point is an outlier, cannot be answered with the same degree of certainty. The leftmost point in the distribution provided in figure 22 is a questionable outlier. Here the layer thickness value of the outlying point is about 75 percent of the average of the layer thickness values of the other points. The leftmost point in the distribution provided in figure 23 may be a legitimate point of a skewed distribution. Here the layer thickness value of the outlying point is about 80 percent of the average of the layer thickness values of the other points. However, even at the very conservative level chosen, the outlying point in figure 22 was identified as an outlier while the outlying point in figure 23 was not. This example illustrates why it was necessary to set the level for declaring a point an outlier very conservatively (in order to not bias the analysis of distribution type) in this study.

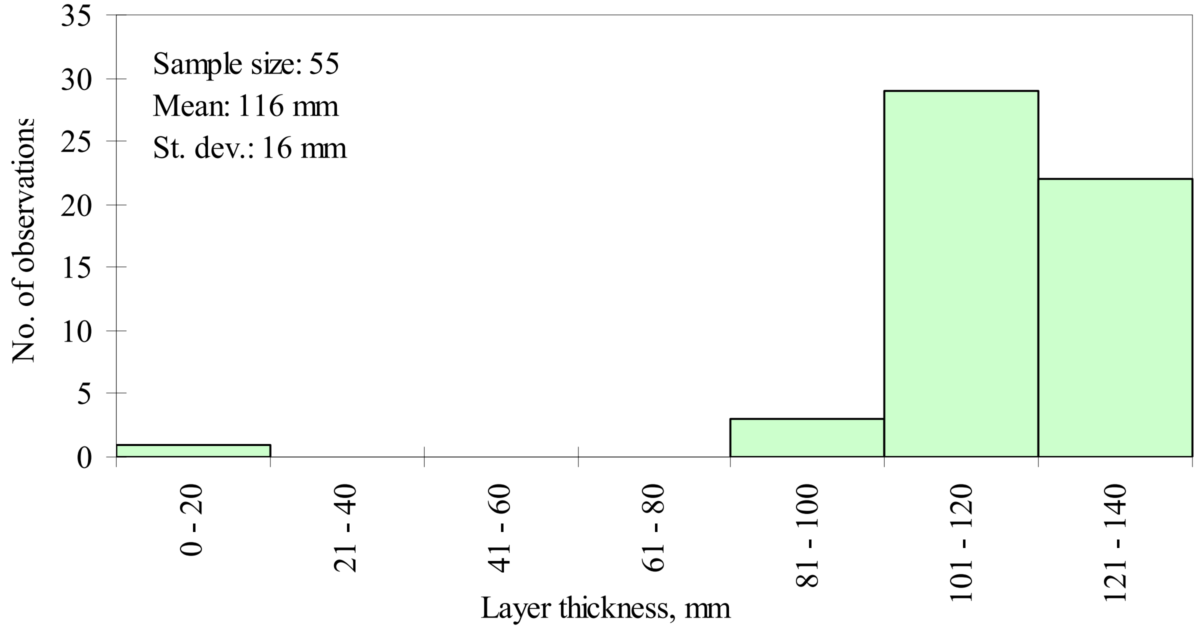


Figure 21: Chart. Example of the AC surface and binder layer thickness distribution with clear outlier detection for the SPS-1 Section 30-0122.

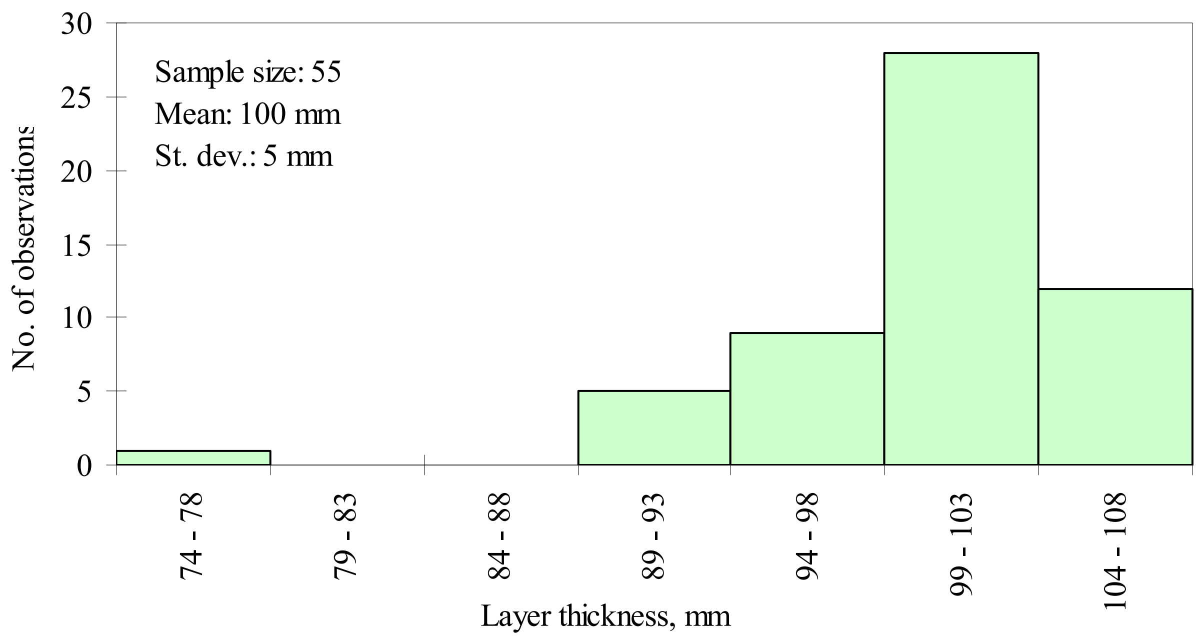


Figure 22: Chart. Example of dense graded aggregate base layer thickness distribution with questionable outlier detection for the SPS-2 Section 20-0210.

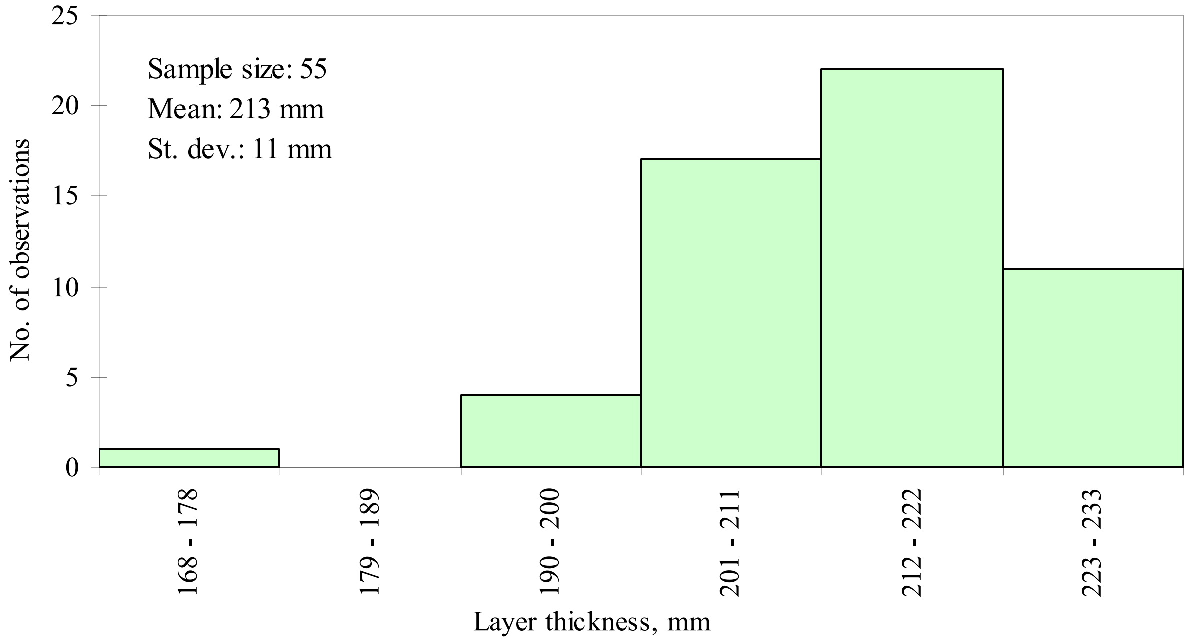


Figure 23: Chart. Example of the dense graded aggregate base layer thickness distribution skewed to the left for the SPS-1 Section 20-0101.

This procedure for identification of the outliers was applied to each SPS structural layer with data available in the SPS*_LAYER_THICKNESS tables. In the whole data set of more than 55,000 data points, only 20 data points were excluded based on this criterion; the list of these excluded points is presented in table 34. These individual layer thicknesses were analyzed using special data distribution plots. The results show that these thickness values are likely to be errors in the database rather than actual thickness measurements. However, the review of the actual field data is required to confirm this conclusion. All anomalous or suspect data thickness values were reported back to the LTPP administrators for data review and possible correction of the thickness values in the LTPP layer thickness data tables.

Table 34. Identified outlier points.

Exp. Type	STATE _CODE	SHRP _ID	Type	Measured Thickness (outlier), mm	Mean Thickness (with outliers), mm	St. dev. (with outliers), mm	Number of Measure ments	Standar dized Difference	t-value at 95.995 percent
SPS-6	40	0608	BC	86	151	13	55	5.09	4.20
SPS-1	12	0102	DGAB	208	307	15	55	6.69	4.20
SPS-1	30	0113	DGAB	102	210	24	55	4.55	4.20
SPS-2	20	0210	DGAB	76	100	5	55	4.41	4.20
SPS-1	5	0122	DGATB	25	97	12	55	6.03	4.20
SPS-1	32	0105	DGATB	150	123	5	55	5.03	4.20
SPS-1	35	0104	DGATB	193	297	25	55	4.23	4.20
SPS-1	40	0116	DGATB	71	304	35	55	6.63	4.20
SPS-2	5	0215	PCCS	328	275	12	55	4.31	4.20
SPS-1	4	0116	SB	122	95	6	55	4.34	4.20
SPS-1	10	0103	SB	46	121	12	55	6.14	4.20
SPS-1	30	0122	SB	18	116	16	55	6.21	4.20
SPS-1	35	0105	SB	170	119	12	55	4.24	4.20
SPS-1	39	0105	SB	41	101	11	55	5.57	4.20
SPS-1	51	0116	SB	33	73	9	55	4.22	4.20
SPS-8	29	A802	SB	142	174	7	63	4.23	4.16
SPS-8	39	0803	SB	185	101	15	55	5.43	4.20
SPS-8	49	0803	SB	58	107	11	55	4.29	4.20
SPS-6	29	A606	SC	36	110	13	55	5.71	4.20
SPS-6	29	0608	SC	119	59	12	50	5.06	4.24

Goodness-of-Fit between Experimental Data and Theoretical Statistical Distribution

Formulation of Statistical Hypothesis

Goodness-of-fit tests are used to evaluate how close the experimental data follow the assumed theoretical distribution. If the targeted theoretical distribution is a "normal" distribution, then the goodness-of-fit test becomes the test for normality. Such a test evaluates the closeness of the experimental data distribution to the normal distribution.

In the goodness-of-fit test, the null and alternative hypotheses are established first:

- The null hypothesis: "Measured field data follows a selected theoretical distribution, Φ."
- The alternative hypothesis: "Measured field data does not follow the theoretical distribution, Φ."

There are two kinds of errors that can be made in testing the hypothesis:

- Type I error: A true null hypothesis can be incorrectly rejected.
- Type II error: A false null hypothesis can fail to be rejected.

In the test of a hypothesis, it is desirable to have a small type I error and large power. Power is equal to 1 minus probability of a type II error and is defined as the probability of rejecting the null hypothesis when the alternative hypothesis is true. Testing whether a measured variable follows a certain theoretical distribution is not straightforward in the sense that the various tests are only powerful against certain types of alternative distributions.

Selection of the Targeted Theoretical Distribution

Based on the assumption that thickness measurements follow the same kind of distribution for any layer, one type of distribution was looked for. To determine the likely distribution shape, the measures of skewness and kurtosis were evaluated. The skewness of all samples ranged from -2.45 to +3.92 with a median of 0.024, while the kurtosis of all samples ranged from -1.56 to +17.78 with a median of -0.033. These measures indicate no particular skewness to either side or either particular long or short tails. This observation was confirmed by inspection of the layer thickness frequency distributions of each sample. While most of the reviewed layer thickness distributions looked fairly normal, as shown in figure 24, some samples had distributions that were skewed to one side or the other side, or looked rather uniformly distributed. Examples of different distribution shapes observed for the LTPP layer thickness measurements are provided in figures 23 to 26. The normal distribution was therefore selected as the most likely theoretical distribution to describe variability in the layer thickness along the LTPP section. This hypothesis was then tested using a goodness-of-fit test.

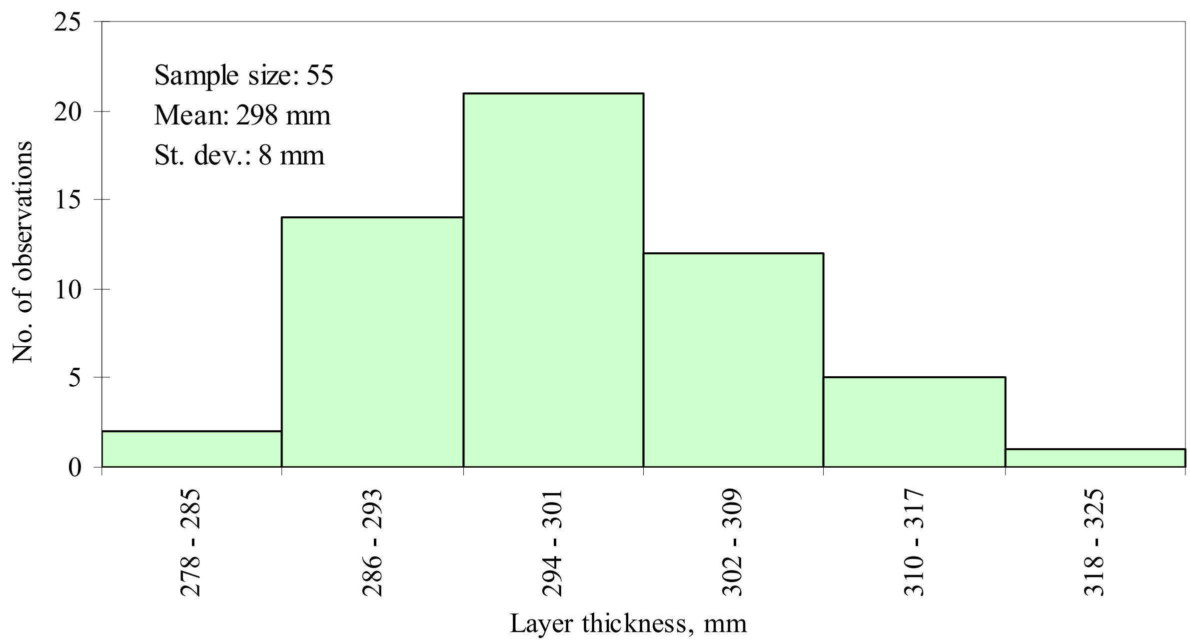


Figure 24: Chart. Example of the normal layer thickness distribution for PCC surface layer, SPS-2, Section 10_0211.

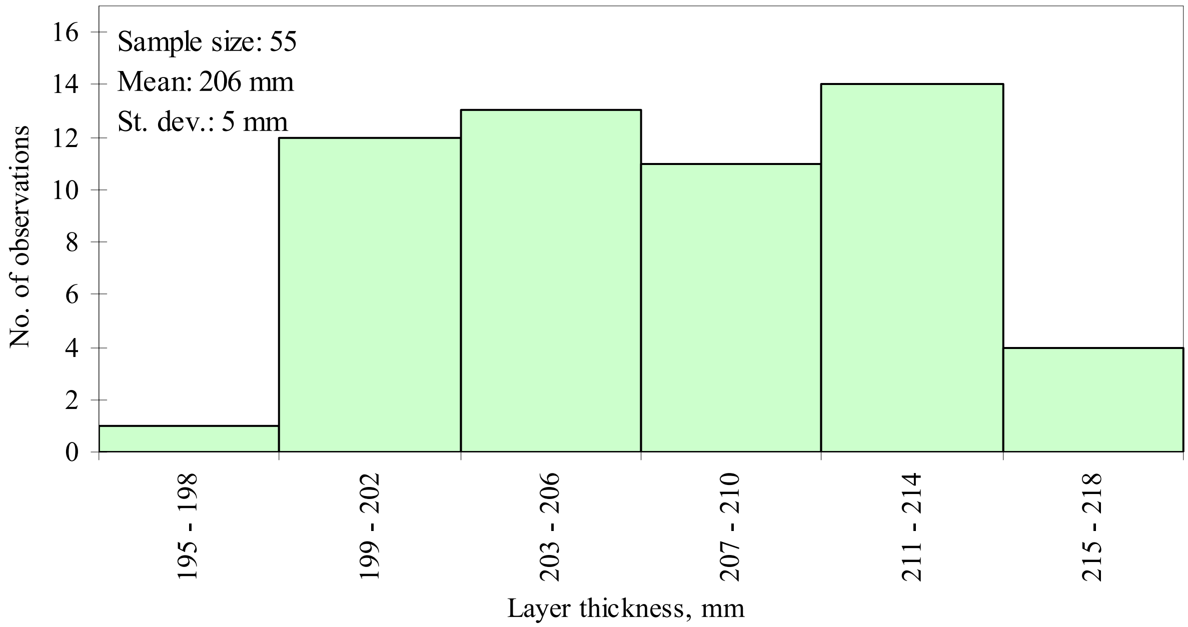


Figure 25: Chart. Example of the uniform layer thickness distribution for dense graded aggregate base, SPS-1, Section 12_0101.

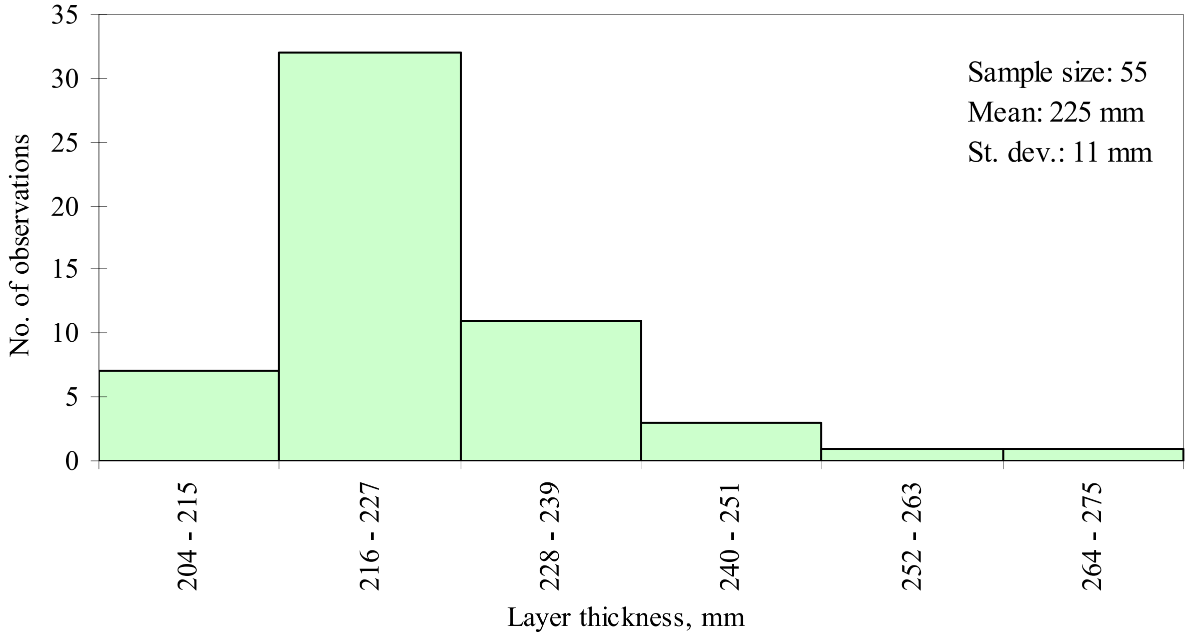


Figure 26: Chart. Example of the layer thickness distribution skewed to the right for PCC surface layer, SPS-2, Section19_0213.

Selection of Testing Procedure

The goodness-of-fit test between assumed theoretical distribution and distribution of the observed data could be done using several methods including:

- Chi-square test
- Kolmogorov-Smirnov test

For the normal distribution more goodness-of-fit methods are available, including:

- Shapiro-Wilk's test
- Tests of kurtosis and skewness

To select the best applicable testing procedure, the LTPP layer thickness data characteristics were analyzed first. Based on the data review the following was established:

- Layer thickness values are measured at multiple locations along the LTPP section.
- Most of layer thickness distributions look fairly normal.
- There is a large number of same thickness measurements (many "ties") in a section.
- The number of data points and locations are different from one section to another and between different experiments.

The assumptions and requirements of different goodness-of-fit tests were reviewed from the point of their applicability and the robustness of the procedure when it is applied to the LTPP layer thickness data. The goal of this review was to find a procedure that could be uniformly used for all the sections with variable number of data points without compromising the test accuracy and without violating any of the underlying test assumptions.

For most theoretical distributions, the choice is limited to tests like the Kolmogorov-Smirnov test or the chi-square goodness-of-fit test [32]. The advantage of the Kolmogorov-Smirnov test is that unlike the chi-square test it does not have strict rules on the required number of data groups and minimum theoretical frequencies that have to be satisfied in order for the test to be meaningful. The Kolmogorov-Smirnov test could be done for the samples with as few as five observations. The Kolmogorov-Smirnov test is also more powerful than the chi-square test.

If the null hypothesis is that the measured variable follows a normal distribution, there are more powerful tests available, such as the Shapiro-Wilk's test [33], the test of skewness or the third sample moment test and the test of kurtosis or the fourth sample moment test [34]. The latter two tests work for a sample with nine observations or more. These tests are preferred to the Kolmogorov-Smirnov test because of the increased power [34] they provide. For a test to work well, it should have high power against all possible alternatives, which is not true for either the Kolmogorov-Smirnov test or the chi-square goodness-of-fit test. For the LTPP layer thickness data the Shapiro-Wilk's test was not appropriate, due to the many thickness measurement values that were the same (many "ties" [34]) for a given pavement layer and LTPP section.

The following table 35 provides a summary of the pros and cons of the reviewed goodness-of-fit testing methods.

Table 35. Evaluation summary of the goodness-of-fit testing methods.

Evaluation Criteria	Chi-Square test	Kolmogorov-Smirnov test	Sharpiro-Wilk test	Skewness-and-Kurtosis test
Test power (for normality only)	very poor	poor	high	high
Minimum number of observations	25	5	3	9
Minimum number of observations in a single bin	5	no restriction	no restriction	no restriction
Handling of "ties"	high	high	poor	high

Based on the review of different goodness-of-fit tests' procedures and analysis of the available layer thickness data, the following conclusions were derived:

- Goodness-of-fit tests are generally only powerful against certain alternative distributions – that is the reason why so many tests have been developed.
- For testing distribution normality, no other tests are as well rounded as the Sharpiro-Wilk test or the Skewness and Kurtosis tests.
- The Sharpiro-Wilk test doesn't handle ties well – which leaves the Skewness and Kurtosis tests as the best alternative for evaluation of within-section layer distribution normality.

The combined skewness and kurtosis test was selected for the evaluation of layer thickness distribution normality. Rejection in either skewness or kurtosis test was considered as a rejection of normality altogether. For example, for a sample to be considered as normally distributed, the analysis of data should pass both the skewness and the kurtosis tests for a selected level of significance.

Selection of the Level of Significance

The level of significance of 1 percent was chosen for the goodness-of-fit tests. The following considerations were taken into account in selecting this desired level of significance:

- In the test of a hypothesis, it is desirable to have a small type I error and large power; however, that cannot happen simultaneously. A compromise is found by setting the level of significance (or type I error) to either 5 percent or 1 percent, or even less.
- In many cases a 5 percent level is reasonable. In these cases, when testing a null hypothesis the researchers very frequently put forward a null hypothesis in the hope that they can discredit it.
- In the case of the goodness-of-fit test, the null hypothesis is that the distribution of the field data and the theoretical normal distribution are the same and the desire is not to reject (or fail-to-reject) this hypothesis.
- A rejection of a null hypothesis is a much stronger statement than a fail-to-reject outcome. A rejection of a null hypothesis says we are certain (at the specified significance level) that the null hypothesis is not true.

- A failure-to-reject means either there was not enough evidence to indicate the discrepancy or the discrepancy was really not there.
- In lieu of the problems with power of the goodness-of-fit tests, it is better to be slightly conservative and use a 1 percent significance level. The lower the significance level, the more the data must diverge from the null hypothesis to be significant.
- For the goodness-of-fit test, in case of rejection, we are 99 percent certain that the distribution is not normal.

<u>Procedures for the Skewness and Kurtosis Test</u>

Based on the assessment of the LTPP layer thickness data from the SPS*_LAYER_THICKNESS tables, a procedure based on the combination of skewness and kurtosis tests was selected as the most appropriate for ascertaining whether the frequency distributions of layer thickness measurements taken along the LTPP section follow a normal distribution. In this procedure, for a sample not to be rejected (as normally distributed), the layer thickness measurements sample should pass both the skewness and the kurtosis tests for a selected level of significance of 1 percent.

The procedure used for the combined skewness and kurtosis test is outlined in the flowchart in figure 27. Detailed statistical formula used to compute test parameters are provided in Appendix B.

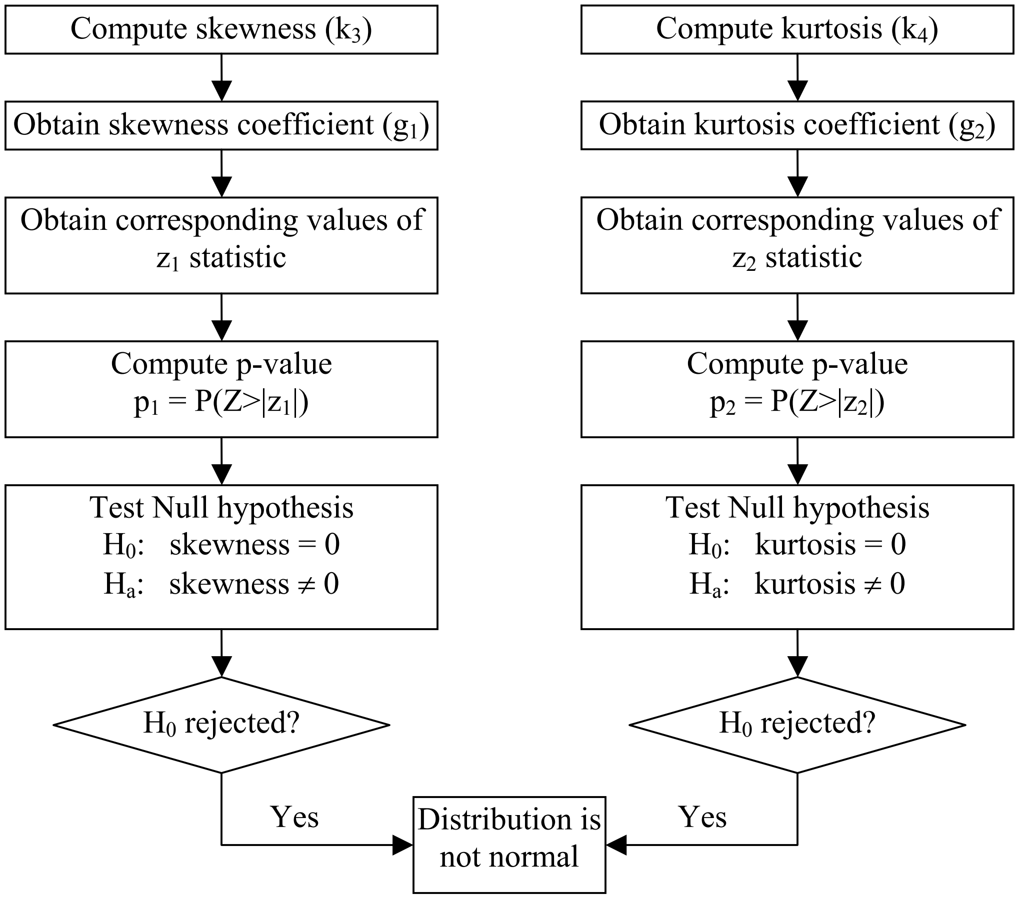


Figure 27: Chart. Flowchart of the kurtosis and skewness test procedures used for the test of layer thickness distribution normality.

The skewness and kurtosis tests are based on evaluations of the third and fourth moments of the measurement distribution. The distribution is not rejected for being normally distributed if the absolute values of the z_1- and z_2-statistics computed separately based on skewness and kurtosis values are less than the Z-value of 2.57.

Z-value is obtained from the standard normal distribution, assuming a 1 percent level of significance. If a sample follows the standard normal distribution, the value Z=2.57 describes the distribution with 0.5 percent of the all the values from the sample greater than 2.57 and 0.5 percent of the values smaller than –2.57. Thus, when Z is equal to 2.57 the level of significance is 1 percent.

The z_1- and z_2-statistics are used to obtain the *p*-values (the probability that values of the standard normal distribution are more extreme than the computed z_1- and z_2-statistics). The *p*-values are defined in figure 28, as follows.

$$p_1 = P(Z>|z_1|)$$
$$p_2 = P(Z>|z_2|)$$

Figure 28: Equation. Definition of *p*-values.

Based on the selected 1 percent level of significance, if p_1- and p_2-values are larger than 1 percent or equivalently if $|z_1|$ and $|z_2| \leq 2.57$, we fail to reject that the data follow a normal distribution.

Example of the Kurtosis and Skewness Tests

The following example provides the comparison of the kurtosis and skewness test results obtained for the same binder course layer in the SPS-6 Section 40_0608, including and excluding an obvious outlier thickness measurement (86-mm [3.4-in] outlier thickness for a sample with 151-mm [5.951-in] mean thickness). Table 36 provides the summary of the test results.

Table 36. Kurtosis and skewness test results summary for binder course layer, SPS-6 Section 40_0608.

Sample Characteristic	Sample Size, n	Mean Sample Thickness, mm	Standard Deviation, mm	g1	g2	z1	z2	Z-value	Is Normal?
Outlier included in the analysis	55	151.15	12.72	-2.60	11.74	-5.51	4.80	2.57	No
Outlier excluded from the analysis	54	152.35	9.17	-0.57	0.68	-1.77	1.14	2.57	Yes

When the outlier point was excluded, the mean does not change much while the standard deviation becomes 0.7 times smaller, and the skewness (g_1) and the kurtosis (g_2) change considerably. For this example, the exclusion of the outlying data point means that the tests for normality change from reject to not reject.

Results of the Kurtosis and Skewness Test of Normality for SPS Structural Layers

Kurtosis and skewness tests of normality were used to evaluate whether the experimental layer thickness data follow the theoretical normal distribution. A total of 1,047 layer thickness samples from the SPS experiments were considered for the analysis. Based on the number of available observations per sample, 13 samples were excluded from the analysis. These samples had fewer than 9 observations—the minimum number required for the kurtosis and skewness tests. All the samples were tested assuming the same evaluation criterion at 1 percent level of significance. The procedure for the kurtosis and skewness tests of normality described in the previous section was utilized.

The results of the kurtosis and skewness tests for different pavement material and layer types indicate that, based on the selected 1 percent level of significance, overall 84 percent of all layer thickness frequency distributions were not rejected for being normally distributed. This finding indicates that in general it is reasonable to assume that the layer thickness measurements taken along the section are normally distributed, but in a small number of sections this is not so. The distribution normality evaluations are summarized in table 37 by SPS experiment number and by layer and material type, respectively.

Table 37. Summary of the normality evaluation results.

Experiment	Number of Layers	Not Rejected (Normal)	Rejected (Not Normal)
AC_SURFACE_COURSE			
SPS-5	93	78 (83.9 %)	15 (16.1 %)
SPS-6	36	30 (83.3 %)	6 (16.7 %)
SURFACE_AND_BINDER			
SPS-1	167	136 (81.4 %)	31 (18.6 %)
SPS-8	22	20 (90.9 %)	2 (9.1 %)
PERM_ASPH_TREAT_BASE			
SPS-1	83	72 (86.8 %)	11 (13.2 %)
SPS-2	46	41 (89.1 %)	5 (10.9 %)
PCC_SURFACE			
SPS-2	139	102 (73.4 %)	37 (26.6 %)
SPS-7	24	23 (95.8 %)	1 (4.2 %)
SPS-8	14	12 (85.7 %)	2 (14.3 %)
LEAN_CONCRETE			
SPS-2	48	40 (83.3 %)	8 (16.7 %)
DENSE_GRD_ASPH_TREAT_BASE			
SPS-1	97	87 (89.7 %)	10 (10.3 %)
DENSE_GRADE_AGG_BASE			
SPS-1	97	84 (86.6 %)	13 (13.4 %)
SPS-2	84	70 (83.3 %)	14 (15.5 %)
SPS-8	38	30 (79.0 %)	8 (21.0 %)
BINDER_COURSE			
SPS-5	33	30 (87.9 %)	3 (12.1 %)
SPS-6	13	12 (92.3 %)	1 (7.7 %)

Figures 29 through 44 provide examples of layer thickness frequency distributions obtained from the elevation measurements data for different layer and material types evaluated in the goodness-of-fit study. The data used to create these frequency distributions were determined to be reasonably normal based on skewness and kurtosis tests at selected level of significance. Theoretical normal distributions are superimposed over field frequency data to provide means for visual comparison between field data and theoretical distributions.

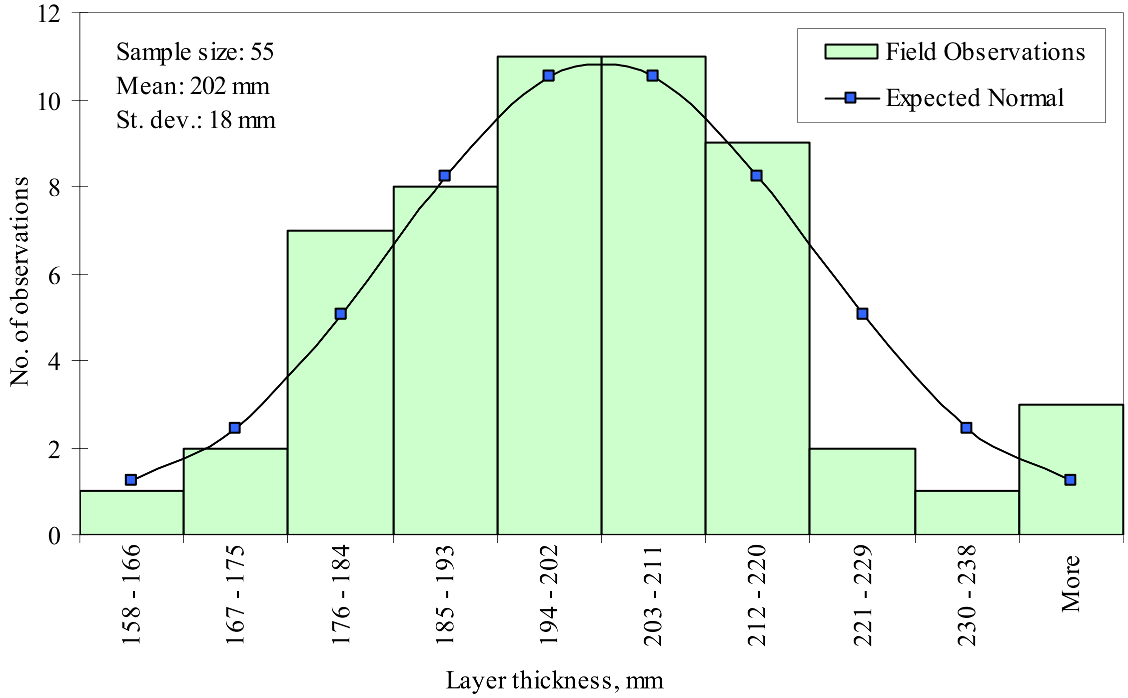


Figure 29: Chart. Example distribution of layer thickness measurements along the section for the DGAB layer for the SPS-1 Section 35-0108.

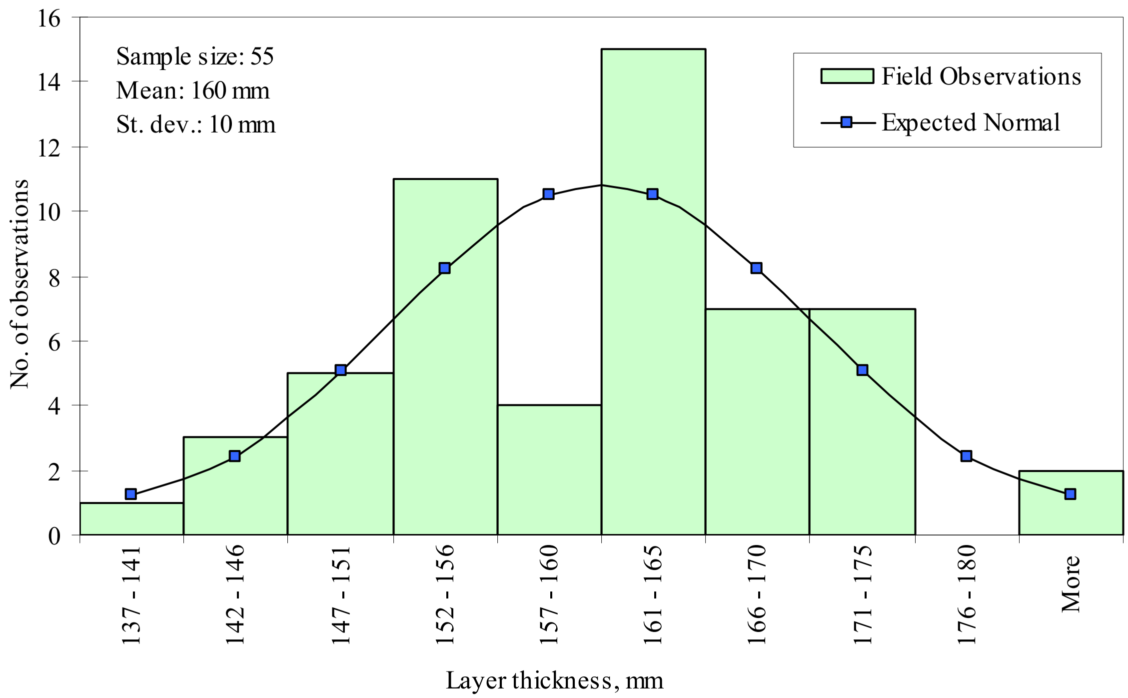


Figure 30: Chart. Example distribution of layer thickness measurements along the section for the DGAB layer for the SPS-2 Section 19-0214.

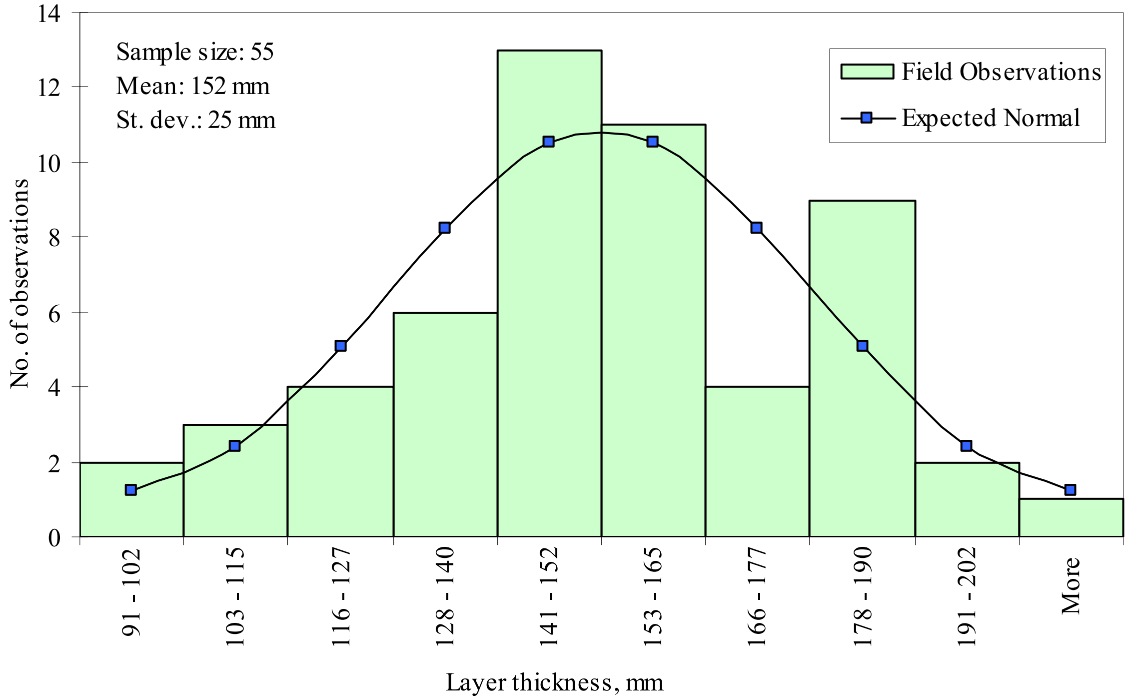


Figure 31: Chart. Example distribution of layer thickness measurements along the section for the DGAB layer for the SPS-8 Section 08-0811.

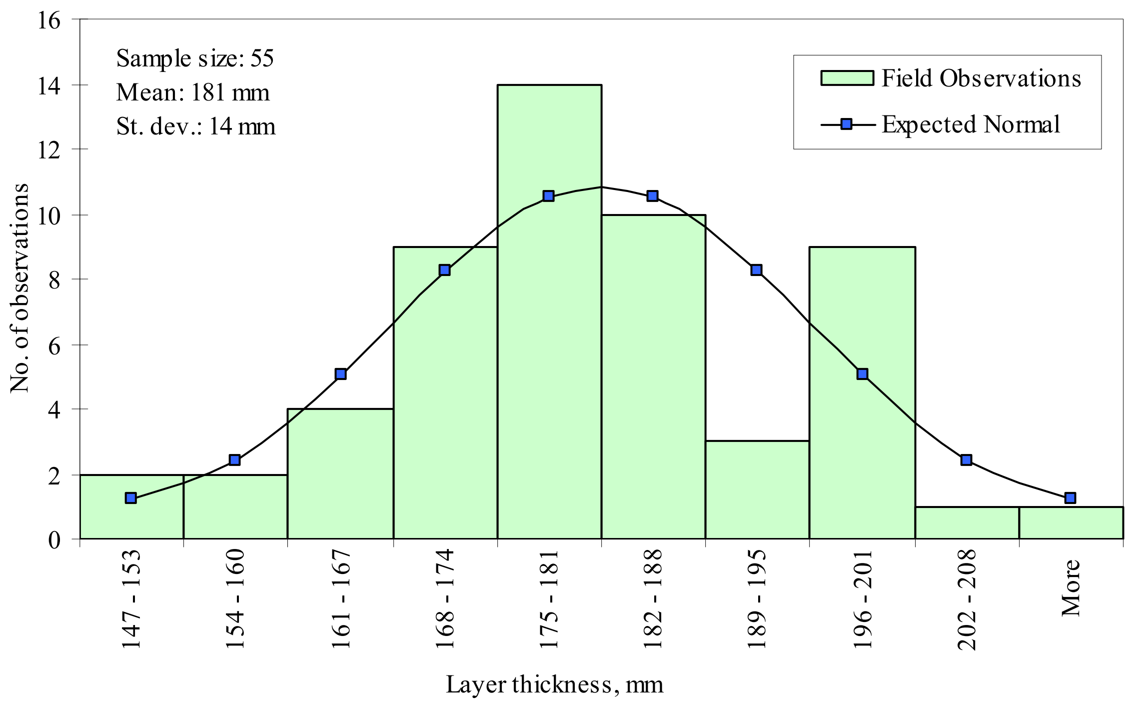


Figure 32: Chart. Example distribution of layer thickness measurements along the section for the DGATB layer for the SPS-1 Section 22-0118.

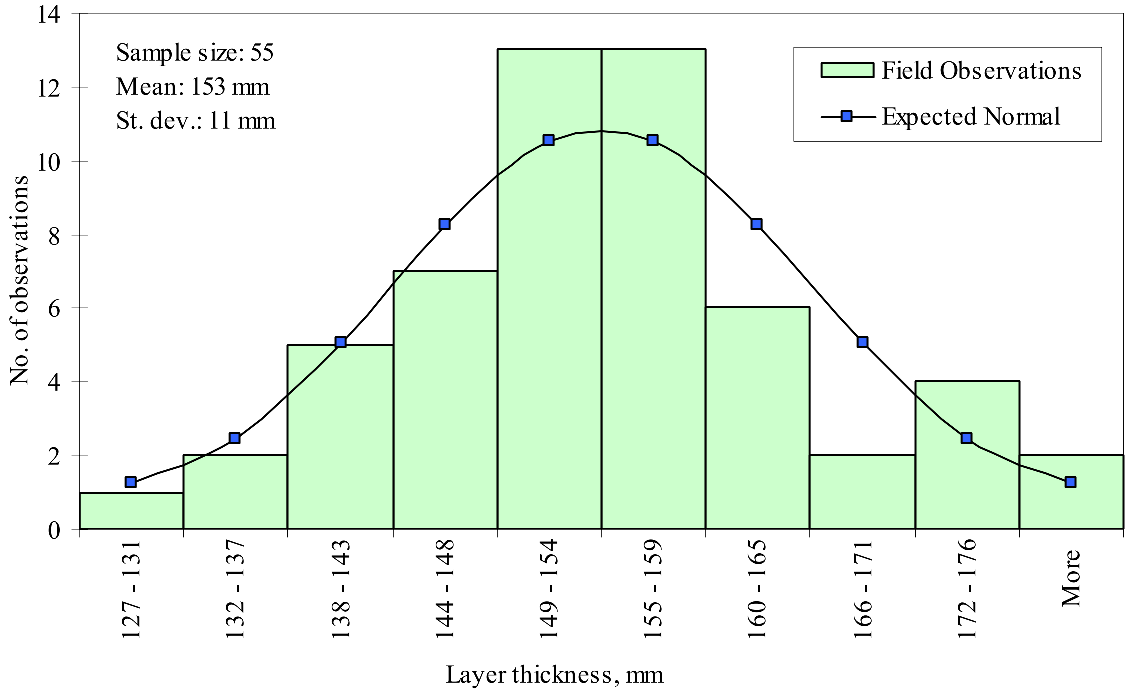


Figure 33: Chart. Example distribution of layer thickness measurements along the section for the LC base layer for the SPS-2 Section 53-0207.

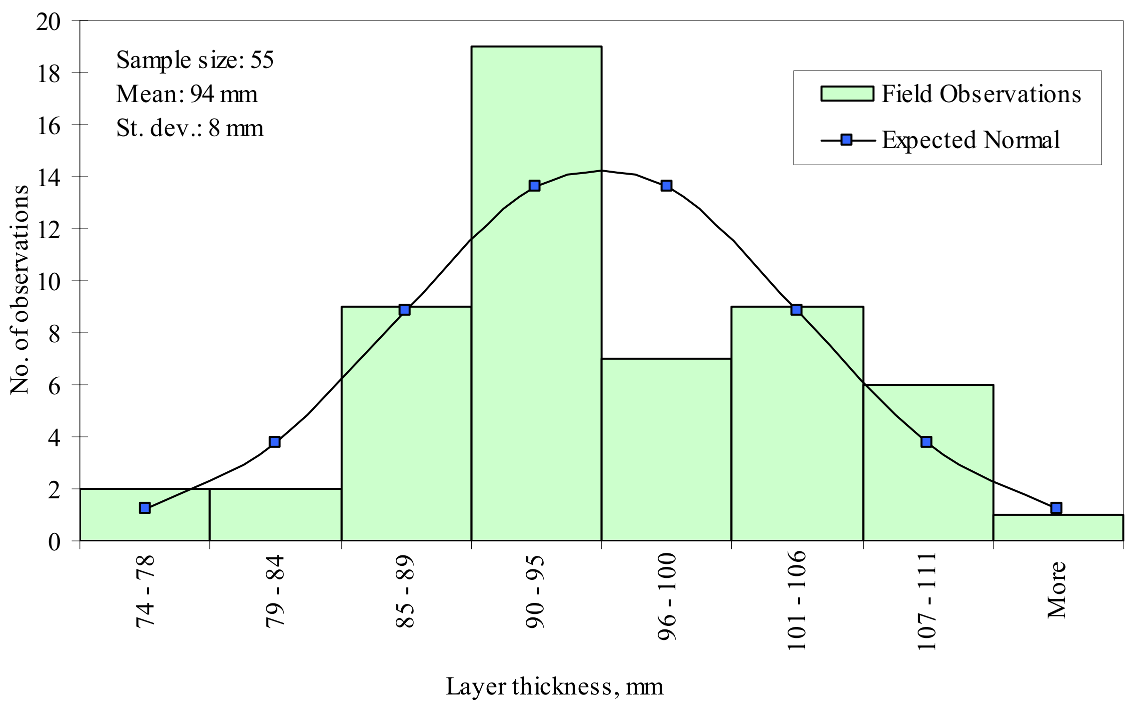


Figure 34: Chart. Example distribution of layer thickness measurements along the section for the PATB layer for the SPS-1 Section 20-0112.

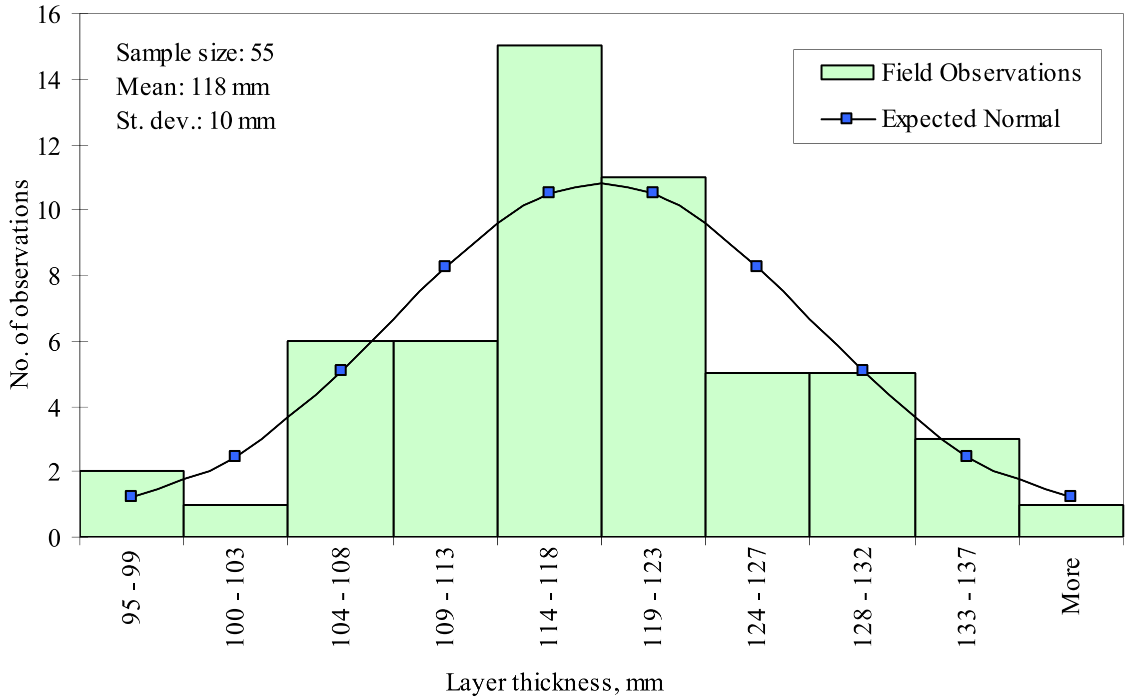


Figure 35: Chart. Example distribution of layer thickness measurements along the section for the PATB layer for the SPS-2 Section 08-0224.

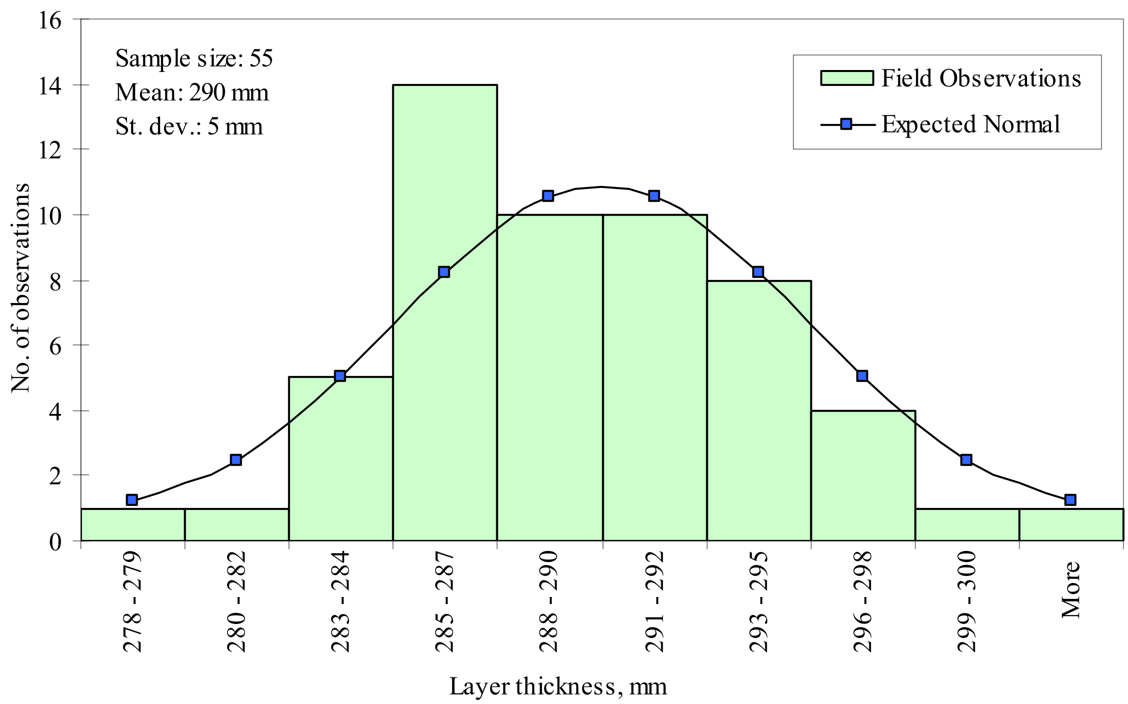


Figure 36: Chart. Example distribution of layer thickness measurements along the section for the PCC surface layer for the SPS-2 Section 08-0215.

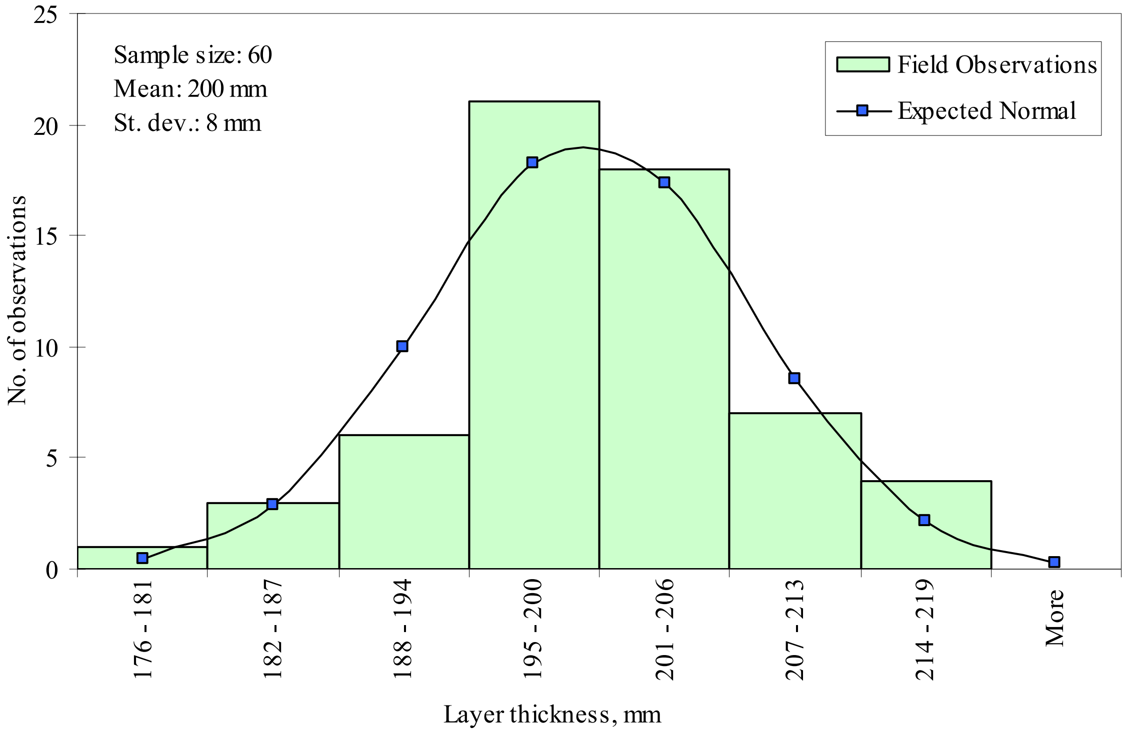


Figure 37: Chart. Example distribution of layer thickness measurements along the section for the PCC surface layer for the SPS-8 Section 39-0809.

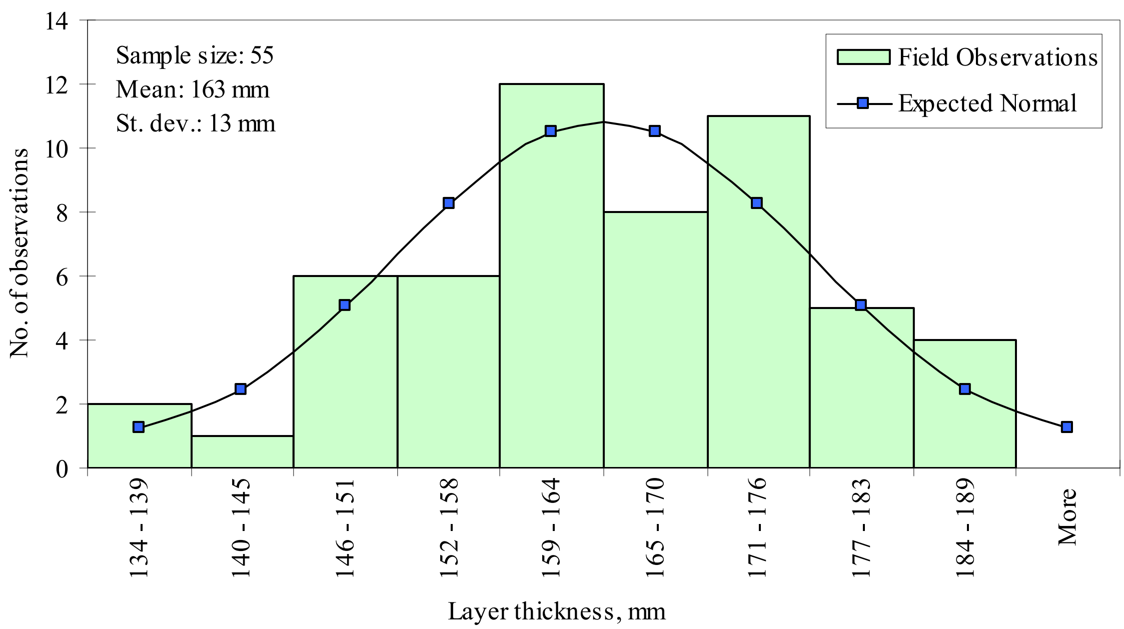


Figure 38: Chart. Example distribution of layer thickness measurements along the section for the PCC surface layer for the SPS-7 Section 19-0706.

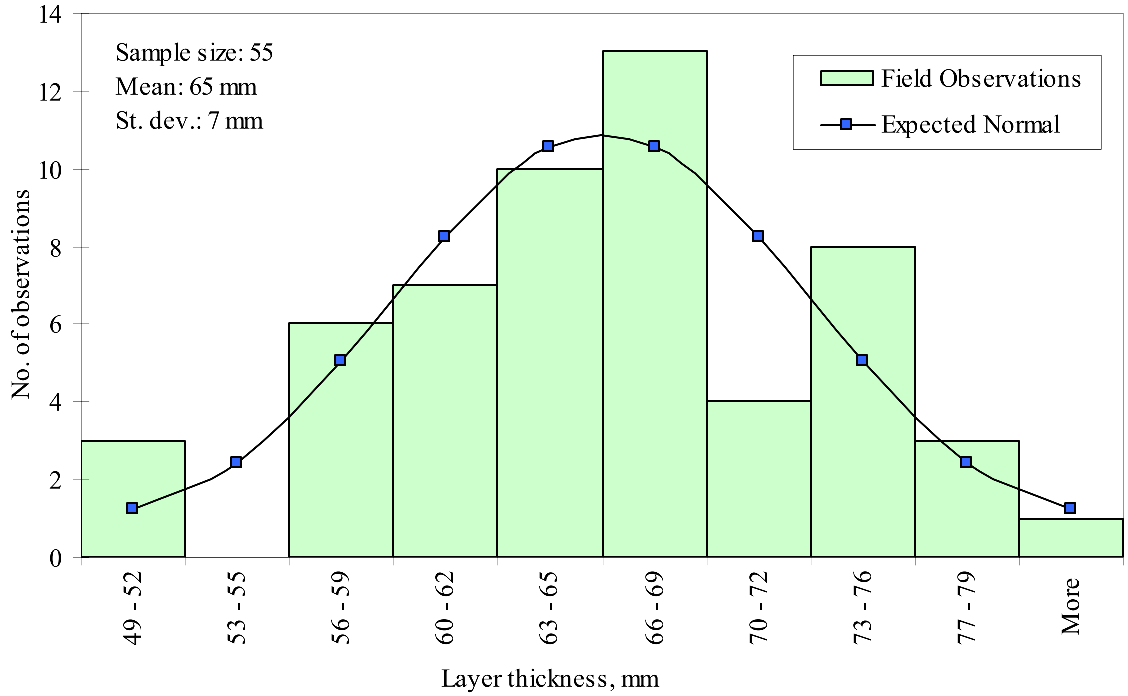


Figure 39: Chart. Example distribution of layer thickness measurements along the section for the surface and binder layer for the SPS-1 Section 55-0118.

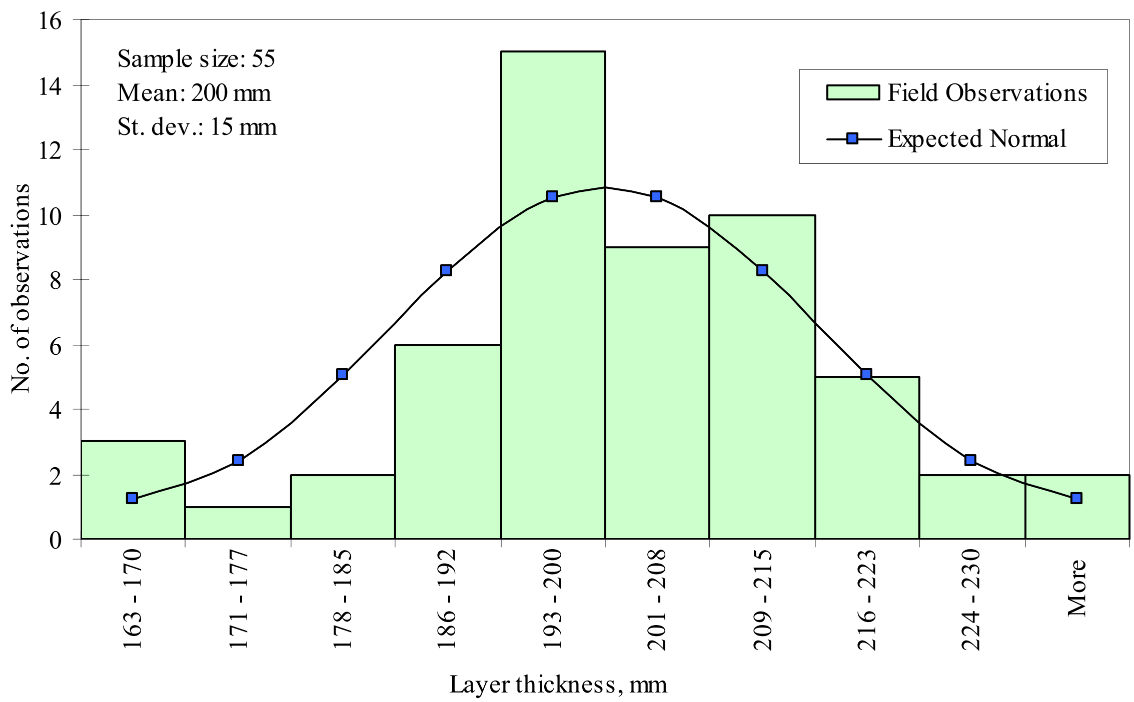


Figure 40: Chart. Example distribution of layer thickness measurements along the section for the surface and binder layer for the SPS-8 Section 48-0802.

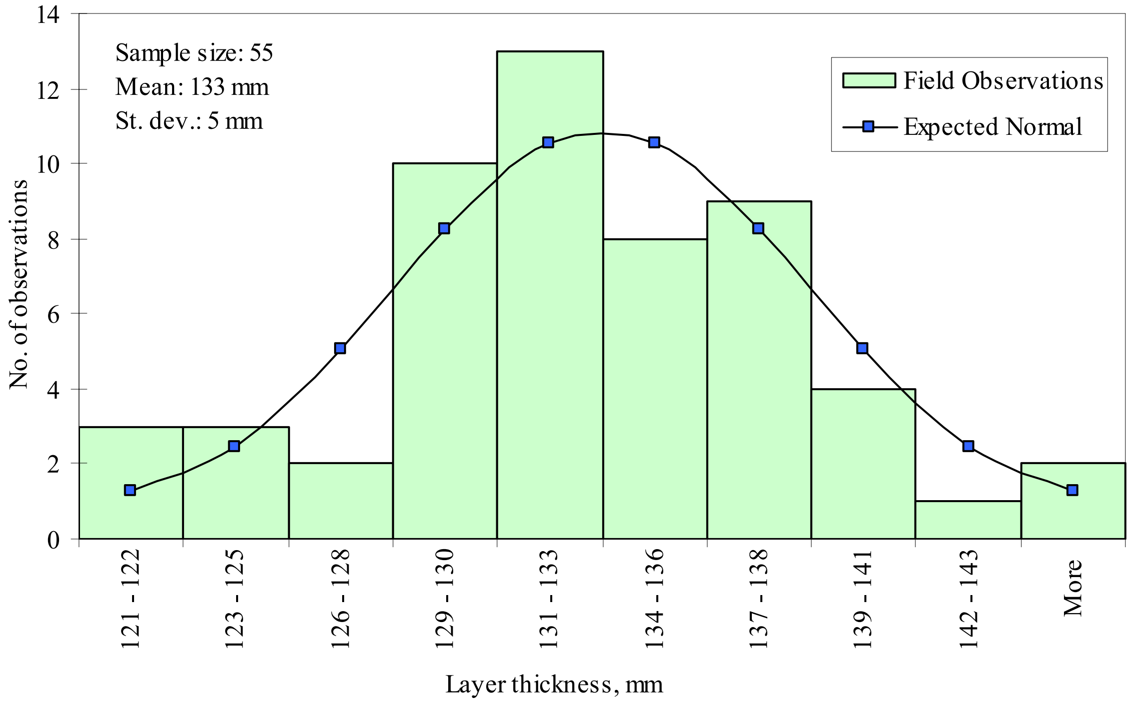


Figure 41: Chart. Example distribution of layer thickness measurements along the section for the surface layer for the SPS-5 Section 35-0507.

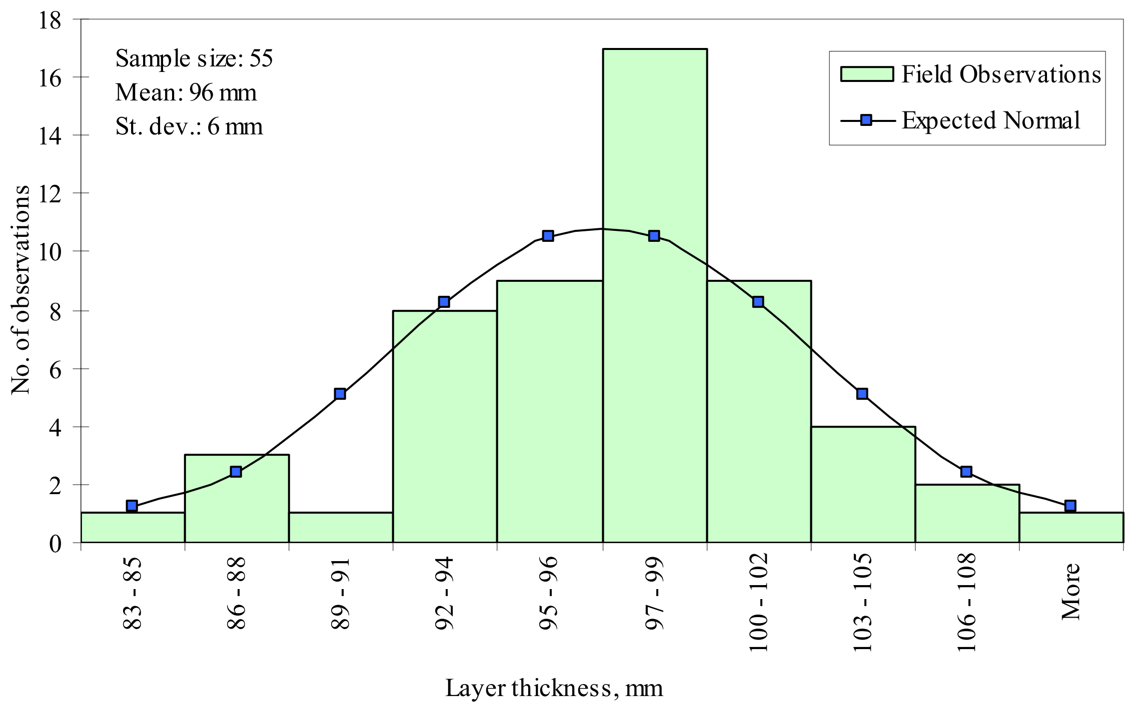


Figure 42: Chart. Example distribution of layer thickness measurements along the section for the surface layer for the SPS-6 Section 42-0603.

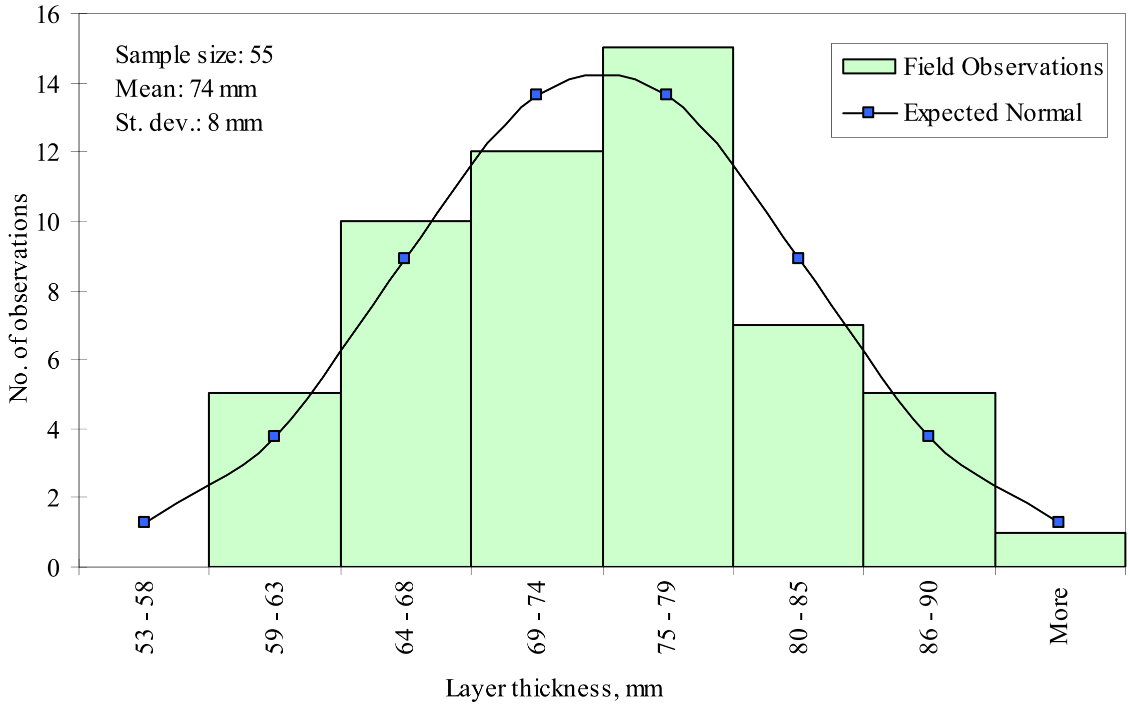


Figure 43: Chart. Example distribution of layer thickness measurements along the section for the AC binder course for the SPS-5 Section 24-0504.

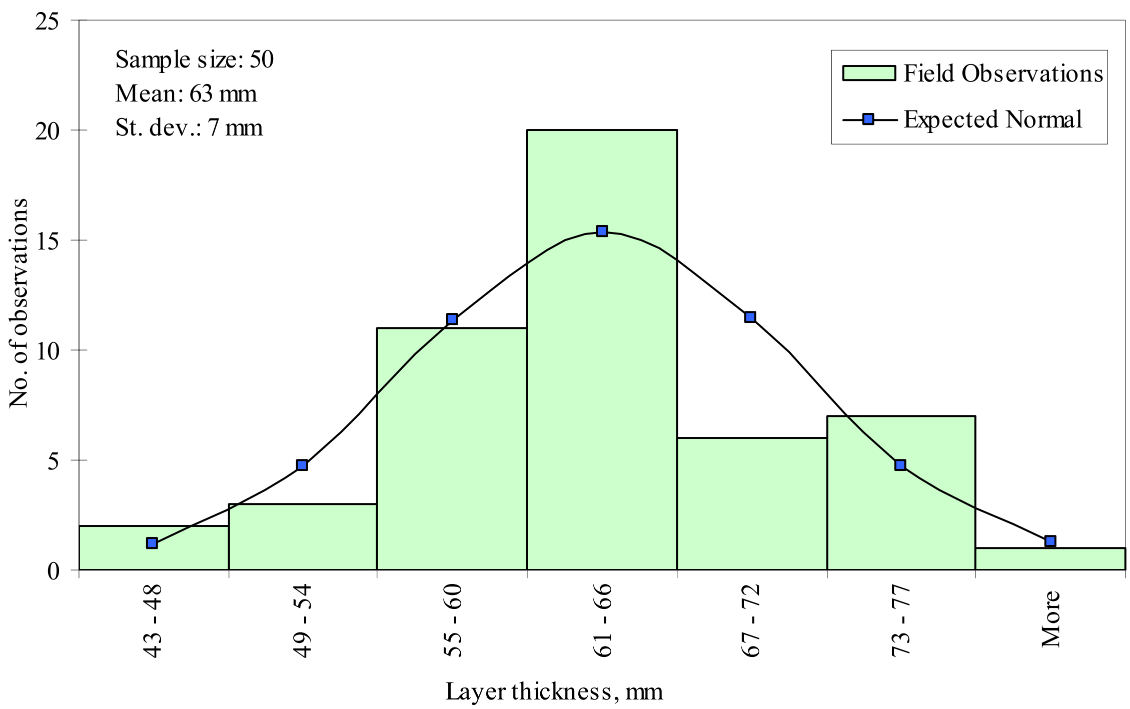


Figure 44: Chart. Example distribution of layer thickness measurements along the section for the binder course for the SPS-6 Section 29-0607.

In addition to the kurtosis and skewness tests, Kolmogorov-Smirnov goodness-of-fit tests were carried out for the layer with thickness data in the SPS*_LAYER_THICKNESS tables. As was discussed earlier in the chapter, this testing procedure is not as powerful for testing normality as the kurtosis and skewness tests. A summary of the Kolmogorov-Smirnov goodness-of-fit testing procedure and evaluation results are presented in the Appendix C.

Summary

In this chapter, layer thickness data from the SPS elevation measurements were analyzed to determine the extent to which the variation of layer thickness within a section follows typical statistical distributions. Data from the SPS*_LAYER_THICKNESS tables were obtained and reviewed. The layers used in the analysis include different material types and functional classifications, such as AC surface courses, combined AC surface and binder courses, AC binder courses, DGAB's, ATB's, LC bases, PCC surface layers, and PCC overlay layers. A methodology for identifying anomalous outlier points based on t-distribution was developed and utilized in evaluation of layer thickness data for each layer in the SPS*_LAYER_THICKNESS tables. All identified anomalous outlier data points were analyzed and reported to FHWA.

To assess layer thickness distribution characteristics, descriptive statistics such as mean, standard deviation, skewness, and kurtosis were computed for each section. Using descriptive statistics, the analysis of likely shapes of layer thickness distribution was conducted. The results of exploratory analysis indicated that, for most of the sections, the distribution is likely to be normal. To perform a more rigorous test of distribution normality, available procedures for goodness-of-fit tests were reviewed and their applicability to the evaluation of layer thickness data was evaluated. Based on the literature review, a combined test for skewness and kurtosis was selected to test normality of layer thickness distribution. A summary of the testing procedure was documented in this chapter. The analysis results for 1,034 SPS layers indicated that for 84 percent of all layer, frequency distributions of thickness values were not rejected for being normally distributed. Thus, LTPP data indicate that layer thickness variation within a section follows a normal distribution in most cases. These results would serve as a very important input to pavement engineering applications involving design reliability implementation.

6. CHARACTERIZATION OF VARIATION BETWEEN AS-DESIGNED AND AS-CONSTRUCTED LAYER THICKNESSES

The main purpose of this chapter is to characterize the extent of differences in the layer thickness data between as-designed and as-constructed (measured) thicknesses for the newly constructed SPS layers. Only these new SPS layers have design thicknesses accurately documented.

Data sources for the analysis are discussed first, followed by an overview of as-designed thicknesses for the newly constructed SPS layers. After that, typical thickness deviations from the target thicknesses are summarized, as well as their distribution types. Finally, the results of the statistical analysis are presented.

Data Sources

Two thickness data sources with multiple measurements on a given layer exist in the LTPP database:

- Elevation measurements in SPS*_LAYER_THICKNESS tables for experiments SPS-1, SPS-2, SPS-5, SPS6, SPS-7, and SPS-8.
- Pavement core measurements in testing tables TST_AC01_LAYER and TST_PC06.

According to the SPS construction guidelines [35-40], rod and level survey measurements are to be taken at a minimum of five offset locations (edge, outer wheel path, midlane, inner wheel path, and inside edge of lane) at longitudinal intervals no greater than 15 m (50 ft). Typically, 55 elevation measurements are available for each regular SPS test section.

The number of cores taken at each section depends on experiment and layer type and is defined in the corresponding Sampling and Testing Guide [6-11]. The number of cores per section ranges between 1 and 9.

All sections with available thickness data in either one of these tables are studied to quantify as-designed versus as-constructed variations in layer thickness.

For the section/layer combination, an analysis cell is defined to represent a specific layer in a test section, for which the target thickness was documented. The following fields from TST_L05B or EXPERIMENT_SECTION table in LTPP database along with the design target layer thickness define a unique analysis cell:

- EXPERIMENT_NO (Experiment number).
- LAYER_TYPE (Layer type).
- MATL_CODE (Material type description)
- Target layer thickness.

Design Thicknesses

For newly constructed SPS layers, the design thicknesses are defined in the corresponding SPS Experimental Designs [12-17]. The design thicknesses are available for the following layer types:

- SB – AC surface and binder thickness (SPS-1, SPS-5, SPS-6, SPS-8).
- DGATB – Dense-graded asphalt-treated base (SPS-1).
- PATB – Permeable asphalt-treated base (SPS1, SPS-2).
- PCC – Portland cement concrete (SPS-2, SPS-7, SPS-8).
- LC – Lean concrete (SPS-2).
- DGAB – Dense-graded aggregate base (SPS-1, SPS-2, SPS-8).

The design thicknesses for all these SPS experiments and layer types are presented in tables 38 through 43.

Table 38. Design layer thicknesses for the SPS-1 experiment.

SHRP_ID	Design Layer Thickness, mm (in)			
	DGAB	PATB	DGATB	SB
0101	203 (8)			178 (7)
0102	305 (12)			102 (4)
0103			203 (8)	102 (4)
0104			305 (12)	178 (7)
0105	102 (4)		102 (4)	102 (4)
0106	102 (4)		203 (8)	178 (7)
0107	102 (4)	102 (4)		102 (4)
0108	203 (8)	102 (4)		178 (7)
0109	305 (12)	102 (4)		178 (7)
0110		102 (4)	102 (4)	178 (7)
0111		102 (4)	203 (8)	102 (4)
0112		102 (4)	305 (12)	102 (4)
0113	203 (8)			102 (4)
0114	305 (12)			178 (7)
0115			203 (8)	178 (7)
0116			305 (12)	102 (4)
0117	102 (4)		102 (4)	178 (7)
0118	102 (4)		203 (8)	102 (4)
0119	102 (4)	102 (4)		178 (7)
0120	203 (8)	102 (4)		102 (4)
0121	305 (12)	102 (4)		102 (4)
0122		102 (4)	102 (4)	102 (4)
0123		102 (4)	203 (8)	178 (7)
0124		102 (4)	305 (12)	178 (7)

Table 39. Design layer thicknesses for the SPS-2 experiment.

SHRP_ID	Design Layer Thickness, mm (in)			
	DGAB	PATB	LC	PCC
0201	152 (6)			203 (8)
0202	152 (6)			203 (8)
0203	152 (6)			279 (11)
0204	152 (6)			279 (11)
0205			152 (6)	203 (8)
0206			152 (6)	203 (8)
0207			152 (6)	279 (11)
0208			152 (6)	279 (11)
0209	102 (4)	102 (4)		203 (8)
0210	102 (4)	102 (4)		203 (8)
0211	102 (4)	102 (4)		279 (11)
0212	102 (4)	102 (4)		279 (11)
0213	152 (6)			203 (8)
0214	152 (6)			203 (8)
0215	152 (6)			279 (11)
0216	152 (6)			279 (11)
0217			152 (6)	203 (8)
0218			152 (6)	203 (8)
0219			152 (6)	279 (11)
0220			152 (6)	279 (11)
0221	102 (4)	102 (4)		203 (8)
0222	102 (4)	102 (4)		203 (8)
0223	102 (4)	102 (4)		279 (11)
0224	102 (4)	102 (4)		279 (11)

Table 40. Design layer thicknesses for the SPS-5 experiment.

SHRP_ID	Design Layer Thickness, mm (in)
	SB
0501	0
0502	51 (2)
0503	127 (5)
0504	127 (5)
0505	51 (2)
0506	51 (2)
0507	127 (5)
0508	127 (5)
0509	51 (2)

Table 41. Design layer thicknesses for the SPS-6 experiment.

SHRP_ID	Design Layer Thickness, mm (in)
	SB
0601	0
0602	0
0603	102 (4)
0604	102 (4)
0605	0
0606	102 (4)
0607	102 (4)
0608	203 (8)

Table 42. Design layer thicknesses for the SPS-7 experiment.

SHRP_ID	Design Layer Thickness, mm (in)
	PCC
0701	0
0702	76 (3)
0703	76 (3)
0704	76 (3)
0705	76 (3)
0706	127 (5)
0707	127 (5)
0708	127 (5)
0709	127 (5)

Table 43. Design layer thicknesses for the SPS-8 experiment.

SHRP_ID	Design Layer Thickness, mm (in)		
	DGAB	PCC	SB
0801	203 (8)		102 (4)
0802	305 (12)		178 (7)
0803	203 (8)		102 (4)
0804	305 (12)		178 (7)
0805	203 (8)		102 (4)
0806	305 (12)		179 (7)
0807	152 (6)	203 (8)	
0808	152 (6)	279 (11)	
0809	152 (6)	203 (8)	
0810	152 (6)	279 (11)	
0811	152 (6)	203 (8)	
0812	152 (6)	279 (11)	

Study Methodology

For both the elevation and core as-constructed thickness measurements, typical mean layer thickness deviations are established by the following:

- Descriptive summary statistics of the average thicknesses deviations between as-designed and as-constructed values for the layers with the same layer material type and same design thickness.
- Kurtosis and skewness tests of the distribution of the mean thicknesses for the layers with the same layer material type and the same design thickness.

Two types of comparisons are made in relation to their as-designed thicknesses or target values:

- Evaluation of the percent of the individual measurements that are either within or outside specific values from the target thickness.
- Statistical analysis of the measured mean thickness values versus the designed values.

Descriptive Summary Statistics of the Thickness Deviations

The mean thickness difference between as-designed and as-constructed thicknesses was computed for each layer using both core and elevation thickness measurements.

The following statistical indicators were computed:

- Total number of sections or layers.
- Mean thickness deviation.
- Minimum thickness deviation.
- Maximum thickness deviation.
- Standard deviation of thickness deviation.
- COV of thickness deviation.

The analyses were done separately for the thickness data obtained from core measurements and for the data from elevation measurements.

Layer Thickness Deviation Distribution Type

Mean thickness deviations from layers or sections were analyzed to determine whether they follow typical statistical distributions. Skewness and kurtosis analyses were conducted for this purpose, using the methodology outlined in chapter 5.

Percentage Distribution of the Individual Measurements

To evaluate the variation between as-designed and as-constructed thicknesses, deviations of the individual measurements in relation to the target values are computed for each analysis cell. These deviations are then summarized into three deviation levels: 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in), for different material types and target thickness values.

This evaluation provides information regarding variations between as-constructed and as-designed thicknesses at individual measurement level.

<u>Statistical Analysis of Sample Measurement Means</u>

Statistical analysis is performed to evaluate variations for each analysis cell. The goal of statistical analysis is to assess deviation of the measurement population means from the target thicknesses. Two types of the thickness comparison are performed for both data sources:

- Two-sided t-tests with 95 percent confidence level for each section and layer, to determine whether the differences between as-designed and as-constructed thicknesses are significant.

  The null hypothesis for this test is that average of core or elevation thickness data is equal to the target thickness, i.e.:

  $$H_O : \mu_{elev.average} - t_{design} = 0 \text{ versus } H_{alt} : \mu_{elev.average} - t_{design} \neq 0 \text{ for elevation data or}$$
  $$H_O : \mu_{core\,average} - t_{design} = 0 \text{ versus } H_{alt} : \mu_{core\,average} - t_{design} \neq 0 \text{ for core thickness data.}$$

  Figure 45: Equation. The null and alternative hypotheses for two-sided t-test.

  If the null hypothesis is rejected (i.e., the result of the two-sided t-test is significant), then the measured mean thickness is different from the design thickness at the 95 percent confidence level. On the other hand, if the null hypothesis is not rejected or the test result is not significant, then there is no evidence that the measured mean thickness is different from the design value.

- One-sided t-tests with 95 percent confidence level for the difference between as-designed thickness and the mean as-constructed thickness and for tolerance level of 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in). The null hypothesis is that the absolute value of the difference between the mean and target thickness is less than or equal to the tolerance level with the alternative hypothesis being that the absolute value of the difference is greater than the tolerance level. For example, for elevation data, for allowance of 6.35 mm (0.25 in), the null and alternative hypotheses are:

  $$H_O : \left|\mu_{elev.average} - t_{design}\right| \leq 6.35\text{mm versus } H_{alt} : \left|\mu_{elev.average} - t_{design}\right| > 6.35\text{mm}$$

  Figure 46: Equation. The null and alternative hypothesis for one-sided t-test.

  If the null hypothesis is rejected (i.e., the result the one-sided t-test is significant), then the measured mean thickness deviates from the design thickness by more than the specified allowance (in this example 6.35 mm) at a 95 percent confidence level. On the other hand, if the null hypothesis is not rejected or the test result is not significant, then there is no evidence that the measured mean thickness deviates from the designed value by more than the specified allowance value, in other words, that the mean thickness is within the allowance value (in this case 6.35 mm) from the designed thickness.

Typical Deviations between Mean Measured and the Design Thicknesses

Descriptive Summary Statistics

Mean layer thickness data for SPS experimental sections with newly constructed layers were obtained from the TST_AC01_LAYER and TST_PC06 tables (core thickness), and from the SPS*_LAYER_THICKNESS tables (elevation thickness), to compute measured thickness deviation from the design value. The analysis was done for the sets of data grouped by target design thickness, material, and layer type. The following statistical indicators were computed:

- Total number of sections or layers
- Mean thickness deviation
- Minimum thickness deviation
- Maximum thickness deviation
- Standard deviation of thickness deviation
- COV of thickness deviation

The analyses were done separately for the thickness data obtained from core measurements and for the data from elevation measurements. Table 44 summarizes layer thickness deviations by different layer and material types based on analysis of elevation measurements. Table 45 summarizes mean core examination layer thickness deviations from their designed values by different layer and material types.

Figures 47 through 61 present the frequency distributions of the thickness deviations for different layer types and target thicknesses for both core and elevation thickness measurements.

The following observations are made based on these summary statistics:

- The computed description statistics using elevation measurement data are different from those using core examination data. However, based on statistical analyses, the differences in the mean layer thicknesses and standard deviations at the section or layer level are not significant for a majority of the layers.
- The mean constructed layer thicknesses for PCC layers and lean concrete base layers are generally above the designed values.
- For the same layer and material type, the mean constructed layer thicknesses tend to be above the designed value for the thinner layers, and below the design value for the thicker layers.

Table 44. Summary of differences between mean elevation thickness measurements and target thicknesses.

Mat. Type	Target Thickness		Total Number of Sections	Mean Difference		Standard Deviation		Min. Difference		Max. Difference	
	mm	in		mm	in	mm	in	mm	in	mm	in
DGAB	102	4	84	0.4	0.01	10.3	0.40	-28.6	-1.13	33.4	1.32
	152	6	55	-1.2	-0.05	14.4	0.57	-51.5	-2.03	38.2	1.51
	203	8	40	0.9	0.04	12.7	0.50	-26.8	-1.05	45.2	1.78
	305	12	40	-6.0	-0.24	30.0	1.18	-173.3	-6.82	34.9	1.37
DGATB	102	4	27	1.8	0.07	8.0	0.31	-12.0	-0.47	21.1	0.83
	203	8	42	0.5	0.02	16.3	0.64	-62.5	-2.46	28.9	1.14
	305	12	28	-2.1	-0.08	15.9	0.63	-35.1	-1.38	38.1	1.50
LC	152	6	48	5.5	0.22	10.6	0.42	-25.8	-1.02	36.9	1.45
PATB	102	4	129	1.2	0.05	10.5	0.41	-17.1	-0.67	41.9	1.65
PCC	76	3	12	18.2	0.72	11.5	0.45	3.4	0.13	42.6	1.68
	127	5	12	16.5	0.65	11.6	0.46	5.1	0.20	39.0	1.53
	203	8	76	5.4	0.21	12.2	0.48	-32.6	-1.28	53.3	2.10
	279	11	77	4.7	0.18	11.0	0.43	-24.8	-0.98	39.0	1.54
SB	51	2	46	4.8	0.19	19.9	0.78	-27.8	-1.10	67.9	2.67
	102	4	125	-2.2	-0.09	18.5	0.73	-58.9	-2.32	31.7	1.25
	127	5	46	-4.4	-0.17	20.1	0.79	-70.6	-2.78	38.3	1.51
	178	7	95	-8.2	-0.32	23.9	0.94	-73.3	-2.89	59.4	2.34
	203	8	7	-2.7	-0.11	22.9	0.90	-36.9	-1.45	36.3	1.43

Table 45. Summary of differences between mean core thickness measurements and target thicknesses.

Mat. Type	Target Thickness		Total Number of Sections	Mean Difference		Standard Deviation		Min. Difference		Max. Difference	
	mm	in		mm	in	mm	in	mm	in	mm	in
DGATB	102	4	22	-0.9	-0.04	10.9	0.43	-22.9	-0.90	20.3	0.80
	203	8	34	1.1	0.04	21.5	0.85	-64.3	-2.53	38.1	1.50
	305	12	22	-5.4	-0.21	25.1	0.99	-88.9	-3.50	21.0	0.83
LC	152	6	36	8.2	0.32	12.6	0.50	-19.1	-0.75	38.9	1.53
PATB	102	4	32	-19.7	-0.78	39.4	1.55	-87.2	-3.43	113.5	4.47
PCC	76	3	10	20.3	0.80	10.7	0.42	5.9	0.23	35.9	1.41
	127	5	12	13.4	0.53	13.5	0.53	-9.9	-0.39	37.1	1.46
	203	8	71	9.8	0.39	14.0	0.55	-22.5	-0.89	52.3	2.06
	279	11	71	-0.7	-0.03	28.3	1.12	-94.7	-3.73	31.8	1.25
SB	51	2	45	16.2	0.64	21.4	0.84	-17.1	-0.68	59.7	2.35
	102	4	114	5.2	0.20	17.0	0.67	-63.5	-2.50	47.0	1.85
	127	5	47	9.1	0.36	23.6	0.93	-39.4	-1.55	73.2	2.88
	178	7	94	-4.3	-0.17	21.8	0.86	-96.5	-3.80	65.4	2.58
	203	8	6	-18.4	-0.73	51.6	2.03	-118.1	-4.65	16.5	0.65

These summary statistics for the differences between as-designed and mean as-constructed layer thicknesses can be used as benchmarks for use in pavement design reliability and other research studies.

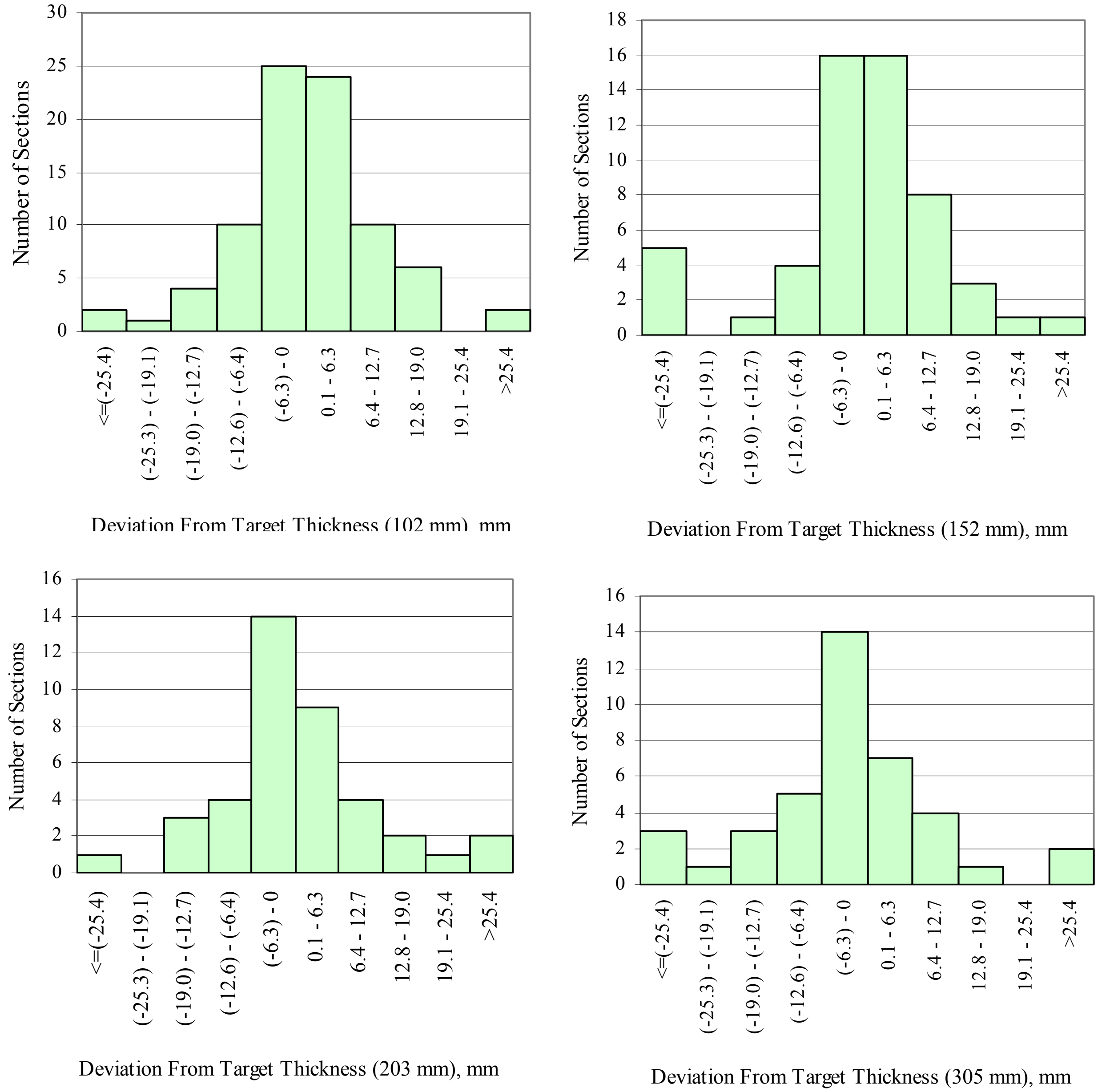


Figure 47: Chart. The Frequency distribution of mean thickness deviations for all four target thicknesses of the DGAB layer.

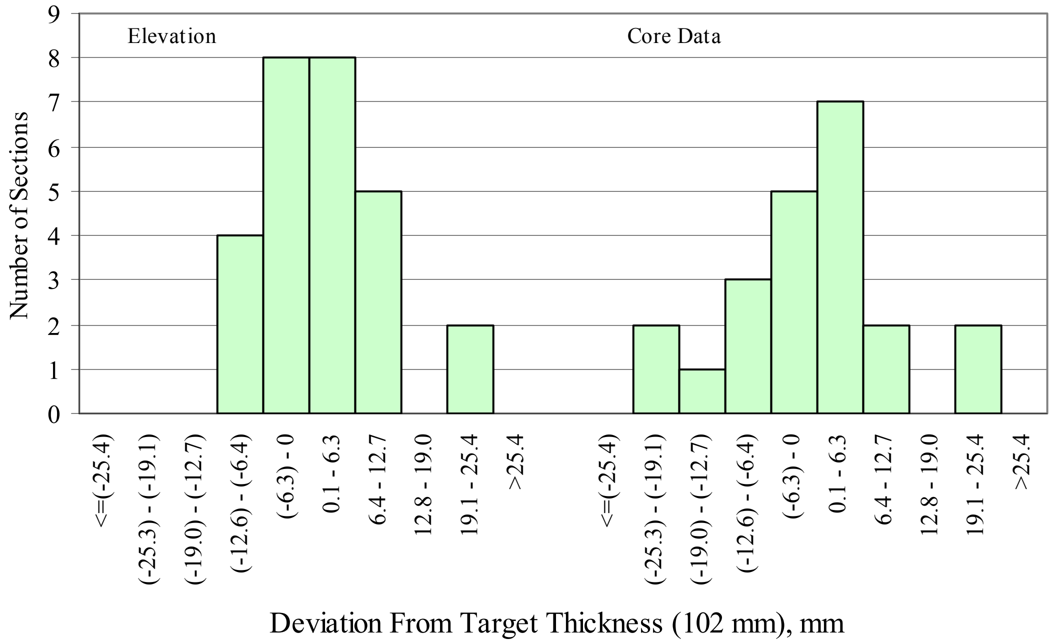


Figure 48: Chart. Frequency distribution of elevation and core thickness measurements deviations for DGATB with 102-mm (4-in) target thickness.

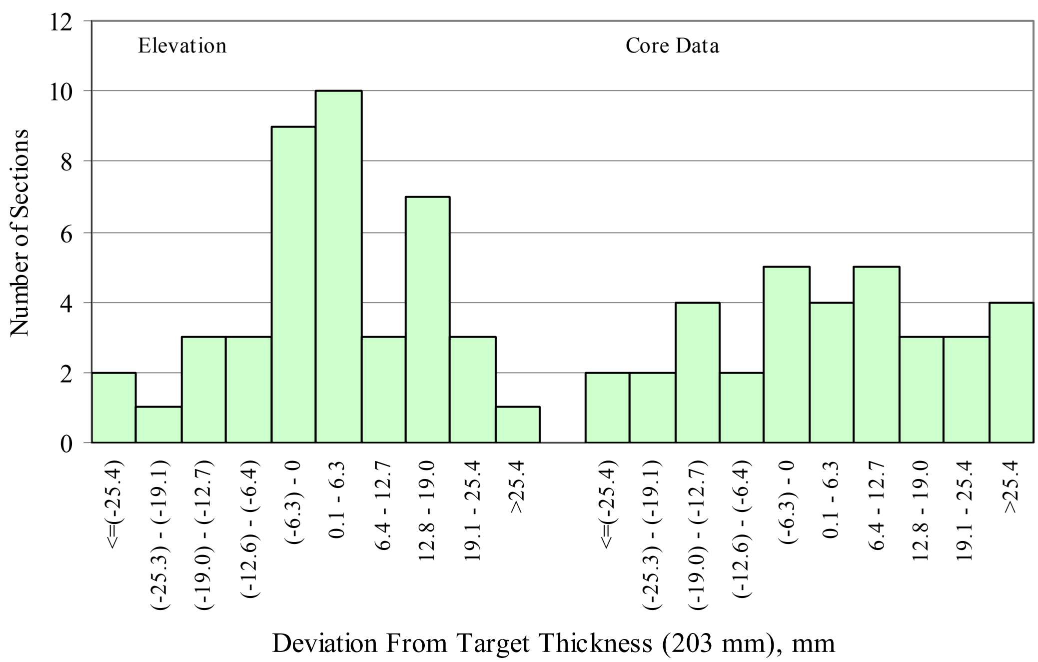


Figure 49: Chart. Frequency distribution of elevation and core thickness measurements deviations for DGATB with 203-mm (8-in) target thickness.

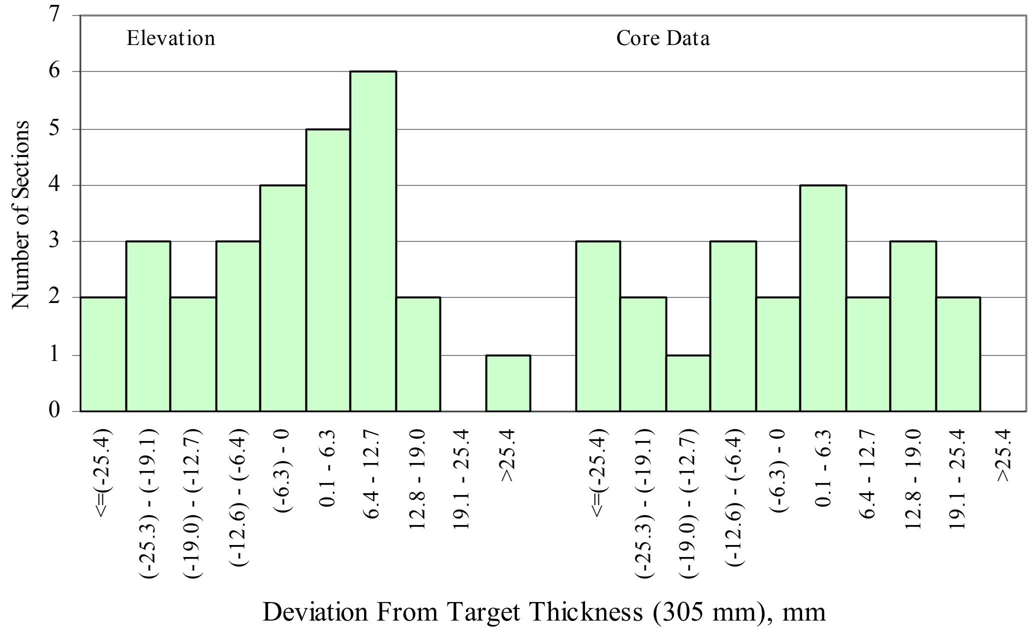


Figure 50: Chart. Frequency distribution of elevation and core thickness measurements deviations for DGATB with 305-mm (12-in) target thickness.

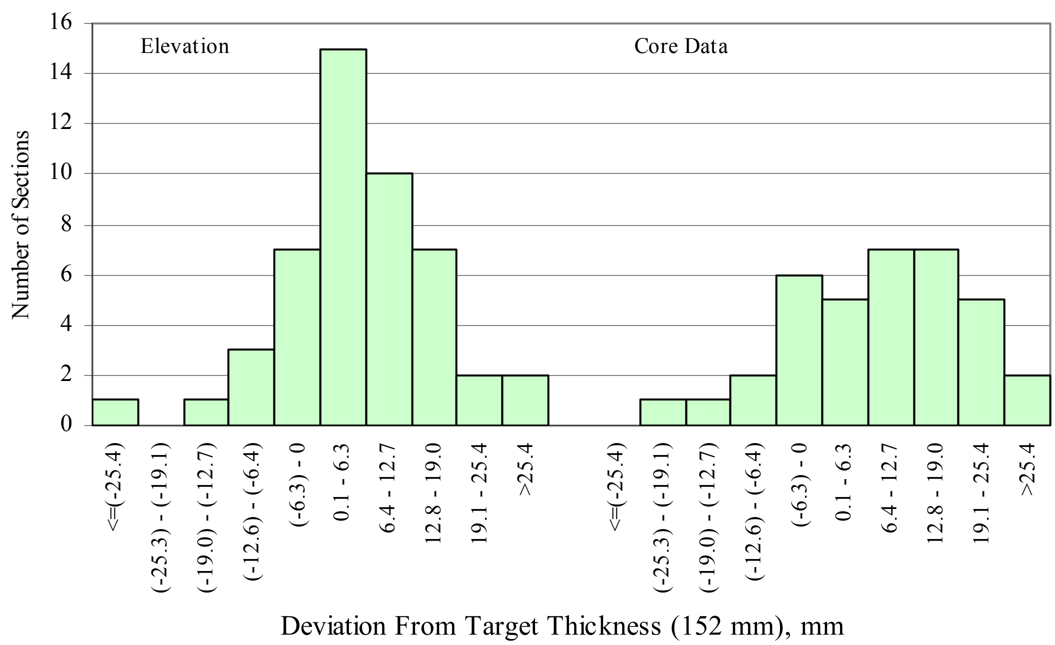


Figure 51: Chart. Frequency distribution of elevation and core thickness measurements deviations for LC with 152-mm (6-in) target thickness.

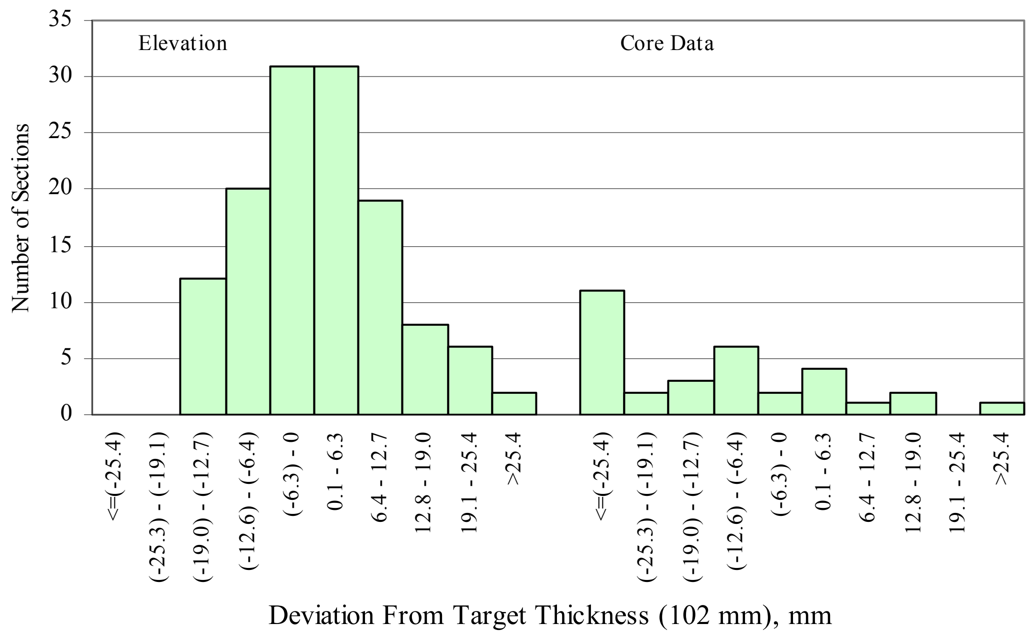


Figure 52: Chart. Frequency distribution of elevation and core thickness measurements deviations for PATB with 102-mm (4-in) target thickness.

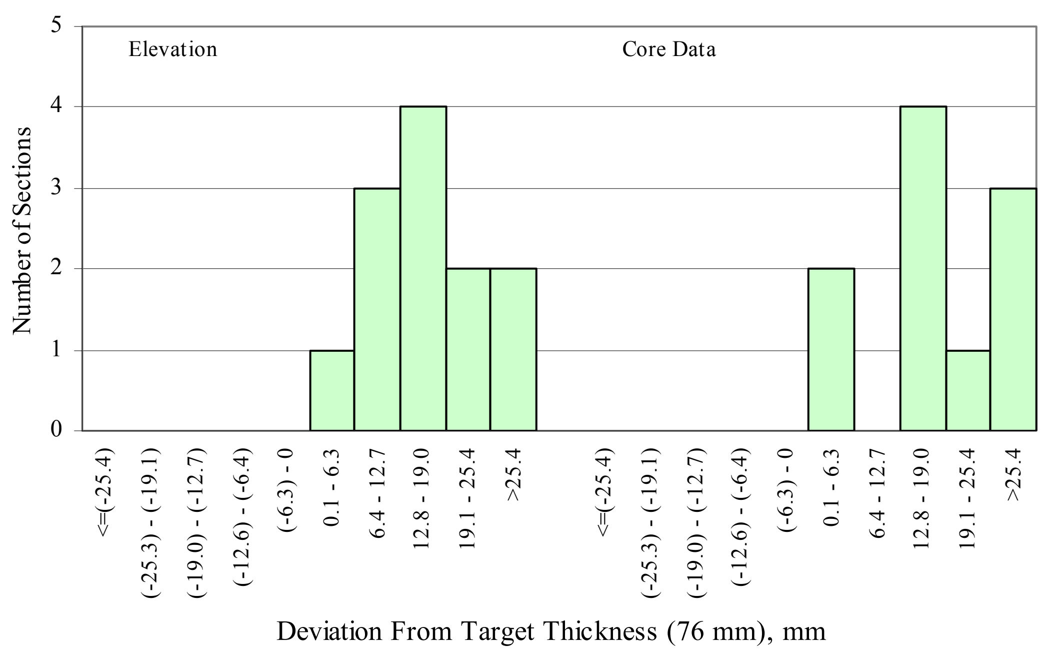


Figure 53: Chart. Frequency distribution of elevation and core thickness measurements deviations for PCC with 76-mm (3-in) target thickness.

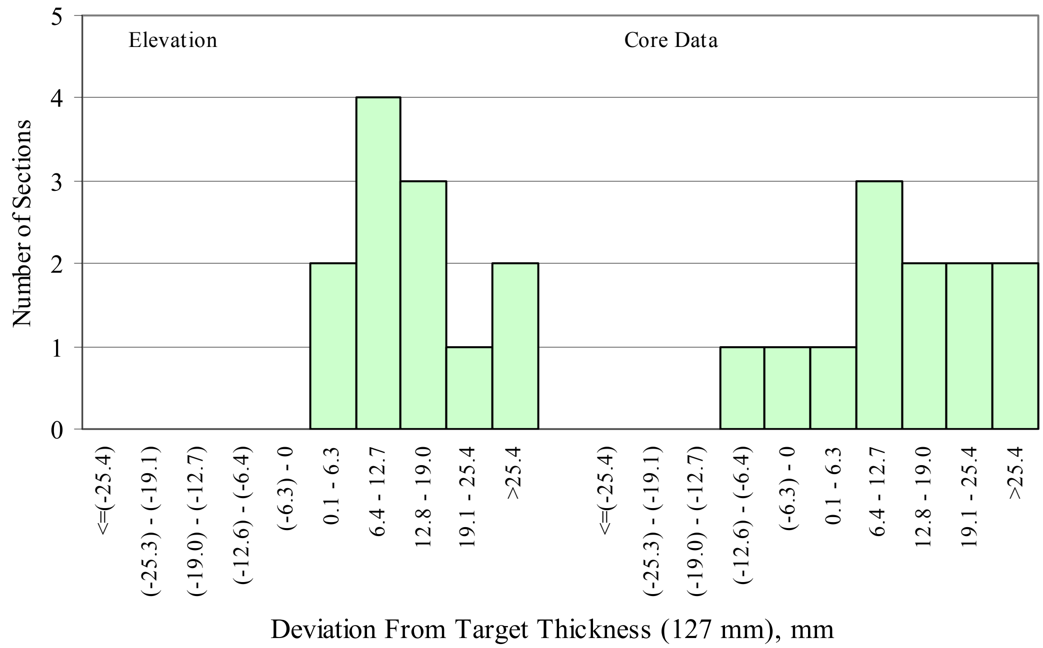


Figure 54: Chart. Frequency distribution of elevation and core thickness measurements deviations for PCC with 127-mm (5-in) target thickness.

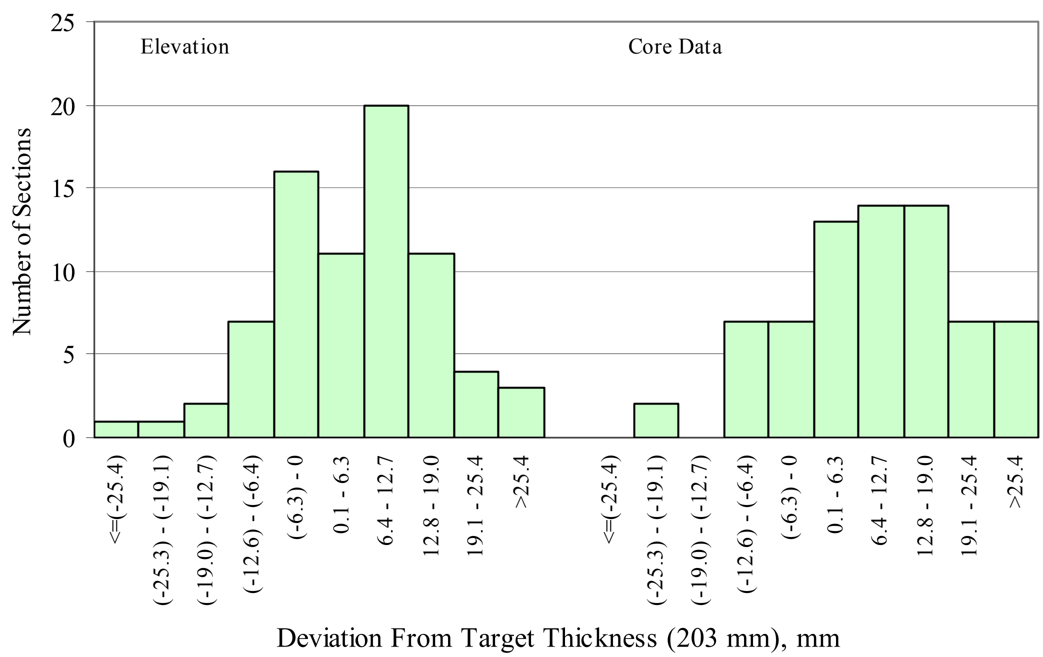


Figure 55: Chart. Frequency distribution of elevation and core thickness measurements deviations for PCC with 203-mm (8-in) target thickness.

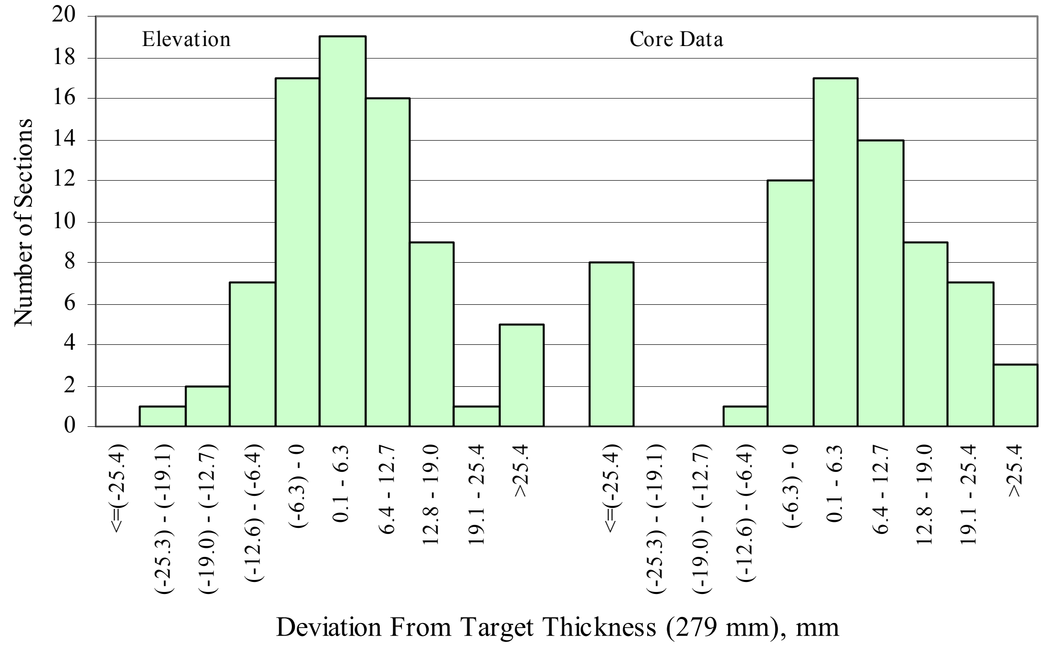


Figure 56: Chart. Frequency distribution of elevation and core thickness measurements deviations for PCC with 279-mm (11-in) target thickness.

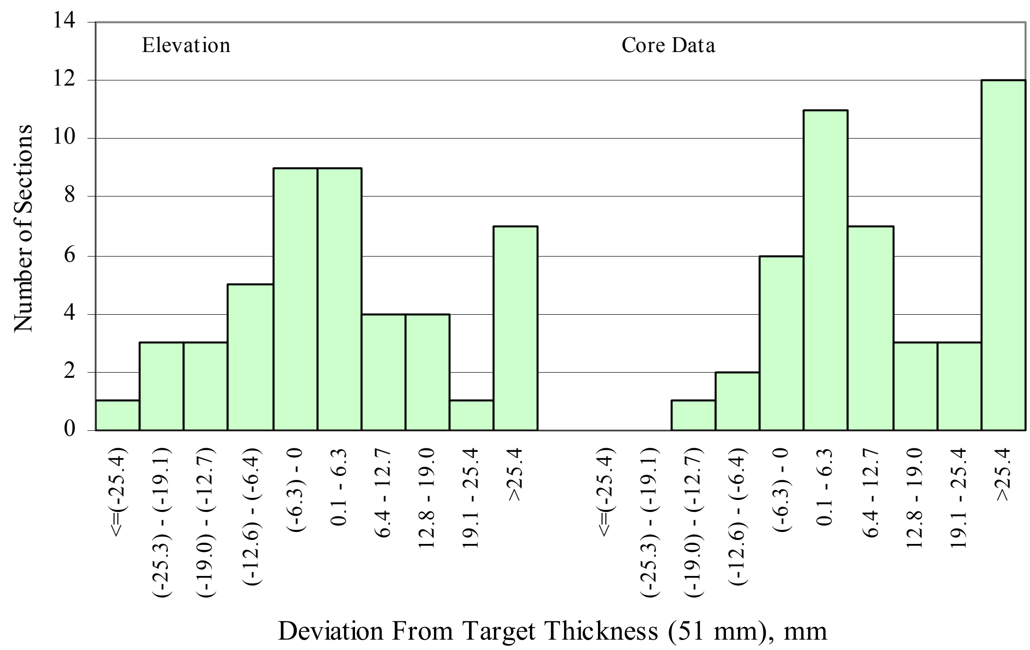


Figure 57: Chart. Frequency distribution of elevation and core thickness measurements deviations for SB with 51-mm (2-in) target thickness.

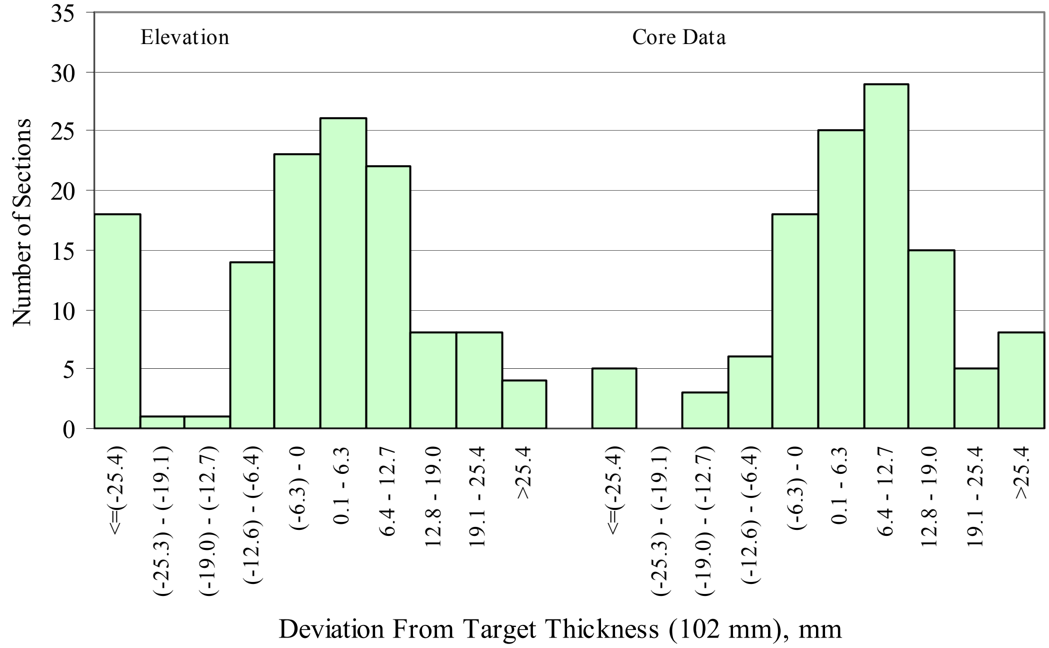


Figure 58: Chart. Frequency distribution of elevation and core thickness measurements deviations for SB with 102-mm (4-in) target thickness.

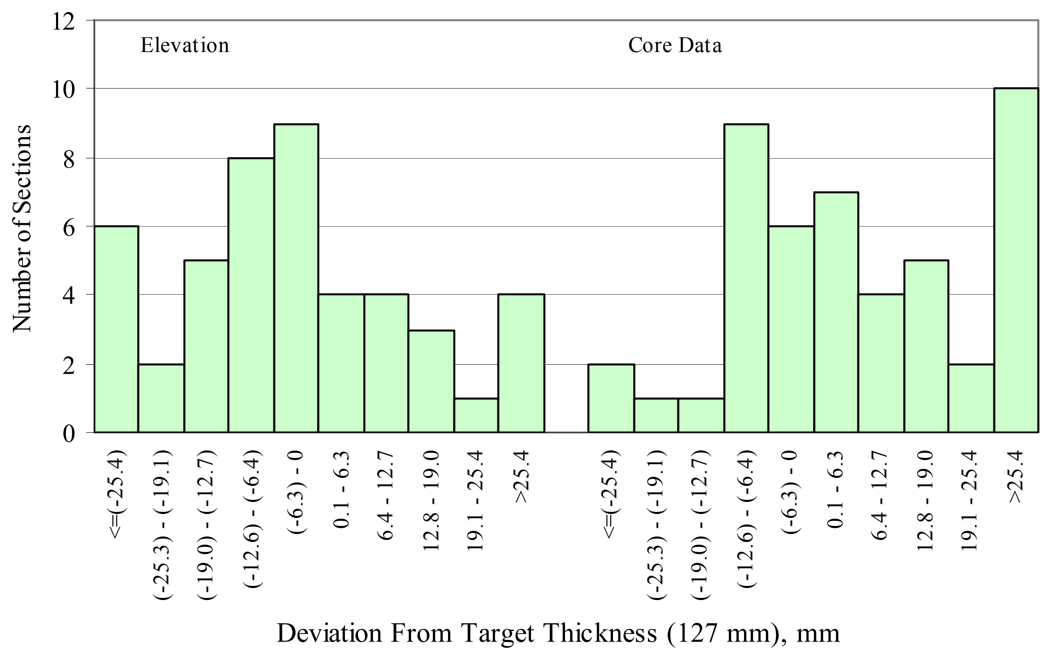


Figure 59: Chart. Frequency distribution of elevation and core thickness measurements deviations for SB with 127-mm (5-in) target thickness.

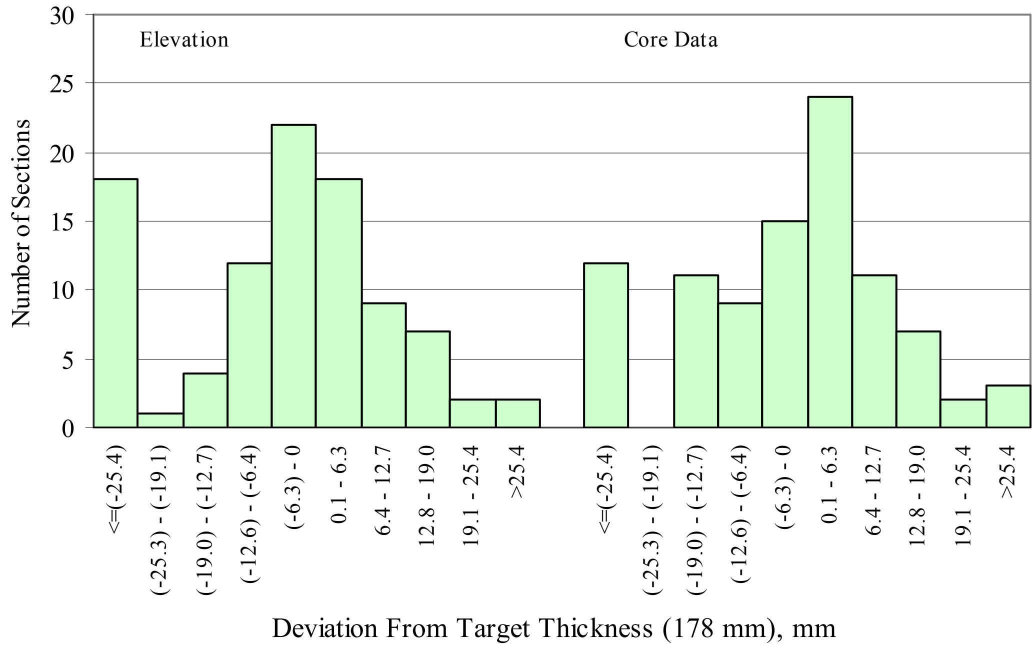


Figure 60: Chart. Frequency distribution of elevation and core thickness measurements deviations for SB with 178-mm (7-in) target thickness.

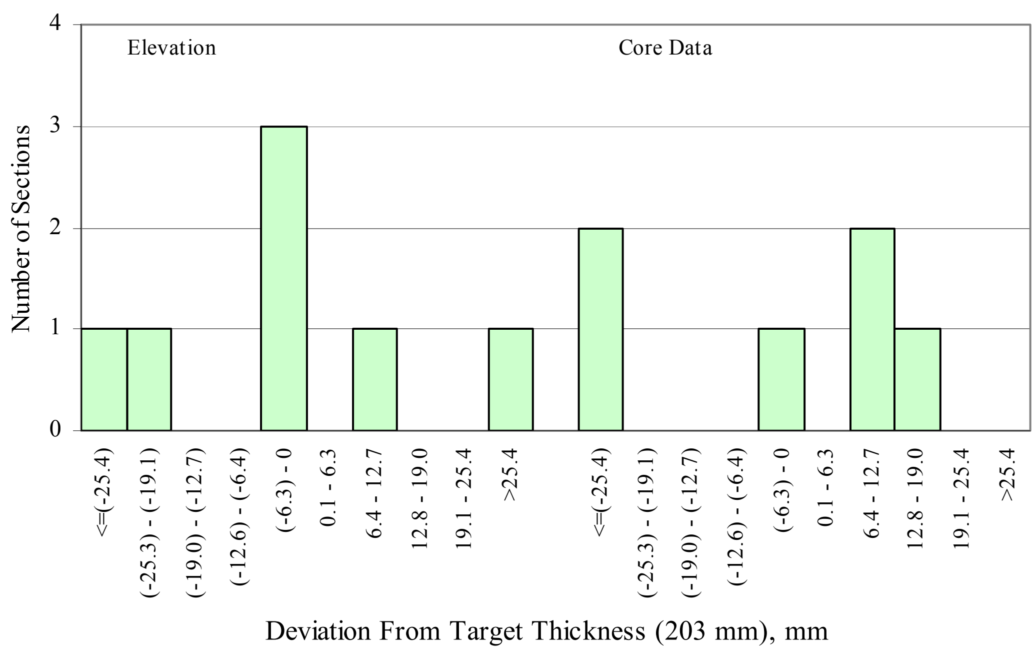


Figure 61: Chart. Frequency distribution of elevation and core thickness measurements deviations for SB with 203-mm (8-in) target thickness.

Layer Thickness Deviation Distribution Type

Mean thickness deviations from layers or sections were analyzed to determine whether they follow typical statistical distributions. Skewness and kurtosis analyses were conducted for this purpose. The statistical test results are presented in table 46 for both the elevation and core mean layer thicknesses. Examples of the thickness deviation distributions are shown in figures 62 and 63.

Table 46. Distribution of the mean thickness deviations from the design thickness based on kurtosis and skewness tests.

Mat. Type	Target Thickness		Elevation Measurement Data		Core Examination Data	
	mm	**in**	**No. Layers**	**Distribution Type**	**No. Layers**	**Distribution Type**
DGAB	102	4	84	Normal	No Data	
	152	6	55	Wide spread and skewed left		
	203	8	40	Wide spread and skewed right		
	305	12	40	Wide spread and skewed left		
DGATB	102	4	27	Normal	22	Normal
	203	8	42	Wide spread and skewed left	34	Normal
	305	12	28	Normal	22	Wide spread and skewed left
LC	152	6	48	Normal	36	Normal
PATB	102	4	129	Skewed right	32	Normal
PCC	76	3	12	Normal	10	Normal
	127	5	12	Normal	12	Normal
	203	8	76	Wide Spread	71	Normal
	279	11	77	Normal	71	Wide spread and skewed left
SB	51	2	46	Skewed right	45	Normal
	102	4	125	Skewed left	114	Wide spread and skewed left
	127	5	46	Normal	47	Normal
	178	7	95	Skewed left	94	Wide spread and skewed left
	203	8	7	Not enough data	6	Not enough data

As shown in table 46, there are some discrepancies between the distribution types drawn from elevation data and core data. For the layers with both elevation and core data, the distribution of the thickness deviation derived from the core data is normal for more layer type and design thicknesses than from the elevation data.

The conclusions drawn from both the descriptive statistics and the kurtosis and skewness tests of their distribution types will be useful for pavement designers and researchers. They will be especially useful in reliability based mechanistic-empirical pavement performance analysis and design.

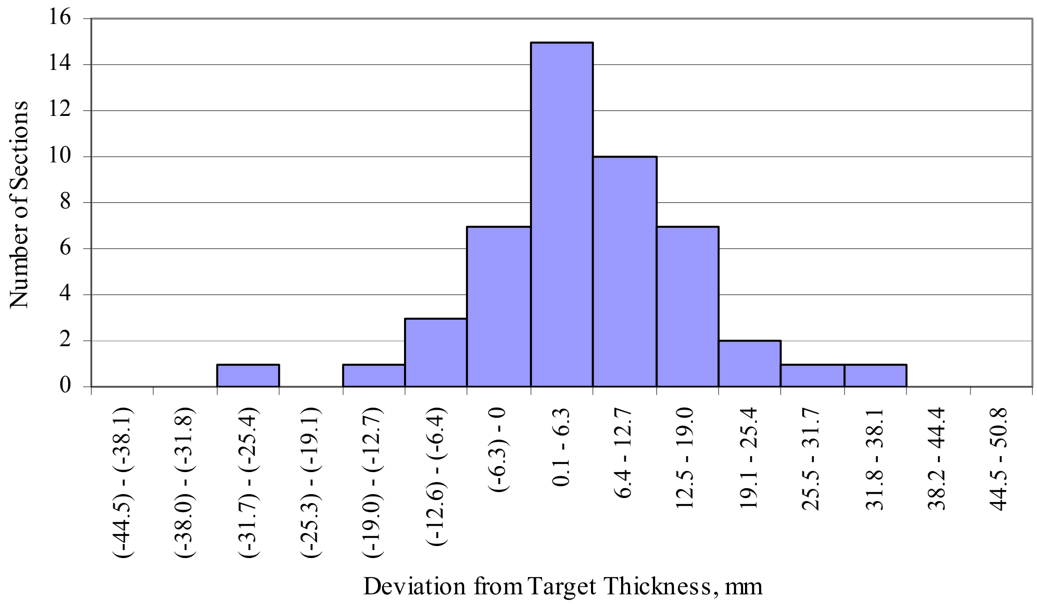


Figure 62: Chart. Example of normally distributed thickness deviations (elevation data, LC, target thickness 152 mm [6 in]).

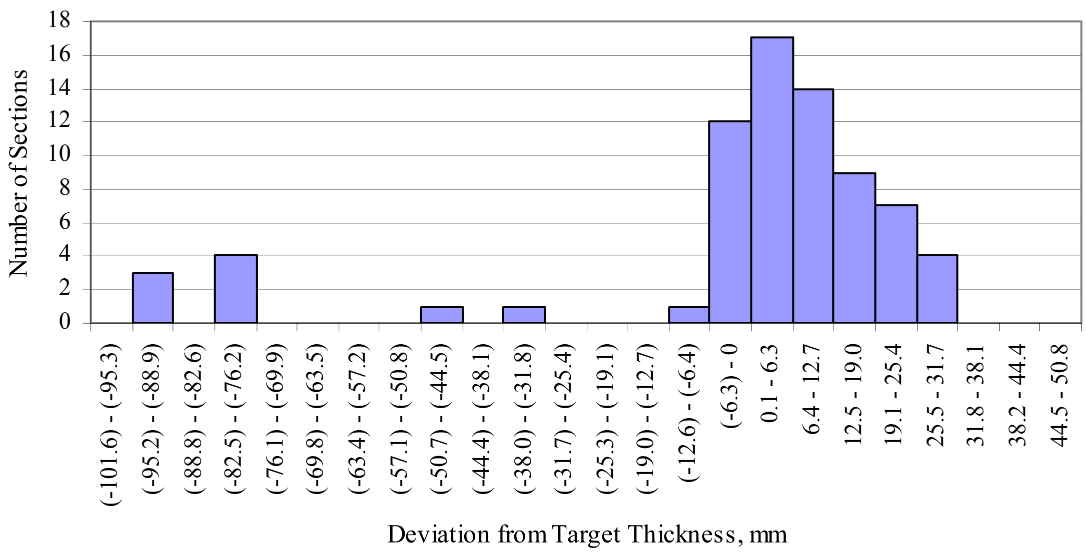


Figure 63: Chart. Example of a skewed distribution for layer thickness deviation (core data, PCC, target thickness 279 mm [11 in]).

Statistical Analysis of Elevation Measurements

Analysis of the Percentage Distribution

The overall percentage distribution of elevation measurements as a function of the three tolerance levels is presented in table 47.

Table 47. Percentage distribution summary of the elevation thickness measurements.

Measured Layer Thickness, t	Difference Between As-Constructed and As-Designed Thickness					
	Diff = 6.35 mm (0.25 in)		Diff = 12.7 mm (0.5 in)		Diff = 25.4 mm (1.0 in)	
	Number of Measurements	Percent of Measurements	Number of Measurements	Percent of Measurements	Number of Measurements	Percent of Measurements
t < TV[1] - Diff	15557	30.30	8481	16.52	3656	7.12
t within TV ± Diff	17788	34.65	32542	63.38	44324	86.33
t > TV + Diff	17996	35.05	10318	20.10	3361	6.55
Total	**51341**	**100**	**51341**	**100**	**51341**	**100**

Notes: [1]Target value

The distribution of measurements by layer type for tolerance levels of 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in) are presented in tables 48, 49, and 50, respectively.

Table 48. Percentage distribution of individual elevation measurements by layer type and design thickness for a tolerance level of 6.35 mm (0.25 in).

Layer Type	Target Thickness		Thickness <TV-6.35 mm (0.25 in)		Thickness Within TV ± 6.35 mm (0.25 in)		Thickness >TV+6.35 mm (0.25 in)		Total Number of Measurem.
	mm	in	Number of Measurem.	Percent of Measurem.	Number of Measurem.	Percent of Measurem.	Number of Measurem.	Percent of Measurem.	
DGAB	102	4	1376	31.9	1686	39.0	1256	29.1	4318
	152	6	820	31.1	1046	39.7	772	29.3	2638
	203	8	675	32.0	679	32.2	756	35.8	2110
	305	12	809	37.8	722	33.7	609	28.5	2140
DGATB	102	4	370	25.9	597	41.8	461	32.3	1428
	203	8	700	30.3	700	30.3	907	39.3	2307
	305	12	570	37.6	499	32.9	446	29.4	1515
LC	152	6	342	13.9	1034	42.1	1082	44.0	2458
PATB	102	4	2059	30.6	2554	37.9	2124	31.5	6737
PCC	76	3	7	1.5	96	21.0	355	77.5	458
	127	5	10	2.2	85	18.5	365	79.3	460
	203	8	706	18.5	1296	33.9	1821	47.6	3823
	279	11	713	18.3	1460	37.5	1721	44.2	3894
SB	51	2	655	27.3	810	33.8	932	38.9	2397
	102	4	2286	33.9	2203	32.6	2259	33.5	6748
	127	5	1107	46.2	617	25.8	671	28.0	2395
	178	7	2201	42.9	1589	30.9	1345	26.2	5135
	203	8	151	39.7	115	30.3	114	30.0	380
Total			**15557**	**30.3**	**17788**	**34.6**	**17996**	**35.1**	**51341**

Table 49. Percentage distribution of individual elevation measurements by layer type and design thickness for a tolerance level of 12.7 mm (0.5 in).

Layer Type	Target Thickness		Thickness <TV-12.7 mm (0.5 in)		Thickness Within TV ± 12.7 mm (0.5 in)		Thickness >TV+12.7 mm (0.5 in)		Total Number of Measurem.
	mm	in	Number of Measurem.	Percent of Measurem.	Number of Measurem.	Percent of Measurem.	Number of Measurem.	Percent of Measurem.	
DGAB	102	4	589	13.6	2990	69.2	739	17.1	4318
	152	6	447	16.9	1796	68.1	395	15.0	2638
	203	8	425	20.1	1284	60.9	401	19.0	2110
	305	12	560	26.2	1168	54.6	412	19.3	2140
DGATB	102	4	104	7.3	1087	76.1	237	16.6	1428
	203	8	384	16.6	1419	61.5	504	21.8	2307
	305	12	370	24.4	851	56.2	294	19.4	1515
LC	152	6	168	6.8	1661	67.6	629	25.6	2458
PATB	102	4	790	11.7	4774	70.9	1173	17.4	6737
PCC	76	3	2	0.4	159	34.7	297	64.8	458
	127	5	2	0.4	214	46.5	244	53.0	460
	203	8	323	8.4	2549	66.7	951	24.9	3823
	279	11	338	8.7	2745	70.5	811	20.8	3894
SB	51	2	374	15.6	1420	59.2	603	25.2	2397
	102	4	1360	20.2	4031	59.7	1357	20.1	6748
	127	5	747	31.2	1241	51.8	407	17.0	2395
	178	7	1380	26.9	2971	57.9	784	15.3	5135
	203	8	118	31.1	182	47.9	80	21.1	380
Total			**8481**	**16.5**	**32542**	**63.4**	**10318**	**20.1**	**51341**

Table 50. Percentage distribution of individual elevation measurements by layer type and design thickness for a tolerance level of 25.4 mm (1 in).

Layer Type	Target Thickness		Mean Thickness <TV-25.4 mm (1in)		Mean Thickness Within TV ± 25.4 mm (1in)		Mean Thickness >TV+25.4 mm (1in)		Total Number of Measurem.
	mm	in	Number of Measurem.	Percent of Measurem.	Number of Measurem.	Percent of Measurem.	Number of Measurem.	Percent of Measurem.	
DGAB	102	4	181	4.2	3910	90.6	227	5.3	4318
	152	6	187	7.1	2310	87.6	141	5.3	2638
	203	8	124	5.9	1807	85.6	179	8.5	2110
	305	12	260	12.1	1688	78.9	192	9.0	2140
DGATB	102	4	9	0.6	1403	98.2	16	1.1	1428
	203	8	134	5.8	2038	88.3	135	5.9	2307
	305	12	170	11.2	1249	82.4	96	6.3	1515
LC	152	6	33	1.3	2228	90.6	197	8.0	2458
PATB	102	4	108	1.6	6378	94.7	251	3.7	6737
PCC	76	3	0	0.0	308	67.2	150	32.8	458
	127	5	0	0.0	336	73.0	124	27.0	460
	203	8	64	1.7	3474	90.9	285	7.5	3823
	279	11	45	1.2	3593	92.3	256	6.6	3894
SB	51	2	72	3.0	1970	82.2	355	14.8	2397
	102	4	925	13.7	5512	81.7	311	4.6	6748
	127	5	298	12.4	1866	77.9	231	9.6	2395
	178	7	983	19.1	3987	77.6	165	3.2	5135
	203	8	63	16.6	267	70.3	50	13.2	380
Total			**3656**	**7.1**	**44324**	**86.3**	**3361**	**6.5**	**51341**

The graphical presentations of percentage distributions of elevation measurements are shown in figures 64, 65, and 66 for different tolerance levels.

The following conclusions may be drawn based on the percentage distributions of the elevation measurements:

- Overall, about 35 percent of the measurements are within ± 6.35 mm (0.25 in) of the target value, with about 30 percent lower than the target value and about 35 percent higher than the target value by more than 6.35 mm (0.25 in).
- Thickness measurements for asphalt concrete surface and binder layers and thin bonded PCC layers consistently show the highest deviations from the target values.
- The percentage of thickness measurements that is greater than the target value for jointed PCC and lean concrete base layers is significantly higher than the percentage of the measurements that are lower than the target value. Only 2 percent of thickness measurements are lower and almost 80 percent are higher than the target value by more than 6.35 mm (0.25 in) for thin PCC bonded layers (76-mm- [3-in-] and 127-mm- [5-in-] thick).
- Thickness measurements for PATB are more evenly distributed around the target value than the thickness measurements for other layer types.

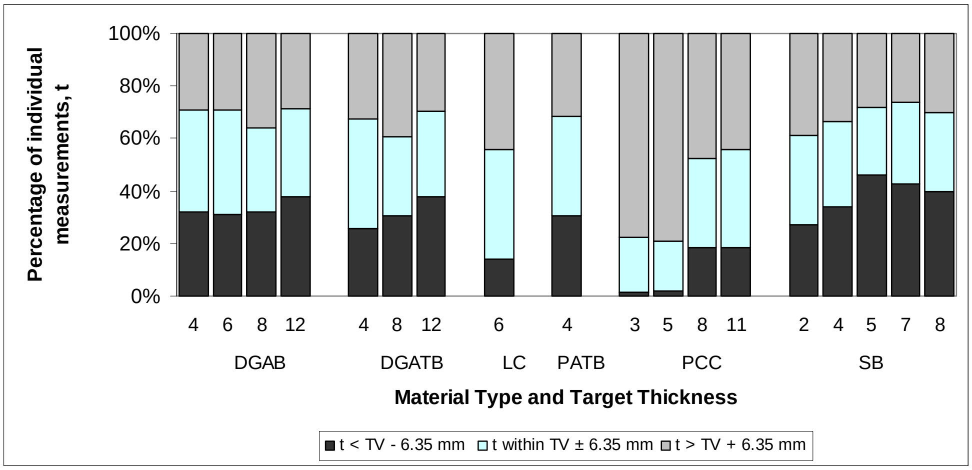


Figure 64: Chart. Percentage distribution of the elevation measurements for a tolerance level of 6.35 mm (0.25 in) for different material types and design thicknesses.

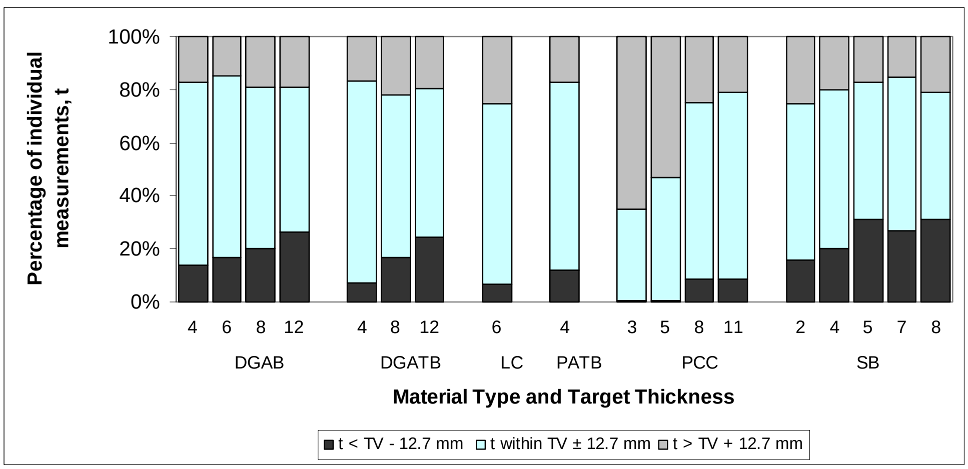


Figure 65: Chart. Percentage distribution of the elevation measurements for a tolerance level of 12.7 mm (0.5 in) for different material types and design thicknesses.

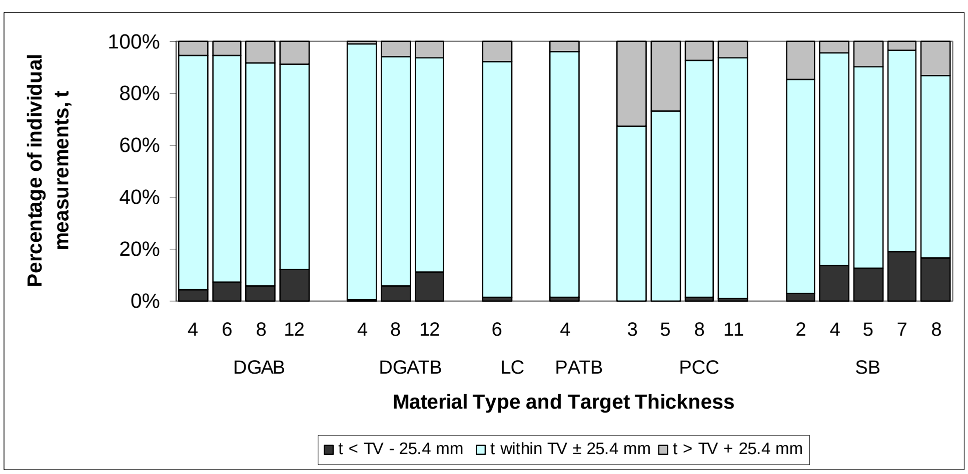


Figure 66: Chart. Percentage distribution of the elevation measurements for a tolerance level of 25.4 mm (1 in) for different material types and design thicknesses.

Statistical Analysis of the Elevation Measurements

Two-sided t-test

After removing the outlying data points (as discussed in chapter 4), t-tests are performed to evaluate whether the mean constructed thicknesses are close to the designed thicknesses. Many of these tests are highly significant, meaning that the mean constructed thickness is significantly different from the designed thickness.

The following notes apply to tables 51 to 56 and tables 61 to 66:

- "Number of layers" is used to summarize number of layers (which can be different layer types and belong to the same or different sections) falling into certain tolerance range. This is normally an overall summary.
- "Number of sections" is used to summarize number of sections with the specified layer type and design thickness falling into certain tolerance range. This is used for summarizing results by layer type and design thickness.

Results of two-sided t-test with 95 percent confidence are presented in table 51. The results of the two-sided t-tests by layer material type and target thickness are given in table 52.

Table 51. Summary of the results of the two-sided t-tests (95 percent confidence level) using elevation measurements.

Mean Thickness	Number of Layers	Percentage of Layers
Significantly lower than the target value	357	36.10
No significant difference from the target value	196	19.82
Significantly higher than the target value	436	44.08
Total	**989**	**100**

The following observations are based on the results of the two-sided t-test for the elevation measurements:

- Overall, only about 20 percent of the layers had mean constructed thicknesses not significantly different from their target thicknesses.
- All 24 sections with 76-mm (3-in) or 123-mm (5-in) target thicknesses for bonded PCC overlays are constructed significantly thicker.
- For only 4 to 15 percent of the sections with SB layers and target thicknesses between 51 mm (2 in) and 178 mm (7 in), the as-constructed mean thickness is not significantly different from the as-designed thickness.
- The lowest deviations from as-designed thickness are observed for DGAB layers, for which more than 30 percent of sections have as-constructed mean thickness not significantly different from the target value.

Table 52. Results of the two-sided t-test for different material types (95 percent confidence level) by layer type and design thickness using elevation measurements.

Layer Type	**Target Thickness**		**Significantly Lower than the Target Value**		**No Significant Difference**		**Significantly Higher than the Target Value**		**Total Number of Sections**
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGAB	102	4	28	33.3	27	32.1	29	34.5	84
	152	6	20	36.4	14	25.5	21	38.2	55
	203	8	12	30.0	15	37.5	13	32.5	40
	305	12	16	40.0	13	32.5	11	27.5	40
DGATB	102	4	10	37.0	5	18.5	12	44.4	27
	203	8	15	35.7	12	28.6	15	35.7	42
	305	12	14	50.0	3	10.7	11	39.3	28
LC	152	6	9	18.8	11	22.9	28	58.3	48
PATB	102	4	48	37.2	26	20.2	55	42.6	129
PCC	76	3	0	0.0	0	0.0	12	100.0	12
	127	5	0	0.0	0	0.0	12	100.0	12
	203	8	20	26.3	11	14.5	45	59.2	76
	279	11	16	20.8	21	27.3	40	51.9	77
SB	51	2	19	41.3	4	8.7	23	50.0	46
	102	4	50	40.0	16	12.8	59	47.2	125
	127	5	29	63.0	2	4.3	15	32.6	46
	178	7	48	50.5	14	14.7	33	34.7	95
	203	8	3	42.9	2	28.6	2	28.6	7
Total			**357**	**36.1**	**196**	**19.8**	**436**	**44.1**	**989**

One-sided t-test

Three one-sided t-tests with a confidence level of 95 percent were performed to evaluate whether the absolute differences between as-constructed and as-designed thicknesses are greater than 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in), respectively. The results of the overall analysis of all data points for all layers are presented in table 53.

The results of the analysis by layer material type for different tolerance levels are presented in tables 54 to 56.

Table 53. Summary of the results of one-sided t-tests using elevation measurements.

Level of Significance (TV – Target Value)	**Difference Between the Mean As-Constructed and As-Designed Thickness**					
	6.35 mm (0.25 in)		**12.7 mm (0.5 in)**		**25.4 mm (1.0 in)**	
	Number of Layers	Percent of Layers	Number of Layers	Percent of Layers	Number of Layers	Percent of Layers
Significantly lower than TV	181	18.3	102	10.3	50	5.1
No significant difference from the TV	562	56.8	760	76.8	908	91.8
Significantly higher than TV	246	26.9	127	12.8	31	3.1
Total	**989**	**100**	**989**	**100**	**989**	**100**

Table 54. Results of one-sided t-test for tolerance level of 6.35 mm (0.25 in) by layer type and design thickness using elevation measurements.

Layer Type	**Target Thickness**		**Mean Thickness <TV-6.35 mm (0.25 in)**		**Mean Thickness Within TV ± 6.35 mm (0.25 in)**		**Mean Thickness >TV+6.35 mm (0.25 in)**		**Total Number of Sections**
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGAB	102	4	12	14.3	59	70.2	13	15.5	84
	152	6	9	16.4	40	72.7	6	10.9	55
	203	8	5	12.5	28	70.0	7	17.5	40
	305	12	9	22.5	25	62.5	6	15.0	40
DGATB	102	4	3	11.1	20	74.1	4	14.8	27
	203	8	8	19.0	22	52.4	12	28.6	42
	305	12	8	28.6	12	42.9	8	28.6	28
LC	152	6	3	6.3	28	58.3	17	35.4	48
PATB	102	4	21	16.3	81	62.8	27	20.9	129
PCC	76	3	0	0.0	2	16.7	10	83.3	12
	127	5	0	0.0	3	25.0	9	75.0	12
	203	8	5	6.6	41	53.9	30	39.5	76
	279	11	8	10.4	44	57.1	25	32.5	77
SB	51	2	9	19.6	24	52.2	13	28.3	46
	102	4	31	24.8	65	52.0	29	23.2	125
	127	5	19	41.3	17	37.0	10	21.7	46
	178	7	29	30.5	47	49.5	19	20.0	95
	203	8	2	28.6	4	57.1	1	14.3	7
Total			**181**	**18.3**	**562**	**56.8**	**246**	**24.9**	**989**

Table 55. Results of one-sided t-tests for tolerance level of 12.7 mm (0.5 in) by layer type and design thickness using elevation measurements.

Layer Type	**Target Thickness**		**Mean Thickness <TV-12.7 mm (0.5 in)**		**Mean Thickness Within TV ± 12.7 mm (0.5 in)**		**Mean Thickness >TV+12.7 mm (0.5 in)**		**Total Number of Sections**
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGAB	102	4	5	6.0	73	86.9	6	7.1	84
	152	6	6	10.9	47	85.5	2	3.6	55
	203	8	3	7.5	33	82.5	4	10.0	40
	305	12	6	15.0	32	80.0	2	5.0	40
DGATB	102	4	0	0.0	25	92.6	2	7.4	27
	203	8	5	11.9	29	69.0	8	19.0	42
	305	12	6	21.4	19	67.9	3	10.7	28
LC	152	6	1	2.1	40	83.3	7	14.6	48
PATB	102	4	5	3.9	111	86.0	13	10.1	129
PCC	76	3	0	0.0	7	58.3	5	41.7	12
	127	5	0	0.0	6	50.0	6	50.0	12
	203	8	4	5.3	60	78.9	12	15.8	76
	279	11	2	2.6	62	80.5	13	16.9	77
SB	51	2	6	13.0	29	63.0	11	23.9	46
	102	4	20	16.0	88	70.4	17	13.6	125
	127	5	10	21.7	29	63.0	7	15.2	46
	178	7	21	22.1	66	69.5	8	8.4	95
	203	8	2	28.6	4	57.1	1	14.3	7
Total			**102**	**10.3**	**760**	**76.8**	**127**	**12.8**	**989**

Table 56. Results of one-sided t-test for tolerance level of 25.4 mm (1 in) by layer type and design thickness using elevation measurements.

Layer Type	Target Thickness		Mean Thickness <TV-25.4 mm (1in)		Mean Thickness Within TV ± 25.4 mm (1 in)		Mean Thickness >TV+25.4 mm (1in)		Total Number of Sections
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGAB	102	4	0	0.0	83	98.8	1	1.2	84
	152	6	4	7.3	50	90.9	1	1.8	55
	203	8	0	0.0	39	97.5	1	2.5	40
	305	12	2	5.0	38	95.0	0	0.0	40
DGATB	102	4	0	0.0	27	100.0	0	0.0	27
	203	8	2	4.8	39	92.9	1	2.4	42
	305	12	1	3.6	26	92.9	1	3.6	28
LC	152	6	0	0.0	46	95.8	2	4.2	48
PATB	102	4	0	0.0	127	98.4	2	1.6	129
PCC	76	3	0	0.0	10	83.3	2	16.7	12
	127	5	0	0.0	10	83.3	2	16.7	12
	203	8	1	1.3	73	96.1	2	2.6	76
	279	11	0	0.0	75	97.4	2	2.6	77
SB	51	2	0	0.0	41	89.1	5	10.9	46
	102	4	18	14.4	104	83.2	3	2.4	125
	127	5	4	8.7	39	84.8	3	6.5	46
	178	7	17	17.9	76	80.0	2	2.1	95
	203	8	1	14.3	5	71.4	1	14.3	7
Total			**50**	**5.1**	**908**	**91.8**	**31**	**3.1**	**989**

The results of the one-sided t-tests for the elevation measurements are shown in figures 67, 68, and 69 for the three different tolerance levels.

The following observations are drawn based on the results of the one-sided t-test for the elevation measurements:

- The AC surface and binder layers have the greatest number of sections with the mean constructed thickness tested to deviate more than their target values plus or minus all three tolerance levels (6.35 mm [0.25 in], 12.7 mm [0.5 in], and 25.4 mm [1 in]).
- For most sections (about 70 percent), the mean constructed thicknesses for the dense-graded aggregate base layers are within ±6.35 mm (0.25 in) of their target thickness values.
- For portland cement concrete slabs and lean concrete bases, a much higher percent of sections had mean thicknesses greater than the target values plus tolerance levels than the ones below the target values. For thin bonded PCC overlays (76-mm- [3-in-] and 127-mm- [5-in-] thick) there are no sections with an as-constructed thickness significantly lower than the target value for all three tolerance levels.
- For all layer material types, except AC surface and binder layers and thin bonded PCC slabs, more than 90 percent of sections have mean layer thicknesses tested within ±25.4 mm (1 in) from their target values.

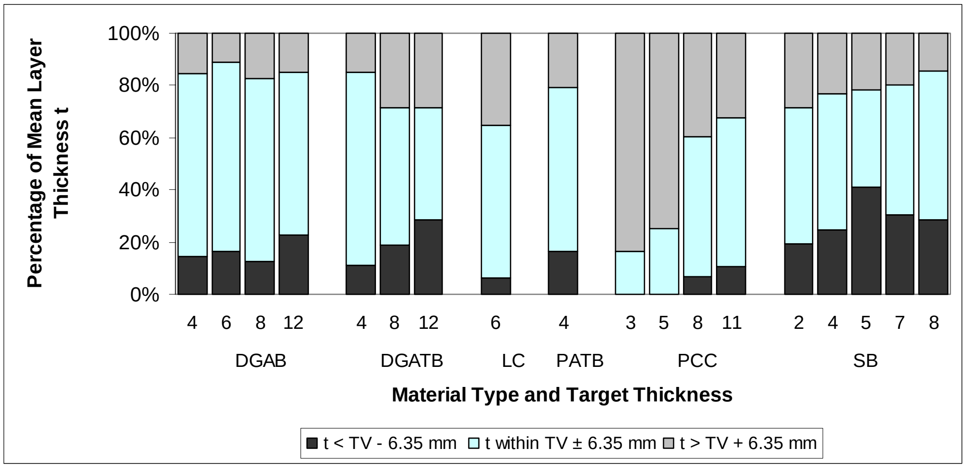


Figure 67: Chart. Results of one-sided t-tests for the differences between mean elevation and design thicknesses for a tolerance level of 6.35 mm (0.25 in).

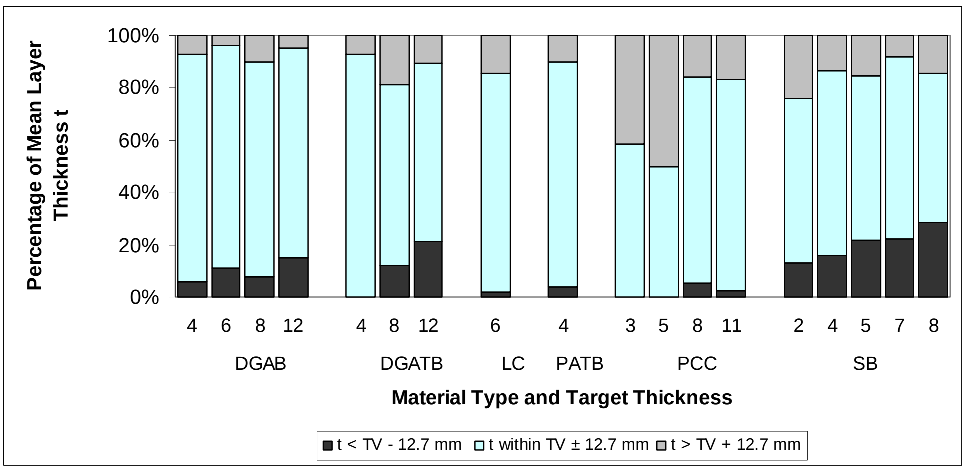


Figure 68: Chart. Results of one-sided t-tests for the differences between mean elevation and design thicknesses for a tolerance level of 12.7 mm (0.5 in).

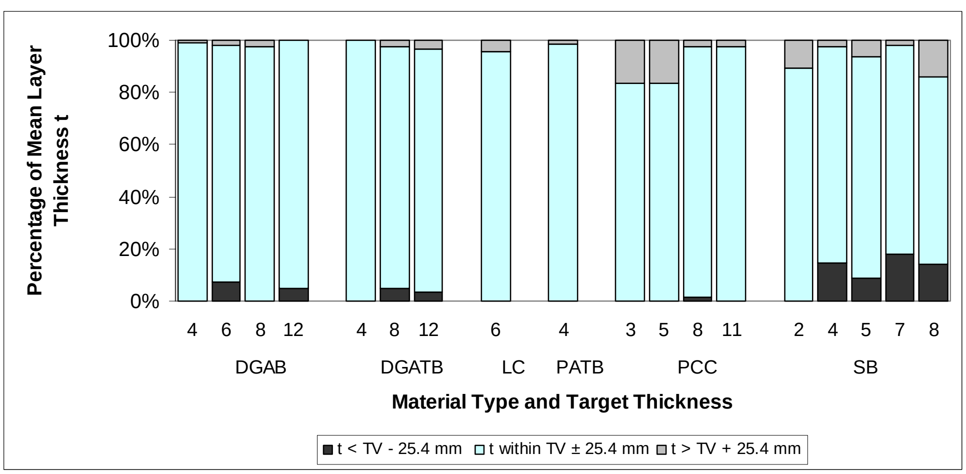


Figure 69: Chart. Results of one-sided t-tests for the differences between mean elevation and design thicknesses for a tolerance level of 25.4 mm (1 in).

Statistical Analysis of the Core Thickness Data

Analysis of the Percentage Distribution

The percentage distribution of core data as a function of different tolerance levels is presented in table 57.

Table 57. Summary of the percentage distribution of the individual core thickness measurements versus the design thickness.

Measured Layer Thickness t	Difference Between As-Constructed and As-Designed					
	Diff = 6.35 mm (0.25 in)		Diff = 12.7 mm (0.5 in)		Diff = 25.4 mm (1.0 in)	
	Number of Measurements	Percent of Measurements	Number of Measurements	Percent of Measurements	Number of Measurements	Percent of Measurements
t < TV[1] – Diff	617	19.04	368	11.35	179	5.52
t within TV ± Diff	1117	34.46	2026	62.51	2720	83.92
t > TV + Diff	1507	46.50	847	26.13	342	10.55
Total	**3241**	**100**	**3241**	**100**	**3241**	**100**

Notes: [1]Target value

The distributions of measurements by layer type for tolerance levels of 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in) are presented in tables 58, 59, and 60 for different layer types and target thickness values.

Table 58. Percentage distribution of core thickness measurements by layer type and design thickness for a tolerance level of 6.35 mm (0.25 in).

Layer Type	Target Thickness		Thickness <TV-6.35 mm (0.25 in)		Thickness Within TV ± 6.35 mm (0.25 in)		Thickness >TV+6.35 mm (0.25 in)		Total Number of Cores
	mm	in	Number of Cores	Percent of Cores	Number of Cores	Percent of Cores	Number of Cores	Percent of Cores	
DGATB	102	4	23	25.0	46	50.0	23	25.0	92
	203	8	42	29.6	46	32.4	54	38.0	142
	305	12	36	40.4	20	22.5	33	37.1	89
LC	152	6	24	13.2	50	27.5	108	59.3	182
PATB	102	4	86	60.6	39	27.5	17	12.0	142
PCC	76	3			5	6.8	68	93.2	73
	127	5	11	6.8	26	16.1	124	77.0	161
	203	8	48	10.2	159	33.8	263	56.0	470
	279	11	67	15.2	182	41.4	191	43.4	440
SB	51	2	10	6.0	63	38.0	93	56.0	166
	102	4	63	11.8	213	39.9	258	48.3	534
	127	5	64	22.1	85	29.4	140	48.4	289
	178	7	134	30.5	180	41.0	125	28.5	439
	203	8	9	40.9	3	13.6	10	45.5	22
Total			**617**	**19.0**	**1117**	**34.5**	**1507**	**46.5**	**3241**

Table 59. Percentage distribution of core thickness measurements by layer type and design thickness for a tolerance level of 12.7 mm (0.5 in).

Layer Type	**Target Thickness**		**Thickness <TV-12.7 mm (0.5 in)**		**Thickness Within TV ± 12.7 mm (0.5 in)**		**Thickness >TV+12.7 mm (0.5 in)**		**Total Number of Cores**
	mm	in	Number of Cores	Percent of Cores	Number of Cores	Percent of Cores	Number of Cores	Percent of Cores	
DGATB	102	4	8	8.7	76	82.6	8	8.7	92
	203	8	22	15.5	90	63.4	30	21.1	142
	305	12	28	31.5	40	44.9	21	23.6	89
LC	152	6	15	8.2	105	57.7	62	34.1	182
PATB	102	4	69	48.6	63	44.4	10	7.0	142
PCC	76	3	0	0.0	25	34.2	48	65.8	73
	127	5	8	5.0	66	41.0	87	54.0	161
	203	8	24	5.1	300	63.8	146	31.1	470
	279	11	38	8.6	315	71.6	87	19.8	440
SB	51	2	4	2.4	96	57.8	66	39.8	166
	102	4	29	5.4	387	72.5	118	22.1	534
	127	5	22	7.6	166	57.4	101	34.9	289
	178	7	93	21.2	290	66.1	56	12.8	439
	203	8	8	36.4	7	31.8	7	31.8	22
Total			**368**	**11.4**	**2026**	**62.5**	**847**	**26.1**	**3241**

Table 60. Percentage distribution of core thickness measurements by layer type and design thickness for a tolerance level of 25.4 mm (1 in).

Layer Type	**Target Thickness**		**Thickness <TV-25.4 mm (1 in)**		**Thickness Within TV ± 25.4 mm (1 in)**		**Thickness >TV+25.4 mm (1 in)**		**Total Number of Cores**
	mm	in	Number of Cores	Percent of Cores	Number of Cores	Percent of Cores	Number of Cores	Percent of Cores	
DGATB	102	4	2	2.2	90	97.8	0	0.0	92
	203	8	10	7.0	123	86.6	9	6.3	142
	305	12	15	16.9	70	78.7	4	4.5	89
LC	152	6	2	1.1	171	94.0	9	4.9	182
PATB	102	4	45	31.7	90	63.4	7	4.9	142
PCC	76	3	0	0.0	51	69.9	22	30.1	73
	127	5	0	0.0	123	76.4	38	23.6	161
	203	8	10	2.1	419	89.1	41	8.7	470
	279	11	32	7.3	387	88.0	21	4.8	440
SB	51	2	0	0.0	123	74.1	43	25.9	166
	102	4	13	2.4	476	89.1	45	8.4	534
	127	5	7	2.4	205	70.9	77	26.6	289
	178	7	37	8.4	379	86.3	23	5.2	439
	203	8	6	27.3	13	59.1	3	13.6	22
Total			**179**	**5.5**	**2720**	**83.9**	**342**	**10.6**	**3241**

The graphical presentation of the percentage distributions of core thickness measurements is shown in figures 70, 71, and 72 for the three different tolerance levels.

The following are observed based on the percentage distributions of the individual core thickness measurements:

- Overall, less than 35 percent of core measurements are within ± 6.35 mm of the design thickness value. For some material types and target thickness values, such as thin PCC layers (76 mm [3 in] or 123 mm [5 in] thick) and 203-mm- (8-in-) thick SB layers, this percentage is below 20.
- For LC and PCC layers, a much larger percentage of cores have thicknesses higher than designed. For PATB, the situation is just the opposite.
- For DGATB, SB, and PCC layers, the percentage of sections with as-constructed thicknesses below the target value increases with target thickness. For PCC layers, the percentage of sections with as-constructed thickness above the target value decreases with increasing target thickness.

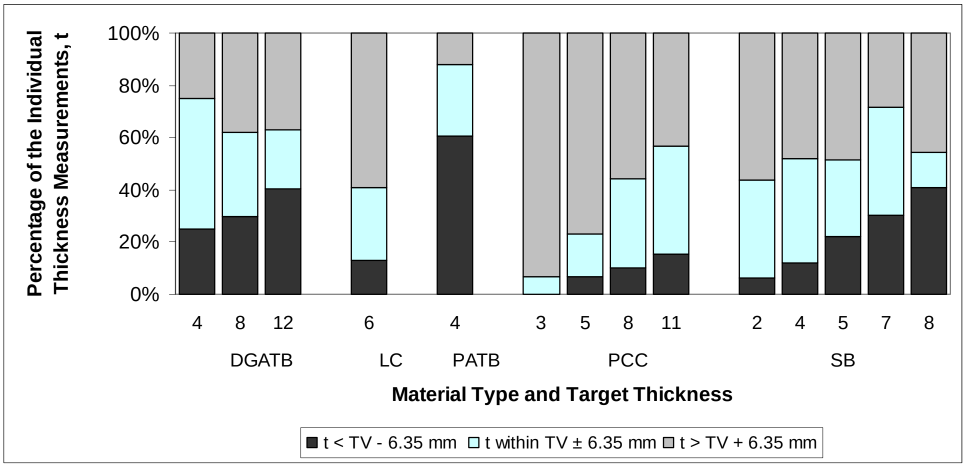


Figure 70: Chart. Percentage distribution of core measurements by layer type and design thickness for a tolerance level of 6.35 mm (0.25 in).

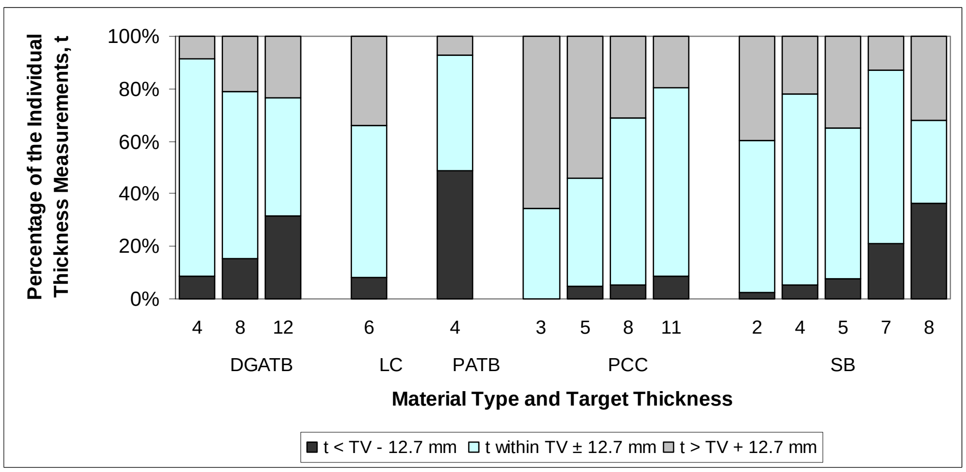


Figure 71: Chart. Percentage distribution of core measurements by layer type and design thickness for a tolerance level of 12.7 mm (0.5 in).

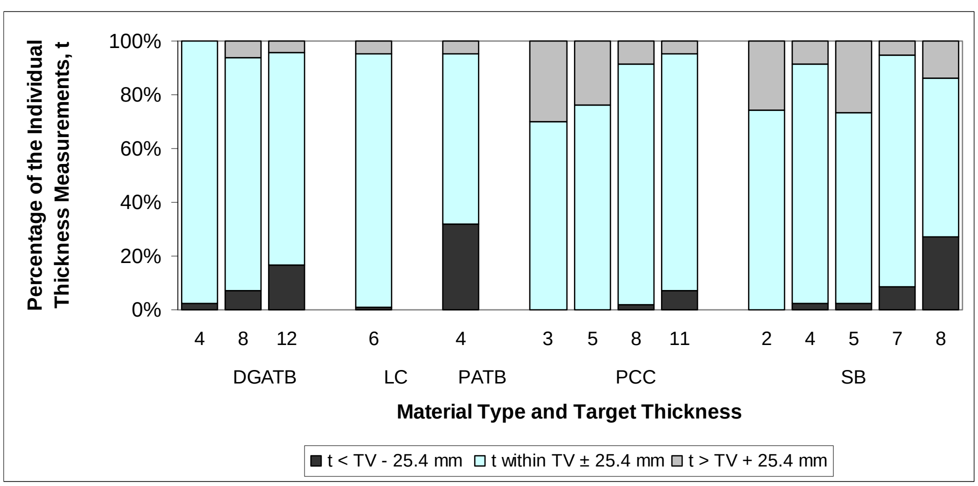


Figure 72: Chart. Percentage distribution of core measurements by layer type and design thickness for a tolerance level of 25.4 mm (1 in).

Statistical Analysis of the Core Data

Two-sided t-test

The results of the two-sided t-tests with 95 percent confidence are presented in table 61. The distribution of differences by different surface type and target thickness is presented in table 62.

Table 61. Summary of the results of the two-sided t-test (95 percent confidence level) using core thickness data.

Difference	**Number of Layers**	**Percentage of Layers**
Significantly lower than the target value	90	15.38
No significant difference from the target value	268	45.81
Significantly higher than the target value	227	38.80
Total	**585**	**100**

Table 62. Distribution of differences by layer type and design thickness (two-sided t-test, 95 percent confidence level) using core thickness data.

Layer Type	**Target Thickness**		**Significantly Lower than the Target Value**		**No Significant Difference**		**Significantly Higher than the Target Value**		**Total Number of Sections**
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGATB	102	4	3	15.8	15	78.9	1	5.3	19
	203	8	5	16.1	16	51.6	10	32.3	31
	305	12	3	15.8	11	57.9	5	26.3	19
LC	152	6	2	5.7	13	37.1	20	57.1	35
PATB	102	4	13	41.9	15	48.4	3	9.7	31
PCC	76	3	0	0.0	2	20.0	8	80.0	10
	127	5	1	8.3	2	16.7	9	75.0	12
	203	8	6	8.5	21	29.6	44	62.0	71
	279	11	12	17.1	32	45.7	26	37.1	70
SB	51	2	3	7.7	18	46.2	18	46.2	39
	102	4	13	11.8	49	44.5	48	43.6	110
	127	5	11	23.9	15	32.6	20	43.5	46
	178	7	17	19.8	54	62.8	15	17.4	86
	203	8	1	16.7	5	83.3	0	0.0	6
Total			**90**	**15.4**	**268**	**45.8**	**227**	**38.8**	**585**

The following are observed based on the results of the two-sided t-test for the core thickness measurements:

- Overall, the mean constructed thickness for more than 45 percent of layers is not significantly different from the target thickness. The percentage is highest for DGATB and lowest for PCC and LC.
- DGATB has the highest number of sections (61 percent) with mean constructed thicknesses not different from the target values. For almost 80 percent of the sections

with DGATB and 102-mm (4-in) target thickness, the constructed thickness is not significantly different from the designed thickness.

- PCC and LC layers have the fewest number of layers (between 34 and 37 percent) with mean constructed thicknesses not significantly different from the target values. For thin PCC slabs, this percentage is 20 or below.

One-sided t-test

Three one-sided t-tests (95 percent confidence level) were performed to check whether the difference between as-constructed and as-designed thickness is lower than 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in), respectively. The results of the overall analysis of all data points for all layers are summarized in table 63.

The results of the analysis by layer type for different tolerance levels are presented in tables 64 through 66.

Table 63. Summary of the results of the one-sided t-tests using core thickness data.

Level of Significance	**Difference Between As-Constructed and As-Designed Thickness**					
	6.35 mm (0.25 in)		**12.7 mm (0.5 in)**		**25.4 mm (1.0 in)**	
	Number of Layers	Percent of Layers	Number of Layers	Percent of Layers	Number of Layers	Percent of Layers
Significantly lower than the target value	58	9.91	34	5.81	22	3.76
No significant difference from the target value	378	64.62	473	80.85	533	91.11
Significantly higher than the target value	149	25.47	78	13.33	30	5.13
Total	**585**	**100**	**585**	**100**	**585**	**100**

Table 64. Results of the one-sided t-test (95 percent confidence level) by layer type and design thickness for tolerance level of 6.35 mm (0.25 in) using core thickness data.

Layer Type	**Target Thickness**		**Mean Thickness <TV-6.35 mm (0.25 in)**		**Mean Thickness Within TV ± 6.35 mm (0.25 in)**		**Mean Thickness >TV+6.35 mm (0.25 in)**		**Total Number of Sections**
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGATB	102	4	1	5.3	17	89.5	1	5.3	19
	203	8	4	12.9	20	64.5	7	22.6	31
	305	12	3	15.8	12	63.2	4	21.1	19
LC	152	6	2	5.7	22	62.9	11	31.4	35
PATB	102	4	13	41.9	16	51.6	2	6.5	31
PCC	76	3	0	0.0	2	20.0	8	80.0	10
	127	5	0	0.0	5	41.7	7	58.3	12
	203	8	2	2.8	40	56.3	29	40.8	71
	279	11	6	8.6	50	71.4	14	20.0	70
SB	51	2	1	2.6	20	51.3	18	46.2	39
	102	4	7	6.4	75	68.2	28	25.5	110
	127	5	5	10.9	27	58.7	14	30.4	46
	178	7	12	14.0	68	79.1	6	7.0	86
	203	8	2	33.3	4	66.7	0	0.0	6
Total			**58**	**9.9**	**378**	**64.6**	**149**	**25.5**	**585**

Table 65. Results of the one-sided t-test (95 percent confidence level) by layer type and design thickness for tolerance level of 12.7 mm (0.5 in) using core examination data.

Layer Type	**Target Thickness**		**Mean Thickness <TV-12.7 mm (0.5 in)**		**Mean Thickness Within TV ± 12.7 mm (0.5 in)**		**Mean Thickness >TV+12.7 mm (0.5 in)**		**Total Number of Sections**
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGATB	102	4	0	0.0	18	94.7	1	5.3	19
	203	8	0	0.0	27	87.1	4	12.9	31
	305	12	2	10.5	14	73.7	3	15.8	19
LC	152	6	0	0.0	27	77.1	8	22.9	35
PATB	102	4	10	32.3	20	64.5	1	3.2	31
PCC	76	3	0	0.0	4	40.0	6	60.0	10
	127	5	0	0.0	6	50.0	6	50.0	12
	203	8	1	1.4	58	81.7	12	16.9	71
	279	11	6	8.6	59	84.3	5	7.1	70
SB	51	2	0	0.0	29	74.4	10	25.6	39
	102	4	5	4.5	97	88.2	8	7.3	110
	127	5	1	2.2	33	71.7	12	26.1	46
	178	7	7	8.1	77	89.5	2	2.3	86
	203	8	2	33.3	4	66.7	0	0.0	6
Total			**34**	**5.8**	**473**	**80.9**	**78**	**13.3**	**585**

Table 66. Results of the one-sided t-test (95 percent confidence level) by layer type and design thickness for tolerance level of 25.4 mm (1 in) using core examination data.

Layer Type	**Target Thickness**		**Mean Thickness <TV-25.4 mm (1 in)**		**Mean Thickness Within TV ± 25.4 mm (1 in)**		**Mean Thickness >TV+25.4 mm (1 in)**		**Total Number of Sections**
	mm	in	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	Number of Sections	Percent of Sections	
DGATB	102	4	0	0.0	19	100.0	0	0.0	19
	203	8	0	0.0	31	100.0	0	0.0	31
	305	12	1	5.3	18	94.7	0	0.0	19
LC	152	6	0	0.0	34	97.1	1	2.9	35
PATB	102	4	7	22.6	23	74.2	1	3.2	31
PCC	76	3	0	0.0	8	80.0	2	20.0	10
	127	5	0	0.0	10	83.3	2	16.7	12
	203	8	0	0.0	68	95.8	3	4.2	71
	279	11	6	8.6	64	91.4	0	0.0	70
SB	51	2	0	0.0	32	82.1	7	17.9	39
	102	4	3	2.7	103	93.6	4	3.6	110
	127	5	0	0.0	37	80.4	9	19.6	46
	178	7	4	4.7	81	94.2	1	1.2	86
	203	8	1	16.7	5	83.3	0	0.0	6
Total			**22**	**3.8**	**533**	**91.1**	**30**	**5.1**	**585**

The graphical presentations of one sided t-test results of core thickness measurements are shown in figures 73, 74, and 75 for the three different tolerance levels.

The following conclusions may be drawn based on results of the t-test for the core thickness measurements:

- The PCC layers have the highest percentage of sections with mean measured thicknesses above their target thicknesses for all three tolerance levels. This percentage decreases with the increased PCC target thickness. For thin bonded PCC layers (76-mm- [3-in-] or 123-mm- [5-in-] thick), there are no sections with layer thicknesses significantly lower than the target value. For very thin bonded PCC overlays (76-mm- [3-in-] thick), 80 percent of the sections have mean thicknesses significantly higher than the target value for more than 6.35 mm (0.25 in). This percentage decreases with increasing target thickness.
- For all material types except PATB and 178-mm- (7-in-) and 203-mm- (8-in-) thick SB layers, a much larger percentage of layers have a mean thickness significantly higher than designed. For PATB, the situation is just the opposite, with more than 40 percent of layers having values that are significantly lower than the target value for more than 6.35 mm (0.25 in). For 203-mm- (8-in-) thick SB layers, there are no sections with a mean measured thicknesses significantly higher than designed.
- For DGATB and SB layers, the number of sections with mean thicknesses below target thickness increases with the design thickness.
- All sections with DGATB and LC layers, except one, have thicknesses within ± 25.4 mm (1 in) of the target thickness.

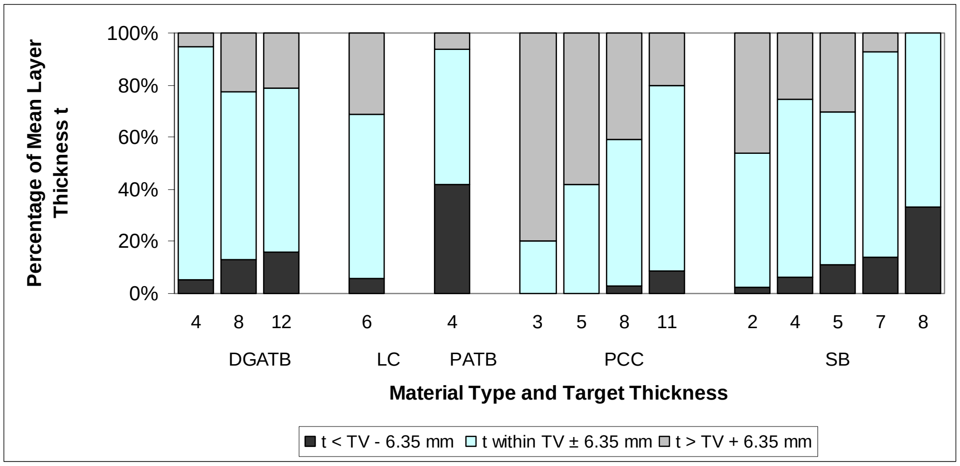


Figure 73: Chart. Results of one-sided t-tests for the differences between core measurements and design thicknesses for tolerance level of 6.35 mm (0.25 in).

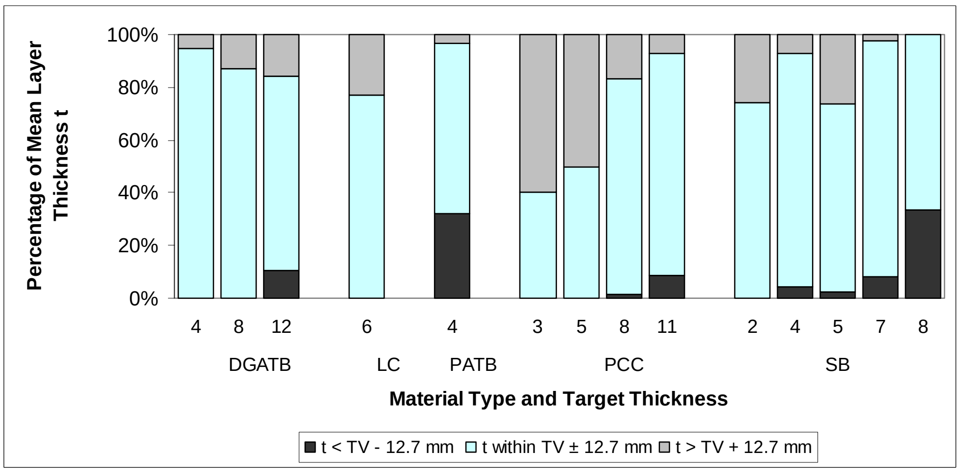


Figure 74: Chart. Results of one-sided t-tests for the differences between mean core and design thicknesses by layer type and design thickness for tolerance level of 12.7 mm (0.5 in).

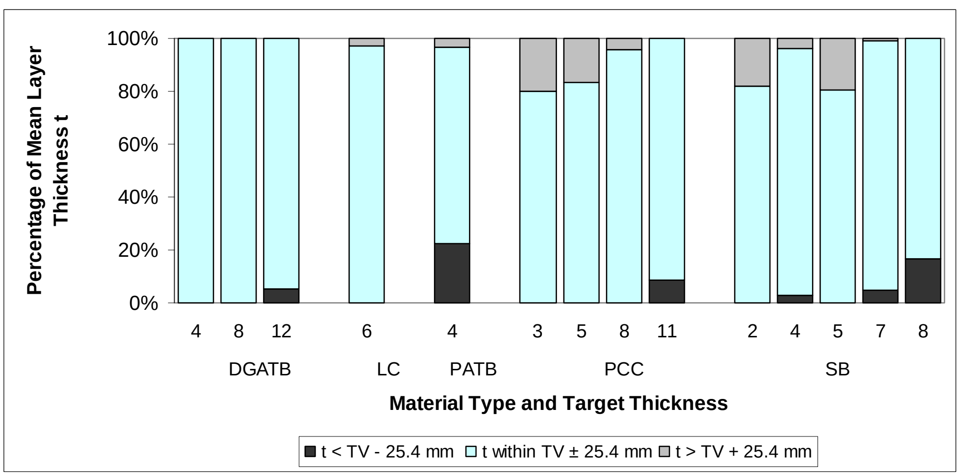


Figure 75: Chart. Results of one-sided t-tests for the differences between mean core and design thicknesses by layer type and design thickness for tolerance level of 25.4 mm (1 in).

Summary

In this chapter, the as-constructed core and elevation grid layer thickness measurements were compared to the design thicknesses for newly constructed SPS layers.

The mean thickness difference between as-designed and as-constructed thicknesses was computed for each layer using both core and elevation thickness measurements and typical thickness deviations from the target thicknesses are summarized, as well as their distribution types.

For both data sources, two types of comparisons are made in relation to their as-designed thicknesses or target values. First, both data sources were evaluated for the percentage of individual measurements either within or outside specific values from the target thickness. Second, a statistical analysis was performed to compare the measured mean thickness values with the designed values. Two types of the thickness comparisons are performed for both data sources. The two-sided t-test with 95 percent confidence level was used for each section and layer to determine whether differences between as-designed and as-constructed thicknesses are significant. One-sided t-tests with 95 percent confidence level were used for each layer to determine if the difference between as-designed thickness and the mean as-constructed thickness had significant allowances of more than 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in), respectively.

Based on the analysis of both data sources, the following conclusions can be made:

- The computed description statistics using elevation measurement data are different from those using core examination data. However, based on statistical analyses, the differences in the mean layer thicknesses and standard deviations at the section or layer level are not significant for a majority of the layers.
- For the same layer and material type, the mean constructed layer thicknesses tend to be above the designed value for the thinner layers and below the design value for the thicker layers.
- The majority of the LC and PCC layers have constructed or measured thicknesses greater than the design values. This is particularly true for thin (76-mm- [3-in-] and 127-mm- [5-in-] thick) PCC slabs.
- Thin PCC and AC surface and binder layers have the highest number of sections with a mean as-constructed thickness that significantly deviates from the design thicknesses.
- Elevation thickness measurements for PATB are more evenly distributed around the target value. However, the core measurements for PATB show that a significant number of sections have thicknesses lower than the target thickness. It appears that for some cores the entire thickness of PATB layer was not obtained. The analysis shows the values currently stored in the database. A feedback report was submitted regarding these questionable data. In some cases, core thicknesses were less than 25.4 mm (1 in), even though the target thickness is 102 mm (4 in).
- About 60 percent of all section/layers have mean thickness within ±6.35 mm (0.25 in) from the target thickness. For a tolerance level of 25.4 mm (1 in) this percentage is above 90 for most layer types and target thickness values.

A comparison between analysis results from the elevation and core thickness measurements shows that the percentage of measurements within the selected limits is approximately the same for all three tolerance levels. However, the percentage of measurements lower than the target value is consistently higher for core measurements than for elevation grid measurements.

Based on elevation measurements, it is observed that more than 70 percent of sections with DGAB have as-constructed thickness within ±6.35 mm (0.25 in) from the design value.

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary and Conclusions

This study was conducted to assess quality and completeness of pavement layering information and layer thickness data and to provide recommendations for improvement of the data that are currently available in the LTPP database. Within-section layer thickness variability was characterized, and as-designed and as-constructed thicknesses were compared. Additionally, a *Guide for LTPP Layer Thickness Data* was developed.

<u>Data Availability and Completeness</u>

In the course of the study, layer thickness data available in the LTPP database were examined to evaluate quality and completeness using Levels A to E data. The layer thickness data availability assessment indicated that the TST_L05B and TST_L05A tables contain the most complete set of information about the representative layer structure and thickness for section-level analysis. Only 16 pavement structures from LTPP regular sections and 1 pavement structure from a supplemental section do not have any layer structure (including thickness) information in either TST_L05B or TST_L05A. Analysis of data completeness at QC Level E revealed 3,457 pavement layer structures in the EXPERIMENT_SECTION table. Some 3,240 of these structures (93.7 percent) had records in table TST_L05B, while 3,229 structures (93.4 percent) had records in table TST_L05A.

<u>Layer Thickness Quality and Consistency</u>

Following the data completeness evaluation, pavement layer thickness and other related data from different data sources were evaluated to determine consistency of layer functional description, material type, and thickness data between different data sources. In addition, layer thickness variability indicators, within-section material type consistency, and material type and thickness reasonableness were evaluated using selected tables where these parameters were available.

The results of the data consistency evaluation showed that the pavement layer functional descriptions are consistent between different LTPP tables for 93 percent of all cross-section layers evaluated in the study. Material type descriptions were found to be consistent between different tables for 79 percent of all section layers evaluated in the study. Evaluation of material type consistency was constrained by the absence of a unified material coding scheme. Representative layer thickness values were found consistent between different tables for 89 percent of all pavement cross-section layers evaluated in the study. In the cases where inconsistency in data from one or more data sources was identified, a layer was flagged for further review. Inconsistencies in pavement layering data were reviewed and reported to the LTPP data managers in the form of the data analysis/operations feedback reports along with recommendations for data anomaly resolution.

Additionally, reasonableness (or validity) of material type description was evaluated. The purpose of the reasonableness check was to evaluate whether the material description code for the layer is consistent with the layer functional description. While most of the records had valid material codes, 642 records out of 41,111 (1.56 percent) had erroneous material codes, and some records were missing material codes. The identified records were reported to the FHWA in a data analysis/operations feedback report.

Reasonableness of layer thickness data was evaluated using the representative layer thickness ranges specified in the SHRP-LTPP Lab Guide [3]. As a result of the layer thickness reasonableness evaluation, thickness values outside the representative thickness ranges were identified and reported to the FHWA.

Within-Section Thickness Variation

The variation in layer thickness data from SPS experiments obtained at different locations within sections was analyzed and characterized using theoretical statistical distributions. The analysis included layers with different material and functional types, including AC surface courses, combined AC surface and binder courses, AC binder courses, dense-graded aggregate bases, dense-graded AC-treated bases, permeable AC-treated bases, lean concrete bases, PCC surface layers, and PCC overlay layers. To assess layer thickness distribution characteristics, descriptive statistics such as mean, standard deviation, skewness, and kurtosis were computed for each section. A combined test for skewness and kurtosis was selected to test the normality of layer thickness distributions for 1,034 SPS layers. The statistical analysis results indicated that, for 84 percent of all layers, thickness variations within a section indicate a normal distribution. These results can serve as a very important input to pavement engineering applications involving reliability of pavement design and also for quality assurance construction specifications.

As-Designed versus As-Constructed Thickness Comparison

As-constructed core and elevation layer thickness measurements were compared to the design (or target) thickness values for newly constructed SPS layers. The data were evaluated to determine the percentage of the individual measurements either within or outside specific values from the target thickness.

Statistical analyses of the measured mean thickness values versus the designed values were performed using t-tests. Two sided t-tests with 95 percent confidence level were used for each section and layer to estimate whether the differences between as-designed and as-constructed thicknesses are significant. One-sided t-tests with 95 percent confidence level were used for each layer for the difference between as-designed thickness and the mean as-constructed thickness and for allowances of 6.35 mm (0.25 in), 12.7 mm (0.5 in), and 25.4 mm (1 in).

Based on the analysis of both data sources, the following conclusions can be made:

- The majority of the LC and PCC layers have constructed or measured thickness above the design values. This is particularly true for thin (76 mm [3 in] and 123 mm [5 in] thick) PCC bonded overlays of PCC slabs.

- Thin PCC and asphalt concrete surface and binder layers have the highest number of sections with mean as-constructed thickness that significantly deviates from the designed thicknesses.
- Elevation thickness measurements for PATB are more evenly distributed around the target value. However, the core measurements for PATB show that a significant number of sections have thicknesses lower than the target thickness. It appears that for some cores the entire thickness of PATB layer was not obtained. The analysis shows the values currently stored in the database. A feedback report was submitted regarding these questionable data. In some cases the core thicknesses were below 25.4 mm (1 in), although target thickness is 102 mm (4 in).
- About 60 percent of section/layers have mean thickness within ±6.35 mm (0.25 in) from the target thickness. For the tolerance level of 25.4 mm (1 in) this percentage is above 90 for most layer types and target thicknesses.

A comparison between analysis results from the elevation and core thickness measurements shows that the percentage of measurements within tolerance limits for all three tolerance levels is approximately the same. However, the percentage of measurements lower than the target value is consistently higher for core measurements than for elevation measurements.

Based on elevation measurements, it is observed that more than 70 percent of sections with DGAB have as-constructed thicknesses within ±6.35 mm (0.25 in) from the design value.

<u>Researcher's Guide for LTPP Layer Thickness-Related Data</u>

One important product from this study is a Researcher's Guide for LTPP Layer Thickness Data. The main purpose of this researcher's guide is to provide guidance for selecting layer material type and thickness data from the LTPP database. The guide also contains a discussion about within-section layer thickness variability and a comparison between as-designed and as-constructed layer thicknesses. The researcher's guide is presented in a separate report.

Recommendations

<u>Computed Quantity Data for Inclusion in the LTPP Database</u>

Along-the-section variability of layer thickness is an essential input for reliability-based pavement design and performance modeling. This input is characterized by the statistical distribution attributes. During the evaluation of within-section layer thickness variability, comprehensive descriptive statistics were obtained from rod and level elevation measurement along the LTPP sections, for pavement structural layers (base and surface course):

- Mean
- Standard deviation
- Skewness
- Kurtosis

These data provide means for evaluating the distribution shape of layer thickness measurements observed along the LTPP sections. Tests of normality were carried out to identify sections and layers that have thickness values distributed normally. This valuable information provides statistical characteristics of the within-section variability in pavement layer thickness for different pavement layers and material types required for pavement engineering studies involving assessment of pavement design reliability, such as mechanistic-empirical pavement design procedures or pavement management procedures involving risk analysis. As such, we recommend including these statistics in the LTPP database as a new computed parameter tables (one table for each SPS experiment). The essential fields recommended for the new tables are:

- Layer type
- Mean
- Standard deviation
- Skewness
- Kurtosis
- Normality indicator

Researcher's Guide to LTPP Layer Thickness Data

Pavement layer material type and thickness data are very important for many types of pavement engineering analyses. The accuracy of layer thickness data has a great impact on the outcome of practically all analyses of pavement performance. As part of the LTPP program data collection effort, a large amount of data related to layer material type and thickness data have been collected from several sources. These data are stored in many different tables. Based on the analysis type, data from one or another table may be more appropriate.

To make the process of navigation through the LTPP layer thickness data more user-friendly, a *Researcher's Guide for LTPP Layer Thickness Data* was developed in this study. This guide discusses the field sampling, materials testing, and other layer thickness data collection activities utilized in LTPP. The layer thickness data that currently reside in the LTPP database are presented in relation to the data collection activities or data sources. The guide also explains how to search for the most appropriate thickness for different research purposes. Characterization of the within-section thickness variation and designed versus constructed or measured thickness data variation for the LTPP sections are also included in the guide. We recommend that this guide be used as a reference when selecting LTPP pavement layering data sources.

Improvement of LTPP Pavement Thickness Data Quantity and Quality

In an attempt to improve LTPP layer thickness data quality and quantity, an extensive review of layer thickness data available in the LTPP database was carried out in this study. As a result, several issues concerning questionable or anomalous data have been identified and reported to FHWA in a form of feedback reports. To improve the quality of existing layer thickness data and to fill in any identified data gaps, the reported data problems should be reviewed by the appropriate parties and, where warranted, the LTPP database should be updated and cleaned to remove anomalous data.

APPENDIX A – CORRELATED MATERIAL CODES

Table 67 presents correlated groupings of "similar" materials used to correlate material codes from inventory and testing tables. The first two columns provide material codes and LTPP material descriptions used in the TST* tables. The second and third columns provided material codes and LTPP material descriptions used in the INV*, RHB*, and SPS* tables. The last column shows "similar" material descriptions developed in this study to link testing and inventory material codes.

Table 67. Correlated material codes.

TESTING		INVENTORY		ANALYSIS
TST Code	**LTPP Description**	**INV Code**	**LTPP Description**	**"Similar" Material Description**
333	Cement-treated Soil	42	Lime-Treated Subgrade Soil	Stabilized Subgrade Soil
338	Lime-Treated Soil	43	Cement-Treated Subgrade Soil	Stabilized Subgrade Soil
101	Fine-Grained Soils: Clay			Clayey Soils
102	Fine-Grained Soils: Lean Inorganic Clay			Clayey Soils
103	Fine-Grained Soils: Fat Inorganic Clay			Clayey Soils
104	Fine-Grained Soils: Clay with Gravel			Clayey Soils
105	Fine-Grained Soils: Lean Clay with Gravel			Clayey Soils
106	Fine-Grained Soils: Fat Clay with Gravel			Clayey Soils
107	Fine-Grained Soils: Clay with Sand			Clayey Soils
108	Fine-Grained Soils: Lean Clay with Sand			Clayey Soils
109	Fine-Grained Soils: Fat Clay with Sand			Clayey Soils
111	Fine-Grained Soils: Gravelly Lean Clay			Clayey Soils
112	Fine-Grained Soils: Gravelly Fat Clay			Clayey Soils
116	Fine-Grained Soils: Gravelly Clay with Sand			Clayey Soils
117	Fine-Grained Soils: Gravelly Lean Clay with Sand			Clayey Soils
118	Fine-Grained Soils: Gravelly Fat Clay with Sand			Clayey Soils
134	Fine-Grained Soils: Gravelly Silty Clay			Clayey Soils
135	Fine-Grained Soils: Sandy Silty Clay			Clayey Soils
136	Fine-Grained Soils: Gravelly Silty Clay with Sand			Clayey Soils

Table 67. Correlated material codes, continued.

TESTING		INVENTORY		ANALYSIS
TST Code	LTPP Description	INV Code	LTPP Description	"Similar" Material Description
113	Fine-Grained Soils: Sandy Clay	52	Sandy Clay	Clayey Soils
114	Fine-Grained Soils: Sandy Lean Clay			Clayey Soils
115	Fine-Grained Soils: Sandy Fat Clay			Clayey Soils
119	Fine-Grained Soils: Sandy Clay with Gravel			Clayey Soils
120	Fine-Grained Soils: Sandy Lean Clay with Gravel			Clayey Soils
137	Fine-Grained Soils: Sandy Silty Clay with Gravel			Clayey Soils
131	Fine-Grained Soils: Silty Clay	53	Silty Clay	Clayey Soils
132	Fine-Grained Soils: Silty Clay with Gravel			Clayey Soils
		51	Clay (Liquid Limit > 50)	Clayey Soils
133	Fine-Grained Soils: Silty Clay with Sand			Clayey Soils
216	Coarse-Grained Soil: Clayey Sand	60	Clayey Sand	Clayey Sand
217	Coarse-Grained Soil: Clayey Sand with Gravel			Clayey Sand
251	Coarse-Grained Soil: Gravel	61	Gravel	Gravel
266	Coarse-Grained Soil: Clayey Gravel	63	Clayey Gravel	Gravel
267	Coarse-Grained Soil: Clayey Gravel with Sand			Gravel
252	Coarse-Grained Soil: Poorly Graded Gravel	62	Poorly Graded Gravel	Gravel
253	Coarse-Grained Soil: Poorly Graded Gravel with Sand			Gravel
254	Coarse-Grained Ssoil: Poorly Graded Gravel with Silt			Gravel
255	Coarse-Grained Soil: Poorly Graded Gravel with Silt and Sand			Gravel
256	Coarse-Grained Soil: Poorly Graded Gravel with Clay			Gravel
257	Coarse-Grained Soil: Poorly Graded Gravel with Clay and Sand			Gravel
258	Coarse-Grained Soil: Well-Graded Gravel			Gravel
259	Coarse-Grained Soil: Well-Graded Gravel with Sand			Gravel
261	Coarse-Grained Soil: Well-Graded Gravel with Silt and Sand			Gravel

Table 67. Correlated material codes, continued.

TESTING		INVENTORY		ANALYSIS
TST Code	LTPP Description	INV Code	LTPP Description	"Similar" Material Description
263	Coarse-Grained Soil: Well-Graded Gravel with Clay and Sand			Gravel
302	Gravel (Uncrushed)	22	Gravel (Uncrushed)	Gravel
308	Soil-Aggregate Mixture (Predominantly Coarse-Grained)	26	Soil-Aggregate Mixture (Predominantly Coarse-Grained Soil)	Gravel
303	Crushed Stone			Processed Granular Base Materials
304	Crushed Gravel			Processed Granular Base Materials
305	Crushed Slag			Processed Granular Base Materials
		23	Crushed Stone, Gravel or Slag	Processed Granular Base Materials
162	Fine-Grained Soils: Organic Soil with Sand			Organic Soil
163	Fine-Grained Soils: Gravelly Organic Soil			Organic Soil
164	Fine-Grained Soils: Sandy Organic Soil			Organic Soil
280	Stone			Stone
283	Cobbles			Stone
282	Rock	65	Rock	Rock
287	Sandstone			Rock
		64	Shale	Rock
294	Other (specify if possible or unknown)			Rock
337	Limerock, Caliche	41	Limerock, Caliche (Soft Carbonate Rock)	Limerock, Caliche
201	Coarse-Grained Soils: Sand	24	Sand	Sand
202	Coarse-Grained Soils: Poorly Graded Sand	58	Poorly Graded Sand	Sand
203	Coarse-Grained Soils: Poorly Graded Sand with Gravel			Sand
204	Coarse-Grained Soils: Poorly Graded Sand with Silt			Sand
205	Coarse-Grained Soils: Poorly Graded Sand with Silt and Gravel			Sand
206	Coarse-Grained Soils: Poorly Graded Sand with Clay			Sand
207	Coarse-Grained Soils: Poorly Graded Sand with Clay and Gravel			Sand
209	Coarse-Grained Soils: Well-Graded Sand with Gravel			Sand

Table 67. Correlated material codes, continued.

TESTING		INVENTORY		ANALYSIS
TST Code	LTPP Description	INV Code	LTPP Description	"Similar" Material Description
210	Coarse-Grained Soils: Well-Graded Sand with Silt			Sand
211	Coarse-Grained Soils: Well-Graded Sand with Silt and Gravel			Sand
213	Coarse-Grained Soils: Well-Graded Sand with Clay and Gravel			Sand
		59	Silty Sand	Sand
306	Sand	57	Sand	Sand
145	Fine-Grained Soils: Sandy Silt	55	Sandy Silt	Silty soils
147	Fine-Grained Soils: Sandy Silt with Gravel			Silty soils
141	Fine-Grained Soils: Silt	54	Silt	Silty soils
142	Fine-Grained Soils: Silt with Gravel			Silty soils
143	Fine-Grained Soils: Silt with Sand			Silty soils
144	Fine-Grained Soils: Gravelly Silt			Silty soils
146	Fine-Grained Soils: Gravelly Silt with Sand			Silty soils
148	Fine-Grained Soils: Clayey Silt	56	Clayey Silt	Silty soils
264	Coarse-Grained Soil: Silty Gravel			Silty gravel
265	Coarse-Grained Soil: Silty Gravel with Sand			Silty gravel
214	Coarse-Grained Soil: Silty Sand			Silty Sand
215	Coarse-Grained Soil: Silty Sand with Gravel			Silty Sand
307	Soil-Aggregate Mixture (Predominantly Fine-Grained)	25	Soil-Aggregate Mixture (Predominantly Fine-Grained Soil)	Subgrade soils
309	Fine-Grained Soils			Subgrade soils
310	Other (Specify if possible)			Subgrade soils
74	Woven Geotextile	74	Woven Geotextile	Geomaterials
75	Nonwoven Geotextile	75	Nonwoven Goetextile	Geomaterials
332	Econocrete			Econocrete
71	Chip Seal	71	Chip Seal Coat	Chip Seal
72	Slurry Seal	72	Slurry Seal Coat	Slurry Seal
73	Fog Seal	73	Fog Seal Coat	Fog Seal
82	Sand Seal	82	Sand Seal	Sand Seal
78	Dense-Graded Asphalt Concrete Interlayer	78	Dense-Graded Asphalt Concrete Interlayer	Dense-Graded, Cold-Laid AC
323	Dense-Graded, Cold-Laid, Central Plant Mix	29	Dense-Graded, Cold-Laid, Central Plant Mix	Dense-Graded, Cold-Laid AC

Table 67. Correlated material codes, continued.

TESTING		INVENTORY		ANALYSIS
TST Code	LTPP Description	INV Code	LTPP Description	"Similar" Material Description
324	Dense-Graded, Cold-Laid, Mixed In-Place	30	Dense-Graded, Cold-Laid, Mixed In-Place	Dense-Graded, Cold-Laid AC
319	HMAC			HMAC
1	Hot-Mixed, Hot-Laid AC, Dense-Graded	1	Hot-Mixed, Hot-Laid Asphalt Concrete, Dense-Graded	Dense-Graded, Hot-Laid AC
322	Dense-Graded, Hot-Laid, Central Plant Mix	28	Dense-Graded, Hot-Laid, Central Plant Mix	Dense-Graded, Hot-Laid AC
2	Hot-Mixed, Hot-Laid AC, Open-Graded	2	Hot-Mixed, Hot-Laid Asphalt Concrete, Open-Graded (Porous Friction Course)	Open-Graded, Hot-Laid AC
325	Open-Graded, Hot-Laid, Central Plant Mix	31	Open-Graded, Hot-Laid, Central Plant Mix	Open-Graded, Hot-Laid AC
326	Open-Graded, Cold-Laid, Central Plant Mix	32	Open-Graded, Cold-Laid, Central Plant Mix	Open-Graded, Cold-Laid AC
327	Open-Graded, Cold-Laid, Mixed In-Place	33	Open-Graded, Cold-Laid, Mixed In-Place	Open-Graded, Cold-Laid AC
10	Plant Mix (Cutback Asphalt) Material, Cold-Laid	10	Plant Mix (Cutback Asphalt) Material, Cold-Laid	Cutback Asphalt Mix
9	Plant Mix (Emulsified Asphalt) Material, Cold-Laid	9	Plant Mix (Emulsified Asphalt) Material, Cold-Laid	Emulsified Asphalt Mix
340	Pozzolanic-Aggregate Mixture	44	Pozzolanic-Aggregate Mixture	High-Strength Stabilized Bases
339	Soil Cement	27	Soil Cement	High-Strength Stabilized Bases
331	Cement Aggregate Mixture	37	Cement-Aggregate Mixture	High-Strength Stabilized Bases
16	Recycled AC, Heater Scarification/Recompaction	16	Recycled Asphalt Concrete Heater Scarification/Recompaction	Recycled AC, Heater Scarification/Recompaction
13	Recycled AC, Hot-Laid, Central Plant Mix	13	Recycled Asphalt Concrete Hot-Laid, Central Plant Mix	Recycled AC, Hot-Laid, Central Plant Mix
328	Recycled Asphalt Concrete, Plant Mix, Hot-Laid	34	Recycled Asphalt Concrete, Plant Mix, Hot-Laid	Recycled AC, Hot-Laid, Central Plant Mix
15	Recycled AC, Cold-Laid Mixed-In-Place	15	Recycled Asphalt Concrete, Cold-Laid, Mixed-In-Place	Recycled Asphalt Concrete, Mixed In-Place
		36	Recycled Asphalt Concrete, Mixed In-Place	Recycled Asphalt Concrete, Mixed In-Place
84	Sand Asphalt	84	Sand Asphalt	Sand Asphalt
320	Sand Asphalt	46	Sand Asphalt	Sand Asphalt
321	Asphalt-Treated Mixture			Sand Asphalt
		40	Sand-Shell Mixture	Sand-Shell Mixture

APPENDIX B – SKEWNESS AND KURTOSIS TEST

Statistical Formulations Used in the Skewness and Kurtosis Test

The following formulations for the combined skewness and kurtosis test were developed based on the reference [41].

For the skewness, we have:

$$skewness \ = \ k_3 = \frac{n}{(n\text{-}1)(n\text{-}2)} \sum (x_i - \bar{x})^3$$

Figure 76: Equation. Skewness definition.

For kurtosis, we have:

$$kurtosis \ = \ k_4 = \frac{1}{(n\text{-}1)(n\text{-}2)(n\text{-}3)} \left(n(n+1) \sum (x_i - \bar{x})^4 - 3\left(\sum (x_i - \bar{x})^2\right)^2 \right)$$

Where:

n = number of layer thickness measurements for the layer

x_i = individual layer thickness measurement along the section

$\bar{x}$ = mean layer thickness

Figure 77: Equation. Kurtosis definition.

To evaluate the skewness and kurtosis tests results, the non-dimensional skewness and kurtosis coefficients are computed, as following:

$$g_1 = k_3/s^3$$

Where:

s = standard deviation

Figure 78: Equation. Non-dimensional skewness coefficient definition.

$$g_2 = k_4/s^4$$

Where:

s = standard deviation

Figure 79: Equation. Non-dimensional kurtosis coefficient definition.

Based on the g_1 and g_2 values, the statistics $\sqrt{b_1}$ and b_2 are found next:

$$\sqrt{b_1} = \frac{(n-2)}{\sqrt{n(n-1)}} g_1$$

Figure 80: Equation. Definition of $\sqrt{b_1}$ statistic.

$$b_2 = \frac{(n-2)(n-3)}{(n+1)(n-1)} g_2 + 3\frac{(n-1)}{(n+1)}$$

Figure 81: Equation. Definition of b_2 statistic.

To find z_1 value, the following parameters are computed using $\sqrt{b_1}$ and b_2 statistics:

$$A = \sqrt{b_1}\sqrt{\frac{(n+1)(n+3)}{6(n\text{-}2)}}$$

Figure 82: Equation. Definition of intermediate parameter *A*.

$$B = \frac{3(n^2 + 27n\text{-}70)(n+1)(n+3)}{(n\text{-}2)(n+5)(n+7)(n+9)}$$

Figure 83: Equation. Definition of intermediate parameter *B*.

$$C = \sqrt{\sqrt{2(B-1)} - 1}$$

Figure 84: Equation. Definition of intermediate parameter *C*.

$$D = \frac{1}{\sqrt{\ln(C)}}$$

Figure 85: Equation. Definition of intermediate parameter *D*.

$$E = \sqrt{\frac{2}{C^2 - 1}}$$

Figure 86: Equation. Definition of intermediate parameter *E*.

The corresponding z_1 value used as a skewness test statistic is the following:

$$z_1 = D \cdot \ln\left(\frac{A}{E} + \sqrt{\left(\frac{A}{E}\right)^2 + 1}\right)$$

Figure 87: Equation. Definition of skewness test statistic z_1.

To find z_2 value, the following intermediate parameters are computed next:

$$meanb_2 = 3\,(n-1)/(n+1)$$

Figure 88: Equation. Definition of the mean of intermediate parameter $meanb_2$.

$$varb_2 = \frac{24n\,(n-2)\,(n-3)}{(n+1)\,(n+1)\,(n+3)\,(n+5)}$$

Figure 89: Equation. Definition of the variance of intermediate parameter $varb_2$.

$$F = \frac{(b_2 - meanb_2)}{\sqrt{varb_2}}$$

Figure 90: Equation. Definition of intermediate parameter *F*.

$$G = \frac{6\,(n^2 - 5n + 2)}{(n+7)(n+9)}\sqrt{\frac{6(n+3)(n+5)}{n(n-2)(n-3)}}$$

Figure 91: Equation. Definition of intermediate parameter *G*.

$$H = 6 + \frac{8}{G}\left(\frac{2}{G} + \sqrt{1 + \frac{4}{G^2}}\right)$$

Figure 92: Equation. Definition of intermediate parameter *H*.

The corresponding z_2 value used as a kurtosis test statistic is the following:

$$z_2 = \frac{1 - \frac{2}{9H} - \left(\frac{1 - \frac{2}{H}}{1 + F\sqrt{\frac{2}{H-4}}}\right)^{1/3}}{\sqrt{\frac{2}{9H}}}$$

Figure 93: Equation. Definition of kurtosis test statistic z_2.

The z_1 and z_2 statistics are used to obtain the *p*-values (the probability that values of the standard normal distribution are more extreme than the computed z_1 and z_2 statistics).

APPENDIX C – KOLMOGOROV-SMIRNOV GOODNESS-OF-FIT TEST

Procedures for the Kolmogorov-Smirnov Goodness-of-fit Test

The Kolmogorov-Smirnov test procedure involves the comparison between the experimental cumulative frequency and an assumed theoretical distribution function. If the discrepancy is large compared to what is normally expected from a given sample size, the theoretical model is rejected.

The Kolmogorov-Smirnov test procedure involves the following steps:

1. Sort layer thickness measurements in the ascending order.
2. Compute cumulative frequencies of each layer thickness observation $S_n(x)$ using the following formula:

$$S_n(x) = \begin{cases} 0 & x < x_{k=1} \\ \dfrac{k}{n} & x_k \leq x \leq x_{k+1} \\ 1 & x \geq x_{k=n} \end{cases}$$

Figure 94: Equation. Cumulative frequencies definition.

   Where x_k is a layer thickness value from sample of n layer thickness measurements sorted in the ascending order by thickness value. The k - index indicates the order of layer thickness observation in the sorted layer thickness array.
3. Select a candidate theoretical distribution function (for example, normal distribution).
4. Using the layer thickness measurements data, compute descriptive statistic values necessary for definition of the selected theoretical distribution (for example, mean and standard deviation).
5. Using selected theoretical distribution function and computed descriptive statistics, compute theoretical cumulative frequency values $F(x_k)$ for each thickness value x_k.
6. Find the difference between the observed cumulative frequency value $S_n(x_k)$ and the theoretically predicted cumulative frequency values $F(x_k)$ for each x_k from the sample of n thickness measurements.
7. Select the maximum difference between the observed cumulative frequency value $S_n(x_k)$ and the theoretically predicted cumulative frequency values $F(x_k)$ called the observed maximum difference D_n or *D-max* statistic. This value is a measure of discrepancy between the theoretical model and the observed data.

$$D_n = \max_x | F(x_k) - S_n(x_k) |$$

Figure 95: Equation. *D-max* statistic definition.

8. Select level of significance α = 1 percent
9. Compute the critical value D_n^{α} based on selected value of α. Based on value of *n*, D_n^{α} is found as following

$$D_n^{\alpha=95} = \begin{cases} if \;\; 5 \le n \le 50, & 0.7688 \cdot n^{-0.4088} \quad (aproximately,\ R^2 = 0.99) \\ if \;\; n > 50, & 1.031 \cdot n^{-\ 0.5} \end{cases}$$

The D_n^{α} statistic is defined as $P(D_n \le D_n^{\alpha}) = 1 - \alpha$

Figure 96: Equation. Critical value D_n^{α} definition.

10. The Kolmogorov-Smirnov test determines whether, for specified level of significance α, the proposed distribution is an acceptable representation of the field data.

If $D_n < D_n^{\alpha}$, the theoretical distribution is acceptable
If $D_n \ge D_n^{\alpha}$, the theoretical distribution is rejected

Figure 97: Equation. Kolmogorov-Smirnov test evaluation criteria.

The following figure 98 demonstrates the results of the Kolmogorov-Smirnov test for a layer that did not pass the test of normality.

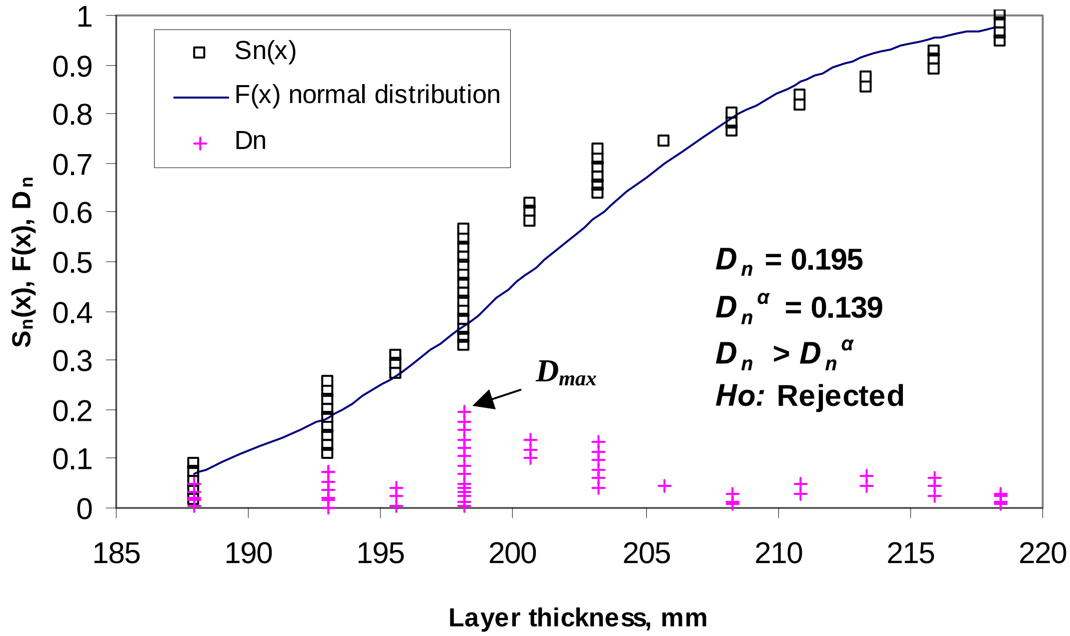


Figure 98: Chart. Example of Kolmogorov-Smirnov normal distribution goodness-of-fit test (DGAB layer SPS-1 LTPP section 01_0101).

Results of the Kolmogorov-Smirnov Goodness-of-fit Tests

The layer thickness measurements taken along the SPS LTPP sections for the structural layers were tested to determine how well the distribution of layer thickness measurements taken along the LTPP section follow selected theoretical distribution. The following table 69 provides the description of the layer and material types used in the SPS experiments. The table also provides information about layer thickness measurement sample sizes available in the LTPP database.

Table 68. Number of pavement layers and number of layer thickness measurements per layer grouped by material and layer type.

Layer-Material Type	Total number of samples	Number of samples with the following number of observations												
		1	5	10	15	20	25	30	35	40	45	50	55	60 or more
AC_SURFACE_COURSE	133	4	0	0	1	1	7	0	0	0	0	3	117	0
BINDER_COURSE	50	1	3	0	0	1	3	0	0	0	0	4	38	0
DENSE_GRADE_AGG_BASE	220	1	0	2	5	0	3	15	0	1	8	1	174	10
DENSE_GRD_ASPH_TREAT_BASE	97	0	0	1	0	0	0	0	0	0	2	2	92	0
LEAN_CONCRETE	48	0	0	0	0	0	0	8	0	0	0	0	35	5
PCC_SURFACE	178	1	0	1	0	0	2	40	1	0	2	3	112	16
PERM_ASPH_TREAT_BASE	130	1	0	2	0	0	1	9	0	0	1	1	111	4
AC_SURFACE_AND_BINDER	191	0	0	2	0	0	0	0	1	0	4	4	177	3

One data sample represents a group of measurements taken along the LTPP section for a specific layer and material type. There are 1,047 layers with thickness measurements along the LTPP section available in the LTPP database for the surface and base courses. The number of thickness measurements per layer and material type taken along the LTPP section ranges from 1 to 60. About 85 percent of all layers have at least 55 observations.

A total of 1034 pavement layers were tested to determine how well variability in layer thickness data along the LTPP section could be described using normal distribution. Kolmogorov-Smirnov goodness-of-fit test evaluated for level of significance alpha equal to 1 percent are summarized in table 70.

The results did not show as strong an indication of layer thickness distribution normality as the results of combined skewness and kurtosis test. This could be explained by lower power of Kolmogorov-Smirnov goodness-of-fit test compared to the combined skewness and kurtosis test. Low power indicates high probability of failing to reject the false null hypothesis.

Table 69. Summary of the goodness-of-fit results using Kolmogorov-Smirnov test with 1 percent level of significance.

Experiment	Number of layers	Not rejected (Normal)	Rejected (Not normal)
AC_SURFACE_COURSE			
SPS-5	93	34 (36.6 %)	59 (63.4 %)
SPS-6	36	12 (33.3 %)	24 (66.7 %)
SURFACE_AND_BINDER			
SPS-1	167	61 (36.5 %)	106 (63.5 %)
SPS-8	22	14 (63.6 %)	8 (36.4 %)
PERM_ASPH_TREAT_BASE			
SPS-1	83	46 (55.4 %)	37 (44.6 %)
SPS-2	46	28 (60.9 %)	18 (39.1 %)
PCC_SURFACE			
SPS-2	139	70 (50.4 %)	69 (49.6 %)
SPS-7	24	21 (87.5 %)	3 (12.5 %)
SPS-8	14	9 (64.3 %)	5 (35.7 %)
LEAN_CONCRETE			
SPS-2	48	26 (54.2 %)	22 (45.8 %)
DENSE_GRD_ASPH_TREAT_BASE			
SPS-1	97	45 (46.4 %)	52 (53.6 %)
DENSE_GRADE_AGG_BASE			
SPS-1	97	63 (64.9 %)	34 (35.1 %)
SPS-2	84	53 (63.1 %)	31 (36.9 %)
SPS-8	38	30 (78.9 %)	8 (21.1 %)
BINDER_COURSE			
SPS-5	33	11 (33.3 %)	22 (66.7 %)
SPS-6	13	7 (53.8 %)	6 (46.2 %)

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