Assessment of Selected LTPP Material Data Tables and Development of Representative Test Tables and Development of Representative Test Tables

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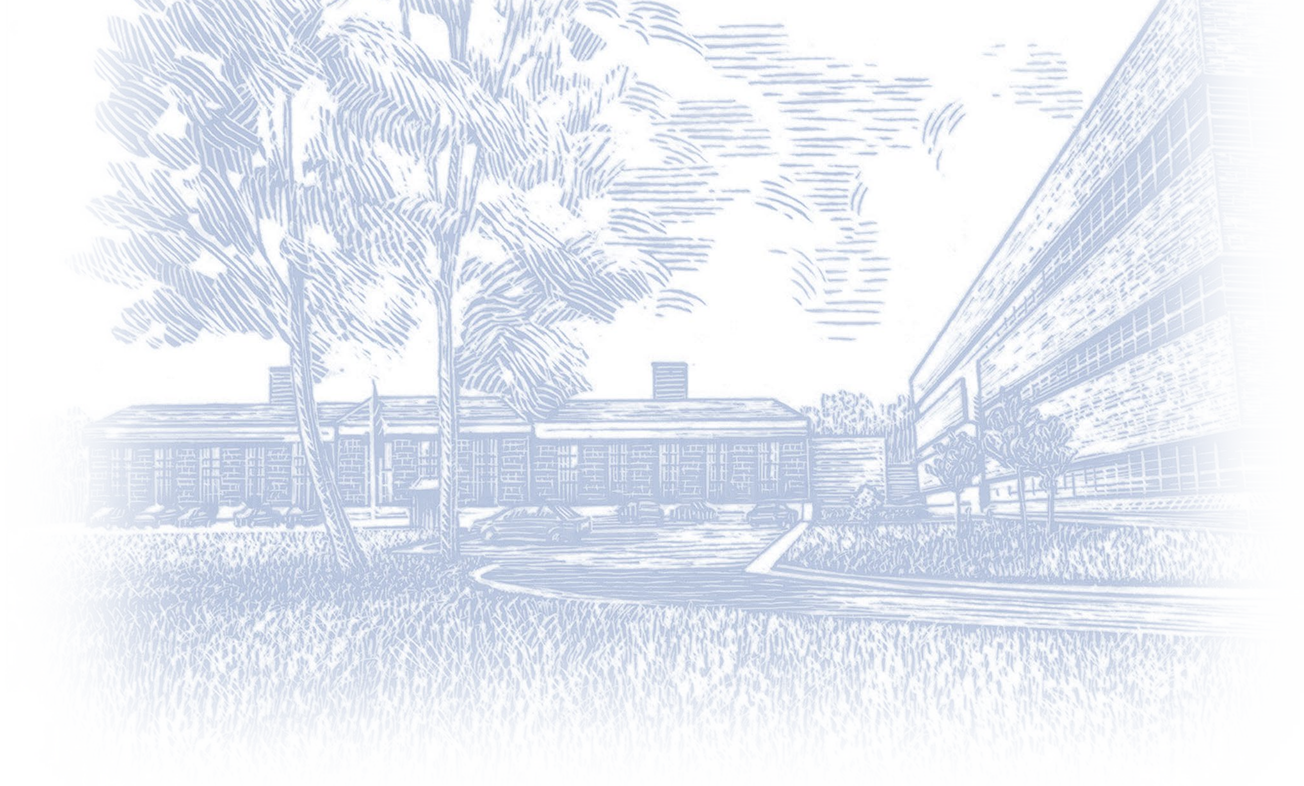

U.S. Department of Transportation
Federal Highway Administration

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Foreword

Accurate and reliable information about pavement material properties is key to predicting the states of stress, strain, and displacement within the pavement structure when subjected to an external wheel and climate-related loading. Computed stress and strain are then used as critical responses that are needed for predicting distress and pavement performance. For example, Portland cement concrete (PCC) cracking is related to the PCC flexural strength, and pumping and faulting can be related to the erodibility of the underlying base/subbase material. The inclusion of accurate material-related data is, therefore, vital in research studies such as the Long-Term Pavement Performance (LTPP) study.

This report documents the state of selected material-related data elements in the LTPP material characterization program. The data were evaluated to assess completeness and quality. Recommendations are also provided regarding the suitability of the data evaluated for future research and analysis. The report also provides information on representative data tables developed as part of this study and recommended for inclusion in the LTPP database. The report is intended for all LTPP data users--from those with considerable experience to those with no familiarity with the LTPP database.

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Director
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Notice

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16. Abstract:

This report documents an evaluation of selected LTPP material data tables as of January 2000. Issues addressed include the availability, characteristics, and quality of the data in the selected tables. Anomalies in the data were identified and corrected where possible, and the "cleaned-out" data were used in developing representative data tables. Recommendations for adjustments in the current data collection process are also presented.

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SI* (Modern Metric) Conversion Factors

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		Temperature (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

Illumination				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
Force and Pressure or Stress				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
Area				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
Volume				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
Mass				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
Temperature (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F

Illumination				
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
Force and Pressure or Stress				
N	newtons	02.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2002)

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1. INTRODUCTION

Information about pavement material properties is required to predict states of stress, strain, and displacement within the pavement structure when subjected to an external wheel load. In both empirical and mechanistic-empirical (M-E) design systems, material properties such as elastic modulus (E), compressive strength (f_c), Poisson's ratio (mu), tensile strength (f_t), and flexural strength (M_R) are mandatory inputs for characterizing pavement systems, computing pavement critical responses (e.g., stress and strain) to applied traffic and climate-related loads, and predicting performance.

Material characterization is vital to pavement design because most of the major distresses that occur in pavements can be associated with the material properties of a component or layer of the pavement structure. For example, portland cement concrete (PCC) cracking is related to the PCC flexural strength, and pumping and faulting can be related to the erodibility of the underlying base/subbase material. Material characterization is also vital in research studies, such as the Federal Highway Administration (FHWA) Long-Term Pavement Performance (LTPP) study, to determine the effects of material properties on pavement performance.

This report documents the state of selected material-related data elements in the LTPP material characterization program. The data were evaluated to assess completeness and quality. Recommendations are also provided regarding the suitability of the data evaluated for future research and analysis.

Overview of LTPP Material Characterization Program

One of the important objectives of the LTPP program is to understand the relationship between pavement material properties and pavement performance. A better understanding of this relationship will ensure that appropriate materials are specified and used in pavement construction to provide the desired level of performance. LTPP material characterization, therefore, serves the following purposes:(1)

- Verify the structure of in-service pavements adopted into the LTPP program.
- Determine and verify the material properties of in-service pavements adopted into the LTPP program.
- Determine the material properties of newly constructed LTPP test pavements.

Material Characterization

The LTPP material characterization program was implemented by:(1)

- Collecting inventory and construction test data from General Pavement Study (GPS) and Specific Pavement Study (SPS) test pavements throughout North America.
- Obtaining material samples and specimens from the existing and newly constructed pavements and performing laboratory testing and analysis.
- Conducting field testing for characterizing pavement layer material properties, such as deflection testing and nuclear density testing.

As of January 2000, over 775 GPS and SPS sites have been sampled as part of the material characterization program. Sampling from these sites included the extraction of almost 14,000 cores (200 tons of bulk samples), the excavation of over 450 test pits, and the performance of over 330 in situ nuclear density tests.(1)

The sampling and testing program was conducted on the following materials:

- Asphalt binder/cement.
- Asphalt concrete.
    - Hot mix asphalt concrete (AC)--dense graded.
    - Hot mix AC--open graded.
    - Hot mix AC--sand asphalt mixtures.
    - Cold mix AC.
    - Asphalt treated materials.
- Portland cement/PCC.
- Cement-treated materials.
    - Lean concrete base (LCB).
    - Soil cement.
    - Lime-treated materials.
    - Pozzolanic-treated materials (e.g., flyash, econocrete).
- Unbound base/subbase.
- Subgrade.

An overview of each category is presented in the following sections.

Asphalt Binder/Cement

Asphalt cement is obtained by the distillation of crude petroleum. At ambient temperatures, it is a black, sticky, semisolid, highly viscous material. The primary use of asphalt cement is to produce AC and asphalt-treated materials for use in the construction of flexible pavements.

The properties of the asphalt cement used in producing AC have a significant influence on the final AC properties. Some of the important AC properties influenced by asphalt cement are:

- Mixture viscosity.
- Resilient properties of the mixture.
- Strength of the mixture.

Several tests are performed on new and extracted asphalt cement materials as part of the LTPP materials characterization program.

Asphalt Concrete

Asphalt concrete describes a broad range of aggregate and filler materials bound together with asphalt cement. It is normally used as the wearing, binder, base, and/or subbase layers of a flexible pavement. Their properties and behavior are heavily influenced by temperature, time rate of loading, mixture proportions, and construction. This category of pavement materials includes many different subgroups--ranging from the hot mix asphalt layer to the asphalt-treated sand. Thus, there is a great deal of variability in properties, behavior, and suitability for pavement design and construction.

Portland Cement and Portland Cement Concrete

Portland cement is the principal strength-giving and property-controlling component of PCC. It is a hydraulic cement that gains strength as it reacts with water. Although the reaction is initially fairly rapid (approximately 40 percent occurs within the first 24 hours), it slows down considerably with the passage of time. The hydration reaction produces a finely divided, fairly porous solid between the fine and coarse aggregate particles in PCC. Portland cement properties are, thus, very important for PCC material design and research into PCC strength and durability.

Cement-Treated Materials/Cementitious Materials

Cement-treated/cementitious materials include lean concrete, lime, and other pozzolanic (chemical)-treated soils. Their properties range from materials that only slightly modify the plasticity characteristics of the original aggregate/soil material to materials having major gains in stiffness, strength, and other key engineering properties. Lime, flyash, and cement are the major types of cementing material in this category.

Unbound Base/Subbase

The major material characteristics associated with unbound base/subbase materials are related to the fact that the strength and deformation of these materials are highly influenced by the stress state (nonlinear) and in situ moisture content. As a general rule, coarse-grained materials become more stiff as the state of stress is increased. In contrast, clay materials tend to have a reduction in stiffness as the deviatoric or octahedral stress component is increased. Thus, although both categories of unbound materials are stress dependent (nonlinear), each behaves in an opposite direction as stress states are increased.

Subgrade

The subgrade provides the foundation of a pavement system. Subgrade characterization is, therefore, an important component of pavement design and construction. Subgrade properties such as gradation, plasticity, strength, moisture sensitivity, permeability, and frost susceptibility are important for characterizing pavement subgrade materials for pavement design.

Characterizing subgrade material variability is key for assessing the reliability of pavement designs. This is especially true for pavements constructed directly over natural subgrade with no form of modifications or treatment with lime, asphalt, or cement.

Laboratory Testing

The LTPP laboratory testing process, conducted to establish material properties and characteristics, involved more than 40 test procedures, including thickness determinations, compressive strength, gradation, Atterberg limits, and resilient modulus.(1)

The sampling and laboratory testing were conducted using Strategic Highway Research Program (SHRP) test protocols documented in the SHRP *Laboratory Material Handling and Testing Guide*.(2) Most of the testing protocols were based on the American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO) approved procedures.(3, 4) Data obtained through material characterization tests are stored in the Materials module in the LTPP database, which currently consists of 76 separate tables containing various data elements obtained through testing.(5)

Objectives of the Materials Assessment Study

This study has the following objectives:

- Examine selected material-related data elements in the LTPP database to evaluate completeness, identify missing or unavailable data elements, and determine data quality.
- Identify anomalous data that require closer examination and explanation.
- Examine and explain possible sources of error for anomalous data and identify remedial actions for correcting anomalies, as appropriate.

- Provide recommendations to eliminate anomalies in future data collection and processing activities.
- Depict differences between as-designed and as-built properties.
- Describe/characterize inconsistencies in the data or test procedures used to obtain them.
- Develop new computed parameters, as appropriate.

Efforts to achieve these objectives were divided into two phases. The scope of Phase I was as follows:

- Identify key material-related data elements to be evaluated.
- Develop a summary of available data and data quality.
- Assess the usefulness of material data-collection guidelines and determine whether they meet future analysis needs.
- List the material-related data elements that are not being collected as part of the LTPP material characterization program but may be needed for future analysis efforts.
- Provide recommendations, as appropriate, for revising the Phase II work plan.

Phase II of the study consisted of tasks to resolve anomalies identified in Phase I to reduce excessive variability in the data and to compute representative test values and new parameters. The scope of Phase II was as follows:

- Identify the causes of erroneous or anomalous data within the LTPP database.
- Perform remedial action to correct the identified anomalies.
- Highlight anomalies that could not be corrected.
- Compute representative test values for the selected material-related data elements for each test section with data.
- Compute new material-related data elements for inclusion in the LTPP database.

Scope of the Report

This report presents the work done to improve the LTPP material data quality and to include new data elements in the database. It addresses work done in assessing and evaluating material data availability and quality of the available data. Chapter 2 of this report presents an overview of the LTPP material characterization program, with emphasis placed on the key material-related data elements being evaluated as part of this study. Chapter 3 discusses various methodologies for assessing data availability, data quality, performance of remedial action, and computing of representative test values.

Chapters 4 through 17 present a detailed summary of data availability and quality for the 13 data elements evaluated in this study. They also present detailed documentation of the procedures used in correcting anomalies, computing missing test results, and computing representative test values and other basic statistics.

Chapter 18 presents conclusions and recommendations. Issues discussed in chapter 18 include the adequacy of current LTPP material data-collection procedures, the need for computing new data elements with respect to meeting future analysis needs, and recommendations for collecting (through sampling and testing) material-related data elements that are not currently available but may be needed for future analysis efforts.

2. OVERVIEW OF LTPP MATERIALS CHARACTERIZATION PROGRAM

Introduction

The LTPP program consists of two complementary experiments, GPS and SPS. GPS experiments are usually existing in-service pavements incorporated into the LTPP program, whereas the SPS experiments are newly constructed or rehabilitated pavements or pavements subjected to various forms of maintenance activities. GPS experiments consist of a single 152-m pavement test section, whereas SPS experiments usually consist of a series of adjacent 152-m test sections with different design and material characteristics or maintenance treatments and rehabilitation strategies. The various GPS and SPS experiments are as follows:[(1)]

- GPS-1 - AC on granular base.
- GPS-2 - AC on bound base.
- GPS-3 - Jointed plain concrete.
- GPS-4 - Jointed reinforced concrete.
- GPS-5 - Continuously reinforced concrete.
- GPS-6A - Existing AC overlay on AC pavements.
- GPS-6B - New AC overlay on AC pavements.
- GPS-7A - Existing AC overlay on PCC pavements.
- GPS-7B - New AC overlay on PCC pavements.
- GPS-9 - Unbonded PCC overlays on PCC pavements.
- SPS-1 - Strategic study of structural factors for flexible pavements.
- SPS-2 - Strategic study of structural factors for rigid pavements.
- SPS-3 - Preventive maintenance effectiveness of flexible pavements.
- SPS-4 - Preventive maintenance effectiveness of rigid pavements.
- SPS-5 - Rehabilitation of AC pavements.
- SPS-6 - Rehabilitation of jointed PCC pavements.
- SPS-7 - Bonded PCC overlays on concrete pavements.
- SPS-8 - Study of environmental effects in the absence of heavy loads.
- SPS-9 - AValidation of SHRP asphalt specification and mix design (Superpave).

Figure 1 shows the typical layout of GPS and adjacent SPS test sections (projects) within an experiment. The typical SPS experiment consists of 12 test sections at a project site.

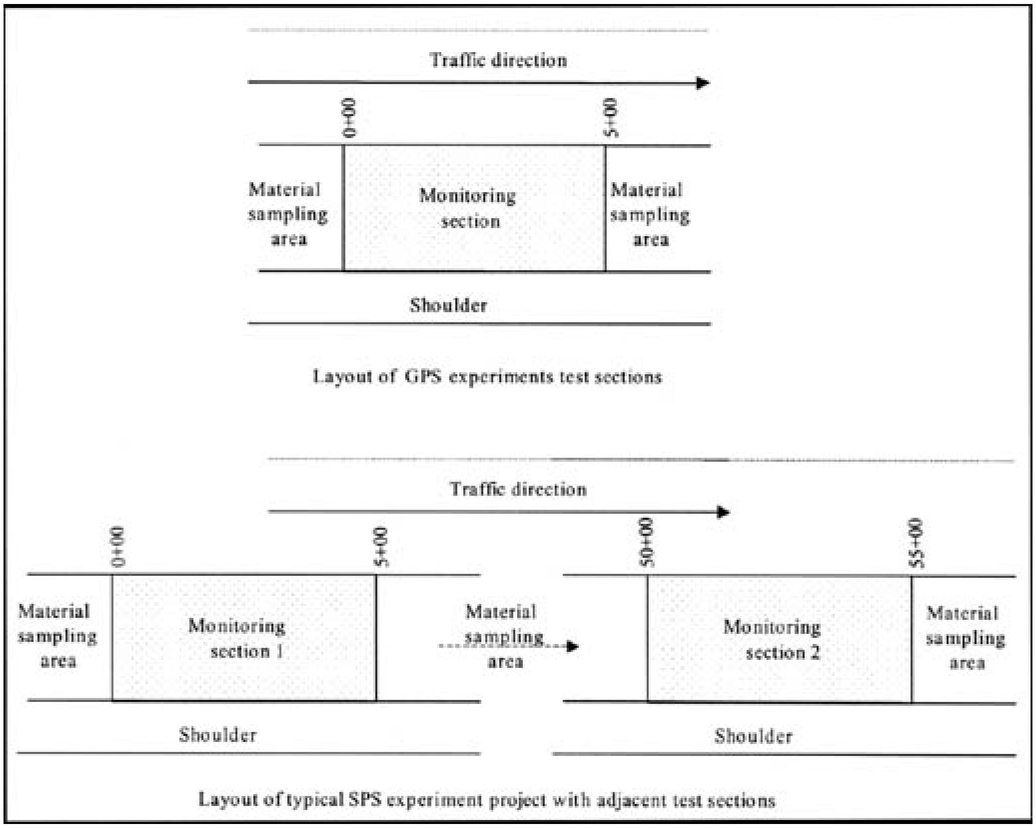


Figure 1. Layout of GPS and SPS experiments.

Material Data Collection Process

Material characterization, distress, climate, traffic, inventory, and other types of data are collected and stored in the LTPP database by four LTPP regional offices, supervised by the LTPP staff. Each regional office is responsible for data collection in a specific group of States, Provinces, and Territories.(1) For material characterization, the regional offices focus on:

- Assembling field and laboratory test data from State highway agencies (SHA's) or other LTPP testing contractors.
- Entering data provided either on paper forms or electronically by the SHA's or LTPP contractors into the database.
- Data quality control.

The technical support contractor is responsible for quality assurance (QA) of all LTPP data. It is also responsible for providing the data to the public and assists the LTPP staff in ensuring that common test procedures and standards are used, so that there is consistency in the data-collection process and quality control (QC) is maintained at all times in the material characterization program. Specific procedures employed to maintain QC are discussed in the next section.

Material Sampling

The LTPP materials characterization effort begins with field sampling and laboratory testing of the sampled paving materials. Undisturbed material samples or disturbed bulk samples are obtained by drilling, coring, or excavating test pits at designated locations within the pavement test sections. Sampling was performed using the plans and guidelines provided in the *Laboratory Material Handling and Testing Operational Guide*.(2)

For GPS experiments, samples were marked and shipped to the designated laboratories for testing by the LTPP regional field material sampling and field testing contractors. For SPS experiments, the samples were marked and shipped to the designated laboratories for testing by the local highway agencies or tested in the agency laboratory facilities. Conditions encountered in the field while sampling were recorded and documented to provide the laboratories with adequate background information on the materials to be tested.

The typical LTPP pavement test section consists of an area 152-m long and one lane wide. Nondestructive tests, such as Falling Weight Deflectometer (FWD) tests to obtain pavement deflection under loading and visual surveys to obtain distress data such as cracks and ruts, are conducted periodically on these sections to characterize pavement performance.[1] For this reason, paving materials for laboratory characterization were retrieved only from the beginning and the end of the designated test sections (just outside the 152-m limits). Sufficient space is left between the adjacent test sections in SPS experiments to facilitate the drilling and retrieval of paving materials for testing. Details of sampling location and dimensions of cores or test pits for the different LTPP experiments are provided in the *Laboratory Material Handling and Testing Operational Guide.*(2)

[1] For a complete history of and information regarding the frequency of NDT and visual distress surveys, refer to appropriate FHWA reference manuals and reports.

Material Handling

After retrieving sample materials from coring or test pits, the sample materials were marked and labeled for easy identification before shipping to the testing laboratory. As a minimum, the following information was included on tags and labels:

- Unique six-digit section identification number.
- Core/sample location (as marked on sample layout plans).
- Sample code (four-digit code, that identifies sample type [e.g., core or bulk sample], material type [e.g., PCC or AC], and sample number).
- Sampling date.
- Field set (one-digit number, which will be 1 for the first round of sampling and 2 where a second round of sampling is performed at the same general location in the future).

Laboratory tests were performed on several paving materials, including AC, extracted aggregate from the AC, treated base and subbase, untreated base and subbase, subgrade, and PCC materials. The tests were performed according to test protocols found in the *SHRP Interim Guide for Laboratory Material Handling and Testing.*(2)

Laboratory Testing

Laboratory testing includes both the material preparation and the actual testing of samples. Testing is done only by accredited laboratories. Accredited laboratories are expected to provide sufficient and suitable materials testing equipment, facilities, and personnel to meet the requirements of ASTM E329-

77, ASTM D3666-83, ASTM D3740-80, and the AASHTO Accreditation Program (AAP), as outlined in the AASHTO Technical Provisions.[3, 4]

Material sampling and testing is performed at least once at the beginning of the section's acceptance into the LTPP program. Additional testing may be performed because of the study requirements or to investigate unexpectedly poor performance. Materials test data are stored in the Materials module in the LTPP database.

Data Processing

LTPP material data processing begins with sample retrieval in the field and continues throughout material characterization until the test results and associated data are placed in the LTPP database at the highest data quality level. Several QA/QC checks are built into the data processing mechanism to ensure that the final data are of the highest quality. Step-by-step operational procedures to ensure QA/QC can be found in several SHRP publications, including *LTPP IMS Data Quality Checks* and the S*HRP Interim Guide for Laboratory Material Handling and Testing.*[2, 6] The following basic definitions related to quality management terminology are used in the SHRP-LTPP material characterization program:

- Quality--conformance to requirements set by LTPP.
- Quality control--doing and checking the work before releasing it to LTPP.
- Quality assurance--quality verification--in other words, verifying that the quality control is operational and adequate.

The QA/QC program provides for review, assessment, and necessary corrective actions of the following:

- Project supervision.
- Sample identification, storage, and disposal.
- Laboratory handling of samples.
- Sample storage and disposal.
- Adherence to the specified laboratory testing protocols.
- Accuracy in measurements.
- Equipment maintenance and calibration.
- Review and checking of data.
- Presentation of data and reports.

The LTPP regional offices perform various QC checks on the data during processing.[1, 6, 7] QC begins during data collection to ensure that material data are collected under comparable conditions, using similar test equipment and testing procedures. QC procedures include review of inputs before and after entry into the LTPP database and checking for errors related to keystroke input, laboratory and field operations and procedures, and test equipment operations.[6, 7]

Other checks, some of which are incorporated in data preprocessing software, review the data by checking for the presence of mandatory data elements (e.g., material description), logic in the data, and range of the specific data values. The QC checks are categorized as levels A through E, as follows:[1, 6]

- Level A--random checks of the data to ensure correct data transfer from the regions to the LTPP database.
- Level B--verifies that the initial experiment assignments are in agreement with inventory data.
- Level C--involves searching the data set for critical elements,[2] such as testing data, layer types (must include a description of the material), layer location in the pavement structure, and a nonzero layer thickness.

- Level D--involves checking specific fields to identify data element values that fall outside an expected typical range (e.g., layer thickness should be nonzero and should not exceed a generally accepted maximum).
- Level E--intramodular checks designed to verify the consistency of data within a record or between records (e.g., the description of the asphalt test results should match the description of the corresponding layer in the pavement structure table).

[2]For a complete list of critical elements, refer to appropriate FHWA QA/QC manuals.

Each data record in the LTPP database includes a letter showing the last QC check that was performed successfully. A quality value of B does not necessarily indicate all QC after level B was unsuccessful; however, it does indicate a problem with the data record, such as a missing supporting data element (e.g., missing layer number or layer description).

The two important tables in the Materials module that describe the pavement structure and are used to link test results with the pavement layers are TST_L05A and TST_L05B. Other important tables that are necessary to describe and fully understand the test pavement structure are EXPERIMENT_SECTION and COMMENTS. Linking these tables with specific material data tables helps the user to determine consistency in the data and, hence, the overall data quality. Additional information on field sampling, laboratory characterization, and material-related data in the LTPP database can be obtained from the FHWA LTPP Web page, http://www.tfhrc.gov/ltpp.htm.

Material Data Elements Evaluated for the Current Study

The material characterization needs of pavement analysts are wide ranging--from standard simple index tests, such as Atterberg limits or gradation of soils, to more rigorous testing of varying complexity, such as coefficient of thermal expansion (CTE), used as input for mechanistic-based analysis. To focus the effort of this study on the most important aspects of the materials data, key data elements were selected to be studied in depth. Selection was based on the following criteria:

- Basic material characteristics used in assessing pavement behavior.
- Usefulness for computing other material parameters.
- Usefulness for data analysis and pavement performance evaluation.

Table 1 presents a list of the key material-related data elements selected for evaluation in this study. These data elements describe fundamental pavement characteristics and will be useful in pavement evaluation and research. The list was developed based on the following criteria:

- Importance and need of the data element in pavement analysis.
- Use of the data element in computing other data parameters.
- Availability of significant amounts of the data in the LTPP database.

Table 1. Material data elements evaluated.

SHRP Test Protocol	Laboratory Test Title	Test Table Designation
P01	Core examination and thickness	TST_AC01
P02	AC bulk specific gravity	TST_AC02
P03	AC maximum specific gravity	TST_AC03
P05	Moisture susceptibility[1]	TST_AC05
P14	Gradation of aggregate	TST_AG04
P32	Unconfined compressive strength of treated base/subbase material	TST_TB02
P41	Particle size analysis of granular base/subbase	TST_UG01_UG02_SS01
P43	Determination of Atterberg limits (subgrade)	TST_SS03
P54	Unconfined compressive strength of subgrade soils[2]	TST_SS10
P61	Determination of compressive strength of in-place concrete[3]	TST_PC01
P63	Coefficient of thermal expansion for PCC	TST_PC03
P66	Visual examination and length measurement of PCC cores	TST_PC06
P69	PCC flexural strength	TST_PC09

[1]Recent research indicates this test may not be very reliable; however, it is currently the LTPP-designated test method for assessing AC susceptibility to moisture damage.
[2]Tests were conducted on both reconstituted and undisturbed (Shelby tubes) specimens.
[3]*In-place concrete* refers to concrete cores specimens extracted from the in-place PCC slab for laboratory testing and not NDT.

Some tables with limited data were evaluated because of their importance (e.g., TST_AC05--moisture susceptibility test). The resilient modulus data for AC and unbound materials were or will be evaluated in separate investigations. A brief description of the data elements selected for evaluation is presented in the next few sections.

Core Examination and Thickness (TST_AC01 and TST_PC06)

Both AC and PCC layer thickness were evaluated as part of this study. These are key inputs required for virtually any analysis related to pavement structural capacity and performance prediction. In addition, AC and PCC thickness are required for computing other pavement material properties, such as backcalculated layer moduli.

Bulk and Maximum Specific Gravity (TST_AC02 and TST_AC03)

Bulk specific gravity (BSG) and maximum specific gravity (MSG) are important AC mixture properties. They are used in mix design and for QA/QC during construction. Both the bulk and maximum specific gravities are used as the basis for assessing and computing volumetric parameters of AC mixtures, such as air voids, voids in mineral aggregates (VMA), voids filled with asphalt (VFA), and relative compaction of the mixture.

Gradation Analysis/Particle Size Analysis (TST_AG04 and TST_UG01_UG02_SS01)

Gradation data from extracted AC cores, unbound base, subbase, and subgrade materials were evaluated as part of this study. AC gradation is a key input for determining the adequacy of the AC design mix and for estimating the volumetric properties of the mixture. For the unbound materials, gradation is a key input for determining numerous material characteristics, including permeability, porosity, effective porosity, coefficient of uniformity, coefficient of gradation/curvature, and soil classification. Gradation can also be used to estimate the stiffness and stability parameters of AC mixtures and base/subbase materials.

AC Moisture Susceptibility (TST_AC05)

A significant proportion of early failures in AC pavements has been linked to durability-related problems with the AC mixtures. Therefore, asphalt-treated materials must be designed at all times to prevent stripping, which is the most significant durability-related distress in AC materials. Stripping can be caused by several factors, including:

- Lack of enough asphalt cement in the mixture to provide sufficient film thickness around the coarse aggregates.
- Use of moisture-susceptible aggregate materials.
- Lack of drainage.

Moisture susceptibility tests have been designed to estimate the susceptibility of an AC material to moisture damage, hence, material durability performance. There is, however, no consensus on the usefulness of current moisture susceptibility tests because of conflicting findings reported by various research studies on the reliability of such test results. The test methods currently available, however, offer the best indicators for assessing the long-term durability and performance of AC paving materials, which is key to research.

AC moisture susceptibility testing data in the LTPP database provide the necessary information required for assessing the suitability of aggregate and AC materials for pavement design to prevent early failure.

Unconfined Compressive Strength (Treated Base/Subbase/Subgrade) (TST_SS10)

Compressive strength is an important parameter in characterizing many bound and unbound materials. The primary use of this parameter is in model development, in which performance characteristics are related to strength parameters. Additional uses include developing correlations with strength and deformation parameters, material classification, and others.

Subgrade Atterberg Limits (TST_SS03)

Atterberg limits are used in soil classification and to differentiate plastic versus nonplastic fines. These indices are important in assessing permanent deformation tendencies, analysis of subgrade rutting, moisture sensitivity, potential for moisture or freezing-induced volume changes, and more.

Compressive Strength of In-Place Concrete (TST_PC01)

Compressive strength is the most widely used measure of PCC quality and frequently serves as the basis for acceptance of the material during construction. The compressive strength can be correlated with the flexural strength, tensile strength, and elastic modulus of the PCC. This test is generally regarded as the easiest of the standard tests to perform on PCC and, therefore, will continue to be widely used in characterization.

Coefficient of Thermal Expansion of PCC (TST_PC03)

The CTE is related to the stresses developed within PCC pavements due to temperature changes. It is very important for mechanistic analysis because it is key for determining thermal-induced stress cycles within PCC pavements. Procedures for determining CTE have recently been developed by the LTPP, and therefore, this study provided an opportunity for characterizing the reasonableness of test results and estimating typical test values.

PCC Flexural Strength (Modulus of Rupture) (TST_PC09)

The flexural strength of PCC is a key parameter in concrete pavement analysis because the flexural test simulates the most common mode of failure in concrete slabs. It is used in M-E analysis to estimate PCC fatigue life, top-down and bottom-up cracking in jointed concrete pavements (JCP), and punchouts in continuously reinforced concrete pavements (CRCP).

Because of its importance, the flexural strength of cast or sawed PCC beams has been related to or correlated with other relatively easy- to-obtain PCC strength parameters, such as compressive strength. The LTPP database is one of the few with both compressive and flexural strength data for PCC pavements that could be used in verifying the accuracy of current models relating PCC flexural and compressive strength or for developing new models, if required.

3. OVERVIEW OF DATA QUALITY EVALUATION TECHNIQUES AND PROCEDURES FOR COMPUTING NEW DATA ELEMENTS

The main objectives of this study were to determine the following:

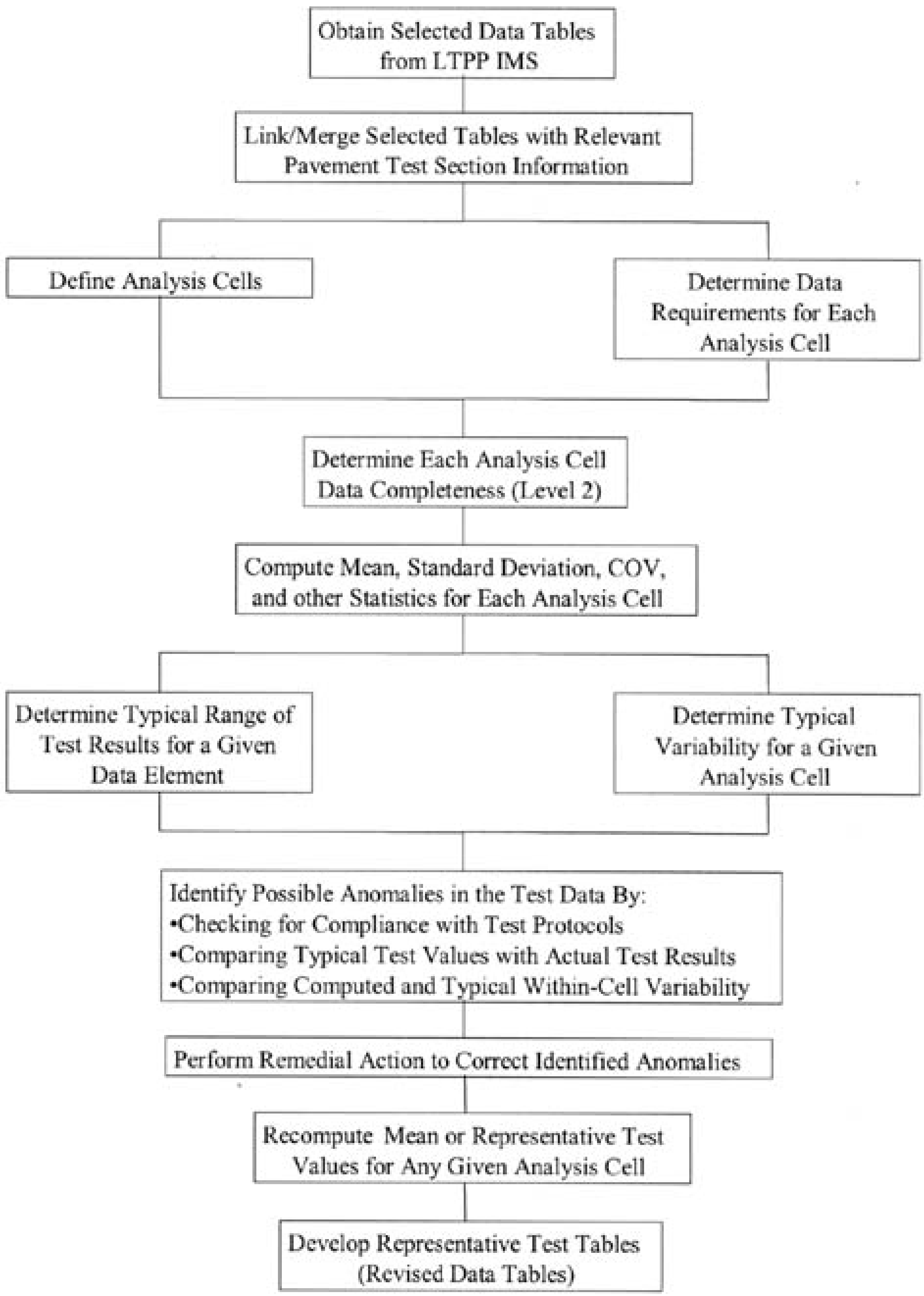
- The status (completeness and quality) of the selected data elements in the LTPP database and identification and rectification of possible anomalies in the data tables
- Representative test values and other statistics of the data within each test section
- New data elements (computed parameters) to augment current data in the LTPP database

Various statistical and analytical techniques were adopted and used in this effort. The techniques presented in this chapter were applicable to most of the data elements examined. However, the analysis methods were modified to suit specific situations, where necessary.(8, 9) The procedure for achieving the objectives of this study is presented in figure 2.

Assembly and Preparation of Selected Data Elements

The first step after selecting key data elements was to assemble the data from the LTPP database. The following data tables were extracted from the following database tables:

- AC core examination and thickness--TST_AC01_LAYER.
- AC BSG--TST_AC02.
- AC MSG--TST_AC03.
- Gradation of extracted aggregate--TST_AG04.
- Moisture susceptibility--TST_AC05.
- Determination of compressive strength of in-place concrete--TST_PC01.
- CTE for PCC--TST_PC03.
- Visual examination and length measurement of PCC cores--TST_PC06.
- Flexural strength--TST_PC09.
- Particle size analysis of granular base/subbase--TST_SS01_UG01_UG02.
- Determination of Atterberg limits (subgrade)--TST_SS03.
- Unconfined compressive strength of subgrade soils--TST_SS10.
- Unconfined compressive strength of treated base/subbase material--TST_TB02.



Potential remedial action for identified anomalies has been presented later in this chapter.

Figure 2. Summary of data tables evaluation procedure.

The data used in the study were obtained from the January 2000 release of the LTPP database. The selected material test data tables were merged (using SHRP identification number, construction number, and layer number) with other inventory and test data tables, such as EXPERIMENT_SECTION and TST_LO5B, to obtain information about the pavement structure, including layer descriptions, experiment type, and age. Data acquisition was facilitated by using Microsoft Access, Microsoft Excel.[10]

Assessing Data Completeness

Data elements were examined for completeness at two levels and are defined as follows:

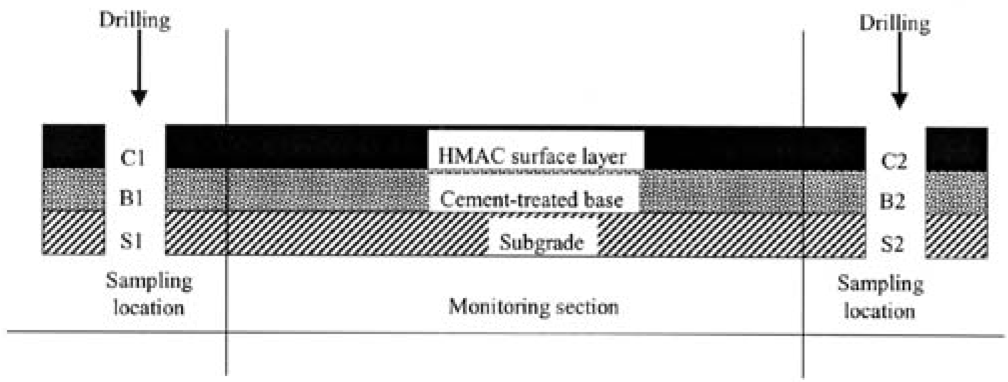
- Level 1 data completeness is the percentage of all test results (data elements) reported in the LTPP database at level E, as compared with the total number of test results reported in the LTPP database (levels A to E).
- Level 2 data completeness is the percentage of analysis cells with the required minimum number of tests conducted and reported, as compared with the total number of analysis cells with as least one test result reported.

Analysis cells are specific to an experiment and test data element, and are defined based on the following factors:

- SHRP identification number.
- State code.
- Construction number.
- Experiment type and number.
- Layer type and number.
- Target thickness.
- Target strength.
- Specimen type (e.g., core or cylinder).
- Specimen age at testing.

In general, for the GPS experiments, an analysis cell is the same as a layer of a given material type within a monitoring test section. However, for SPS experiments, the definition of an analysis cell is more complicated because factors such as specimen age at testing, target strength, or target thickness of specimens within a given experiment must be considered in defining cells. Also, using layer numbers for defining analysis cells in SPS experiments may be misleading because the same layer number may be prescribed to different material types along adjacent test sections within the experiment (e.g., dense-graded aggregate base [DGAB] in test section 201 may have a layer number 2 while a DGAB in test section 205 may have a layer number 3).

Finally, the sampling locations for the typical SPS experiment did not necessarily include all 12 individual test sections in the experiment. However, analysis cells were defined such that they represented test sections within the experiment with the given material or layer description (e.g., asphalt content of all asphalt-treated base material or all hot mix asphalt concrete [HMAC]). Figure 3 shows an example of how analysis cells could be defined for GPS pavement test sections. Level 2 data analysis and all other analyses thereafter were done using only level E data.



Samples taken from locations C1 and C2 form an analysis cell for data elements related to hot mix asphalt concrete (HMAC; e.g., HMAC moisture susceptibility).
Samples taken from locations B1 and B2 form an analysis cell for data elements related to the cement-treated base (CTB; e.g., CTB compressive strength).
Samples taken from locations S1 and S2 form an analysis cell for data elements related to subgrade(e.g., Atterberg limits).

Figure 3. Example of typical analysis cells for a GPS test pavement.

Level 1--Data Completeness

The objective of level 1 data completeness was to estimate the amount of data still moving through QC checks and data that failed QA/QC. Data still undergoing QA/QC may be available for use in analysis at a later date. Rejected data are those that were collected and entered into the LTPP database but failed QC and are, therefore, held at a quality level less than E, unsuitable for release and use by the public. Level 1 data completeness analysis did not include data that had not yet been entered into the LTPP database.

Level 1 data completeness was determined as follows:

1. Summarize the total number of test results reported at level E in the LTPP database.
2. Summarize the total number of test results reported at all levels in the LTPP database.
3. Determine the percentage of test results at level E.
4. Determine the number of analysis cells represented by the level E test results.

Level 2--Data Completeness

Level 2 data completeness consisted of the determination (for each test table evaluated) of the number of analysis cells with the minimum number of tests conducted and reported at level E, as required by the applicable data collection guidelines. This was done by comparing the actual number of test results reported per analysis cell with the minimum required. Level 2 data completeness was reported as the percentage of the total number of analysis cells in a test table with the minimum number of test results.

Level 2 data completeness is important because it relates directly to data quality. If an inadequate number of samples/specimens are tested for a given analysis cell within a test section, the resulting representative test results reported for the cell may be biased. Biased representative test results may not be a true reflection of the analysis cell within the pavement test section's material properties.

Assessing Data Quality

Data quality for the selected material data elements was assessed as follows:

- Determine whether data are reasonable.
  - Use univariate analysis and scatter plots to evaluate reported test results in the LTPP database.
  - Use bivariate analysis and plots to determine whether the test results are consistent with expected trends.
- Determine data quality.
  - Assess the possibility of sampling and testing bias in test results.
  - Assess compliance with test protocols and procedures.
  - Assess reasonableness of within-analysis cell variability.

The following is a summary of the procedure used to assess data quality:

1. Group the data into analysis cells of similar pavement design, construction, and material properties. For most of the data elements analyzed, analysis cells were defined based on factors such as SHRP_ID number, State code, construction number, pavement layer, specimen age at testing, target strength, and target thickness, within a specific test section or experiment.
2. Determine from published literature the range of typical test values (this is similar to the level D QC checks described earlier) for the specific data element being evaluated. In determining typical test values, factors such as the test condition, material preparation, specimen age, test type and protocol, and test equipment must be taken into account.
3. Determine typical or allowable within-cell variability. This may be estimated from precision and bias statements of the test standard or protocol and other published literature.
4. Use appropriate statistical techniques (e.g., scatter plot, univariate analysis) to determine the range of test values within the data tables.
5. Compare the actual test results with the expected range of test values to determine whether they are within or outside the expected range. Data that fall outside the typical range of test values are unreasonable and could be erroneous.
6. Estimate within-cell variability (e.g., standard deviation) for each analysis cell with multiple test results.
7. Compare the results in step 6 with the allowable variability (step 3) and determine the percentage of the data with acceptable variability.

Figure 4 illustrates this process as a flow chart.

Assessing Reasonableness of Data

Data reasonableness was determined using univariate analysis, scatter plots, and bivariate (time-series) plots. The procedures used are described in the following sections.

Univariate Analysis and Scatter Plots

Data reasonableness was determined by developing scatter plots of the data or performing a univariate analysis to determine the range of the values of the test data. The range of test values was then compared with the range of typical test values to determine whether the LTPP test results were typical. Determining typical values depended on many factors related to both material properties and testing method.[(11)] As an example, the typical flexural strength of a PCC core depends on the mix properties (e.g., cement content, water/cement ratio, and coarse aggregate content), age at testing (e.g., 7-, 14-, 28-day, or long-term testing), and test method used (e.g., specimen dimensions, rate of loading, and test type [center- or third-point loading]).[(11)]

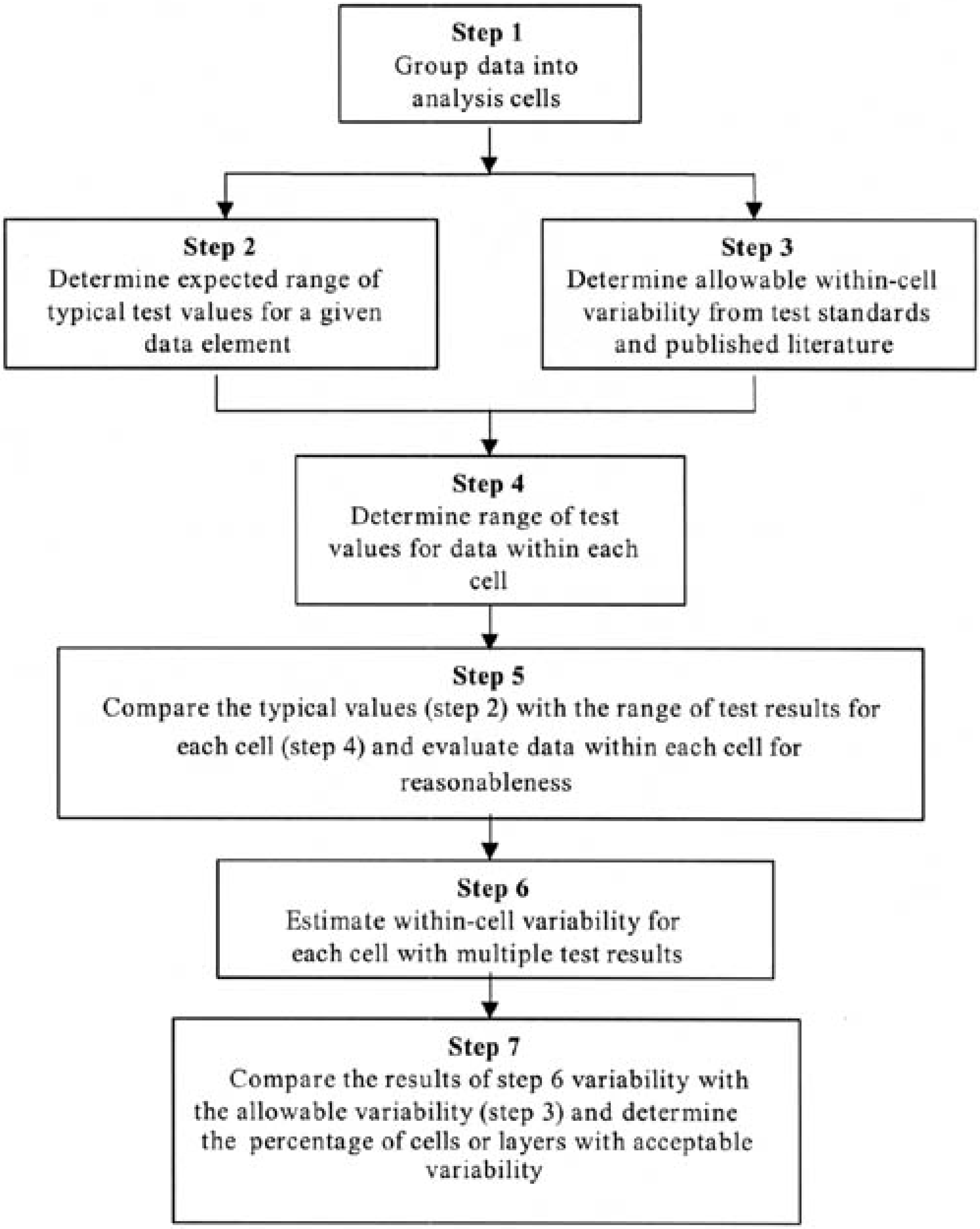


Figure 4. Flow chart for assessing data quality.

An example of the information required for evaluating the reasonableness of thickness data is presented in table 2 and figure 5. Both table 2 and figure 5 show the range of thickness values observed for a given database. The observed or calculated range can easily be compared with typical values to determine reasonableness. The information presented can also be used to identify obvious anomalies, such as negative thickness values, thickness values close to zero, or extraordinarily high (e.g., 1,000-mm) thickness values.[1]

Analysis cells with erroneous test results are likely to exhibit excessive variability. For LTPP test sections with target test values (e.g., designed thickness = 200 mm), the information assembled by the univariate analysis or scatter plots can be used to determine whether the specified target values were obtained. Test results that are not close to the intended target values do not necessarily imply the presence of anomalies. Such results mean only that the targets were not achieved.

Table 2. Descriptive statistics for evaluating reasonableness of test data.

Cell Type (layer 1, SHRP_ID 001)	Number of Specimens	Mean Thickness, mm	Target Thickness, mm[1]	Min Thickness Range, mm	Max Thickness Range, mm
GPS-XX					
GPS-XX					
SPS-XX					
SPS-XX					

[1]If applicable.

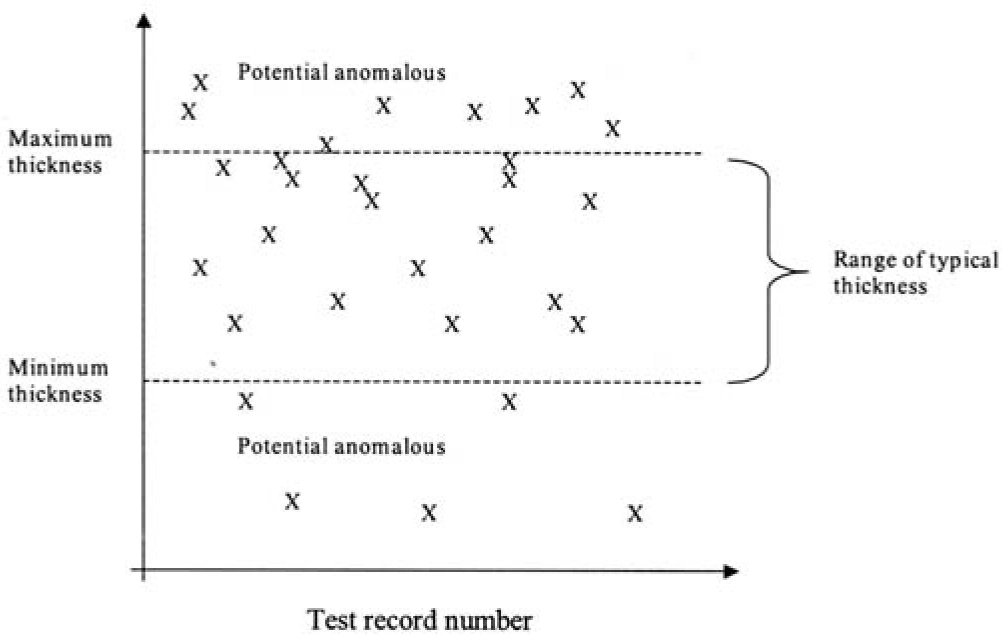


Figure 5. Scatter diagram used in assessing reasonableness of data.

The focus of this study was not to identify experiments not achieving the target material properties; however, variability from set targets is an indication of poor construction quality control or poor measurement and the potential for excessive variability in test results.

It was not possible to determine typical test values for all data elements. For such data elements (e.g., gradation), reasonableness was determined only by observing the trends in the data by performing a comprehensive bivariate analysis (e.g., for gradation test results, the percentages passing consecutive sieve sizes are expected to decrease as the sieve size decreases).

Bivariate Analysis

Bivariate plots were developed for time-series test results or for test results with expected trends to determine the reasonableness of observed trends. For example, time-series plots were used in determining data reasonableness for compressive and flexural strength of PCC cores. Past research and analysis has shown that there will most likely be an increase in PCC strength with increasing age. The rate of increase is quite rapid within the first few days after placement and subsequently decreases with age. Therefore, reasonable data are expected to show such a trend. Compressive strength test results showing the opposite trend indicate potential erroneous data. An example of a time-series plot is shown in figure 6.

Data Quality

Data quality was evaluated by assessing the data within analysis cells for sampling and testing bias, compliance with test protocols or standards, and excessive variability. The procedures used in evaluating data quality are discussed in the following sections.

Assessing Data for Sampling or Testing Bias

Bias is a systematic error in testing or sampling that contributes to the difference between sample mean and a true reference value (population mean). Poor sampling methods and procedures, using noncalibrated test equipment, or untrained laboratory personnel are the usual causes for bias.

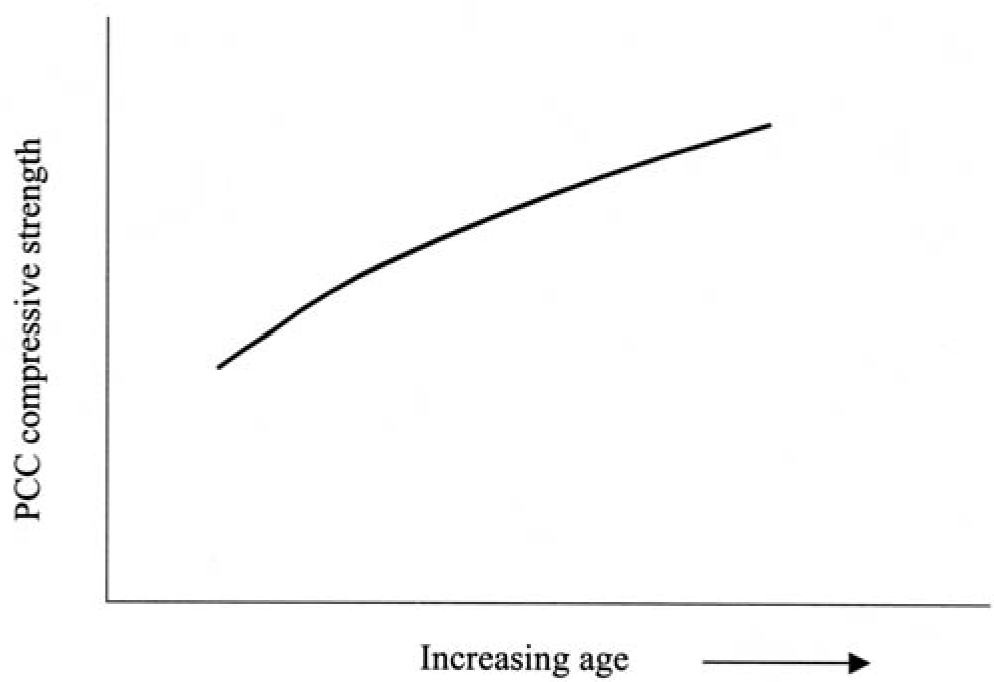


Figure 6. Time-series plot used in data quality evaluation.

The LTPP material characterization plan is very comprehensive and should eliminate bias in computed mean test values. However, the mean test values for analysis cells with incomplete sampling and testing may be biased, especially if all the limited number of samples tested were collected from either the approach or leave ends of the test pavement. Results from such test sections (where sampling was incomplete) must be evaluated for potential bias to avoid placing unrepresentative test results in the LTPP database for use in research and analysis. Figure 7 shows examples of incomplete sampling that may lead to bias in test results.

Assessment of Compliance with Test Protocols or Procedures

Another potential source of error, variability, and bias in test results is the lack of compliance with test procedures. Compliance with test protocols involves any or all of the following:

- Sample extraction and preparation.
- Sample storage and handling.
- Test equipment.
- Procedures for computing test results and units of measurement.
- Precision of measurements and rounding up of test values.

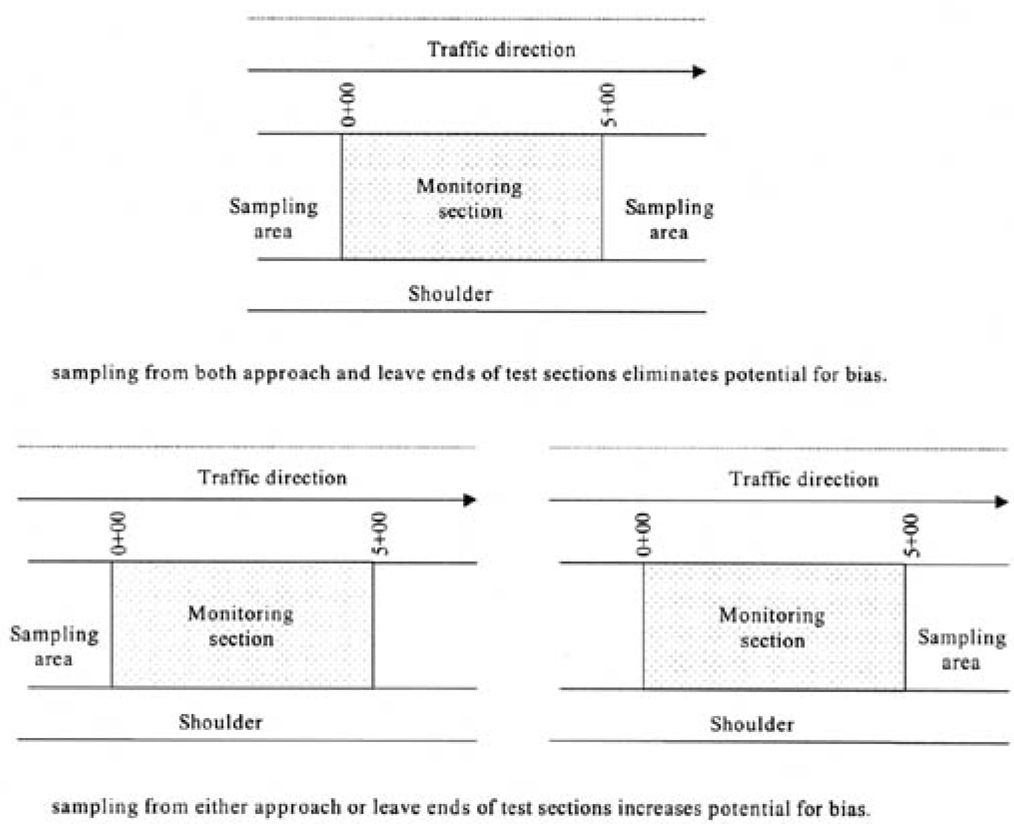


Figure 7. Examples of sampling bias.

Assessment of Within-Cell Variability

Statistics such as standard deviation and coefficient of variation (COV) were used to characterize within-cell variability. Variability can be computed only for analysis cells with multiple data points (multiple test results reported for a given analysis cell). The following are definitions of the statistics used in assessing variability:[12]

Variance--a measure of the scatter or spread in a given data set. It is defined as the sum of the squared deviations of each observation from the sample average, divided by the sample size minus 1 (see equation 1).[12] Because variance is expressed as the square of the units of the data element being analyzed, it is not always readily understood because it is not in the native units of the data element being evaluated.

$$S^2 = \frac{\sum_{i=1}^{n}(X_i - X_m)^2}{n-1} \qquad (1)$$

where:

X_i = Test result from the i^{th} specimen
X_m = Sample mean
S = Sample standard deviation
n = Number of specimens

Standard Deviation--a measure of the scatter or spread in a given data set. It is defined as the square root of the sum of the squared deviations of each observation from the sample average divided by the sample size minus one (see equation 2).[12] Standard deviation is expressed in the units of the data element being analyzed and is therefore more easily understood when evaluating variability.

$$S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_m)^2}{n-1}} \qquad (2)$$

Coefficient of Variation--the ratio of standard deviation and sample mean. It is defined as follows:[12]

$$CV = \frac{S}{X_m} \qquad (3)$$

The sample mean used in calculating the COV is the average of all individual test results for a given cell. It is a measure of the central tendency of the test results and is defined as:[12]

$$X_m = \frac{\sum_{i=1}^{n} X}{n} \quad (4)$$

These statistics (calculated for each analysis cell) were then compared with typical allowable variability to assess data quality.

Establishing Typical Variability

The fundamental statistic underlying all indices of typical variability is standard deviation. Typical variability measured as standard deviation is a summation of the following:(13)

- Material variability.
- Testing variability (operator and equipment).
- Sampling variability.

They are summed up as shown in figure 8. Typical variability can be computed as follows:

Figure 8. Summation of testing, sampling, and material variability to yield typical variability.(13)

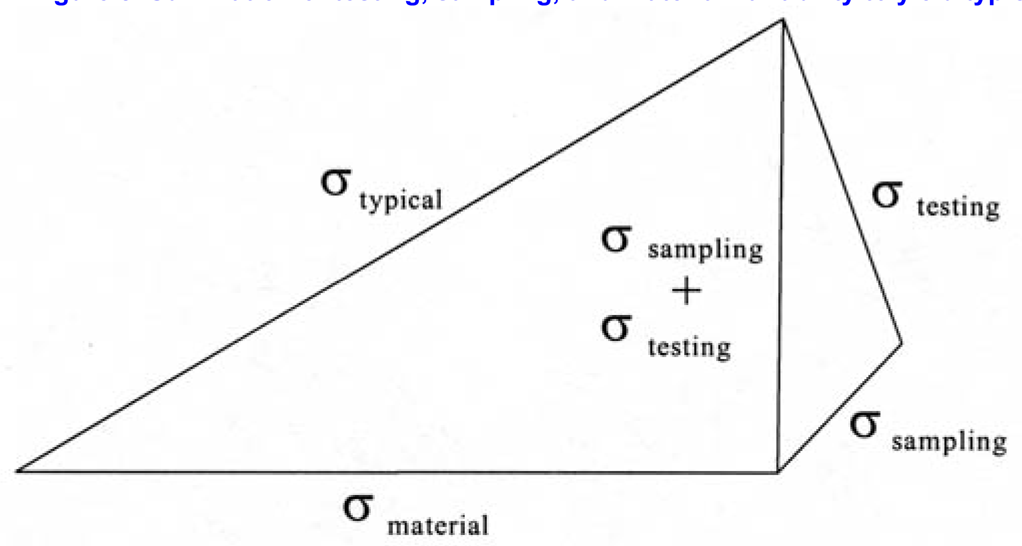


Figure 8. Summation of testing, sampling, and material variability to yield typical variability. (13)

1. Compute variability due to sampling and testing:

$$\sigma_{ST}^2 = \sigma_S^2 + \sigma_T^2 \quad (5)$$

where:

$sigma_{ST}$ = Variability due to sampling and testing
$sigma_S$ = Sampling variability
$sigma_T$ = Testing variability

2. Compute typical variability

$$\sigma_{TYP}^2 = \sigma_{ST}^2 + \sigma_M^2 \quad (6)$$

where:

$sigma_{TYP}$ = Typical variability
$sigma_{ST}$ = Variability due to sampling and testing
$sigma_M$ = Material variability

The significance of each of these components is discussed in the next few sections.

Material Variability--Material variability is the true random variability of any paving material. It is a function of the characteristics of the material itself and, therefore, varies in magnitude from material to material. Several studies have shown that material variability is one of the smallest sources of variability in test results in projects with adequate QA/QC.(13)

Sampling Variability--Sampling variability is a function of sampling technique, material, testing, and construction variability. It is detected when a sample taken from one location of a pavement will not indicate the same test result as one taken from another location of the same pavement.(13) Sampling variability can be assessed at two levels, namely, within-location and location-to-location.

Within-location variability is the magnitude of the difference in the measurements between two or more samples taken from the same location within the pavement. Within-location variability is a function of the sampling technique, material, and testing variability. Classic examples of within-location variability are variations in core thicknesses and core strengths of a concrete pavement for adjacent cores in the same location.(13)

Location-to-location variability is usually the largest source of variability in the paving process and, hence, paving materials. It represents the difference in test results from one location to other locations of the same material from the same pavement.(13) It includes all the causes of within-location sampling variability and construction variability by the paving process. Location-to-location sampling variability is greatest when the paving process is termed *out-of-control*. This type of variability is best exposed through multiple sampling along the pavement.

Testing Variability--Testing variability is the lack of repeatability of test results between test samples. It includes the effects of reducing sample increments to test portion size. Operators, equipment condition and calibration, and test procedure are a few of the important factors that can cause high testing variability.(13) Testing variability is often expressed as a precision statement.(12, 13)

Precision statements for test procedures provide guidance on the magnitude of variability that can be expected between test results when the same test method is used in one or more laboratories. ASTM E177, *Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods*, discusses the concepts used in developing precision statements for various types of tests in great detail.(12) The precision of a measurement process is a generic concept related to the closeness of agreement between test results obtained under prescribed like conditions from the measurement process being evaluated. Two kinds of precision statements are commonly used in assessing testing variability: within-laboratory precision (sometimes called s*ingle-operator precision*) and between-laboratory precision (called *multilaboratory precision*). ASTM C670, *Preparing Precision and Bias Statements for Test Methods for Construction Materials*, defines the two types of precision statements.(12)

For this study, typical variability incorporated all possible sources of variability (i.e., material, sampling, testing, and construction variability). Typical variability was established as close to the expected conditions of sampling and testing as possible. For this reason, the conditions under which variability is observed and reported in published literature was considered before being adopted for use in establishing typical variability.(13, 14)

Relationship between Variability, Accuracy, and Bias

The terms *variability*, *accuracy*, and *bias* are often confused and may be used misleadingly. Accuracy is a concept of exactness related to the closeness of agreement between the average of one or more test results and an accepted reference value. Accuracy may be thought of as an absence of bias--the consistent or systematic difference between a set of test results from a process and the true value, or reference value, of the property being measured. The definitions of precision, accuracy, and bias are best explained using a series of bulls-eye targets, shown in figure 9. Excessive variability does not always result in inaccurate average values, when compared with the true reference average value. It could, however, introduce bias and error. It is, therefore, a cause of concern and should be limited as much as possible. Bias always leads to erroneous results and should be avoided.

Recommendations for Remedial Action to Correct Identified Anomalies

The preceding sections of this chapter discussed the methods that were applied to identify potential anomalies in the selected LTPP material test data. The next step was to perform remedial action where possible to correct the identified anomalies. This section presents a general overview of some of the common anomalies with suggested remedial action. It must be noted that some anomalies are unique to the particular data element, test conditions, and LTPP test section to be evaluated. Such anomalies and remedial actions to correct them will be explained and discussed throughout this report.

Identification of Anomalous Data

Table 3 lists common anomalies, their potential effects on data quality, and potential remedial actions. The anomalies listed are the most commonly encountered in data analysis for completeness and quality.

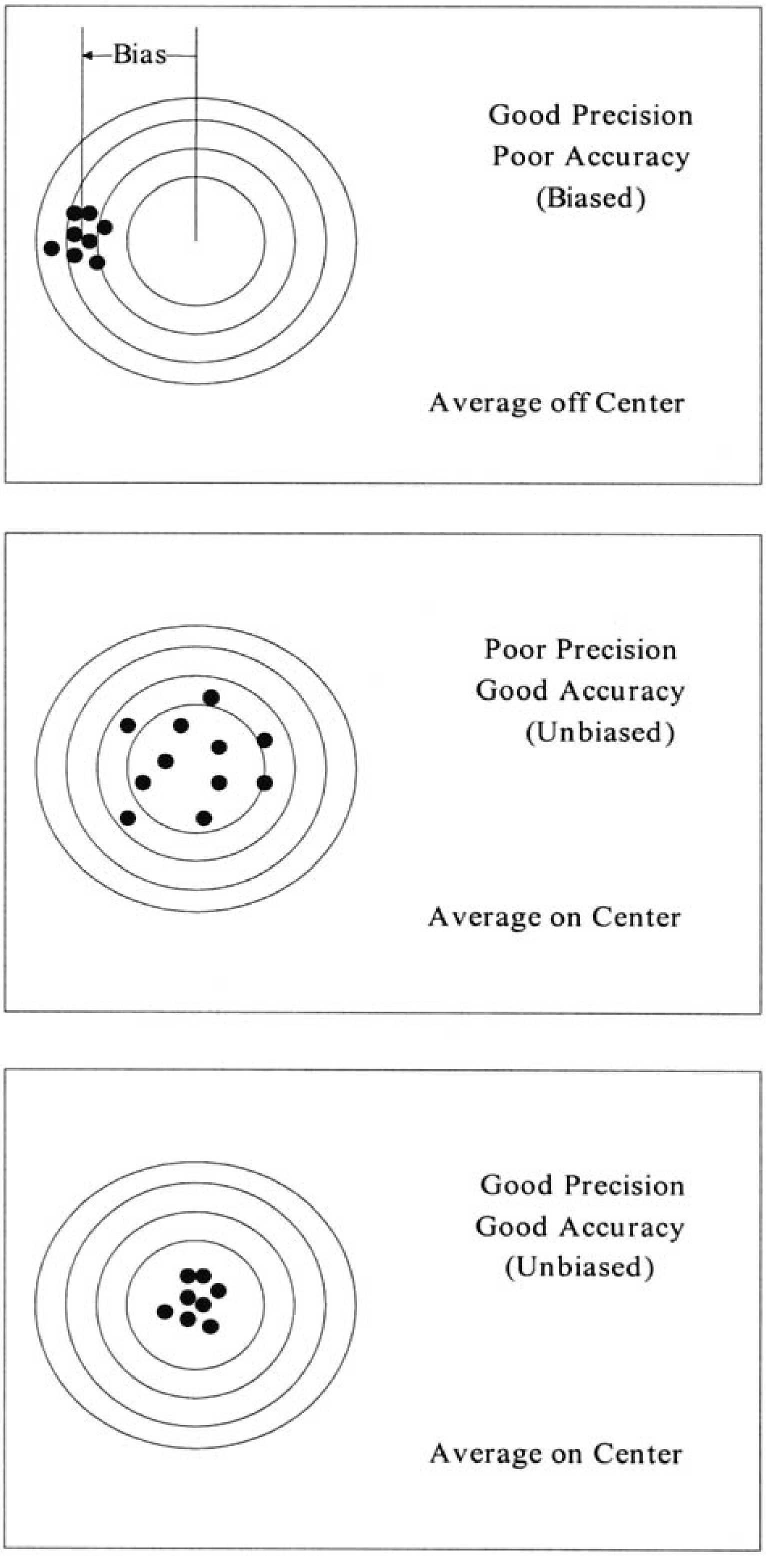


Figure 9. Relationship between precision, accuracy, and bias.[13]

Table 3. Potential anomalies in material test data and recommended remedial action.

Identified Anomaly	Effect on Data Quality	Recommended Remedial Action
Insufficient data at level E due to test results still undergoing QA/QC at levels A to D	Data are inadequate for analysis (data might not represent test section)	Upgrade representative data tables when QA/QC process is complete
Insufficient data at level E due to insufficient testing and/or test results failing QA/QC checks between levels A to D	Data are inadequate for analysis (data might not represent test section)	Adopt representative values from similar sections
Insufficient data at level E due to insufficient testing and/or test results failing QA/QC checks between levels A to D	Data are inadequate for analysis (data might not represent test section)	Backcast or forecast from time-series data
Insufficient data at level E due to insufficient testing and/or test results failing QA/QC checks between levels A to D	Data are inadequate for analysis (data might not represent test section)	Estimate data from analytical models or techniques
Inadequate sampling (e.g., single test values)	Possible bias due to unrepresentative test values	Check sampling locations to verify that the data adequately represent test section
Inadequate sampling (e.g., single test values)	Possible bias due to unrepresentative test values	Resampling and testing to obtain more representative test results
Noncompliance with testing protocol	Excessive variability in multiple test results (assuming only a few of the test values are noncompliant)	Identify individual noncompliant test values as potential outliers and study their effect on variability
Noncompliance with testing protocol	Potential for systematic bias if all tests on multiple specimens are noncompliant.	Perform forensic testing
Unreasonable multiple test values	Excessive variability in multiple test results (assuming only a few of the test values are unreasonable)	Identify individual unreasonable test values as potential outliers and study their effect on variability. Remove outliers from developing representative data tables if they are the cause of the excessive variability
Unreasonable single test values	Unreliable data	Perform forensic testing
Unexplained excessive variability	Unreliable data	Identify potential outliers and errors using statistical techniques (ASTM E178)

Missing experiment type and layer information	--	Consult materials testing and construction data sheets or other data tables with the database to determine the required information
Missing specimen testing age or anomalous computed ages	--	Consult materials testing and construction data sheets or other data tables with the database to determine the required information

Although the potential impact of individual anomalies on data quality is clear, the effect of the interactions of various anomalies is not. Other possible remedial actions not presented in table 3 are discussed below.

Outlier Analysis

Outliers can cause excessive variability in multiple test results. They can be identified by checking for compliance with the testing and sampling procedures and comparing the test results with typical values, or through statistical analysis. The former two methods are straightforward and have already been discussed.

When it is clear that the source of excessive variability cannot be attributed to any known cause, statistical analysis can be performed to determine whether the data point is, indeed, a true outlier. There are a number of statistical tests and criteria for identifying outliers within a group of test results. For this study, the recommended procedure in ASTM E178, *Standard Practice for Dealing with Outlying Observations*, was used for outlier identification.(12) The procedure is summarized as follows:

- Calculate the numerical value of a sample test statistic (T-statistic), using all test values (include the doubtful test result or observation in the calculation).
- Compare the calculated test statistic with a critical value of the statistic based on the theory of random sampling to determine whether the doubtful observation is to be retained or rejected.

The *critical value* is the value that the calculated sample test statistic would exceed by chance with some specified (small) probability. This is based on the assumption that all the observations did, indeed, constitute a random sample from a common system of causes, a single parent population, distribution, or universe. The specified small probability is called the *significance level*, the choice of which depends on the complexities and circumstances of the problem under investigation and the risk that one is willing to take in rejecting a good observation.

Further, almost all criteria for determining outliers are based on the assumption that the population or distribution of test results is normal or approximately normal. Outlier analysis based on data not normally or approximately normally distributed could result in erroneous conclusions.

Resampling and Testing

When there is inadequate sampling information at level E and most data at lower levels failed LTPP QA/QC checks, the only way to obtain information that is representative of the test section is to resample and test again. Although highly unusual, this might be necessary in some cases.

Forensic Testing

When there is a reason to believe that the testing was not performed in compliance with test protocols, forensic testing might be a viable option to obtain more representative test values.

4. AC CORE EXAMINATION AND THICKNESS

Introduction

Variation in layer thickness has a significant influence on the structural characteristics and performance of in-service pavements. Variable asphalt pavement layer thicknesses affect pavement characteristics such as back-calculated layer moduli, key input for characterizing the structures adequacy of an existing pavement and for the design of overlays. It is, therefore, necessary to minimize thickness variability for all pavement layers, especially AC layers.

Collecting AC layer thickness data is an important aspect of the LTPP material characterization program. Thickness data are obtained from AC cores extracted from selected locations at the approach and leave ends of the pavement test section. The cores are also examined for possible defects and suitability for testing. AC core examination and thickness measurements were done based on SHRP protocol P01--*Visual Examination and Thickness of Asphaltic Concrete Cores*--and the test standard AASHTO T148--*Measuring Length of Drilled Concrete Cores* (ASTM C174).[2, 3, 4]

The test protocol and standard provide guidance on material sampling, preparation and testing of specimens, computation, and presentation of test results. The test results are stored in the LTPP database (table TST_AC01_LAYER) after undergoing several levels of quality checks. Data classified at level E have undergone and successfully passed all the QA/QC checks required by the LTPP. Data classified at levels A to D may still be undergoing QA/QC or may have failed QA/QC. Table TST_AC01_LAYER contains the following information:

1. SHRP_ID.
2. State code.
3. Field layer number.
4. Field set.
5. Test number.
6. Layer number.
7. Location number.
8. Construction number.
9. Field layer comment.
10. Layer description.
11. Layer thickness.
12. Record status.

Material Sampling for AC Core Thickness

Material sampling was performed according to guidelines provided in several LTPP documents and reports, including the SHRP-LTPP *Interim Guide for Laboratory Material Handling and Testing* and the SPS *Guidelines for Nominations and Evaluation of Candidate Projects*. (See references 2, 15 through 20.) For GPS experiments, test samples were collected at specific locations outside the monitoring sections of the LTPP test sections. For SPS projects, cores were extracted from designated locations adjacent to the pavement test sections. Core thickness examination and thickness measurements were performed on all cores retrieved. Basically, two types of cores were extracted: (See references 2, 15, 1through 20.)

- Type A--152-mm diameter cores obtained from the approach and leave ends of a monitoring section.
- Type C--102-mm diameter cores obtained from the approach and leave ends of a monitoring section.

Sampling and testing requirements for AC core examination and thickness testing are presented in tables 4 and 5. The tables show the minimum number of core specimens required for testing for the various LTPP experiments, along with the sampling locations. The sampling requirements were used to define analysis cells for data completeness and quality evaluation, as follows:

- For GPS experiments, an analysis cell was defined as any asphalt-treated layer (including the surface layer) within a given test section.
- For SPS experiments, an analysis cell was defined as a given asphalt-treated material type within the SPS experiment. Asphalt-treated layers with the same materials descriptions (e.g., permeable asphalt-treated base material [PATB]) located in different test sections (e.g., 102 or 103) were considered as belonging to the same analysis cell.

The data fields used for defining analysis cells for GPS and SPS test sections are presented in table 6.

AC Core Data Completeness

The AC core data completeness evaluation was conducted at two levels. The level 1 data completeness evaluation involved the determination of the amount of the total data available in table TST_AC01_LAYER, the percentage at level E, and the number of analysis cells represented by the level E data. Level 2 data completeness consisted of determining the percentage of analysis cells with the minimum required number of test results reported at level E. The January 2000 release of table TST_AC01_LAYER was used for the analyses.

Table 4. Sampling requirements for visual examination and thickness of AC cores.

Experiment Type	Layer Type	LTPP Designation	SHRP Protocol	Minimum Number of Tests per Layer	Sampling Location
GPS 1, 2, 6, and 7	AC	AC01	P01	16	All 100-mm and 150-mm-diameter cores
SPS-1	Asphalt treated base	AC01	P01	34	102-mm OD coresC1-C10, C21-C34,C47-C56
SPS-1	AC surface and binder	AC01	P01	60	102-mm OD coresC1-C60
SPS-3	Asphalt treated base	AC01	P01	34	102-mm OD coresC1-C10, C21-C34,C47-C56
SPS-3	AC surface and binder	AC01	P01	60	102-mm OD coresC1-C60

SPS-5 Preconstruction	AC	AC01	P01	26	All Type-C cores
SPS-5 Postconstruction	AC	AC01	P01	40	All cores
SPS-6	AC	AC01	P01	20	All cores
SPS-8	AC	AC01	P01	16	All cores
SPS-9 Preconstruction	AC	AC01	P01	6	A01A01,A02A01,A01A02A02A02,A01A03,A02A03
SPS-9 Postconstruction	AC	AC01	P01	8	--

OD = outside diameter.

Level 1--Data Completeness

The first step in assessing data completeness was the extraction and assembly of the thickness and visual examination test data from the LTPP database. The layer and material description information in table TST_AC01_LAYER was cross-referenced with similar information in other LTPP material-related test tables, such as TST_ LO5B and EXPERIMENT_SECTION, by combining these tables with TST_AC01_LAYER. Cross-referencing the data made it possible to check for anomalies in material description, layer type, and layer number information in table TST_AC01_LAYER. Test results or records with anomalies in material and layer information were flagged for further evaluation. The results of the level 1 data completeness analysis are presented in table 7.

Table 5. Details of sampling requirements for visual examination and thickness of AC cores for SPS experiments.

Experiment Type	Test Section	Material Description	Min. No. of Cores Required(Surface and binder/ATB)	Sampling Location
SPS-1	0101 (0113)	AC	6/0	C41-C46
SPS-1	0102 (0114)	AC	4/0	C57-C60
SPS-1	0103 (0115)	AC	4/4	C47-C50
SPS-1	0104 (0116)	AC	4/4	C1-C4
SPS-1	0105 (0117)	AC	6/6	C51-C56
SPS-1	0106 (0118)	AC	6/6	C5-C9
SPS-1	0107 (0119)	AC	6/0	C35-C40
SPS-1	0108 (0120)	AC	6/0	C15-C20
SPS-1	0109 (0121)	AC	4/0	C11-C14
SPS-1	0110 (0122)	AC	4/4	C21-C24
SPS-1	0111 (0123)	AC	4/4	C31-C34

SPS-1	0112 (0124)	AC	6/4	C25-C30
SPS-5 (Preconstruction)	0501	AC	2	C1,C2
SPS-5 (Preconstruction)	0502	AC	4	C3-C6
SPS-5 (Preconstruction)	0503	AC	2	C7-C8
SPS-5 (Preconstruction)	0504	AC	2	C9-C10
SPS-5 (Preconstruction)	0505	AC	2	C11-C12
SPS-5 (Preconstruction)	0506	AC	5	C13-C17
SPS-5 (Preconstruction)	0507	AC	2	C18-C19
SPS-5 (Preconstruction)	0508	AC	5	C20-C24
SPS-5 (Preconstruction)	0509	AC	2	C25-C26
SPS-5 (Postconstruction)	0501	AC	0	--
SPS-5 (Postconstruction)	0502	AC	4	C27-C30
SPS-5 (Postconstruction)	0503	AC	6	C31-C35
SPS-5 (Postconstruction)	0504	AC	6	C37-C42
SPS-5 (Postconstruction)	0505	AC	4	C43-C46
SPS-5 (Postconstruction)	0506	AC	4	C47-C50
SPS-5 (Postconstruction)	0507	AC	6	C51-C56
SPS-5 (Postconstruction)	0508	AC	6	C57-C62
SPS-5 (Postconstruction)	0509	AC	4	C63-C66
SPS-6 (Preconstruction)	0601	AC	3	C1-C3
SPS-6 (Preconstruction)	0602	AC	3	C3-C6
SPS-6 (Preconstruction)	0603	AC	2	C11-C12
SPS-6 (Preconstruction)	0604	AC	2	C13-C14

SPS-6 (Preconstruction)	0605	AC	4	C7-C10
SPS-6 (Preconstruction)	0606	AC	2	C15-C16
SPS-6 (Preconstruction)	0607	AC	2	C17-C18
SPS-6 (Preconstruction)	0608	AC	2	C19-C20
SPS-6 (Postconstruction)	0603	AC	4	C21-C24
SPS-6 (Postconstruction)	0604	AC	4	C25-C28
SPS-6 (Postconstruction)	0606	AC	4	C29-C32
SPS-6 (Postconstruction)	0607	AC	4	C33-C36
SPS-6 (Postconstruction)	0608	AC	4	C37-C40
SPS-8	0801, 0803, 0805	AC	8	C1-C8
SPS-8	0802, 0804, 0806	AC	8	C9-C16
SPS-9	0901, 0902, 0903	AC	8	--

ATB = asphalt-treated base.

Table 6. Data fields used for defining analysis cells for AC thickness.

Data Fields	GPS	SPS
SHRP_ID	X	X
State Cored	X	X
Layer number	X	X
Construction number	X	X

Table 7. Level 1 data completeness for table TST_AC01_LAYER.

Experiment Type	Expt. Number	Total Number of Records at All Levels	Total Number of Records at Level E	Percentage of Records at Level E	Number of Analysis Cells Represented at Level E
GPS	1	8069	8067	99.6	488
GPS	2	5655	5655	100	349
GPS	3	159	159	100	13
GPS	4	30	30	100	2
GPS	5	275	275	100	22
GPS	6A	3496	3496	100	218
GPS	6B	3359	3359	100	189
GPS	6C	505	500	99	35
GPS	6D	128	128	100	9
GPS	6S	1584	1561	99	104
GPS	7A	1185	1183	99.8	72
GPS	7B	529	529	100	29
GPS	7C	36	36	100	2
GPS	7S	189	189	100	8
GPS	9	322	312	96.9	27
SPS	1	1977	1965	99.4	423
SPS	3	1928	1928	100	958
SPS	5	2577	2550	99	568
SPS	6	248	248	100	64
SPS	8	237	237	100	31
SPS	9	625	559	89.4	52

Note: There were a total of 1,680 records from SPS supplemental sections not listed in this table.

A total of 34,793 records were available in table TST_AC01_LAYER. Of these, 1,680 were from SPS supplemental sections. Approximately 99 percent of the AC layer thickness data were at level E. The records pertaining to SPS supplemental sections were kept out of the further analysis, because they fall out of the scope of this study.

Level 2--Data Completeness

Analysis cells consisting of level E data were further evaluated to determine whether the minimum required number of tests was performed and reported at level E. This was done by checking the number of test results or records available in each analysis cell and comparing it with the sampling and testing requirements presented in SHRP P01. Analysis cells with at least the minimum number of test records required were categorized as complete, whereas analysis cells will less than the minimum required test results at level E were classified as incomplete. The results of the level 2 data completeness evaluation are presented in table 8.

Table 8. Summary of level 2 data completeness for TST_AC01_LAYER.

Experiment Type	Number of Analysis Cells with Data	Min. Number of Test Results Required	Analysis Cells with Minimum Number of Test Results	Percentage Analysis Cells with Minimum Test Results
GPS-1	459	16	392	85.4
GPS-2	340	16	291	85.6
GPS-6A	212	16	186	87.7
GPS-6B	182	16	141	77.5
GPS-6C	30	16	16	53.3
GPS-6D	8	16	3	37.5
GPS-6S	79	16	38	48.1
GPS-7A	65	16	48	73.9
GPS-7B	27	16	18	66.7
GPS-7C	2	16	2	100
GPS-7S	8	16	8	100
SPS-1	228	5/3[1]	135	59.2
SPS-3	914	3	138	15.1
SPS-5	471	3/4[2]	311	66.0
SPS-6	39	2	36	2.3
SPS-8	21	4	21	100

[1]For each section in the SPS-1 project, five tests are required for the AC surface and binder layers, and three tests are required for the asphalt treated base.
[2]For each section in the SPS-5 project, three tests are required on the original AC surface preconstruction, and four tests are required on the overlay postconstruction.

Of the 3,139 analysis cells with test data at level E in table TST_AC01_LAYER, 57 percent (1,784) had the minimum number of test results reported and, therefore, were classified as complete. The remaining 43 percent were incomplete, possibly because of data still undergoing QA/QC, missing test data, inadequate sampling, or untestable AC core specimens. The effect of inadequate data on the data analysis (computing representative test results and basic statistics) will be discussed in later sections of this chapter.

AC Core Visual Examination and Thickness Data Quality

Data quality was evaluated for all the data in table TST_AC01_LAYER. The first step was to evaluate the data for reasonableness by comparing core measurement data with typical AC and asphalt-treated material layer thickness. There is a wide range of "typical" layer thickness; however, negative, extremely small (< 2.5 mm), or extremely high (> 600 mm) thickness values can be classified as unreasonable. Such data will require further evaluation.

The next step was to determine variability for the test data within each analysis cell. The within-cell variability was compared with typical variability reported in published literature and classified as acceptable or questionable, based on whether computed variability was greater or less than typical.

Data Reasonableness

The SHRP-LTPP *Interim Guide for Material Handling and Testing* provides typical ranges expected for AC layer thickness, based on the layer and material type.(2) The typical ranges of thickness values are presented in table 9 for GPS experiments. Table 10 presents a detailed breakdown of the core thickness data and descriptive statistics in TST_AC01_LAYER. For GPS experiments, approximately 99 percent of the cores from overlays had thickness values within the recommended range. The remaining 1 percent was evaluated for potential anomalies.

Similarly, 94 percent of the core specimens from the seal coat layers had thickness values within the recommended range. SPS-1 surface layers have two target thicknesses, 102 mm and 178 mm. The average core thicknesses and standard deviation for test data in the two thickness groups were 107 and 18 mm and 168 and 32 mm, respectively. SPS-5 experiments also have two different target thicknesses, 51- and 127-mm overlays. The average measured thicknesses of the overlays were 74.3 and 150.1 mm for the 51- and 127-mm sections, respectively.

For SPS-6 experiments, the target thicknesses of overlays was 102 and 204 mm. Average thickness values reported for these sections were 104 and 211 mm, respectively, which were very close to the target thickness values. SPS-8 experiments have surface layer target thicknesses of 102 and 178 mm, and the average measured thicknesses for these sections were 104 and 170 mm, which are very close to the target thickness values. Figures 10 through 12 show the distribution of the core specimen thicknesses for selected layer types (overlay, surface, and base). The information presented confirms the trends presented in table 10.

Table 9. Range of thickness for various GPS AC layers.(2)

LTPP Layer Description Code Number	Material/Layer Description	Typical Thickness Range, mm	No. of Test Records With Thickness within Range	No. of Analysis Cells With Thickness within Range	Number of Test Records out of range
1	Overlay	12.5 - 150	3848	228	26
2	Seal coat	2.5 - 37.5	1836	115	35
3	Original surface	12.5 - 325	7830	474	72
4	AC layer below surface	12.5 - 250	5712	368	99
5	Base	25 - 600	1253	86	12
6	Subbase	75 - 1200	30	2	0
8	Interlayer	2.5 - 150	574	40	0
9	Friction course	2.5 - 62.5	1838	112	0
10	Surface treatment	2.5 - 37.5	77	5	0

Table 10. Summaries of descriptive statistics for core thickness data in table TST_AC01_LAYER.

Expt. Type	**Layer Description**	**Target Thickness, mm**	**Number of Core Specimens**	**Mean Thickness, mm**	**Standard Deviation, mm**	**COV, percent**	**Min. Thickness Range, mm**	**Max. Thickness Range, mm**
GPS	Overlay	12.5 - 150	3874	54.7	27	49.4	2.5	191
GPS	Seal coat	2.5 - 37.5	1871	9.3	10	108.0	2.5	97
GPS	Original surface	12.5 - 325	7962	68	51	74.6	5.1	401
GPS	AC layer below surface	12.5 - 250	5838	88	61	68.9	25	406
GPS	Base	25 - 600	1263	142	66	46.4	51	363
GPS	Subbase	75 - 1200	30	101	10	10.0	86	127
GPS	Interlayer	2.5 - 150	574	25	28	113.4	2.5	109
GPS	Friction course	2.5 - 62.5	1838	17	12	66.6	2.5	69
GPS	Surface treatment	2.5 - 37.5	77	3.4	2.2	63.6	2.5	10
SPS-1	Surface	102	50	106.5	18.2	17.1	53	147
SPS-1	Surface	178	45	168.2	32.3	16.5	41	201
SPS-5	Overlay	51	45	74.3	23.7	31.9	42	119
SPS-5	Overlay	127	48	150.1	25.6	17.1	114	200
SPS-6	Overlay	102	16	103.7	9.0	8.7	86	120
SPS-6	Overlay	203	4	210.0	7.4	3.5	199	215
SPS-8	Surface	102	7	105.3	10.5	10.0	91	119
SPS-8	Surface	178	7	171.2	15.7	9.2	142	187

Note: Standard deviation and COV values reported are for all samples within a given experiment.

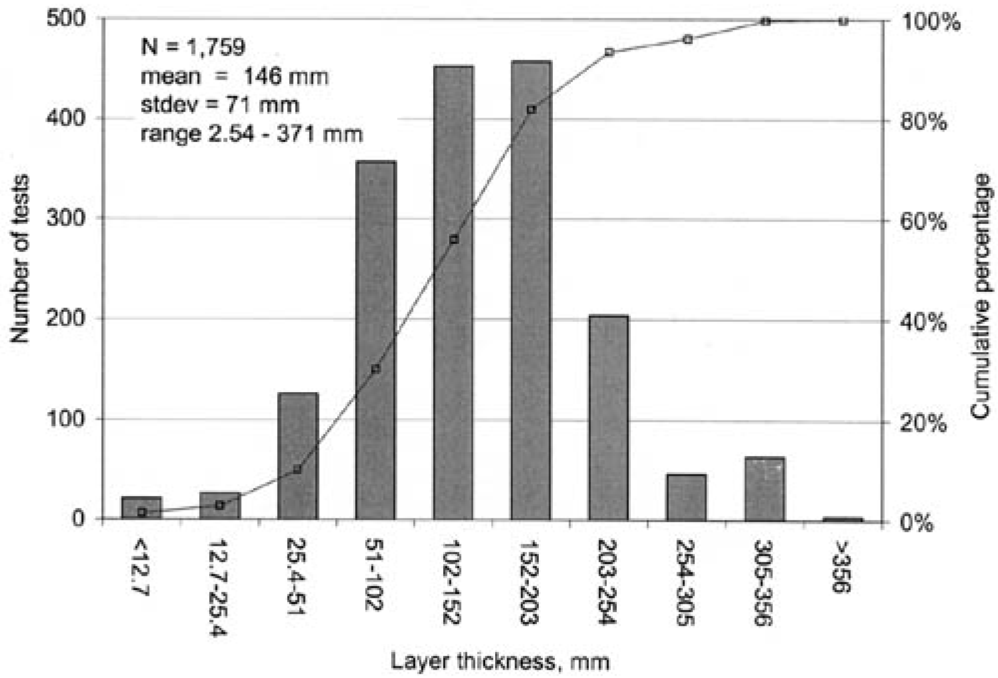


Figure 10. Distribution of AC core thickness for base layers.

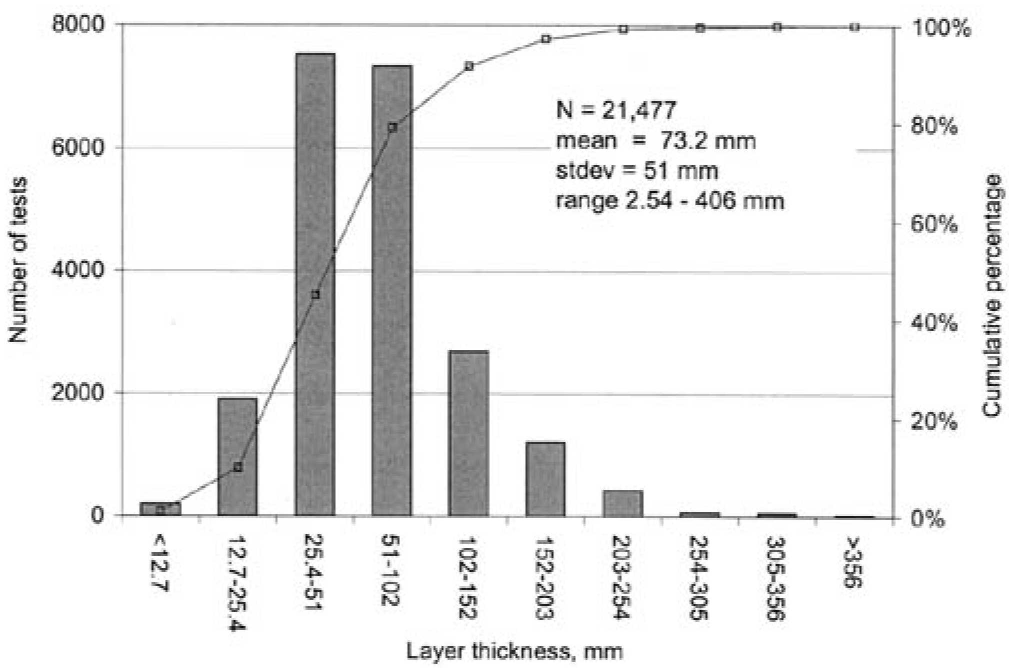


Figure 11. Distribution of AC core thickness for surface layers.

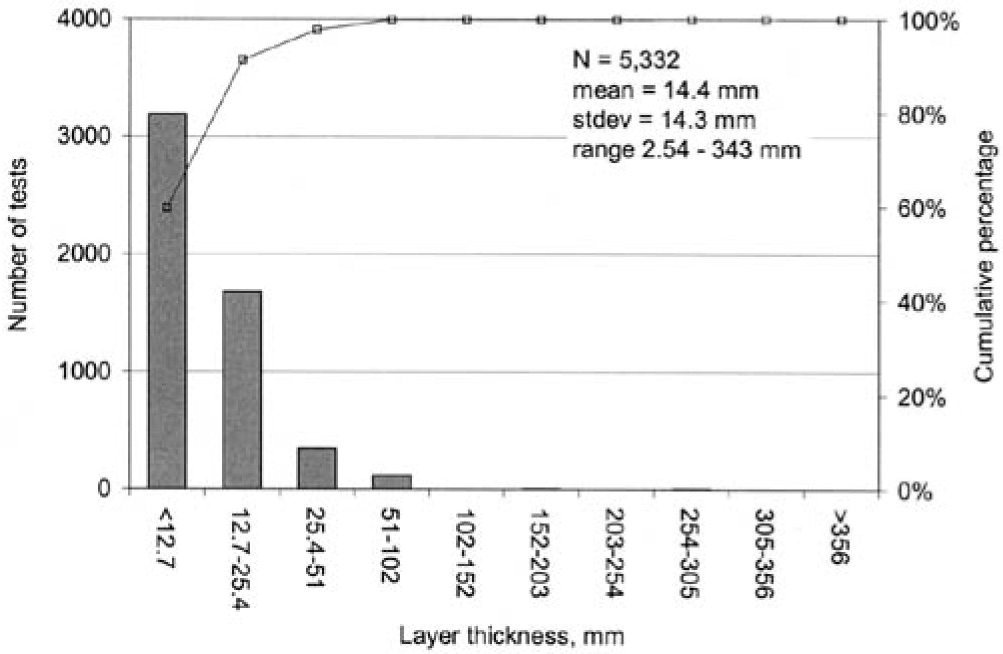


Figure 12. Distribution of AC core thickness for overlays.

Assessing AC Core Thickness Data Quality

The first step in assessing AC core thickness data quality was to determine typical variability expected for cores belonging to the same analysis cell. This was done by reviewing typical variability measured as standard deviation or COV in published literature (see table 11). The AASHTO T148 (ASTM C174) test standard provides no recommendations on testing variability, a component of typical variability.

The typical standard deviation for measured core thickness ranges from 5.6 to 26.4 mm, whereas typical COV ranges from 4 to 25 percent. Hughes reported that, for AC core thickness evaluation, variability measured as COV tends to be more stable than standard deviation.(13) Therefore, COV was adopted as the measure of variability for evaluating data quality. A COV of 20 percent was used as the threshold value for the classification of acceptable and questionable analysis cells.

Figures 13 and 14 present the distribution of COV for the analysis cells evaluated for GPS and SPS experiments. Approximately 87 percent of the analysis cells from the GPS experiments and 86 percent of the analysis cells from SPS experiments had acceptable variability.

Table 11. Typical variability for HMAC- and asphalt-treated layers.(13, 21)

Data Source	Layer Type	Average Thickness, mm	Standard Deviation, mm	COV, percent
New Jersey	Surface	44	6.6	15.0
New Jersey	Surface/binder	57	8.4	14.7
New Jersey	Surface/binder	85	10.6	12.5
New Jersey	Base	100	14.0	14.0
New Jersey	Base	150	14.0	9.3
Kansas DOT[1]	Surface/base	112	5.6	5.0
Kansas DOT[1]	Surface/base	71	6.6	9.3
Kansas DOT[1]	Surface/base	487	19.3	4.0
Kansas DOT[1]	Surface/base	67	5.6	8.4
Kansas DOT[1]	Surface/base	188	22.1	11.7
Kansas DOT[1]	Surface/base	356	6.1	1.7
Kansas DOT[1]	Surface/base	272	26.4	9.7
Kansas DOT[1]	Surface/base	319	22.6	7.1

Average Standard Deviation, mm, 12.9
Average COV, percent, 9.4
[1]Consists of core for binder, surface layer, and base layers.

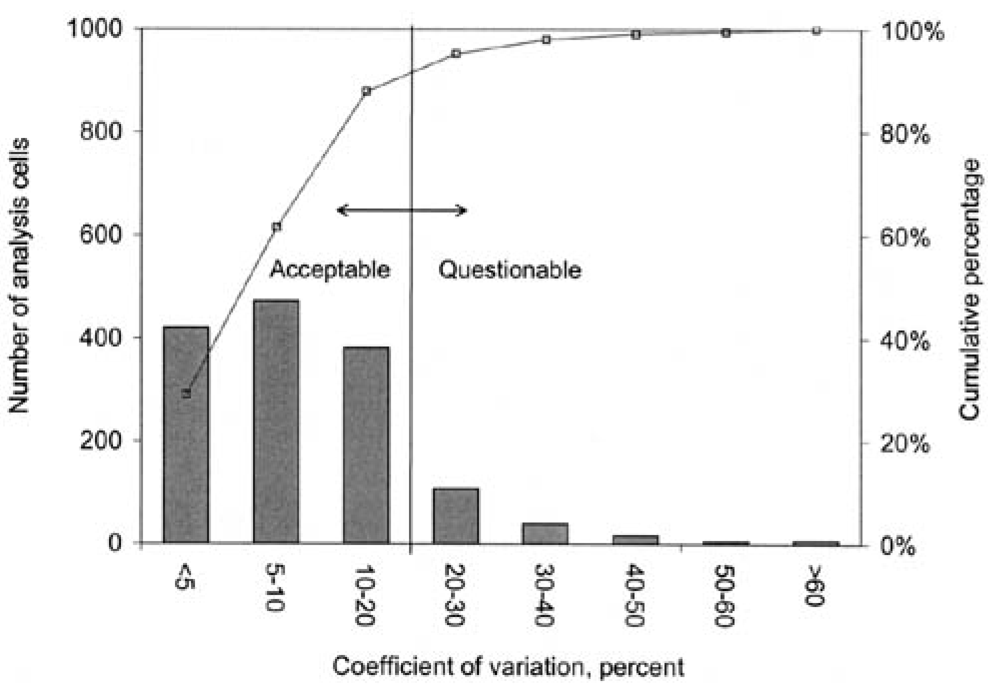


Figure 13. Distribution of COV for analysis cells from GPS experiments.

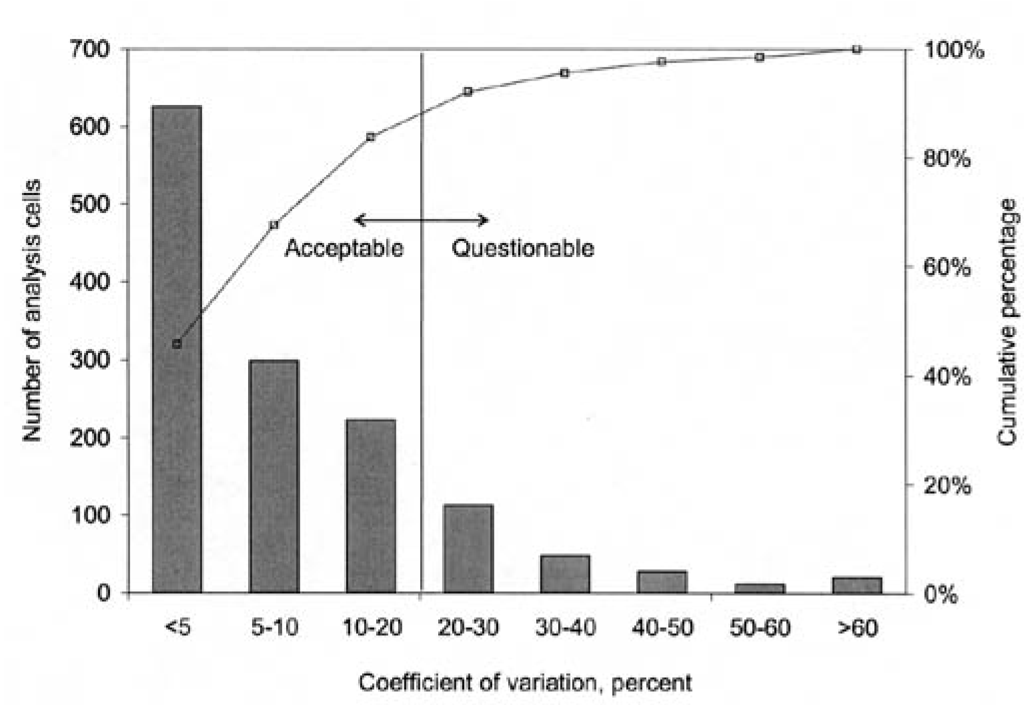


Figure 14. Distribution of COV for analysis cells from SPS experiments.

Analysis cells classified as questionable were further evaluated to determine the causes of excessive variability. Identified anomalies were rectified where possible or flagged to inform users of the existence of excessive variability.

Identification of Anomalous Data

The focus of the discussion presented so far has been on the data availability and quality. Data availability was assessed at two levels. The anomalies found in the data during the various analyses performed are described below, along with the discussion of possible causes of their occurrence. Corrective or remedial measures taken to address the anomalies are also discussed.

Anomaly 1: Erroneous Material Type

There was some AC core examination and thickness data in table TST_AC01_LAYER with erroneous material description (i.e., nonbituminous materials). Table TST_AC01_LAYER should contain only AC or asphalt-treated material core thickness.

A total of 24 records had erroneous material descriptions--two records from GPS experiments and 22 from SPS experiments. A feedback report was generated and sent to the FHWA for the data in these records to be reassessed and rectified. Meanwhile, the records were retained and used to develop the representative data table. A comment code was assigned to them to explain the anomaly. The FHWA will rectify this anomaly.

Anomaly 2: Excessive Variability

A total of 436 analysis cells had excessive variability in the test data. The breakdown of these data was as follows:

- GPS experiments--13.3 percent (195 of the 1,466 analysis cells with multiple test values) had excessive within-cell variability.
- SPS experiments--14.4 percent (241 of the 1,673 analysis cells) had excessive within-cell variability.

For analysis cells with excessive variability, potential outliers were identified by:

- Considering all test data within an analysis cell that fell outside four standard deviations of the mean as suspicious and, hence, outliers.
- Applying the ASTM C178 procedure to identify potential outliers.

Test results classified as outliers were not used in developing the representative data table and summary statistics. All other test data in analysis cells with excessive variability were included in the representative data table. However, a comment code was assigned to such data, explaining the reason for excessive variability, where possible.

For the analysis cells in GPS experiments, no apparent reason for excessive variability was found in 5.3 percent (78 of 1,466) of the cells. For SPS experiments, the percentage of cells with no apparent reason for excessive variability was 7.5 (126 of 1,673). Excessive variability in some analysis cells (56 GPS cells and 74 SPS cells) was caused by noncompliance with test protocols (i.e., measurement of very thin AC cores). Average COV for core specimens from these analysis cells was generally greater than typical. However, these data had a standard deviation of less than 5 mm.

Sampling location in a given test section (i.e., approach vs. end section) had a significant influence on within-cell variability. Approximately 3 percent (42 of 1,466) of GPS cells and 1 percent (14 of 1,673) of SPS cells showed excessive variability, due to significantly different thickness results reported for cores taken from the approach and leave sections of the test pavement. This implies that the layer thickness increased or decreased consistently along the test section. No remedial action was taken to correct such data because the data are not erroneous. Test sections with this anomaly were flagged in the representative data table.

Approximately 2 percent (20 of 1,466) of the GPS cells and 1 percent (19 of 1,673) of the SPS cells had outliers causing excessive variability and, thus, were not used in developing the representative summary statistics data tables.

Anomaly 3: Unreasonable Thickness Values (Outside the Recommended Range)

The LTTP material testing guide provides typical thickness ranges for asphalt-treated materials based on layer type.[(2)] A total of 244 core specimens from GPS experiments had thickness values outside the recommended range. For SPS experiments, 94 core specimens had thickness values outside the recommended thickness range.

No remedial action was taken. However, comment codes were assigned to the analysis cells containing such data in the representative data tables.

Remedial Action--Summary

The implementation of appropriate remedial action resulted in a significant reduction of variability in 39 out of the 436 analysis cells originally exhibiting excessive variability. The 39 cells were reclassified as acceptable. The remaining 397 analysis cells still had excessive variability. They were identified in the representative data table with appropriate comment codes indicating the excessive variability.

Schema of the Representative AC Core Examination and Thickness Data Table (TST_AC01_LAYER_REP)

A representative AC core thickness data table, TST_AC01_LAYER_REP, was developed after addressing the identified anomalies, and it is recommended for inclusion into the LTPP database. The data fields in this table are as follows:

1. State code.
2. SHRP identification number.
3. Layer number.
4. Construction number.
5. Number of specimen tested.
6. Mean thickness.
7. Maximum thickness.
8. Minimum thickness.
9. Standard deviation of thickness data.
10. COV of thickness data.
11. QA_Comment_1.
12. QA_Comment_2.
13. QA_Comment_3.
14. QA_Comment_4.
15. QA_Comment_5.
16. QA_Comment_6.
17. QA_Comment_Other.
18. Data source.
19. Record status.

The first four fields define the analysis cell used in computing summary statistics of the measured thickness for each analysis cell. Fields 5 through 10 present the representative test results and associated statistics. Comments are included in fields 11 to 17 through describe the quality status of the data (e.g., excessive variability or incomplete sampling), based on the quality assurance analysis performed as part of this study. The comments describe the anomaly types encountered in data evaluation and remedial action implemented to correct them. Anomalies that were not remedied are also identified. The remaining fields describe the source of the data and record status.

5. BULK SPECIFIC GRAVITY OF AC CORES

Introduction

Bulk specific gravity plays a critical role in the design, construction, and quality control of HMAC paving mixtures. It is also a key input in making weight-volume conversions and in calculating the void content in compacted HMAC. Table TST_AC02 contains BSG test results from all relevant LTPP test sections.

Testing is done using guidelines presented in SHRP protocol P02, *Bulk Specific Gravity of Asphaltic Concrete* and the test standard AASHTO T166, *Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens (Method A)*. SHRP P02 requires that for test samples with a percent water absorbed greater than 2 percent, AASHTO T166 should be replaced with AASHTO T275, *Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens (Method A)*.[2, 3, 4]

The test protocol and standards provide guidance on material sampling, preparation of test specimens, testing, computation of test results, and presentation of results. The test results are stored in the LTPP database after undergoing several levels of quality checks. Data classified at level E are stored in table TST_AC02. Table TST_AC02 has a total of 22 fields of information:

1. SHRP_ID.
2. State code.
3. Layer number.
4. Field set.
5. Location number.
6. Construction number.
7. Sample number.
8. Lab code.
9. Sample area number.
10. BSG.
11. Water absorption.
12. Paraffin coated.
13. Sample number.
14. Test date.
15. Comment 1.
16. Comment 2.
17. Comment 3.
18. Comment 4.
19. Comment 5.
20. Comment 6.
21. Comment other.
22. Record status.

Material Sampling for Bulk Specific Gravity of AC Cores

Several LTPP documents provide guidelines for material sampling (extraction of core specimens) and handling, laboratory testing, and QA/QC. (See references 2 and 15 through 20.) Testing was performed on 102-mm and 150-mm-diameter cores (4-in and 6-in-diameter cores) extracted from specific locations at the approach and leave sections of the pavement test section. Details of core locations are provided in SHRP P02 and the relevant SPS *Guidelines for Nomination and Evaluation of SPS Candidate Projects* documents. (See references 2 and 15 through 20.) The extracted cores were packaged, labeled, and shipped to designated SHRP laboratories for testing.

Sampling requirements for BSG testing are presented in tables 12 and 13. The tables show the minimum number of core specimens required per AC layer for the various LTPP experiments, along with the core sampling locations.

Bulk Specific Gravity Data Completeness

Data completeness for AC BSG data in table TST_AC02 was evaluated at two levels. Level 1 data completeness evaluation consisted of the total amount of test data available in table TST_AC02 (levels A to E), the percentage of the data at level E, and the number of analysis cells represented by the data at level E.

- For GPS experiments, every AC layer in a test section was considered an analysis cell. Therefore, an analysis cell is defined as a unique combination of State_code, SHRP_ID, and Layer_No.
- For SPS experiments, an analysis cell was defined as an AC layer within an SPS test section within an experiment. Therefore, it has a unique combination of State_code, SHRP_ID, Material_Code, and Layer_Type. Table 12 presents a summary of the fields used in defining analysis cells for GPS and SPS experiments.

Level 2 data completeness consisted of determining the percentage of analysis cells with the minimum number of test results required and reported at level E. The minimum number of tests required by LTPP is summarized in tables 13 and 14. The January 2000 update of table TST_AC02 was used in data evaluation and analysis.

Table 12. Data fields used for defining analysis cells for BSG.

Data Fields	GPS	SPS[1]
SHRP_ID	X	X
State code	X	X
Layer number	X	X
Layer description		X
Material code		X

[1]SPS 1, 2, 5, 6, 7, 8, and 9A.

Table 13. Sampling and testing requirements for BSG of AC cores for GPS experiments.

Experiment Type	Layer Type	LTPP Designation	SHRP Protocol	Minimum Number of Tests per Layer	Sampling Location
GPS-1, -2, -6, and -7	AC	AC02	P02	2	A1, A2, C7, C9, C10, C19, C21, C22, (C12, C24 if needed)

Table 14. Details of sampling and testing requirements for BSG of AC cores for SPS experiments.

Expt Type	Construction Stage	LTPP Designation	Sections	Minimum Number of Tests per Layer	Source/Sampling Location
SPS-1	Asphalt-treated base	AC02	--	34	102-mm OD cores C1-C10, C21-C34, C47-C56
SPS-1	AC surface and binder	AC02	--	60	102-mm OD coresC1-C60
SPS-5	Preconstruction	AC02	--	9	C3, C4, C5, [C13,C14,C15], [C22,C23,C24]
SPS-5	Postconstruction	AC02	--	40	All cores
SPS-6	--	AC02	--	20	All cores
SPS-8	--	AC02	--	16	All cores
SPS-9	Mix design	AC02	01 and 03	3	LA01AXX-LA03AXX
SPS-9	Compacted bulk samples	AC02	02	18	LA01A02-LA07LA02, LA15A02, LA38A02, DA02A02,DA03A02, DA04A02, DA06A02, DA16A02, DA22A02, DA31A02, DA32A02, DA33A02
SPS-9	QA test	AC02	01 and 03	6	BA01AXX-BA06AXX
	Postconstruction	AC02	01, 02, and 03	8	CA02tXX, CA06tXX, CA11txx, CA15txx, CA19tXX, CA24tXX, CA28tXX, CA33tXX

Note: Postconstruction cores to be tested at 0, 6, 12, 18, 24, and 48 months after construction.

Level 1 Data Completeness

The first step in assessing level 1 data completeness was the extraction and assembly of all BSG data from the LTPP database table TST_AC02. The layer and material description information in table TST_AC02 was cross-referenced with similar information in other LTPP tables, such as TST_ LO5B and EXPERIMENT_ SECTION, by combining these tables with TST_AC02. Cross referencing the data made it possible to check for anomalies in materials description, layer type, and layer number information in table TST_AC02. Test results or records with anomalies in material and layer information were further evaluated to determine the causes of the anomalies. The results of the level 1 data completeness analysis are presented in table 15.

The information presented in table 15 shows that TST_AC02 contained a total of 9,016 records. The 992 records representing test data from SPS supplementary sections were excluded from further analysis because their evaluation falls outside of the scope of this study. Approximately 97 percent of the remaining records were at level E.

Table 15. Level 1 data completeness for table TST_AC02.

Experiment Type	Experiment No.	Total Number of Records at All Levels	Total Number of Records at at Level E	Percentage of Records at Level E	Number of Analysis Cells Represented at Level E
GPS	1	1831	1829	99.89	320
GPS	2	1472	1470	99.86	239
GPS	3	40	40	100	10
GPS	4	6	6	100	2
GPS	5	89	89	100	23
GPS	6A	780	779	99.87	138
GPS	6B	385	378	98.18	92
GPS	6C	28	28	100	6
GPS	6D	12	11	91.67	2
GPS	6S	174	172	98.85	40
GPS	7A	226	226	100	49
GPS	7B	125	125	100	24
GPS	7C	16	16	100	2
GPS	7S	8	8	100	4
GPS	9	22	22	100	7
SPS	1	1035	1010	97.6	42
SPS	5	1190	1079	90.7	54
SPS	6	186	130	69.9	9
SPS	8	100	100	100	9
SPS	9	299	256	85.6	11

Note: There were a total of 992 records from SPS supplemental sections not listed in this table.

Level 2 Data Completeness

The analysis cells were further evaluated to determine whether the minimum number of tests required had been performed and reported at level E. Level 2 data completeness consisted of checking the amount of test records available in each analysis cell and comparing it to the sampling and testing requirements presented in SHRP P02 protocol and other relevant SHRP documents. (See references 2, 15 through 20.) Analysis cells with at least the minimum number of test records required were categorized as complete, whereas analysis cells with less than the minimum required test results at level E were classified as incomplete. Results of level 2 data completeness are presented in table 16.

Table 16. Summary of level 2 data completeness for table TST_AC02.

Experiment Type	No. of Analysis Cells with Data	Min. Number of Test Results Required	No. of Analysis Cells with Min. Number of Test Results	Percent Analysis Cells with Minimum Test Results
GPS-1	298	2	293	98.3
GPS-2	234	2	229	97.9
GPS-3	10	2	8	80.0
GPS-4	1	2	1	100
GPS-5	23	2	23	100
GPS-6A	135	2	129	95.6
GPS-6B	92	2	79	85.9
GPS-6C	6	2	6	100
GPS-6D	2	2	1	50.0
GPS-6S	33	2	30	90.9
GPS-7A	45	2	44	97.8
GPS-7B	22	2	22	100
GPS-7C	2	2	2	100
GPS-7S	4	2	4	100
GPS-9	4	2	4	100
SPS-1[1]	24	60/34	2	8.3
SPS-5[2]	60	9/40	13	22.0
SPS-6	7	20	3	43.0
SPS-8	6	16	3	50.0

[1]For the SPS-1 project, 60 tests are required for the AC surface and binder layers, and 34 tests are required for the asphalt-treated base.
[2]For the SPS-5 project, nine tests are required on the original AC surface preconstruction, and 40 tests are required on the overlay postconstruction.

Table 16 shows that level 2 data completeness for GPS experiments ranged from 80 to 100 percent; most of the sampling and testing is complete. For SPS test sections, data completeness ranged from 8 to 50 percent, indicating that there is still a significant amount of testing ongoing. This is reasonable because there still are SPS test pavements under construction.

Bulk Specific Gravity of AC Cores Data Quality

Data quality was evaluated for all the data in table TST_AC02. The first step was to evaluate the test data for reasonableness by comparing test values with typical AC BSG test values. The range of typical test values was obtained from published literature.[22] The data were then further evaluated to determine how much variability exists within each analysis cell. The variability was compared with the typical variability and classified as acceptable or questionable.

Data Reasonableness

Bulk specific gravity of a compacted AC mixture is influenced by the following mixture properties:

- Aggregate specific gravity.
- Specific gravity of the asphalt binder.
- Percentage of air voids in the compacted mixture.

In compacted asphalt mixes, about 90 percent of the volume consists of aggregates. Therefore, the specific gravity of aggregates predominantly controls the BSG for the AC mixtures as a whole. Bulk specific gravity values of some of the common types of rocks found in North America and used in AC mixtures are shown in the table 17.[22] Based on the data presented in table 17, a typical range in BSG values of 1.8 to 2.8 was adopted. Most of the BSG test values evaluated were found to be within the typical range of 1.8 to 2.8. The 7 results outside the typical range are listed in table 18. These test results required further evaluation. Feedback reports documenting the possible error in such data were generated and sent to the FHWA for evaluation.

Table 17. Typical values of specific gravity for selected aggregate.[22]

Type of Rock	Specific Gravity	Absorption (percent)
Granite	2.65	0.3
Syenite	2.74	0.4
Diorite	2.92	0.3
Felsite	2.66	1.8
Limestone	2.66	0.9
Dolomite	2.70	1.1
Shale	1.8-2.5	> 1.0
Sandstone	2.54	1.8

Table 18. Summary of nontypical BSG test data.

SHRP_ID	BSG	Possible Anomaly
481119	3.347	Higher than typical test values
481119	3.402	Higher than typical test values
491005	0.49	Lower than typical test values
483669	1.617	Lower than typical test values
483669	1.734	Lower than typical test values
483679	1.554	Lower than typical test values
483679	1.580	Lower than typical test values

The distributions of BSG test results are presented in figures 15 and 16 for GPS experiments and in figures 17 and 18 for SPS experiments. Approximately 80 percent of the cores tested from GPS experiments had BSG values ranging from 2.20 to 2.40. For SPS cores, approximately 90 percent had BSG values ranging from 2.20 to 2 .60.

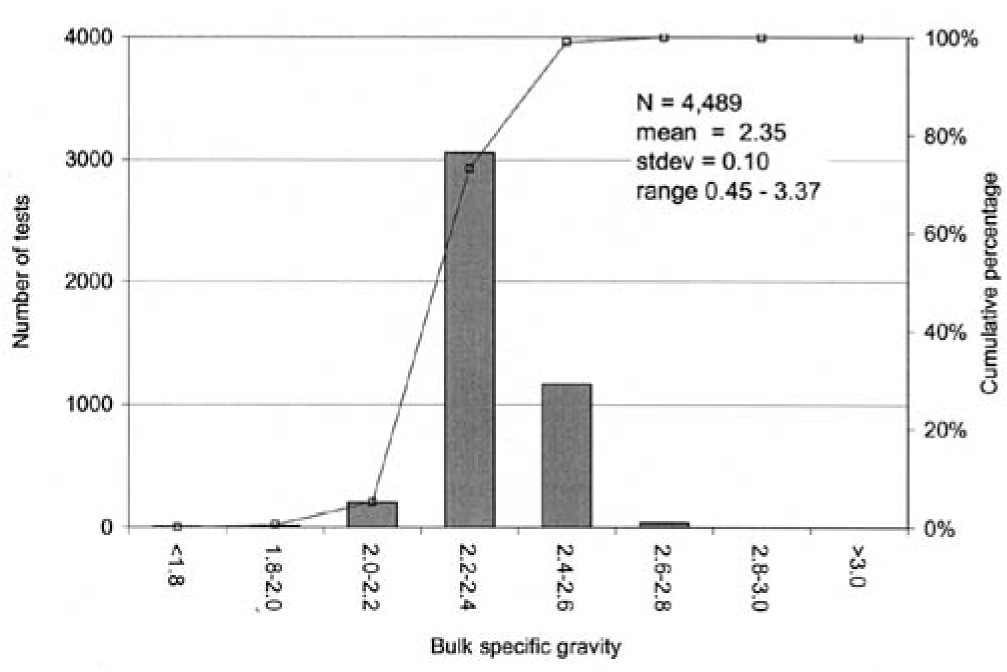


Figure 15. Distribution of BSG test results for GPS surface layers.

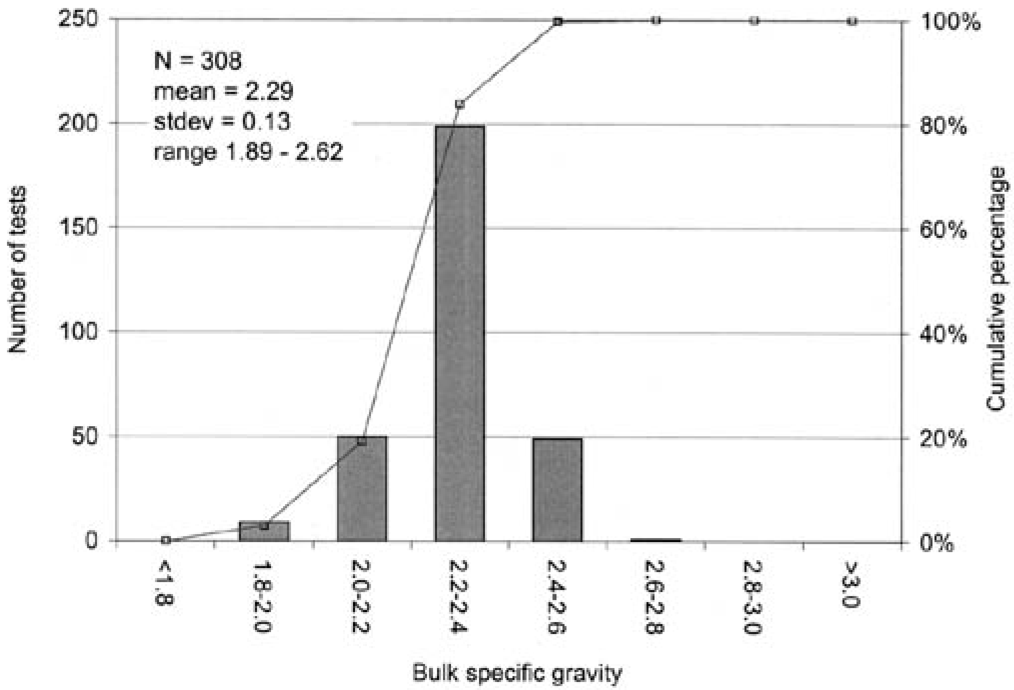


Figure 16. Distribution of BSG test results for GPS base layers.

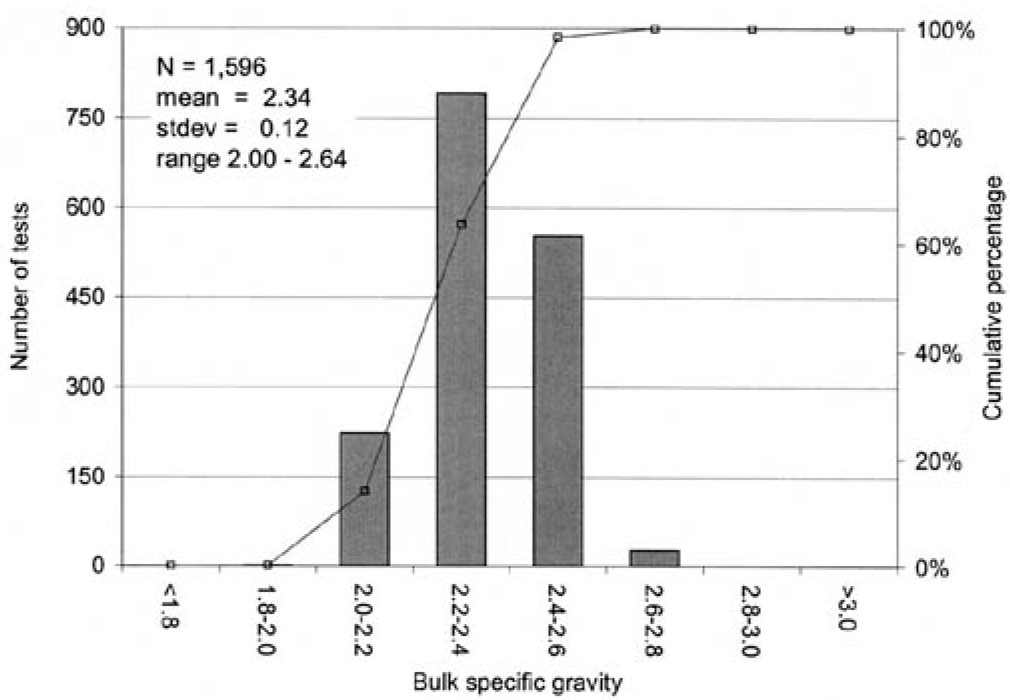


Figure 17. Frequency distribution of BSG measurements for all dense-graded HMAC of SPS surface layers.

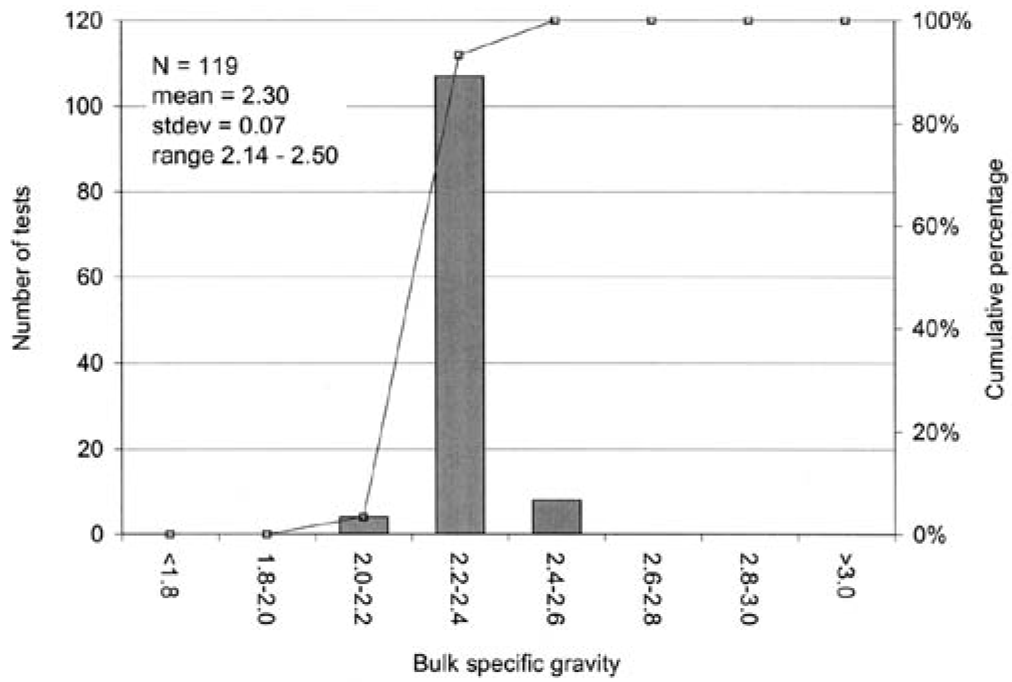


Figure 18. Frequency distribution of BSG measurements for all dense-graded HMAC of SPS base layers.

Assessing Bulk Specific Gravity Data Quality

The first step in assessing BSG data quality was to determine typical variability expected for cores belonging to the same analysis cell. This was done by reviewing typical variability measured as standard deviation or COV in published literature.(21) The AASHTO T166 test standard recommends a precision (i.e., testing variability) of 0.02 BSG between two test results for a field compacted sample. Assuming a mean BSG value of 2.3, this translates to a COV of 0.9 percent.

There is very little information in published literature on the typical variability of BSG test results. However, there is considerable information on the typical variability of AC air voids. The information available is summarized in table 19.[22] AC air voids variability data was used to augment the data available for BSG, because air voids content is directly related to BSG, and the same levels of variability can be expected for each parameter. The relationship between AC air voids and BSG is as follows:

$$PAVC = 100 * \frac{(MSG - BSG)}{MSG} \quad (7)$$

where:

PAVC = percent air voids content
MSG = maximum specific gravity
BSG = bulk specific gravity

Table 19. Typical variability for air voids.[22]

Data Source	Method	Standard Deviation, percent
California	Cores	1.9
New Jersey	Cores	1.5
Ontario	Cores	1.6
Colorado	Cores	1.0
Washington	Nuclear	0.9
Virginia	Cores	1.3

A COV of 2 percent was adopted as the typical variability expected between BSG test results from a common source. It will be the threshold value for the classification of acceptable and questionable analysis cells. A COV greater than 2 percent is, however, not unusual. It is simply an indicator of poor field compaction. Figures 19 and 20 present the distribution of COV for the GPS and SPS analysis cells, respectively. Approximately 90 percent of the analysis cells from GPS experiments had acceptable within-cell variability (COV less than 2 percent). For SPS experiments, approximately 82 percent had acceptable within-cell variability. The causes of excessive variability and other anomalies were further evaluated and possible remedial action implemented, as described in the next few sections of this chapter.

Identification of Anomalous Data

This discussion has so far focused on data availability and quality assessment. Data quality checks were performed to verify data reasonableness, protocol compliance, and within-cell variability. The anomalies found in the data during the various analyses performed are described in this section, along with possible causes of their occurrence. Where possible, corrective or remedial measures were implemented to address the identified anomalies, as described in the following sections.

Anomaly 1: Erroneous Material Type

Six records in this table had erroneous material type descriptions (nonbituminous material). A feedback report was generated for these records and sent to the FHWA for possible remedial action to be taken. Meanwhile, the records were retained in the representative data table, with a comment code assigned to them.

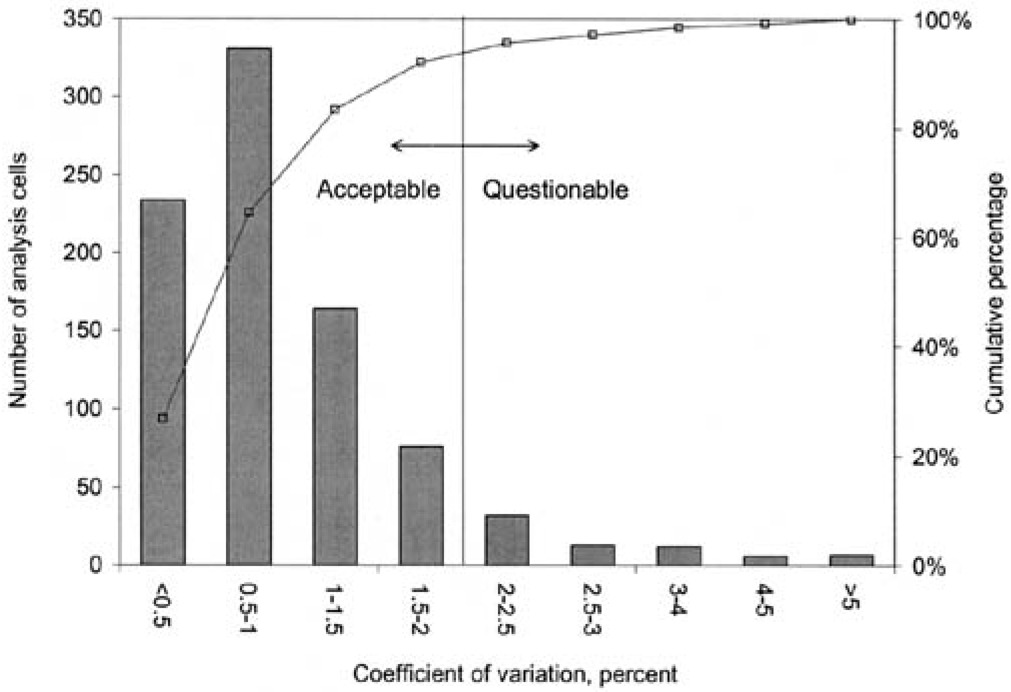


Figure 19. Distribution of COV of BSG for GPS analysis cells.

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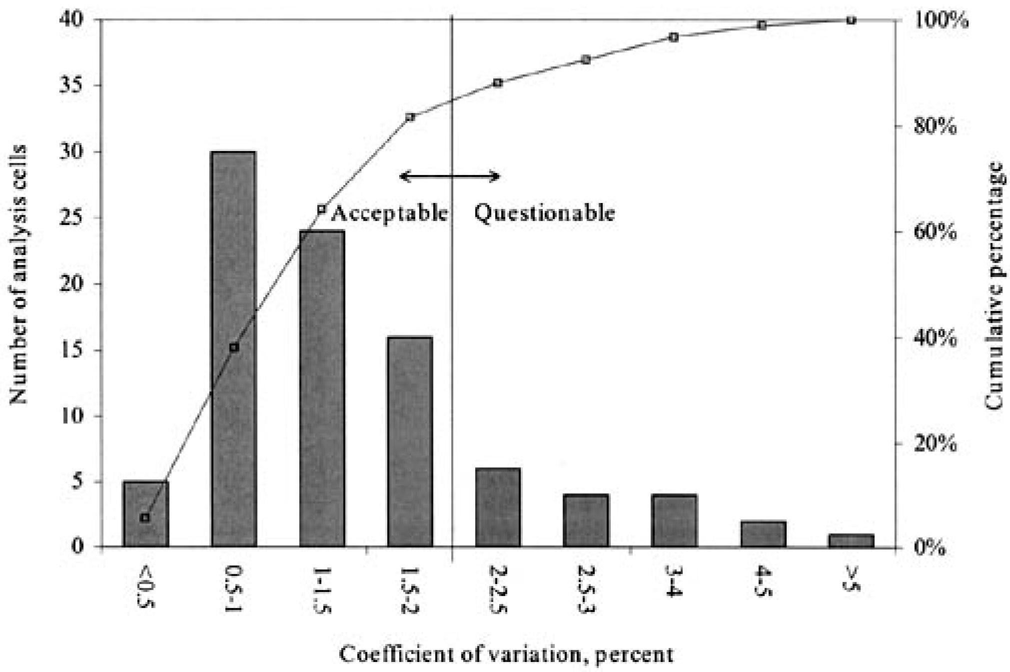

Figure 20. Distribution of COV of BSG for SPS analysis cells.

Anomaly 2: Compliance with Test Protocol (Minimum Thickness)

SHRP P02 states that all cores thicker than 38 mm shall be eligible for testing for BSG, and cores less than 38 mm thick (e.g., chip seal, seal coat, surface treatment or patching materials) shall not be tested. The evaluation of the data in table TST_AC02 revealed 24 analysis cells (22 from SPS experiments and two from GPS experiments) contained test results from cores less than 38 mm thick. Test values from such cores are clearly not in compliance with test protocols and were reevaluated for suitability.

Although the testing of cores less than 38 mm is not permitted, they were not removed from the representative data tables unless they were found to be erroneous or outliers. They were, however, assigned proper comment codes in the representative data tables.

Anomaly 3: Excessive Variability

A total of 97 analysis cells (80 from GPS and 17 from SPS experiments) had excessive variability (within-cell variability COV > 2 percent). These analysis cells constitute approximately 10 percent of the total number of analysis cells in table TST_AC02.

Test results outside the mean ± 4 standard deviations were deemed to be suspicious and, hence, were classified as outliers. They were not used for developing the representative data table. Outliers identified using procedures outlined in ASTM 178 were also not used in developing the representative data table. All the remaining data were retained in the representative data tables. A comment code was assigned to the retained data, explaining the possible causes of excessive variability.

Remedial Action--Summary

The individual test records for data within analysis cells with excessive variability were reviewed to determine possible causes of the anomaly. Of the 97 analysis cells with excessive variability, 24 were found to contain two distinct groups of test results within the analysis cell. When evaluated separately, each group within the analysis cell has acceptable variability. Another 10 analysis cells were found to contain suspect test results (test data outside of the mean ± 4 standard deviations). For the remaining 63 analysis cells, no reasonable causes for the anomaly were found.

After taking appropriate remedial action and recomputing the within-cell variability, 10 of the 97 analysis cells originally exhibiting excessive variability were reclassified as acceptable. The remaining 87 analysis cells still had excessive variability. They were retained in the database with appropriate comment codes.

Schema of the Representative Bulk Specific Gravity of AC Cores Tables TST_AC02_REP_GPS and TST_AC02_REP_SPS)

Representative BSG of AC cores tables, TST_AC02_REP_GPS and TST_AC02_REP_SPS were developed after addressing the identified anomalies, and they are recommended for inclusion into the LTPP database. The data fields in the tables are presented in table 20. The first four fields in the GPS schema and the first six fields in the SPS schema define the analysis cell used in computing summary statistics of the measured BSG values. Comment fields were included to describe the quality status of the data (e.g., excessive variability or incomplete sampling), followed by a field describing the record status.

Table 20. Schema for representative data tables TST_AC02_REP_GPS and TST_AC02_REP_SPS.

Number	TST_AC02_REP_GPS	TST_AC02_REP_SPS
1	State code	State code
2	SHRP identification number	SPS cell identification number
3	Layer number	Description of Layer
4	Construction number	Material code for the layer
5	Number of specimen tested	Construction number
6	Mean BSG	Number of specimen tested
7	Maximum BSG	Mean BSG
8	Minimum BSG	Maximum BSG
9	Standard deviation of BSG data	Minimum BSG
10	COV of BSG data	COV of BSG data
11	QA_Comment_1	Standard deviation of BSG data
12	QA_Comment_2	QA_Comment_1
13	QA_Comment_3	QA_Comment_2
14	QA_Comment_4	QA_Comment_3
15	QA_Comment_5	QA_Comment_4
16	QA_Comment_6	QA_Comment_5
17	QA_Comment_Other	QA_Comment_6

18	Record status	QA_Comment_Other
19	--	Record status

6. MAXIMUM SPECIFIC GRAVITY OF ASPHALT CONCRETE

Introduction

Maximum specific gravity, also called *Rice specific gravity*, is defined as the ratio of the weight in air of a unit volume of an uncompacted bituminous mixture to the weight of an equal volume of gas-free distilled water at a given standard temperature. It is described as the voidless specific gravity of AC mixtures and is one of the important properties of asphalt mixtures. Maximum specific gravity of AC is used in the calculation of the volumetric properties of AC mixtures, including air voids, voids in mineral aggregates, and voids filled with asphalt.

Table TST_AC03 contains the MSG test results for all LTPP test sections. Testing was based on SHRP protocol P03--*Maximum Specific Gravity of Asphaltic Concrete*--and the test standard AASHTO T209--*Maximum Specific Gravity of Bituminous Paving Mixtures* (ASTM D2041). The test protocols and standards provide guidance on material sampling, preparation of test specimens, testing of a specimens, and computation and presentation of the test results. After undergoing several levels of QA/QC checks, the test results are stored in table TST_AC03 in the LTPP database. Table TST_AC03 contains the 20 fields of information listed below:

1. SHRP identification number.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.
8. Lab code.
9. Sample area number.
10. MSG.
11. Sample number.
12. Test date.
13. Comments 1.
14. Comments 2.
15. Comments 3.
16. Comments 4.
17. Comments 5.
18. Comments 6.
19. Comments other.
20. Record status.

Material Sampling for AC Maximum Specific Gravity Testing

Material sampling was performed according to guidelines provided in several LTPP documents and reports, including the SHRP *Interim Guide for Laboratory Material Handling and Testing* and the SPS *Guidelines for Nominations and Evaluation of Candidate Projects*. (See references 2 and 15 through 20.) For GPS experiments, test core samples were collected at specific locations outside the distress monitoring sections of the LTPP pavement test sections. For SPS projects, cores were extracted from designated locations adjacent to individual test sections. The core specimens were collected, packaged, labeled, and shipped for testing to the SHRP-designated laboratories according to the procedures described in the SHRP P03 protocol. For SPS experiments, bulk samples were collected both pre- and postconstruction.

Sampling and testing requirements for MSG were used to define analysis cells for GPS and SPS experiments for data quality evaluation (see table 21). In general, an analysis cell was defined as follows:

- For GPS experiments, each layer within a test section was considered an analysis cell. An analysis cell was, therefore, defined as a unique combination of State_code, SHRP_ID, and Layer_No.
- For SPS experiments, an analysis cell was defined as a unique combination of State_code, SHRP_ID, Material_Code, and Layer_Type.

The sampling and testing requirements are presented in tables 22 and 23.

Data Completeness for Maximum Specific Gravity of AC Cores

MSG data completeness was evaluated at two levels:

- Level 1--involved the determination of the total amount of data available in table TST_AC03, the percentage at level E, and the number of analysis cells represented by the level E data.
- Level 2--consisted of determining the percentage of analysis cells with the minimum number of tests performed and results reported at level E.

The January 2000 release of table TST_AC03 was used for the analyses.

Table 21. Data fields used for defining analysis cells for BSG.

Data Fields	GPS	SPS[1]
SHRP_ID	X	X
State code	X	X
Layer number	X	X
Layer description		X
Material code		X

[1]SPS 1, 2, 5, 6, 7, 8, and 9A.

Table 22. Sampling and testing requirements for MSG of AC for GPS experiments.

Expt. Type	Layer Type	LTPP Designation	SHRP Protocol	Minimum Number of Tests per Layer	Sampling Location
GPS-1, -2, -6, and -7	AC	AC03	P03	2	A1, A2

Table 23. Details of sampling and testing requirements for MSG for SPS experiments.

Expt. Type	Construction Stage	SHRP Protocol	Sections	Minimum Number of Tests per Layer	Source/Location
SPS-1	Asphalt-treated base	P03	--	3	B19, B20, B21from paver
SPS-1	AC surface and binder layer	P03	--	3	B25, B26, B27from paver
SPS-5	Preconstruction	P03	--	3	BA1-3, TP, BA4-6
SPS-5	Postconstruction	P03	--	6	BV1, BV2, BV3, BR1, BR2, BR3
SPS-6	--	P03	--	3	BV1, BV2, BV3,
SPS-8	--	P03	--	3	BV-01, BV-02, BV-03,
SPS-9	Mix design	P03	01 and 03	1	NA01AXX
SPS-9	Compacted bulk samples	P03	02	3	NA15A02, BA06A02, BA22A02
SPS-9	QA test	P03	01 and 03	2	BA02AXX BA04AXX
SPS-9	Postconstruction	P03	01, 02, and 03	8	CA02tXX, CA06tXX, CA11txx, CA15txx, CA19tXX, CA24tXX, CA28tXX, CA33tXX

Note: Postconstruction cores to be tested at 0, 6, 12, 18, 24, and 48 months after construction.

Level 1--Data Completeness

The level 1 data completeness evaluation began with the extraction and assembly of the MSG test data from table TST_AC03 in the LTPP database. The layer and material description information in table TST_AC03 was cross-referenced with similar information in other LTPP tables, such as TST_ LO5B and EXPERIMENT_SECTION, by combining these tables with TST_AC03. Cross-referencing the data made it possible to check for anomalies in material description, layer type, and layer number information in table TST_AC03. Test results or records with anomalies in material and layer information were evaluated to determine possible causes of the anomalies. The results of the level 1 data completeness analysis are presented in table 24.

Table 24. Level 1 data completeness for AC03 table.

Expt Type	Expt Number	Total Number of Records at All Levels	Total Number of Records at Level E	Percentage of Records at Level E	Number of Analysis Cells Represented at Level E
GPS	1	610	608	99.70	306
GPS	2	609	607	99.70	213
GPS	3	6	6	100.00	4
GPS	4	2	2	100.00	1
GPS	6A	257	256	99.60	129
GPS	6B	162	159	98.10	85
GPS	6C	10	10	100.00	5
GPS	6D	4	3	75.00	2
GPS	6S	63	61	96.80	32
GPS	7A	123	123	100.00	49
GPS	7B	52	50	96.20	24
GPS	7C	2	2	100.00	1
GPS	7S	8	8	100.00	4
GPS	9	14	14	100.00	7
SPS	1	124	124	100.00	35
SPS	2	6	6	100.00	1
SPS	5	174	174	100.00	42
SPS	6	66	10	15.20	4
SPS	8	21	21	100.00	9
SPS	9	45	41	91.10	9

Note: There were a total of 78 records from SPS supplemental sections not listed in this table.

There were a total of 2,436 records at (all levels) in table TST_AC03. Approximately 94 percent (2,285 of 2,436) were at level E. The 2,285 records at level E represented 962 analysis cells. Seventy-eight records were from SPS supplementary sections and, thus, removed from further analysis.

Level 2--Data Completeness

The level E data were further evaluated to determine whether the minimum number of tests required had been performed and results reported at level E. This was done by checking the amount of test results or records available in each analysis cell and comparing it with the sampling and testing requirements presented in the SHRP P03 protocol and summarized in tables 21 and 22. Analysis cells with at least the minimum number of test records required were categorized as complete, whereas analysis cells with less than the minimum required test results at level E were classified as incomplete. Results of the level 2 data completeness analysis are presented in table 25.

Table 25. Level 2 data completeness assessment for table TST_AC03.

Experiment Type	No. of Analysis Cells with Test Data and Material Information	Min. Number of Test Results Required	Analysis Cells with Minimum Number of Test Results	Percent Analysis Cells with Minimum Test Results
GPS-1	289	2	269	93.10
GPS-2	209	2	200	95.70
GPS-3	4	2	2	50.00
GPS-6A	126	2	118	93.70
GPS-6B	85	2	72	84.70
GPS-6C	5	2	5	100.00
GPS-6D	2	2	1	50.00
GPS-6S	25	2	23	92.00
GPS-7A	45	2	42	93.30
GPS-7B	23	2	23	100.00
GPS-7C	1	2	1	100.00
GPS-7S	4	2	4	100.00
GPS-9	4	2	4	100.00
SPS-1	20	3	18	90.00
SPS-2	1	NR[1]	1	100.00
SPS-5	39	3/6[2]	10	26.00
SPS-6	3	3	1	33.00
SPS-8	5	3	2	40.00

[1]NR -- Not required by the materials testing plan.

[2]For the SPS-5 project three tests are required on the original AC surface preconstruction, and six tests are required on the overlay postconstruction.

Approximately 80 percent of the analysis cells had the minimum number of tests performed and results reported at level E. Level 2 data completeness for GPS experiments ranged from 50 to 100 percent, whereas that for SPS experiments ranged from 26 to 100 percent. Level 2 data completeness for SPS-5 experiments was particularly low (26 percent), possibly because sampling and testing is still ongoing for some SPS projects.

MSG Data Quality

Data quality checks for MSG data consisted of evaluating the individual test results for reasonableness and evaluating the within-cell variability of test results in table TST_AC03. The data were evaluated for reasonableness by comparing the MSG test values in table TST_AC03 with typical test results in published literature.(21) Subsequently, the data were evaluated for compliance with the relevant SHRP test protocol. Within-cell variability for the analysis cells with multiple test data was also evaluated for reasonableness by comparing with typical values in the literature.

Data Reasonableness

MSG test values are influenced by the following:

- Specific gravity of the coarse and fine aggregate used in the mixture.
- Specific gravity of the asphalt binder used in the mixture.

The specific gravity of aggregate materials typically ranges from 1.8 to 2.8, whereas that for asphalt binders is approximately 1.0. AC mixtures typically consist of a 3 to 7 percent by weight AC binder content, with the remainder being aggregates. Because of the low percentage of asphalt binder in AC mixtures, mix specific gravity is dominated by the aggregate specific gravity. Therefore, it is reasonable to assume that the typical range of aggregate specific gravity will not be significantly different from the typical range of specific gravity for the AC mixture as a whole. MSG test results outside the range of 1.8 to 2.8 are, therefore, questionable and were evaluated further; however, it must be noted that test results outside this range are not necessarily erroneous.

Figures 21 and 22 present the distribution of GPS surface and base layer MSG test results for all the records in table TST_AC03 at level E. The figures show that 80 percent (1,397 of 1,746) were within the range of 2.40 to 2.60, 15 percent were within the range of 2.2 to 2.4, and 5 percent were within the range of 2.6 to 2.8. Only four records were found out of the specified typical range of 1.8 to 2.8 percent, and these results were evaluated further to determine their effect on within-cell variability. Test results causing excessive variability were not used in developing the representative test values and summary statistics, as discussed later in this chapter.

Figures 23 and 24 present the distribution of SPS surface and base layer MSG test results for all the records in table TST_AC03 at level E. The figures show that 83 percent (204 of 246) were within the range of 2.40 to 2.60, 12 percent were within the range of 2.2 to 2.4, and 5 percent within the range of 2.6 to 2.8. No records were outside of the specified typical range of 1.8 to 2.8 percent.

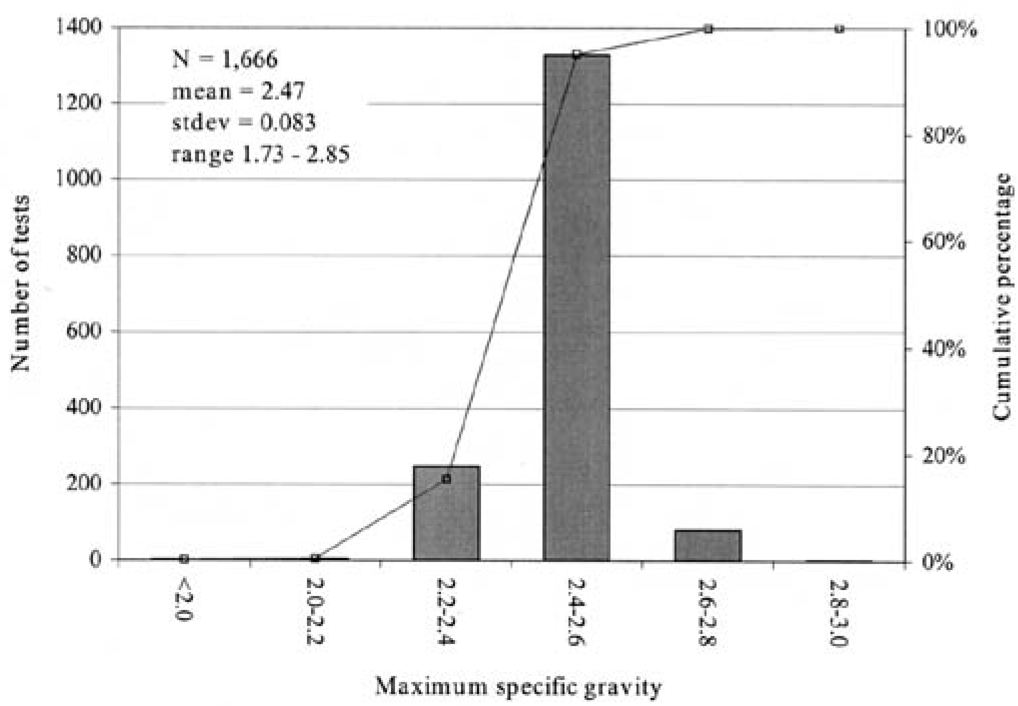

Figure 21. Distribution of MSG test results for GPS experiments (surface layers).

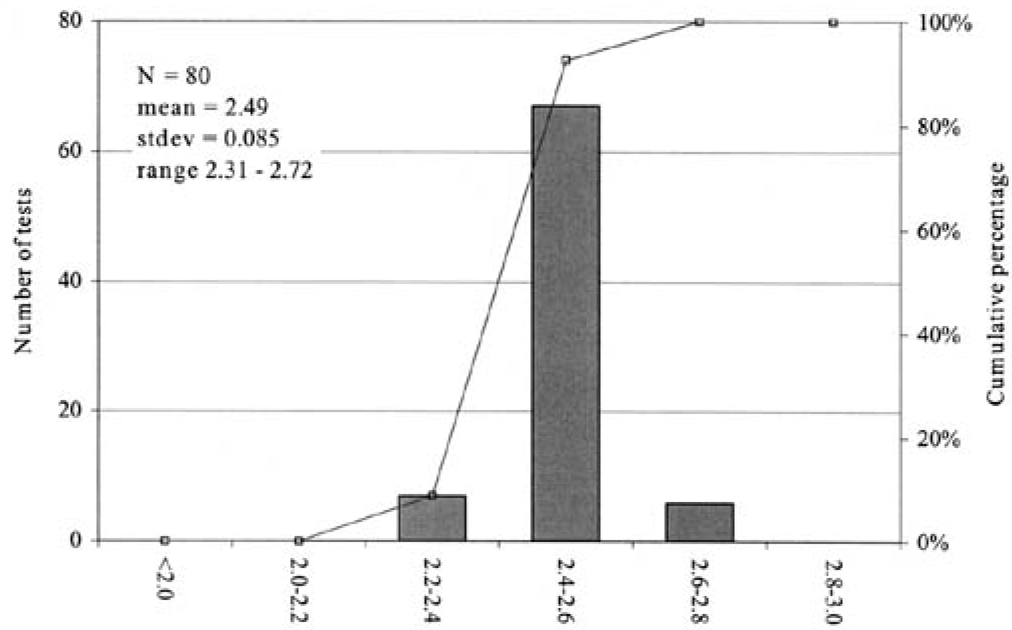

Figure 22. Distribution of MSG test results for GPS experiments (base layers).

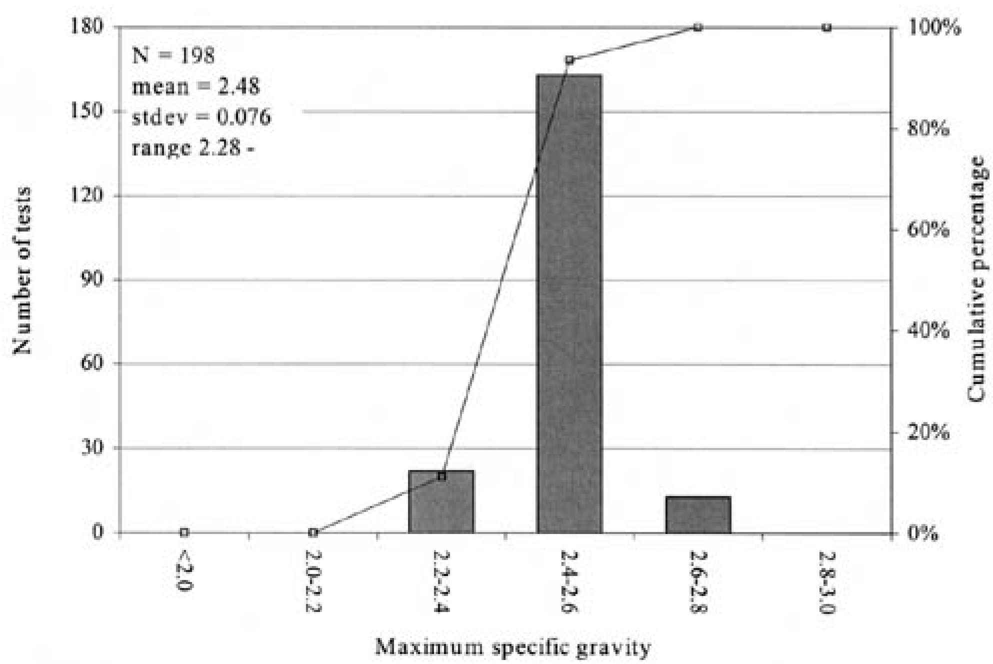

Figure 23. Distribution of MSG test results for GPS experiments (surface layers).

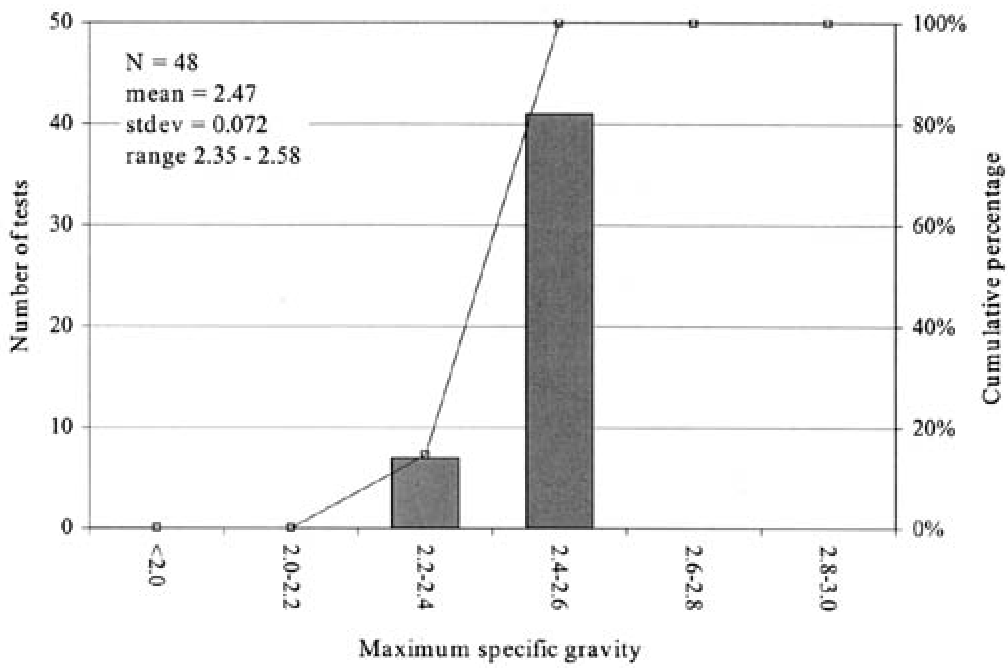

Figure 24. Distribution of MSG test results for SPS experiments (base layers).

Assessing MSG Data Quality

Data quality assessment began with determining the appropriate typical variability expected in MSG test data obtained from specimens with similar properties and characteristics. Typical variability (as defined in preceding chapters) consists of testing, material, sampling, and construction variability expected from field samples tested in the laboratory. Table 26 presents a summary of testing variability recommended by AASHTO T209.(4)

Table 26. MSG testing recommended variability.(4)

Condition of Test	Standard Deviation	Acceptable Range for Two Test Results
Single operator (not based on the use of section 7 of AASHTO T209)[1]	0.0004	0.011
Multiple operator (not based on the use of section 7 of AASHTO T209)[1]	0.00064	0.019
Single operator (based on the use of section 7 of AASHTO T209)[2]	0.00064	0.018
Multiple operator (based on the use of section 7 of AASHTO T209)[2]	0.0193	0.055

[1]Basis of estimate: three replicates, five materials, and five laboratories.
[2]Basis of estimate: two replicates, seven materials, and ten laboratories.

The test condition in table 26 that matches the LTPP testing conditions (multiple operator testing and applying section 7 of AASHTO T209) had a test standard deviation of 0.0193. However, because typical variability consists of not only testing variability, it will be greater than the AASHTO-recommended testing variability.

MSG test results in table TST_AC03 had a mean of 2.5. The testing standard deviation of 0.0193, therefore, converts to a COV of 0.8 percent. To account for the other sources of variability, a COV of 1 percent was adopted as the threshold value for classifying the within-cell variability as acceptable or questionable. Analysis cells classified as questionable were further evaluated to determine the sources of excessive variability. Remedial actions were implemented, where possible, to correct identified anomalies.

Basic statistics, such as mean, standard deviation, and COV, were computed for all the analysis cells in table TST_AC03 with multiple test data. Figures 25 and 26 show the distribution of variability measured as COV for the analysis cells evaluated. Approximately 91 percent of the analysis cells from the GPS experiments and 94 percent of analysis cells from SPS experiments had acceptable variability (COV < 1 percent).

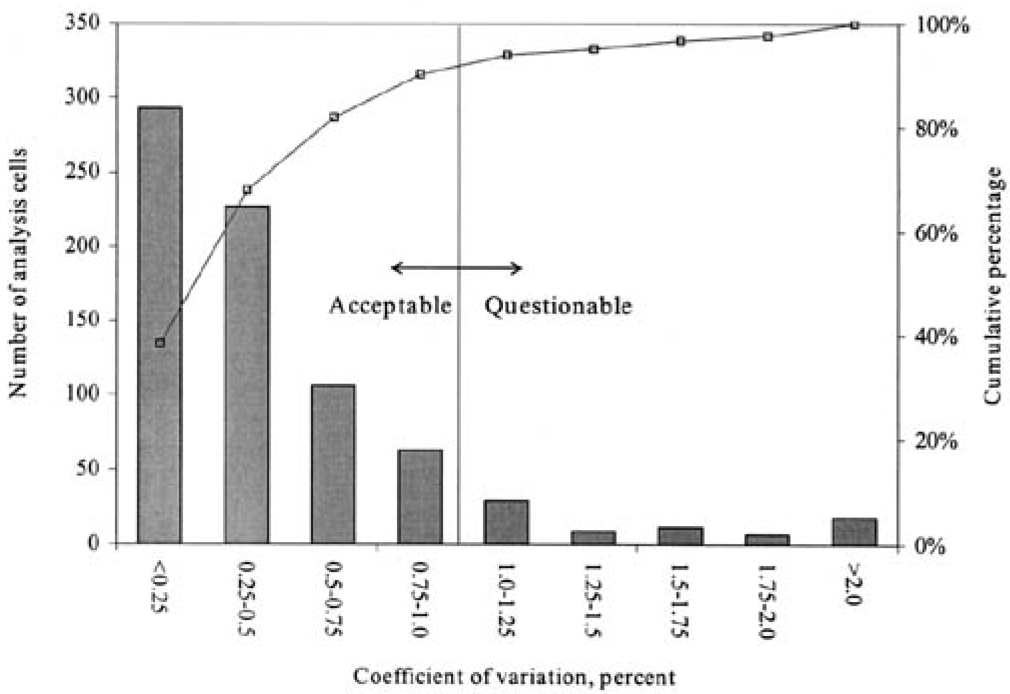

Figure 25. Distribution of COV for MSG analysis cells from GPS experiments.

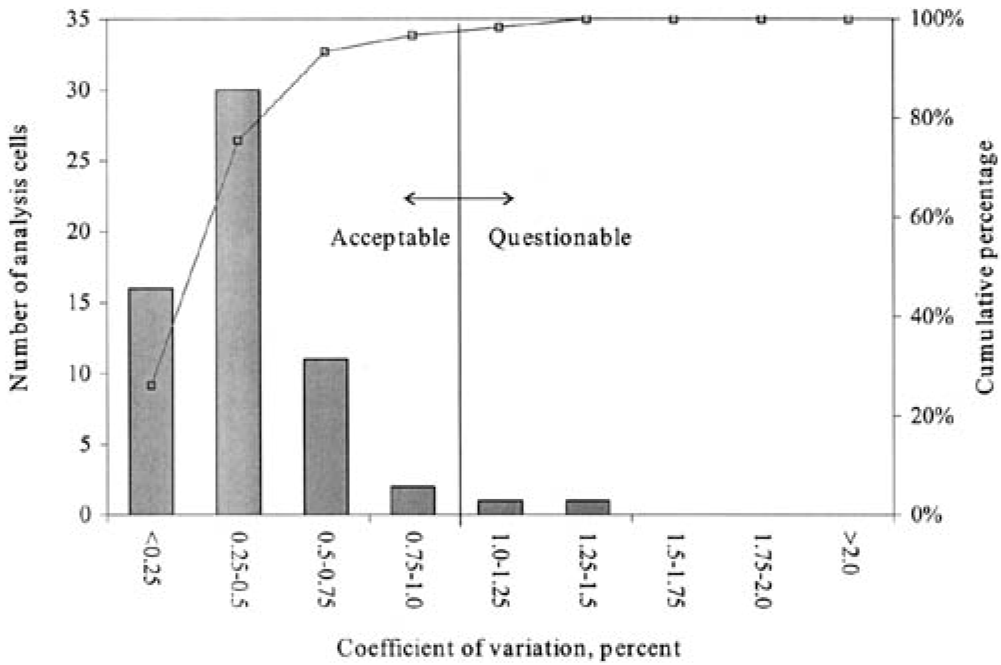

Figure 26. Distribution of COV for MSG analysis cells from SPS experiments.

Identification of Anomalous Data

The anomalies identified in the MSG test data and recommended remedial actions are presented in the following sections.

Anomaly 1: Erroneous Data Entry

Six records in table TST_AC03 had erroneous materials type descriptions (i.e., nonbituminous materials). A breakdown of the affected records is as follows:

- GPS-6, SHRP_ID 422001 contained two records with material type description--crushed aggregate base.
- SPS-1, SHRP_ID 311001 contained four records with material type description--cement-treated base.

It is obvious that MSG cannot be determined for nonbituminous materials, and the entries are erroneous.

A feedback report was generated and sent to the FHWA. The erroneous data were excluded from the representative data table. They will be included at a future date, when the anomaly is rectified by the FHWA.

Anomaly 2: Compliance with Test Protocol (Minimum Thickness)

SHRP P03 states that only cores with a minimum thickness of 38 mm shall be eligible for testing. Cores less than 38 mm thick (e.g., chip seal, seal coat, surface treatment, or patching materials) shall not be tested. The evaluation of the data in table TST_AC03 revealed 18 analysis cells (one from SPS experiments and 17 from GPS experiments), with test results from cores that should not have been tested (less than 38 mm thick). Test results from such cores were clearly not in compliance with test protocols and, hence, their suitability for inclusion in the representative data tables was evaluated.

Such data were evaluated for reasonableness or whether they were outliers and causing excessive variability in their respective analysis cells. Unreasonable test results or outliers were excluded from the representative data tables.

Anomaly 3: Excessive Variability

A total of 79 analysis cells (75 from GPS experiments and four from SPS experiments) had excessive within-cell variability (COV > 1 percent). These analysis cells constitute approximately 9 percent of the total number of analysis cells in table TST_AC02.

Test results outside ± 4 standard deviations of the mean were assumed to be erroneous and not used for developing the representative data table. Appropriate comment codes were assigned to the analysis cells with excessive variability to explain possible causes of the excessive variability. Two of the 79 analysis cells with excessive variability contained erroneous test data (test data outside ± 4 standard deviations of the mean test value for the given analysis cell). No plausible reason for the excessive variability was found in the remaining 77 analysis cells.

Schema of the Revised MSG Data Table TST_AC03_REP

Two data tables, TST_AC03_REP_GPS and TST_AC03_REP_SPS, containing representative MSG of AC for GPS and SPS experiments, respectively, were developed and are recommended for inclusion in the LTPP database. The data fields in the tables are presented in table 27.

The first four fields in the GPS schema and first six fields in SPS schema define the analysis cell used in computing summary statistics of the measured MSG values. Comment fields are included to describe the quality status of the data (e.g., excessive variability and incomplete sampling), followed by a field describing record status.

Table 27. Schema for representative data tables TST_AC02_REP_GPS and TST_AC02_REP_SPS.

Number	GPS	SPS
1	State code	State code
2	SHRP identification number	SPS cell identification number
3	Layer number	Description of layer
4	Construction number	Material code for the layer
5	Number of specimen tested	Construction number
6	Mean MSG	Number of specimen tested
7	Maximum MSG	Mean MSG
8	Minimum MSG	Maximum MSG
9	Standard deviation	Minimum MSG
10	COV	COV
11	QA_Comment_1	Standard deviation
12	QA_Comment_2	QA_Comment_1
13	QA_Comment_3	QA_Comment_2
14	QA_Comment_4	QA_Comment_3
15	QA_Comment_5	QA_Comment_4
16	QA_Comment_6	QA_Comment_5
17	QA_Comment_Other	QA_Comment_6
18	Record status	QA_Comment_Other
19	--	Record status

7. ASPHALT CONTENT OF ASPHALTIC CONCRETE

Introduction

Asphalt content of an AC mixture is a very important factor ensuring satisfactory performance. AC mixtures with low asphalt contents are generally less durable than mixtures with optimum asphalt contents, and mixtures with high asphalt contents are generally less stable. Asphalt content directly affects mixture properties such as:

- Asphalt film thickness
- Voids
- Stability
- Flow

Asphalt content of a mixture is, therefore, essential for design and research into the behavior of AC materials.

Asphalt content of a mixture is measured by an extraction test. For the LTPP material characterization program, the test protocol and test standard adopted were SHRP protocol P04 and AASHTO T164 (ASTM D2172)--*Quantitative Extraction of Bitumen from Bituminous Paving Mixtures.*[2,3] Asphalt content of mixtures is measured as percentage by weight of the total mix. The test data are stored in table TST_AC04 in the LTPP database. Table TST_AC04 has the following 20 fields of information:

1. SHRP identification number.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.
8. Lab code.
9. Sample area number.
10. Mean asphalt content.
11. Sample number.
12. Test date.
13. Comments 1.
14. Comments 2.
15. Comments 3.
16. Comments 4.
17. Comments 5.
18. Comments 6.
19. Comments other.
20. Record status.

Material Sampling for Asphalt Content of AC Mixtures

SHRP P04 and AASHTO T164 provide guidance on material sampling, preparation of test specimens, testing of specimens, computation of test results, and presentation of results. For test sections in GPS experiments, testing is performed on 300-mm-diameter core specimens retrieved from the approach and leave ends of the test pavement's monitoring section. Testing is also performed on block samples taken from test pits at the leave section of the test pavement. For SPS experiments, core specimens are extracted from specific locations within the entire SPS experiment (between adjacent projects). Detailed information on sample locations and core descriptions for SPS experiments may be found in several SHRP documents. (See references 2 and 15 through 20.)

Table 28 presents the sampling and testing requirements for the determination of asphalt content for GPS test pavements. A detailed summary of SPS sampling requirements is presented in table 29.

Table 28. Sampling and testing requirements for extracted asphalt content.

Expt. Type	Layer Type	SHRP Protocol	Minimum Number of Tests per Layer	Sampling Location
GPS-1, -2, -6, and -7	AC	P04	2	TP, BA1

Table 29. Sampling and testing requirements for extracted asphalt content for SPS projects.

Expt Type	Construction Stage	SHRP Protocol	Sections	Min. No. of Tests per Layer	Source/Location
SPS-1	Asphalt-treated base	P04	--	3	B19, B20, B21from paver
SPS-1	AC surface and binder layer	P04	--	3	B25, B26, B27from paver
SPS-2	Asphalt-treated base	P04	--	3	B16 to B18from paver
SPS-5	Preconstrution	P04	--	3	BA1-3, TP, BA4-6
SPS-5	Postconstrution	P04	--	6	BV1, BV2, BV3, BR1, BR2, BR3
SPS-6	--	P04	--	3	BV1, BV2, BV3,
SPS-8	--	P04	--	3	BV-01, BV-02, BV-03,
SPS-9	Mix design	P04	01 and 03	0	--
SPS-9	Compacted bulk samples	P04	02	6	BA01A02, BA06A02, BA11A02, BA16A02, BA22A02, BA34A02
	QA test	P04	01 and 03	2	BA02AXX-BA04AXX
SPS-9	Post construction	P04	01, 02, and 03	8	CA02tXX, CA06tXX, CA11txx, CA15txx, CA19tXX, CA24tXX, CA28tXX, CA33tXX

Data Completeness for Asphalt Content of AC Mixtures

Data completeness was evaluated at two levels. Level 1 data completeness consisted of assessing the total number of test records in table TST_AC04, the percentage at level E, and the number of analysis cells represented by the data at level E. For level 2 data completeness, the number of test results in each analysis cell was checked against the minimum required. Cells with at least the minimum required number of tests were classified as complete, whereas those with less than the minimum were classified as incomplete. The January 2000 release of table TST_AC04 was used in the analysis. Analysis cells are defined for GPS and SPS experiments, using the fields presented in table 30.

Table 30. Data fields used for defining analysis cells for asphalt content.

Key Fields	GPS	SPS[1]
SHRP_ID	X	X
State code	X	X
Layer number	X	X
Construction number	X	X
Layer type		X
Material code		X

[1]SPS-1, -2, -5, -6, -7, -8, and -9A.

Level 1--Data Completeness

The data in table TST_AC04 were extracted and assembled from the LTPP database and checked for level 1 data completeness. Data assembly involved merging table TST_AC04 with other tables, such as TST_L05B and EXPERIMENT_SECTION. Important material and layer description information from all the merged tables was cross-referenced to check for accuracy and consistency. The merged data set was then evaluated for level 1 data completeness, as follows:

- Determine all available data in table TST_AC04 (levels A to E).
- Determine the percentage of the test data at level E.
- Determine the number of analysis cells represented by the data at level E.

Approximately 98.2 percent (2,447 of 2,562) of the asphalt content data in table TST_AC04 was at level E. One hundred records were from SPS supplementary sections and, therefore, removed from any further analysis. Table 31 presents a summary of the level 1 data completeness results.

Table 31. Summary of level 1 data completeness evaluation for asphalt content.

Expt Type	Expt Number	Total Number of Records at All Levels	Total Number of Records at Level E	Percentage of Records at Level E	Number of Analysis Cells Represented at Level E
GPS	1	602	599	99.50	302
GPS	2	607	607	100.00	214
GPS	3	5	5	100.00	3
GPS	4	2	2	100.00	1
GPS	6A	262	261	99.60	133
GPS	6B	189	187	98.90	84
GPS	6C	16	16	100.00	6

GPS	6D	4	3	75.00	2
GPS	6S	77	77	100.00	23
GPS	7A	118	118	100.00	49
GPS	7B	52	49	94.20	23
GPS	7C	2	2	100.00	1
GPS	7S	12	12	100.00	4
GPS	9	12	12	100.00	7
SPS	1	141	136	96.50	42
SPS	2	28	28	100.00	12
SPS	5	181	181	100.00	40
SPS	6	6	6	100.00	3
SPS	8	21	21	100.00	9
SPS	9A	125	125	100.00	10

Level 2--Data Completeness

The analysis cells were further analyzed for data completeness by comparing the number of tests required by SHRP with the actual number of test data available in each analysis cell. Analysis cells with at least the minimum number of test data required were classified as complete. Analysis cells with less than the minimum required test data were classified as incomplete. Approximately 72 percent of the analysis cells were classified as complete. The remaining 28 percent were incomplete and were further evaluated to check for possible bias and other anomalies. The checks performed are presented throughout the remainder of this chapter. A summary of level 2 data completeness is presented in table 32.

Asphalt Content Data Quality Evaluation

The asphalt content data in the table TST_AC04 were evaluated for reasonableness and quality. Assessing data reasonableness consisted of comparing individual test results with typical test values. Test data that were within the range of typical values were classified as reasonable. All other data were classified as questionable and required further evaluation. The test data grouped as analysis cells were also assessed for quality by computing within-cell variability. The computed variability was compared with typical variability expected from field data and laboratory testing.

Table 32. Level 2 data completeness from asphalt content data.

Expt. Type	No. of Analysis Cells with Test Data and Material Information	Min. Number of Test Results Required	Analysis Cells with Minimum Number of Test Results	Percent Analysis Cells with Minimum Test Results
GPS-1	288	2	271	94.10
GPS-2	208	2	201	96.60
GPS-3	3	2	2	66.70
GPS-6A	129	2	126	97.70
GPS-6B	84	2	74	88.10
GPS-6C	6	2	6	100.00
GPS-6D	2	2	1	50.00
GPS-6S	18	2	18	100.00
GPS-7A	45	2	41	1.10
GPS-7B	22	2	21	95.50
GPS-7C	1	2	1	100.00
GPS-7S	4	2	4	100.00
GPS-9	4	2	2	50.00
SPS-1	31	3	23	74.00
SPS-2	7	NR[1]	6	86.00
SPS-5	36	3/6[2]	11	31.00
SPS-6	3	3	1	33.00
SPS-8	5	3	2	40.00

[1]NR--Not required by the materials testing plan.
[2]For the SPS-5 projects, three tests are required on the original AC surface preconstruction, and six tests are required on the overlay postconstruction.

Analysis cells with variability equal to or less than typical were classified as acceptable, whereas those with variability greater than typical were classified as questionable. A detailed summary of the data quality evaluation is presented in the next few sections.

Data Reasonableness

The percentage of asphalt content in a mixture depends on several variables, including:

- Aggregate gradation.
- Aggregate porosity.
- Mixture type.

The AC content of dense-graded AC mixtures and stone matrix asphalt (SMA) mixtures typically ranges from 3 to 7 percent.(13) The typical range for large-stone asphalt mixtures and asphalt-treated bases could be considerably less than 4 percent. A range of 3 to 7 percent was selected as the typical range expected for the surface and base layers and used in assessing data reasonableness. The data were grouped into four categories for evaluation, as follows:

1. GPS surface layer AC materials.
2. SPS surface layer AC materials.
3. GPS base layer AC materials.
4. SPS base layer AC materials.

Figures 27 and 28 illustrate the distribution of asphalt content for GPS and SPS surface layer AC materials. Approximately 98 percent of the GPS surface layer AC materials had an asphalt content ranging from 3 to 7 percent. For SPS surface layer AC materials, figure 28 shows a range of 2.4 to 7.9 percent. Approximately 97 percent of the asphalt content data fell within the typical range of 3 to 7 percent. Only 2 percent of the test results from GPS surface layers and 3 percent from the SPS surface layers are out of the typical range. Test data outside the typical range were evaluated further to determine their effect on within-cell variability, which is presented later in this chapter.

The distributions of asphalt content for AC base layers for GPS and SPS experiments are presented in figures 29 and 30. The data presented in the figures are summarized as follows:

- Approximately 93 percent of the test results from GPS experiments fell within the typical ranges of 3 to 7 percent. Asphalt content ranged from 2.7 to 7.4 percent.
- Approximately 90 percent of the test results from SPS experiments fell within the typical ranges of 3 to 6 percent. Asphalt content ranged from 1.8 to 6.3 percent.

Even though a majority of the asphalt content values fell within the typical range, some test values from the SPS experiments were significantly less than the minimum of the typical range (2.0 to 2.5 percent). Such data were evaluated further to determine their effect on within-cell variability, which is presented later in this chapter.

Assessing Asphalt Content Data Quality

Several studies have been conducted to determine the typical variability between AC content test results from core specimens. (See references 11 through 16.) SHRP protocol P04 and AASHTO T164 (ASTM D2172) provide guidance on the variability expected from testing.[2,3,4] The recommended testing standard deviation for core specimens tested at multiple laboratories was 0.22 percent. The typical variability observed from field data (i.e., sampling, the material's natural variability, and construction variability) is summarized in table 33.[13]

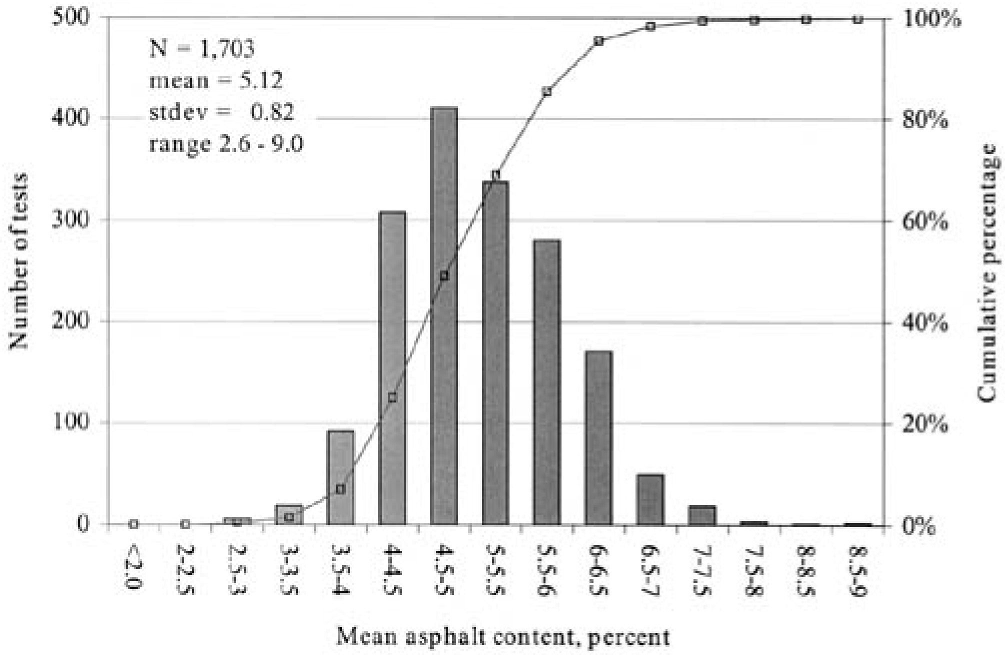

Figure 27. Distribution of asphalt content for HMAC surface material for GPS experiments.

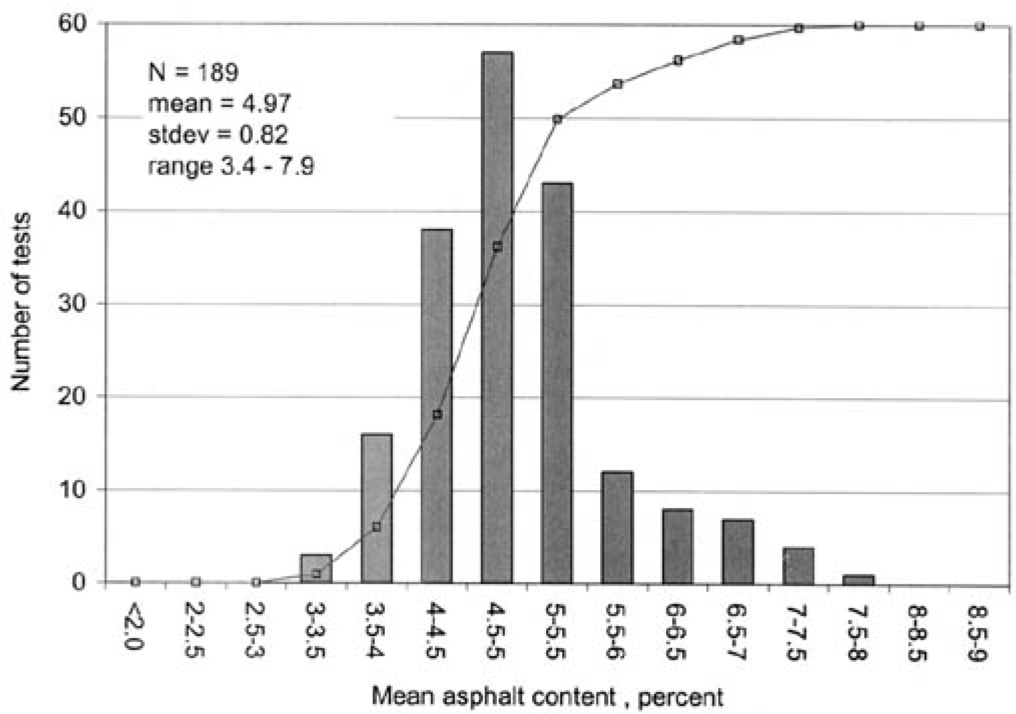

Figure 28. Distribution of asphalt content for HMAC surface material for SPS experiments.

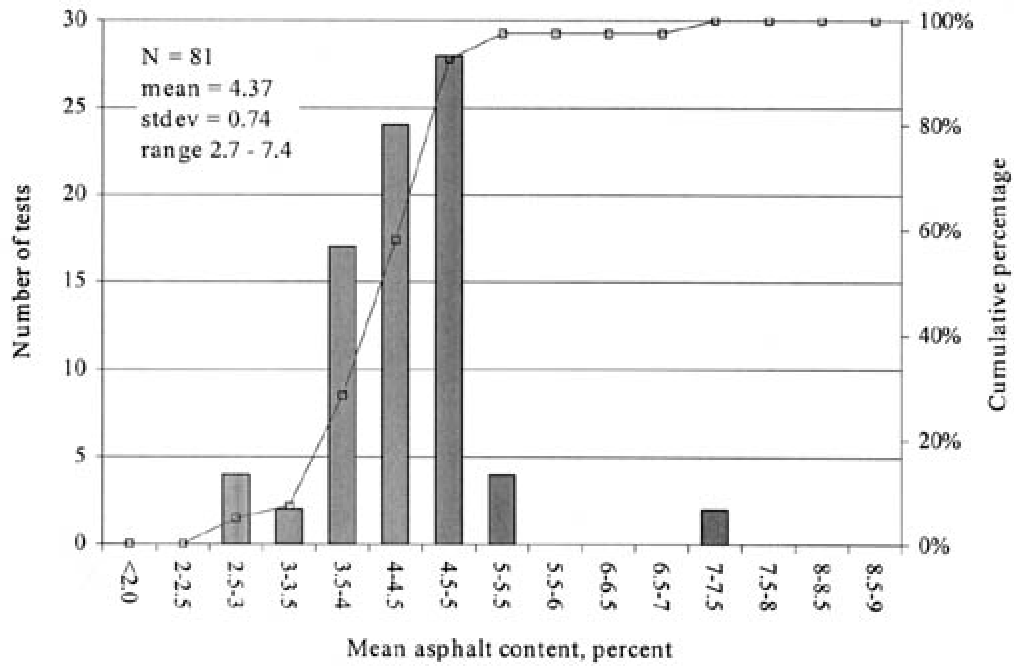

Figure 29. Distribution of asphalt content measurements for HMAC base layers from GPS experiments.

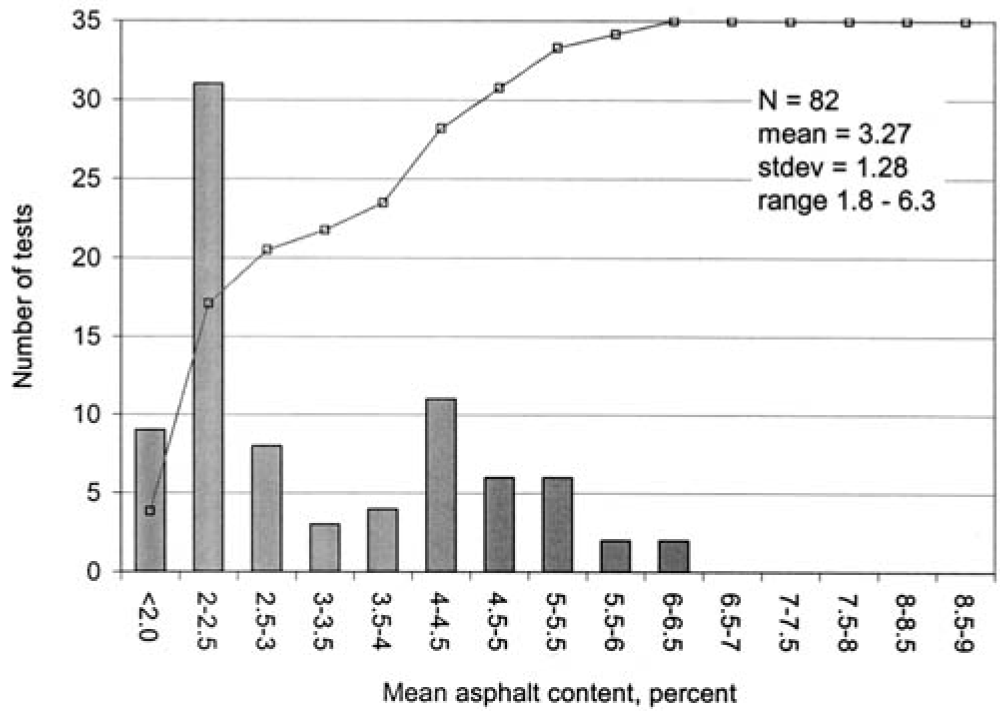

Figure 30. Distribution of asphalt content measurements for HMAC base layers from SPS experiments.

Table 33. Summary of typical variability in asphalt content field data.[13]

Data Source	Year	Test Method	Standard Deviation, percent
Virginia	1994	Extraction	0.18
Virginia	1994	Nuclear	0.21
NCAT	1994	Nuclear	0.19
NCAT	1994	Centrifuge	0.44
Washington	1993	Extraction	0.24
Colorado	1993	Extraction	0.15
Pennsylvania	1980	Extraction	0.25

Based on the information presented in table 33, a standard deviation of 0.5 percent was adopted. This translates to a COV of 10 percent (assuming a mean asphalt content of 5.0). An analysis cell with a COV greater than 10 percent was, therefore, classified as questionable, whereas a COV of less than or equal to 10 percent was classified as acceptable.

Figures 31 and 32 present the distribution of COV for analysis cells from GPS and SPS experiments. Approximately 88 percent and 77 percent of the analysis cells from the GPS and SPS experiments, respectively, were acceptable.

Identification of Anomalous Data

Several anomalies were identified in the checks described in the preceding sections of this chapter. The anomalies and remedial actions implemented to rectify them are presented in the next few sections.

Anomaly 1: Erroneous Data Entry

There were six records in table TST_AC04 with erroneous material type descriptions (nonbituminous material descriptions). Because it is not possible to obtain asphalt content test results from nonbituminous materials, these entries are erroneous. Feedback reports documenting possibly erroneous entries of material data types were sent to the FHWA for appropriate remedial action. Meanwhile, the records were retained in the database with a comment code assigned to them.

Anomaly 2: Noncompliance with Test Protocol (Minimum Thickness of Testable Layer)

The SHRP *Interim Guide for Laboratory Material Handling and Testing* states that AC core specimens with a thickness less than 38 mm shall not be tested for asphalt content.[2] Table TST_AC04 contains a total of 17 analysis cells (one from SPS experiments and 16 from GPS experiments) with test results from cores that were less than the minimum required thickness.

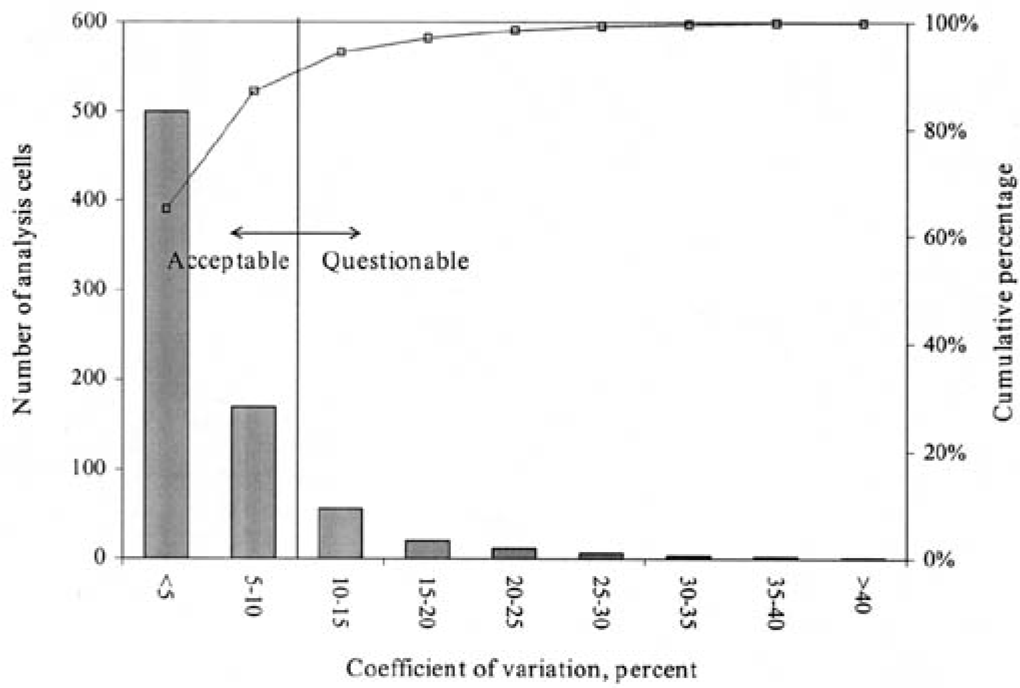

Figure 31. Distribution of COV of asphalt content analysis cells from GPS experiments.

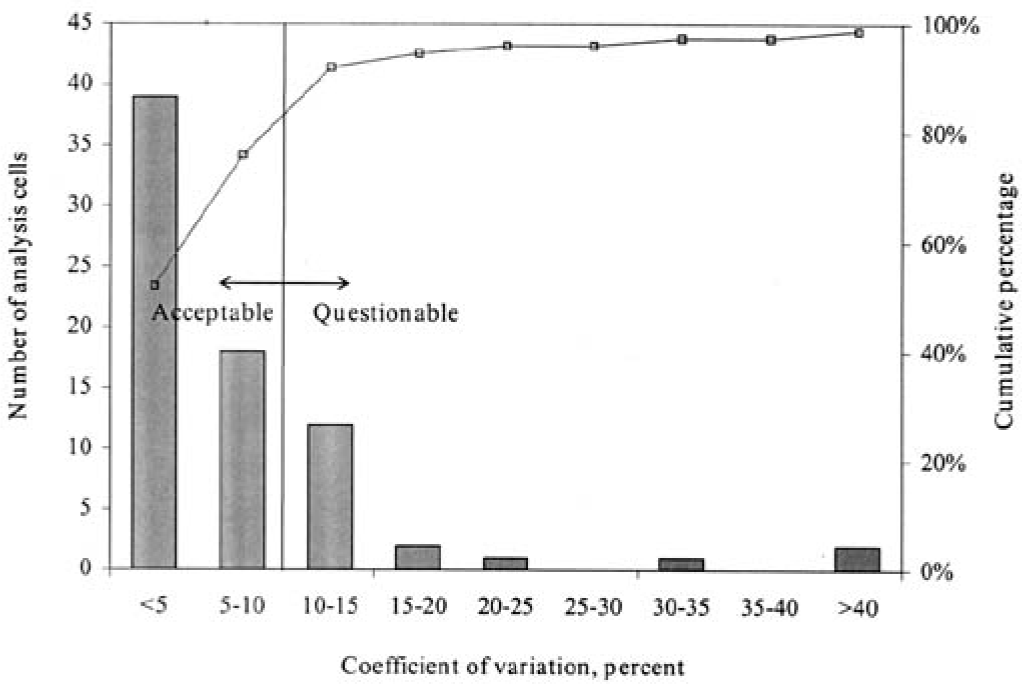

Figure 32. Distribution of COV of asphalt content analysis cells from SPS experiments.

Test values resulting from testing that was not in compliance with test protocols (cores less than 38 mm thick) were evaluated for reasonableness and whether they were outliers causing excessive variability in their respective analysis cells. Unreasonable test results or outliers were excluded from the development of the representative data tables.

Anomaly 3: Excessive Variability

For this test table, analysis cells were classified as questionable if they had a variability (COV) greater than 10 percent. Approximately 12 percent (99 of 814) of the analysis cells with multiple test results from the GPS experiments had excessive variability. For SPS experiments, 23 percent (19 of 82) of the analysis cells had excessive variability.

All supporting information provided in table TST_AC04, such as comments about the testing process and materials sampling, was carefully reviewed to determine possible causes of the excessive variability. Individual test results were checked for compliance with test protocols, and those with anomalies (such as noncompliance with the test protocol) were not used in the development of the representative data table. Variability and other statistics were recomputed, and comments were provided to describe the remedial action taken. For analysis cells with no plausible reason for excessive variability, all the individual test results were retained; however, comments were provided to indicate excessive variability.

Schema of the Representative Asphalt Content of AC Data Tables (TST_AC04_REP_GPS and TST_AC04_REP_SPS)

Two tables, TST_AC04_REP_GPS and TST_AC04_REP_SPS, containing representative test values of asphalt content of AC for GPS and SPS experiments, respectively, were developed and are recommended for inclusion into the LTPP database. The schema for the new data table is presented in table 34. The first four fields in the GPS schema and first six fields in SPS schema define the analysis cell used in computing summary statistics of the measured asphalt content test values. This is followed by a description of the test results and basic statistics. Comment fields are provided to describe the quality status of the data (e.g., excessive variability and incomplete sampling), followed by a field describing the record status.

Table 34. Schema for tables TST_AC04_REP_GPS and TST_AC04_REP_SPS.

Number	GPS	SPS
1	State code	State code
2	SHRP identification number	SPS cell identification number
3	Layer number	Description of layer
4	Construction number	Material code for the layer
5	Number of specimen tested	Construction number
6	Mean asphalt content	Number of specimen tested
7	Maximum asphalt content	Mean asphalt content
8	Minimum asphalt content	Maximum asphalt content
9	Standard deviation of asphalt content	Minimum asphalt content
10	COV of asphalt content	COV of asphalt content
11	QA_Comment_1	Standard deviation of asphalt content

12	QA_Comment_2	QA_Comment_1
13	QA_Comment_3	QA_Comment_2
14	QA_Comment_4	QA_Comment_3
15	QA_Comment_5	QA_Comment_4
16	QA_Comment_6	QA_Comment_5
17	QA_Comment_Other	QA_Comment_6
18	Record status	QA_Comment_Other
19	--	Record status

8. MOISTURE SUSCEPTIBILITY OF ASPHALT CONCRETE

Introduction

AC mixture properties can be influenced significantly by moisture. Key properties that determine the effect of moisture on mix properties are porosity and aggregate--asphalt interaction. Good adhesion between the asphalt and aggregate is particularly important for mixtures exposed to moisture for prolonged periods because the moisture may compete successfully with the asphalt binder for adsorption onto the aggregate surface, resulting in aggregate--asphalt separation or stripping.

Stripping, which causes mixture disintegration and eventual failure of the pavement, is evaluated by determining the moisture susceptibility of the mixture. For the LTPP test pavements, AC moisture susceptibility is evaluated using SHRP protocol P05 and the test standard AASHTO T283--*Resistance of Compacted Bituminous Mixture to Moisture Induced Damage* (ASTM D4867--*Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures)*.[2, 3, 4]

For this test method, moisture susceptibility is evaluated by comparing the indirect tensile strength of control and conditioned laboratory compacted AC cylinders with similar properties. The test cylinders were conditioned by subjecting them to vacuum saturation at specified temperatures. A significant difference in the mean indirect tensile strengths of the control and test specimens implies that the mixture is moisture susceptible and will be adversely affected by prolonged exposure to moisture. The difference in the conditioned and control indirect tensile strengths is characterized by computing the parameter tensile strength ratio (TSR).

The TSR is an indicator of the resistance of the asphalt mix to moisture and is the ratio of the average tensile strength of moisture-conditioned specimens to the average tensile strength of dry specimens of asphalt concrete. High TSR values (values closer to the maximum of 1.0) indicate a higher resistance of the AC mixture to moisture damage. A TSR value greater than 0.8 is generally acceptable for pavement design. TSR is defined as follows:

$$\text{TSR} = \frac{\text{Average tensile strength of moisture conditioned specimens}}{\text{Average tensile strength of dry specimens}} \tag{8}$$

The test protocols and standards provide guidance on material sampling, preparation of test specimens, testing of specimens, computation of test results, and presentation of results. The test results are stored in the table TST_AC05 in the LTPP database after undergoing several levels of quality checks. Table TST_AC05 contains the following fields:

1. SHRP identification number.
2. State code.
3. Layer number.
4. Field set.
5. Location number.
6. Construction number.
7. Sample number.
8. Lab code.
9. Sample area number.
10. Method of compaction.
11. MSG.
12. Sample no. (six fields).
13. Sample height (six fields).
14. Sample diameter (six fields).
15. BSG after molding (six fields).

16. Percent air voids (six fields).
17. BSG after vacuum saturation (three fields).
18. Maximum load (six fields).
19. Tensile strength (six fields).
20. Average tensile strength unconditioned.
21. Average tensile strength conditioned.
22. TSR.
23. Relative variation.
24. Coarse aggregate stripped.
25. Fine aggregate stripped.
26. Test date.
27. Comments (six fields).
28. Test date.
29. Other comments.
30. Record status.

Overview of Moisture Susceptibility Test Methods

There are several types of AC moisture susceptibility tests currently being used by highway agencies throughout the U.S. The most common are:[(23)]

- Tensile ratio test (ASTM D4867).
- Visual rating.
- Boiling water rating.
- Water susceptibility cycles.

Of the four methods listed, one the visual rating is not a true test method. It is part of ASTM D4867 and requires a technician to evaluate moisture damage visually following conditioning and testing. To date, a good correlation between visual rating and tensile strength has not yet been found, making visual rating as a stand-alone moisture susceptibility test suspect.[(23)]

The boiling water test rating (ASTM D3625) for AC moisture susceptibility also does not correlate well with AC tensile strength. This makes the test procedure unreliable and not applicable until a better procedure can be found for interpreting test results.[(23)]

The main limitation to the water susceptibility test method for determining AC moisture susceptibility is estimating the surface area of the aggregates in the AC mix (especially for mixtures with additives). This is because, in most situations, the actual mix gradation used to estimate surface area is significantly different from the design mix gradation. Until a more efficient methodology can be found for estimating aggregate surface area, this test method will not be reliable.[(23)]

Currently, ASTM D4867 or AASHTO T283 is the most widely used method for determining HMA moisture susceptibility. However, many state highway agencies have reported only mixed success with the method. Several research projects have dealt with its shortcomings, resulting in suggested "fixes," but the method remains empirical and liable to give either false positives or false negatives in the prediction of moisture damage. One such study was the SHRP Asphalt Research Program. It extensively investigated fundamental mechanisms of moisture damage and developed new methods for its prediction. The Environmental Conditioning System (ECS; originally AASHTO TP34, *Determining Moisture Sensitivity of Compacted Bituminous Mixtures Subjected to Hot and Cold Climate Conditions*) was designed to determine the moisture susceptibility of compacted HMA specimens under realistic conditions of temperature, moisture saturation, and dynamic loading found in actual pavements.[(23)]

The ECS test showed promise, but the visual stripping, permeability, and modulus procedures used in TP34 to evaluate moisture damage gave results that were not significantly more precise or accurate than those of AASHTO T283. For this reason, AASHTO T283 was retained in the Superpave mix design method to evaluate HMA moisture susceptibility. AASHTO T283 was also adopted by the LTPP as the test method for assessing AS moisture susceptibility and, hence, damage.

There are several ongoing or recently completed research studies investigating possible new testing methods for AC moisture susceptibility. NCHRP Project 09-19, *Superpave Support and Performance Models Management*, is one such study, and it recommended several new simple performance tests (SPT's) for asphalt mixes. Combining one or more of these tests with the conditioning procedure in the original ECS method may offer an enhanced ability to predict HMA moisture damage potential. When an improved test is developed and accepted, there may be a need to modify existing moisture susceptibility test results in the LTPP database.

Material Sampling for AC Moisture Susceptibility Testing

This test was required on asphalt concrete samples from SPS experiments only. SHRP *Interim Guide for Laboratory Material Handling and Testing* provides detailed information on material sampling.(2) Samples are collected as directed by the SHRP P05 protocol. Test specimens are retrieved from the paver during construction from the designated locations (i.e., approach, leave, and midsections of the pavement test section). The sample materials were collected during the paving operation to ensure that sampling does not adversely affect the test pavement. The materials retrieved are compacted to simulate field conditions before testing. (See reference 15 through 19.) Table 35 presents a summary of the sampling and testing requirements for moisture susceptibility testing for AC mixtures.

Table 35. Sampling and testing requirements for moisture susceptibility of bituminous mixtures.

Experiment Type	Layer Type	LTPP Designation	SHRP Protocol	Minimum Number of Tests per Layer	Sampling Location
SPS-1	Asphalt treated base	AC05	P05	3	B19, B20, B21 from paver
SPS-1	AC surface and binder	AC05	P05	3	B25, B26, B27from paver
SPS-5 (Postconstruction)	AC	AC05	P05	6	BV1, BV2, BV3, BR1, BR2, BR3
SPS-6	AC	AC05	P05	3	BV1, BV2, BV3,
SPS-8	AC	AC05	P05	3	BV-01, BV-02, BV-03,

Information in this table was used to define analysis cells for data evaluation (i.e., unique combination of State_Code, SHRP_ID, and Material_Code). Table 36 presents the fields used in defining analysis cells for the various SPS experiments.

Table 36. Data fields used for defining analysis cells for AC moisture susceptibility.

Key fields	GPS	SPS[1]
SHRP_ID	X	X
State code	X	X
Layer number	X	X
Construction number	X	X
Layer type		X
Material code		X

[1]SPS-1, -2, -5, -6, -7, -8, and -9A

Data Completeness for Moisture Susceptibility Data

Data completeness was evaluated at two levels. Level 1 data completeness consisted of determining all the test data in table TST_AC05 (levels A through E), the percentage at level E, and the number of analysis cells represented by the data at level E. Level 2 data completeness consisted of checking all the individual analysis cells to determine whether the minimum required testing has been performed and the results presented at level E. The January 2000 release of table TST_AC05 was used in the analysis.

Level 1--Data Completeness

Moisture susceptibility test data for SPS experiments in table TST_AC05 were extracted from the LTPP database. The extracted data were merged with other data tables with material and layer descrpition information, such as TST_ LO5B and EXPERIMENT_SECTION. The accuracy of the materials and layer information in table TST_AC05 was assessed by cross-referencing it with similar information in the merged table. Test data with anomalies in material and layer description were identified for further evaluation. The results of the level 1 data completeness analysis is presented in table 37.

There were a total of 133 records (at all levels) of data in table TST_AC05. Of these, approximately 55 percent (63 of 133 records) had TSR test values at level E. Also, most of the supporting data, such as asphalt content in table TST_AC05 (94 percent), were at level E. However, of the 63 records of TSR test data at level E, 33 did not have layer and material description information and were not used in further analysis. A feedback report was sent to the FHWA to determine material type. These test results will be added to the representative data table when the status of the material type information is made available.

Table 37. Level 1 completeness for table TST_AC05.

Expt. Type	Expt. Number	Total Number of Records at All Levels	Total Number of Records at Level E	Percentage of Records at Level E	Number of Analysis Cells Represented at Level E
GPS	6S	2	--	--	--
SPS-1	1	57	33	57.9	13
SPS-5	5	32	21	65.6	7
SPS-8	8	22	9	40.9	3

A total of 20 records were from SPS supplementary sections. Test data from SPS supplemental sections were removed from further analysis.

Level 2--Data Completeness

For level 2 data completeness, the analysis cells were further evaluated for completeness. Checking for completeness involved the following:

- Determine the minimum number of test results required for each analysis cell.
- Determine the actual number of test results at level E for each analysis cell.
- Compare the actual and required number of test results for each analysis cell.

Analysis cells with less than the required number of test data were classified as incomplete, whereas those with at least the minimum number of test were classified as complete. Approximately 56 percent of the analysis cells evaluated were complete. Table 38 presents a detailed summary of the results of the level 2 data completeness analysis.

Table 38. Summary of level 2 data completeness assessment for table TST_AC05.

Expt. Type	No. of Analysis Cells with Test Data and Material Information	Min. Number of Test Results Required	Analysis Cells with Minimum Number of Test Results	Percent Analysis Cells with Minimum Test Results
SPS-1	6	3	4	67
SPS-5	3	6	0	0
SPS-8	2	3	2	100

Quality Assessment of Moisture Susceptibility of Asphalt Concrete Data

Data quality was evaluated by checking for compliance with test protocols, by checking the reasonableness of each individual test result, and by checking the level of variability in each analysis cell. Descriptions of the data quality checks and results are presented in the next few sections.

Compliance with Test Protocols

The test data were evaluated for compliance with testing protocols. SHRP P05 and AASHTO T283 recommend that all test specimens should have the following properties:

- Percent air voids content--Test specimens should be compacted to an air voids content between 6 to 8 percent or the air void content expected in the field (3 to 5 percent).
- Specimen thickness--Recommended specimen thickness is 63.5 mm.
- Specimen diameter--Recommended specimen diameter is 102 mm.

The specimens used in testing were evaluated to check for compliance with the SHRP and AASHTO recommendations.

Percent Air Voids

Most of the test specimens had air void contents within either the target range of 3 to 5 percent or the range proposed by AASHTO T283 (6 to 8 percent). They were, therefore, in compliance with the testing protocol.

Specimen Thickness

The specimens used for testing generally were in agreement with the SHRP and AASHTO recommendations, with the exception of specimens from site 490800. Specimen thickness from this site ranged from 68.8 to 71.4 mm, which is much higher than the recommended 63.5 mm. The results were checked further to determine their effect on test results. The average specimen thicknesses for the remaining specimens were 65 mm, which is reasonable.

Specimen Diameter

SHRP P05 recommends a specimen diameter of 102 mm. With the exception of the specimens from site 490800 and 530800, which had diameters of 101.6 mm, all remaining specimen diameters were 102 mm. A specimen diameter of 101.6 mm was found not to significantly affect test results.

Data Reasonableness

The test data were evaluated for reasonableness. Theorectically, TSR could range from 0 to 1.0. However, most test data typically fall between 0.35 and 0.95. For the test results in table TST_AC05, TSR ranged from 0.49 to 1.05.[23]

Test results from test section 490800 (SPS-8) had a TSR of 1.05, which seems unreasonable, though statistically possible. A review of the test records for these results shows that the specimens had severe stripping and loss of fine and coarse aggregate.

The remaining test results were reasonable, showing no obvious anomaly. The distribution of TSR test values in table TST_AC05 is presented in figure 33. Approximately 70 percent of the TSR values fall within a range of 0.7 to 0.9.

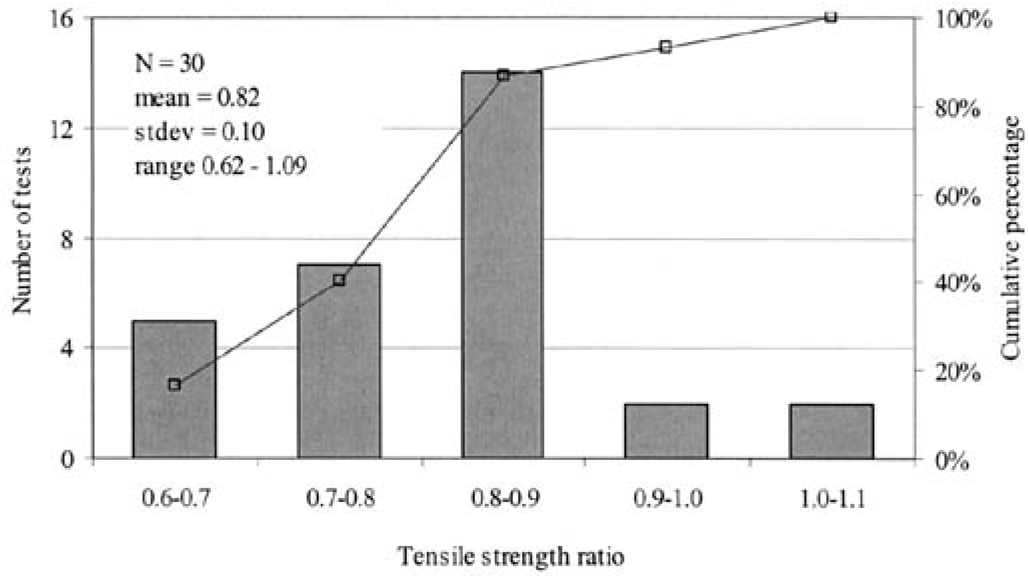

Figure 33. Distribution of the TSR in table TST_AC05.

Missing Values

Some of the test records for test section 530800 were missing. Feedback reports[3] were sent to the FHWA reporting the anomaly. The FHWA will implement the appropriate remedial actions and upgrade the relevant test tables accordingly.

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[3]Feedback reports enable users of the LTPP database to report any situations encountered during FHWA-sponsored data analysis that suggest or demonstrate the need for corrective actions or further investigation. Such situations include, but are not limited to:

- The absence of critical data for specific test sections.
- Data that appear to be incorrect, contradictory, or otherwise suspect.
- Data that are not currently collected but are needed to fill voids identified during analysis.
- Recommendations arising from the analysis of how data collection procedures might be improved.

Assessing TSR Data Quality

The first step in assessing TSR data quality was to determine typical variability expected for test results from cores belonging to the same analysis cell. This was done by reviewing typical variability measured as standard deviation or COV in published literature.(23) A summary of typical variability in measured tensile strength is as follows:(23)

- Tensile strength--350 to 1,900 kPa.
- TSR--0.35 to 0.85.
- Standard deviation--15 to 80 kPa.

- COV--1.9 to 11.2 percent.

A COV of 10 percent was, therefore, adopted and used in data evaluation. The TSR data in table TST_AC05 had only one analysis cell with COV greater than 10 percent. The distribution of COV for analysis cells with TSR test results is presented in figure 34.

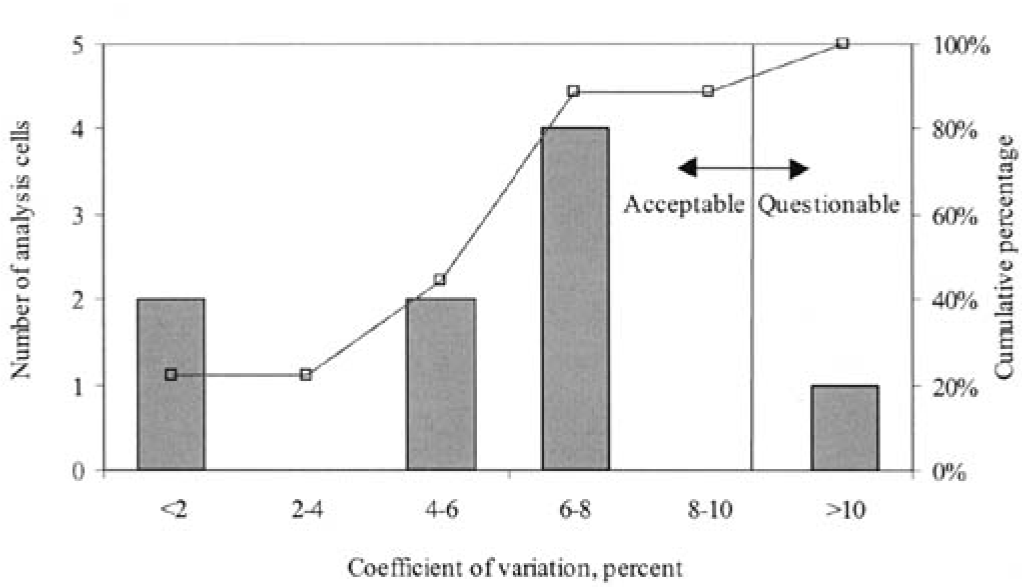

Figure 34. Distribution of COV for TSR.

Identification of Anomalous Data

The anomalies found in the data during the various analyses performed are described below. Where possible, corrective or remedial measures were implemented to address the identified anomalies.

Anomaly 1: Noncompliance with Test Protocols

Some of the test results were obtained using testing practices (e.g., specimen preparation and dimension) that did not comply with the test protocol. Test results obtained using non-compliant procedures were not used in the development of the representative data tables.

Anomaly 2: Excessive Variability

A single analysis cell (1 of 10) had excessive variability (COV > 10 percent) and was classified as questionable. Test data that fall outside the 4 standard deviation of the mean were classified as erroneous and not used in developing the representative data table and summary statistics. This was duly noted with an appropriate comment code in the representative test table.

Schema of the Representative Moisture Susceptibility Data Table TST_AC05_REP

The representative moisture susceptibility data table TST_AC05_REP was developed and recommended for inclusion into the LTPP database. The schema for the representative data table is as follows:

1. State code.
2. SHRP identification number.
3. SPS cell identification number.
4. Layer description.
5. Material code.
6. Construction number.
7. Number of TSR tests.
8. Mean TSR.
9. Maximum TSR.
10. Minimum TSR.
11. COV of TSR.
12. Standard deviation of TSR.
13. QA_Comment_1.
14. QA_Comment_2.
15. QA_Comment_3.
16. QA_Comment_4.
17. QA_Comment_5.
18. QA_Comment_6.
19. QA_ Comment_Other.
20. Record status.

Moisture susceptibility testing is conducted only for SPS experiments . The first six fields in the schema define the analysis cell used in computing summary statistics of the measured TSR values. The representative test results and basic statistics are presented in fields 7 to 12, followed by comment fields that describe the quality status of the data (e.g., excessive variability or incomplete sampling) and the record status of the data.

Recommendations

It is recommended that additional information be added to the data in table TST_AC05 to describe the condition (e.g., stripping and raveling) of AC cores from both GPS and SPS experiments. This will provide additional information as to whether the AC mixture survived under prevailing pavement conditions. The age of the specimen at the time of inspection is also very relevant to place the data on the state of the AC core in its proper context. Finally, information on the type and amount of antistripping agents applied should be provided, where relevant.

9. VISUAL EXAMINATION AND LENGTH MEASUREMENT OF PCC CORES

Introduction

Visual examination and length measurement are performed on PCC core specimens as part of the material characterization program for the LTPP study. These basic tests are conducted on all PCC cores before they are subjected to other tests (e.g., compressive strength, split tensile strength, and static modulus of elasticity testing).

Cores are usually taken at specified periods (e.g., 14, 28, and 365 days) after construction for newly constructed pavements and several years after construction for in-service pavements adopted into the LTPP program. The number of cores taken from a given location depends on both the pavement test section properties and LTPP experiment type.

Procedures used for measuring core length (layer thickness) and examining the cores are presented in the following SHRP test protocol and AASHTO/ASTM test procedures:

- SHRP P66--Visual examination and length measurement of PCC cores.(2)
- AASHTO T148--Measuring length of drilled concrete cores.(4)
- ASTM C856--Petrographic examination of hardened concrete.(3)

The relevant GPS and SPS materials test and data collection guides provide guidance on all aspects of material sampling and testing (See references 7, 17 through 20, and 23.) These guidelines include:

- Core specimen sampling.
- Sample preparation.
- Laboratory testing.
- Computation of test results.
- Presentation of test results.

The PCC core specimens are examined visually to determine their general condition, presence of distresses, presence of defects such as cracks, voids, D-cracking, alkali-silica reactivity, and problems with layer separation (for overlaid pavements).(2,3,4) The general type and shape of aggregates (e.g., rounded gravel or angular crushed stone) were also documented. The cores were also examined to determine their suitability for length measurements and other testing. Cores with serious defects, such as uneven surfaces and segregated aggregates, were noted and not used for further testing.(2, 3, 4)

Visual examination does not include detailed core examination, such as petrographic and stereo microscopic examinations. Results of visual examination are reported using standard SHRP codes as described in SHRP protocol P66 attachment A.(2)

The length measurement and visual examination test results are stored in the LTPP database after undergoing QC checks that ensure anomalies (e.g., negative PCC core thickness values) are identified and corrected. Data that are of acceptable quality after the QC checks are classified as level E and are stored in table TST_PC06. The following information is maintained in table TST_PC06:

1. SHRP identification number.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.

8. Laboratory code.
9. Sample area number.
10. Core average thickness.
11. Visual examination 1.
12. Visual examination 2.
13. Visual examination 3.
14. Visual examination 4.
15. Visual examination 5.
16. Visual examination 6.
17. Visual examination other.
18. Comments (six fields).
19. Comments other.
20. Test date.
21. Sample number.
22. Record status.

Material Sampling

Core specimens are collected as directed by the SHRP P66 protocol from designated locations within the GPS and SPS experiments (GPS experiments are cored by SHRP contractors; SPS experiments are cored by SHA's or contractors). Cores are then prepared according to procedures outlined in SHRP P66, AASHTO T148, and ASTM C856 before being shipped to certified laboratories for testing.

For GPS pavements, cores are taken from both the approach and leave ends of the pavement test section. Both core locations are sited some distance from the monitored test section to avoid damaging the test section. For SPS experiments, cores are taken at designated locations from various test sections within a given site. Full details of the sampling plans, material preparation, and testing are presented in the relevant SHRP protocols, AASHTO test procedures, and the Data Collection Guidelines for SPS Experiments. (See references 17 through 23.)

For SPS experiments, sampling can be complicated because these experiments consist of a diverse matrix of test sections, some of which are newly constructed with different PCC target strengths (e.g., SPS-2), and the others are in-service pavements that have been overlaid and, therefore, consist of both in-service and newly constructed (e.g., SPS-7). For SPS-2 experiments, cores are taken from the different test sections to obtain samples representing the different target strength levels. SPS-7 pavements are cored pre- and postoverlay to obtain cores for both layers. Sampling was, therefore, experiment-specific, and the minimum number of core specimens required for testing differed for the GPS and SPS experiments.

PCC Core Thickness Data Completeness

The first step in assessing data completeness was the extraction and assembly of the data available in table TST_PC06 in the LTPP database (January 2000 release); this process was described in detail in the introductory chapters of this report.

Level 1--Visual Examination and Thickness Data Completeness

A summary of the visual examination and thickness data collected for all GPS and SPS experiments at all record status levels (A to E) is presented in table 39. SPS experiments 2, 6, 7, and 9 have sublevel E data, which are outside the scope of this study and will not be considered in the analysis. Further, not all the records available at level E were usable because the data either pertained to supplemental SPS experiments, did not contain material type information from the corresponding TST_L05B database table, had missing core thickness values, or had been wrongly included in the database (ascertained based on the material code from TST_L05B table). The extent of data in each of these categories is also noted in table 39. Recall that supplemental sections are also outside the scope of this study. TST_L05B material type information is important to identify analysis cells, as well as to verify whether the data belong in the table. Without this information, data analysis cannot be carried out with confidence.

Figures 35 and 36 present total data availability for GPS and SPS pavement test sections, along with the amount of usable data at level E. In all, 657 of 4,897 records were excluded from further analysis for reasons such as missing thickness information or belonging to SPS supplemental sections (that fall out of the scope of this study).

Table 39. Summary of average core thickness data available in table TST_PC06.

Expt. Type	Expt. No.	No. of Records at Levels A to E	No. of Records at Level E	No. of Usable Records at Level E	Percent Usable Records at Level E	Total Number of Analysis Cells Represented
GPS	3	824	818	818[1]	99	123
GPS	4	440	436	436[2]	99	61
GPS	5	545	540	540[3]	99	81
GPS	7A	330	330	324[4]	98	35
GPS	7B	67	67	60[5]	90	7
GPS	9	331	331	324[6]	98	48
SPS	1	26	0	0	0	--
SPS	2	1354	1121	990[7]	73	116--PCC 36--LCB
SPS	6	231	168	168	73	51
SPS	7	552	536	502[8]	91	25--Original 28--Overlay
SPS	8	16	16	16	100	2
SPS	9	170	82	30[9]	18	2

[1]Six records do not have corresponding L05B information.
[2]Four records are missing thickness information.
[3]Five records are missing thickness information.
[4]Six records are missing thickness information.
[5]Two records are missing thickness information; five records have discrepancies in material type descriptions.
[6]One record is missing thickness information; six records do not have corresponding L05B information.
[7]Eighty-eight records do not have corresponding L05B information; 41 records are missing thickness information; 2 records have discrepancies in material type descriptions.
[8]Eleven records do not have corresponding L05B information; 23 records are missing thickness information.
[9]Fifty-two records pertaining to supplemental sections are present at level E.

Definition of Analysis Cells

Table 39 presents a summary of the analysis cells represented by the level E data. For the thickness test data, an analysis cell was defined as a layer of a given material and construction type within a test section for which data were available. Analysis cells are extremely useful in the level 2 data completeness analysis, as well as in data quality evaluation.

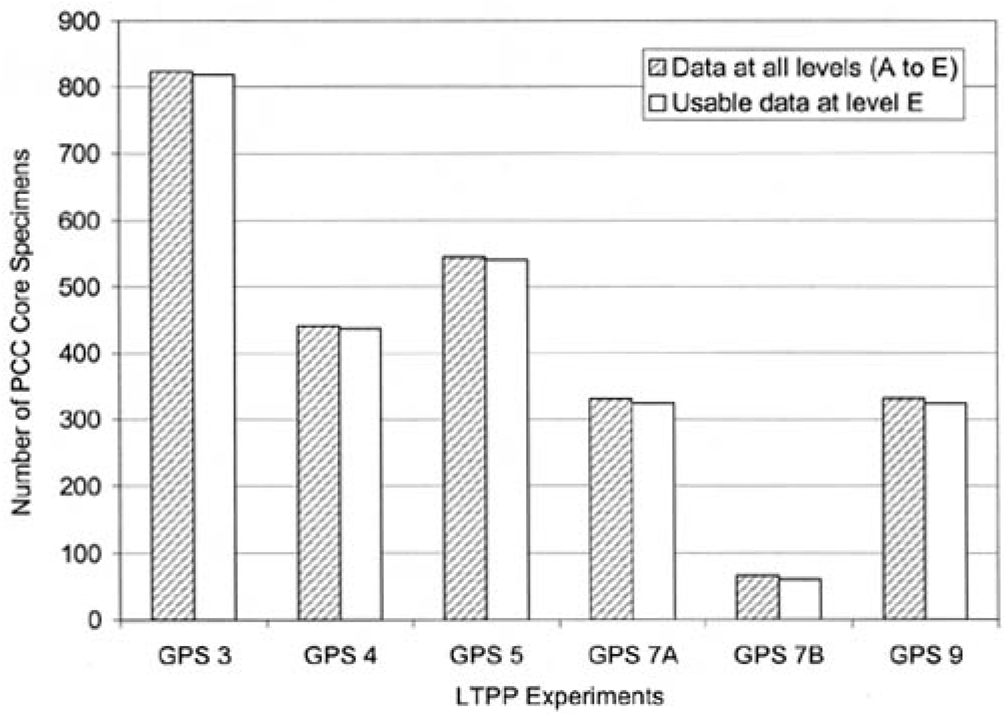

Figure 35. Histogram of PCC core specimen data availability for GPS pavement sections.

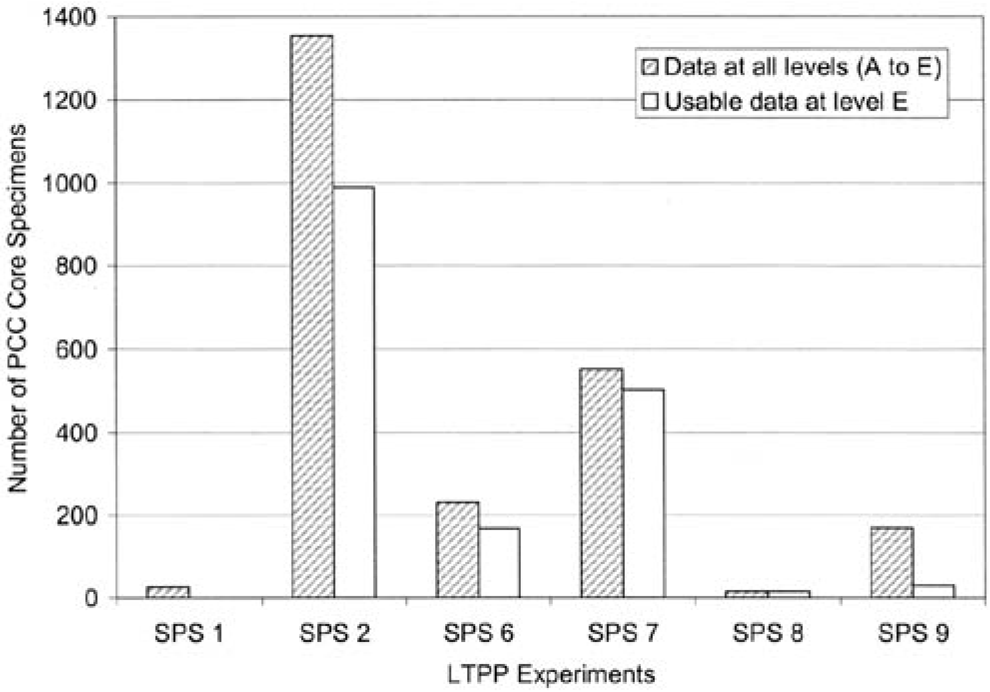

Figure 36. Histogram of PCC core specimen data availability for SPS pavement sections.

Table 40. Analysis cell definitions for test table TST_PC06.

Key Fields	GPS Experiments (All)	SPS Experiments (All)
Experiment type	X	X
Experiment number	X	X
SHRP_ID	X	X
State code	X	X
Construction number	X	X
Layer number	X	X
Material code	X	X

Table 40 presents a list of fields that make up analysis cells for both GPS and SPS experiments for test table TST_PC06. Note that the SHRP_ID field was part of the analysis cell definition for SPS experiments. This was because LTPP sampling for PCC thickness measured ensured that adequate amounts of specimens were obtained from individual test sections (within the SPS experiments) for testing (see table 41). This was unlike testing for other data elements, where sampling was done from selected test sections and averaged to represent the whole experiment.

Level 2--Thickness and Visual Examination Data Completeness

Level 2 data completeness consisted of checking each analysis cell to determine whether the required minimum number of samples were collected and tested, as per the material sampling and testing requirements.

As a first step in checking level 2 data completeness, the number of specimens tested and reported in table TST_PC06 for each analysis cell was computed. The computed number of tests per cell was then compared with the minimum number of tests required by LTPP.

Table 41 presents a summary of the minimum core specimens required by the LTPP materials testing and sampling program for core length measurements and visual examination for each LTPP experiment. Although the minimum number of tests per layer indicated in the table directly translates to the required minimum tests per analysis cell for GPS projects, the same is not true for SPS projects. Therefore, a more detailed description of the testing requirements for the various SPS experiments is presented in table 42.

Analysis cells with the minimum number of test results were categorized as complete, whereas those with less than the minimum were classified as incomplete. Table 43 presents a summary of level 2 data completeness for all the analysis cells in table TST_PC06. Table 43 also indicates the number of analysis cells with single test values. Procedures employed to analyze the reasonableness and validity of the data contained in cells with single test values differ from those with information from multiple tests because characterizing variability is not possible for these cells.

Table 41. Summary of the sampling and testing plan for thickness measurement and visual examination of PCC cores.

Experiment Type	Layer Type	Test Type	LTPP Designation	LTPP Protocol	Minimum Number of Tests per Layer	Sampling Location[1]
GPS-3, 4, 5, & 9	PCC	Core examination and thickness	PC06	P66-61	2	C2, C8
GPS-7	PCC	Core examination and thickness	PC06	P66-61	2	C8, C20
GPS-3, 4, 5 & 9	PCC	Core examination and thickness	PC06	P66-62	2	C5, C11
GPS-7	PCC	Core examination and thickness	PC06	P66-62	2	C11, C23
GPS-3, 4, 5 & 9	PCC	Core examination and thickness	PC06	P66-64	2	C1, C7
GPS-7	PCC	Core examination and thickness	PC06	P66-64	2	C7, C19

SPS-2	PCC	Core examination and thickness	PC06	P66	99 per site/project	All cores
SPS-2	LCB	Core examination and thickness	PC06	P66	24 per site/project	--
SPS-6	PCC	Core examination and thickness	PC06	P66	23 per site/project	C1-C20 A1 A2 A3
SPS-7	PCC--overlay (postconstruction)	Core examination and thickness	PC06	P66	99 per site/project	C10-20 C21-64 C65-108
SPS-7	PCC--overlay (preconstruction)	Core examination and thickness	PC06	P66	47 per site/porject	C10-20 C21-64 C65-108
SPS-8	PCC	Core examination and thickness	PC06	P66	26 per site/project	C1-C26
SPS-9A	PCC	Core examination and thickness	PC06	P66	6 per site/project	--

[1]Details of the core locations are presented in the respective LTPP materials sampling guides.

Table 42. Details of sampling for core visual examination and length measurement for SPS experiments.

Experiment Type	Test Section	Layer Type	Min. No. of Specimens Required per Layer	Sampling Location[1]
SPS-2	201 (215)	PCC	8	C10-C17
SPS-2	202 (216)	PCC	8	C59-C66
SPS-2	203 (213)	PCC	9	C34-C42
SPS-2	204 (214)	PCC	8	C83-C90
SPS-2	205 (219)	PCC	8	C21-C25C18-C20, C22-C24
SPS-2	206 (220)	PCC	8	C73-C74C67-C72
SPS-2	207 (217)	PCC	8	C29-C33C26-C28, C30-C32
SPS-2	208 (218)	PCC	8	C78, C82C75-C77, C79-C81
SPS-2	209 (223)	PCC	9	C1-C9
SPS-2	210 (224)	PCC	8	C51-C58
SPS-2	211 (221)	PCC	8	C43-C50
SPS-2	212 (222)	PCC	9	C91-C99
SPS-2	205 (219)	LCB	6	C18-C20, C22-C24
SPS-2	206 (220)	LCB	6	C67-C72

SPS-2	207 (217)	LCB	6	C26-C28, C30-C32
SPS-2	208 (218)	LCB	6	C75-C77, C79-C81
SPS-6	601	Original PCC	3	C1-C3
SPS-6	602	Original PCC	4	C4-C6, A1
SPS-6	603	Original PCC	3	C11-C12
SPS-6	604	Original PCC	2	C13-C14
SPS-6	605	Original PCC	4	C7-C10
SPS-6	606	Original PCC	2	C15-C16
SPS-6	607	Original PCC	3	C17-C18, A3
SPS-6	608	Original PCC	2	C19-C20
SPS-7	701	Original (Overlay)	1 (0)	A1
SPS-7	702	Original (Overlay)	1 (8)	A2 (C21-C24, C65-C68)
SPS-7	703	Original (Overlay)	3 (9)	C1-C3 (C10, C25-C28, C69-C72)
SPS-7	704	Original (Overlay)	1 (8)	A3 (C29-C32, C73-C76)
SPS-7	705	Original (Overlay)	4 (8)	A4, BA1-BA3 (C33-C36, C77-C80)
SPS-7	706	Original (Overlay)	3 (11)	C4-C6 (C11-C13, C37-C40, C81-C84)
SPS-7	707	Original (Overlay)	1 (17)	A5 (C14-C16, C44-C50, C88-C94)
SPS-7	708	Original (Overlay)	1 (16)	A6 (C17-C18, C51-C57, C95-C101)
SPS-7	709	Original (Overlay)	3 (16)	C7-C9 (C19-C20, C58-C64, C102-C108)
SPS-8	807, 809, 811	Overlay	13	C1-C13
SPS-8	808, 810, 812	Overlay	13	C14-C26
SPS-9A	901, 902, 903	Original	2	--

[1]Details of the core locations are presented in the respective LTPP materials sampling guide.

Table 43. Summary of core thickness data available for GPS and SPS experiments.

Experiment Type	Layer Type	Total Number of Cells	Number of Cells with Less Than Minimum Number of Tests	Percent Cells with Incomplete Data
GPS-3	PCC original	123	0	0
GPS-4	PCC original	61	0	0
GPS-5	PCC original	81	0	0
GPS-7A	PCC original	35	0	0
GPS-7B	PCC original	7	1 (1 single test value)	14
GPS-9	PCC original	48	0	0
SPS-2	PCC	116	60 (1 single test value)	52
SPS-2	LCB	36	12 (1 single test value)	33
SPS-6	PCC	51	12 (5 single test values)	24
SPS-7	PCC original	25	5 (2 single test values)	20
SPS-7	PCC overlay	28	28 (1 single test value)	100
SPS-8	PCC	2	2	100
SPS-9A	PCC	6	0	0

Thickness and Visual Examination Data Quality

The quality of the thickness data was determined by evaluating the data for reasonableness of test values, compliance with test protocols, and variability in test values (for analysis cells with multiple specimens).

For quality evaluation of visual examination data, results from each core specimen were reviewed to determine the condition of the specimen and possible conflicts in visual examination results. Specimens with discrepancies were identified. This evaluation is important in identifying the source of anomalies, not only for the thickness data under investigation in this chapter, but for all other data elements obtained through testing the PCC cores after visual examination and thickness measurement testing. A summary of results from the data quality evaluation is presented in the following sections.

Reasonableness of Core Thickness Values

Evaluating whether PCC core thickness measurements are reasonable involved examining the core thickness values for each layer to detect obvious errors and anomalies, such as negative values and values close to zero. Analysis cells that were termed incomplete due to inadequate testing were also evaluated for bias in the core thickness values. The thickness data from all 4,208 core specimens evaluated did not contain any obvious anomalies. Table 44 presents basic statistics of the core thickness data available in table TST_PC06.

Table 44. Summaries of descriptive statistic for core thickness data in table TST_PC06.

Experiment Type	Target Thickness, mm	Number of Specimens	Mean Thickness, mm	Standard Deviation, mm[1]	COV, percent[1]	Min Thickness Range, mm	Max Thickness Range, mm
GPS-3	--	818	240.9	31.6	13.1	152.4	370.8
GPS-4	--	436	240.2	20.9	8.7	190.5	302.3
GPS-5	--	540	221.8	27.5	12.4	154.9	335.3
GPS-7A	--	324	215.6	22.4	10.4	165.1	261.6
GPS-7B	--	60	225.1	23.7	10.5	190.5	271.8
GPS-9	--	324	218.6	25.2	11.5	165.1	335.3
SPS-2 (203-mm sections)	203.2	414	211.5	17.3	8.2	127.0	287.0
SPS-2 (279-mm sections)	279.4	390	277.8	28.5	10.3	129.0	325.1
SPS-2 (sections with LCB)	152.4	186	162.4	14.8	9.1	120.9	213.4
SPS-6	--	168	232.4	17.1	7.4	198.1	266.7
SPS-7 (original PCC layer)	--	203	192.5	29.9	15.6	53.3	218.4
SPS-7 (75-mm overlay sections)	76.2	114	164.4	91.3	55.5	74.7	307.3
SPS-7 (125-mm overlay sections)	127.0	185	166.8	64.8	38.8	101.6	353.1
SPS-8 (200-mm sections)	203.2	9	193.0	6.7	3.5	183.4	200.7
SPS-8 (275-mm sections)	279.4	7	283.1	5.8	2.1	278.4	294.1
SPS-9	--	30	227.4	13.6	6.0	203.2	246.4

[1]Standard deviation and COV values reported are for all samples within a given experiment.

The data were broadly classified by experiment type, but further subdivisions based on layer type and target strength were made, where applicable, for clarity and for assessing whether the data were reasonable.

For data from GPS experiments, conclusions regarding the reasonableness of data can be drawn by considering the range of core thicknesses within each experiment. The PCC core thicknesses for the GPS, SPS-6, and SPS-9 projects (all original pavements) ranged from 152 mm to 371 mm. The range of values observed seem to be in line with normal range of PCC thicknesses commonly encountered in practice. The standard deviations and COV's noted in the table for GPS 1 through 9, SPS-6, and SPS-9 experiments are just an indication of the spread of PCC layer thicknesses across all projects within each experiment. These values should not be confused with the variability in thickness data associated with multiple specimens from a given analysis cell, which is discussed later in this chapter.

The range of core thicknesses of the SPS-7 original pavement sections was between 53 mm and 218 mm. Closer examination of the data revealed that there were 19 records with thicknesses less than 125 mm. All these cores have been commented as "broken short cores," which explains the unusually low PCC layer thicknesses noted in the range. The rest of the cores range in thickness from 125 mm to 218 mm, which is well within the normal range of concrete slab thicknesses encountered in practice.

A more detailed evaluation of SPS-2 and SPS-8 thickness data was possible because these experiments identify each section with a specific target thickness. Although the focus of this study was not to identify pavement test sections that do not achieve target thickness, excessive variation from set targets is an indication of poor quality control and the potential for excessive variability in test results from PCC layers within those pavement sections.

Based on the information presented in table 44, the SPS-2 and SPS-8 experiments, in general, had thicknesses close to the target layer thickness. The difference between measured mean core thickness and target thickness for these experiments ranged from 2 to 10 mm. However, for the SPS-7 experiment overlay sections, there was a vast difference in target and measured thickness for PCC overlays. The difference was over 100 percent for the 75-mm overlay sections and approximately 31 percent for the 125-mm overlay sections. This level of variability is excessive and needs further investigation.

Figures 37 and 38 show plots of the distribution of core thicknesses for 75-mm overlay and 125-mm overlay sections, respectively. For the overlay sections with a target thickness of 75 mm, all but one of the cores had a thickness greater than the target value. More importantly, approximately 64 percent of the core specimens were between 100 and 150 mm thick. Most of the remaining specimens have thicknesses way beyond the target value and are concentrated between 275 and 325 mm. For the 125-mm overlay sections, 87 percent of the cores have core thicknesses ranging from 100 to 175 mm. This shows that a majority of the data is within reasonable proximity of the target value. However, as with the 75-mm thick overlay sections, a majority of the remaining cores have thicknesses far in excess of the target value and are concentrated in the range of 300 to 375 mm. Further analysis revealed that all the sections showing large deviations between the specified and as-constructed values were concentrated in one particular State. It must be noted here that some State highway agencies, in pursuance of their local policies, may have adopted overlay thicknesses that were different from specified values.

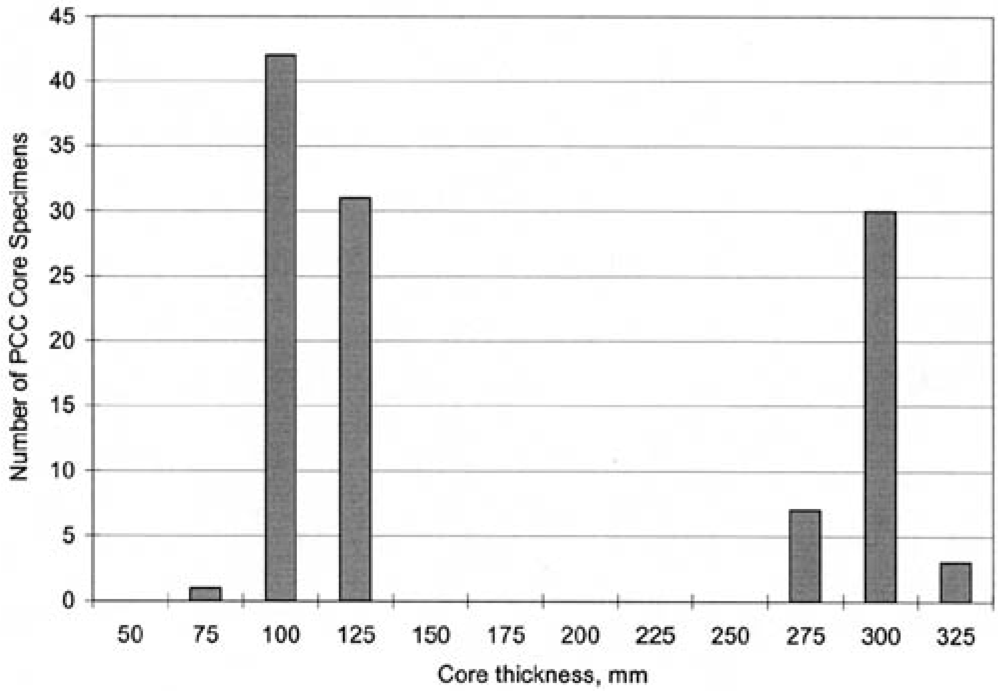

Figure 37. Plots of distribution of core thickness for SPS-7 75-mm overlay sections.

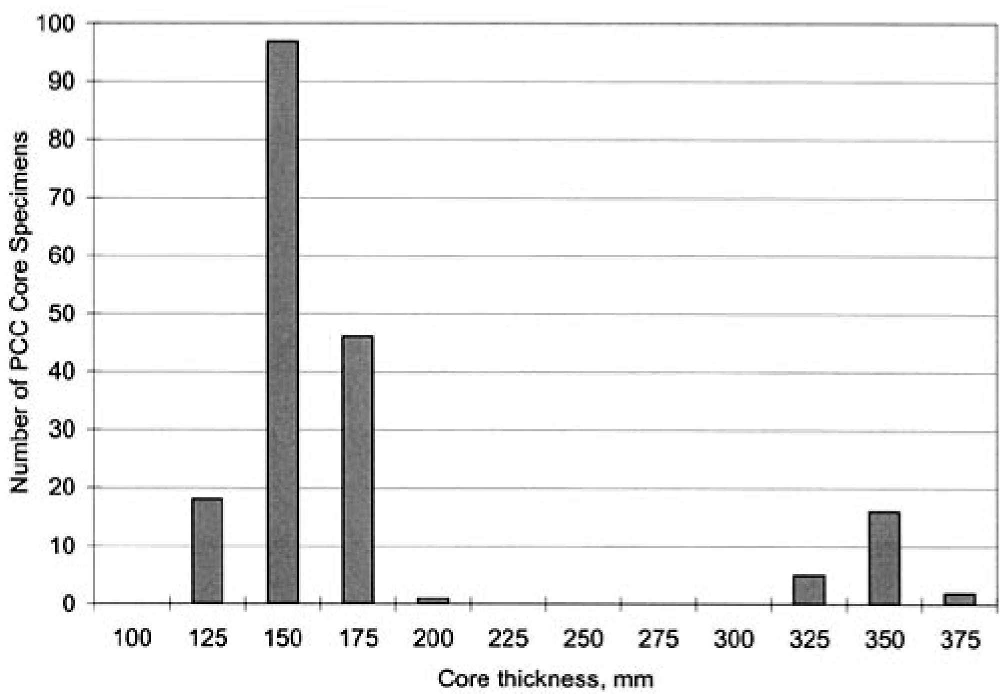

Figure 38. Plots of distribution of core thickness for SPS-7 125-mm overlay sections.

In summary, all the thickness values presented in table 44 appear to be reasonable. Even the core thicknesses from the SPS-7 sections are within reasonable ranges (when the thickness data from test sections with thicknesses greater than the target values are factored out). Further, even the data from the test sections with PCC thickness greater than the target thickness values were consistent with each other.

Evaluation for Noncompliance with Testing and Sampling Procedures

The next stage in assessing data quality was to identify pavement test sections with possible bias in results due to inadequate sampling or deviations from test procedures. The SHRP P66 test protocol and AASHTO T148 had no recommendation for assessing bias due to testing, and there were no obvious deviations from recommended testing procedure. Bias assessment was, therefore, limited to the component contributed by incomplete sampling and testing. Pavement test sections sampled according to the relevant portions of SHRP P66 and AASHTO T148 should experience no sampling bias; however, for pavements with less than the required number of tests performed, the test results may not be representative of the whole pavement test section.

Test pavements with less than the minimum number of core specimens tested were classified as incomplete (has a high potential for bias), whereas those with the minimum cores tested were classified as complete (no sampling bias). Test completeness for all the PCC and SPS-2 LCB analysis cells was previously summarized in table 43.

It can be inferred from the table that the GPS cells, with the exception of one cell in the GPS-7B experiment, had more than the required number of core specimens tested and, therefore, had no sampling bias. The GPS-7B cell has a single test value. This was treated as an anomaly, and appropriate remedial actions were adopted to rectify this anomaly, where possible.

In contrast, most of the SPS experiments had a significant amount of incomplete cells. The most affected was the SPS-7 experiment, which, incidentally, has a very high number of tests required per test section (see table 42). An examination of these analysis cells showed that most contained more than four test results from cores drawn from various locations within the test section. A high number of test results (though less than the required number of test results) reduces the likelihood of bias in representative test values. Further, it was discovered that a substantial amount of SPS-2 and SPS-6 data are still undergoing QA/QC checks. It is, therefore, likely that any apparent bias in representative test values due to incomplete testing is transitory and that more material testing data will available at level E in the near future.

Thickness Data Variability

Pavement test sections with multiple thickness data for PCC and LCB layers were evaluated to determine the level of variability in test results within the test sections. Analysis cells with single test values (see table 43) could not be considered in the analysis, for obvious reasons. Test data for the sections with multiple specimen thickness measurements were classified as acceptable or questionable, based on the level of variability estimated. The analysis was performed separately for layers with complete and incomplete testing to investigate whether the core thickness variability in these two categories differed. Any differences can be attributed to bias introduced by inadequate testing. The AASHTO T148 (ASTM C174) standard for measuring length of drilled concrete cores has no statement on the precision. However, several pavement construction and reliability studies have published typical variability expected for PCC layer thickness along a highway. Table 45 presents a summary of the range of typical COV's and standard deviations for thickness of PCC layers published in various literature.

Based on the data presented in table 45, a standard deviation of 8 mm was adopted and used for categorizing acceptable and questionable PCC layer thickness data. The same cutoff value (8 mm) was adopted for evaluating LCB layer thickness data (from SPS-2 experiments) included in table TST_PC06.

This assumption was reasonable because the same procedures and protocols used in placing, testing, and evaluating PCC layers were used for LCB layers.

Thickness Data Quality Classification

Mean, standard deviation, and COV of the PCC and LCB thickness were computed for analysis cells with multiple test data. For GPS experiments, all specimens cored for a given pavement section were used in determining the statistics. For SPS experiments, the statistics were calculated from cores taken from each individual test section (e.g., 201, 202, 205, 206, 209, and 210 for SPS-2 experiments) within a given SPS experiment, as indicated in table 42. Figures 39 and 40 show the distribution of COV for all PCC and LCB analysis cells with complete and incomplete testing, respectively.

Table 45. Typical allowable variability for thickness data.

Data Item	Reference	Specimen Type	COV, percent	Standard Deviation
PCC Thickness	Terzaghi et al.(24)			
PCC Thickness	SHRP SPS-2(25)	Cores	2 to 3[1]	
PCC Thickness	Yoder and Witzak(26)	Cores		2.5 to 12.5 mm
PCC Thickness	Darter(27)	Cores	3.1 to 3.2	8 mm
PCC Thickness	Hoerner et al.(28)	Cores	3.3	8 mm
PCC Thickness	Neaman et al.(29)	Cores	1.1	--
PCC Thickness	McMahonet al.(30)	Cores	--	7 mm
PCC Thickness	Hughes et al.(31)	Cores	1.9 to 5.1	5 to 13 mm
PCC Thickness	Lytton et al.(32)	Cores	5 to 12	--

[1]Thicknesses must be within 6 mm of target values.

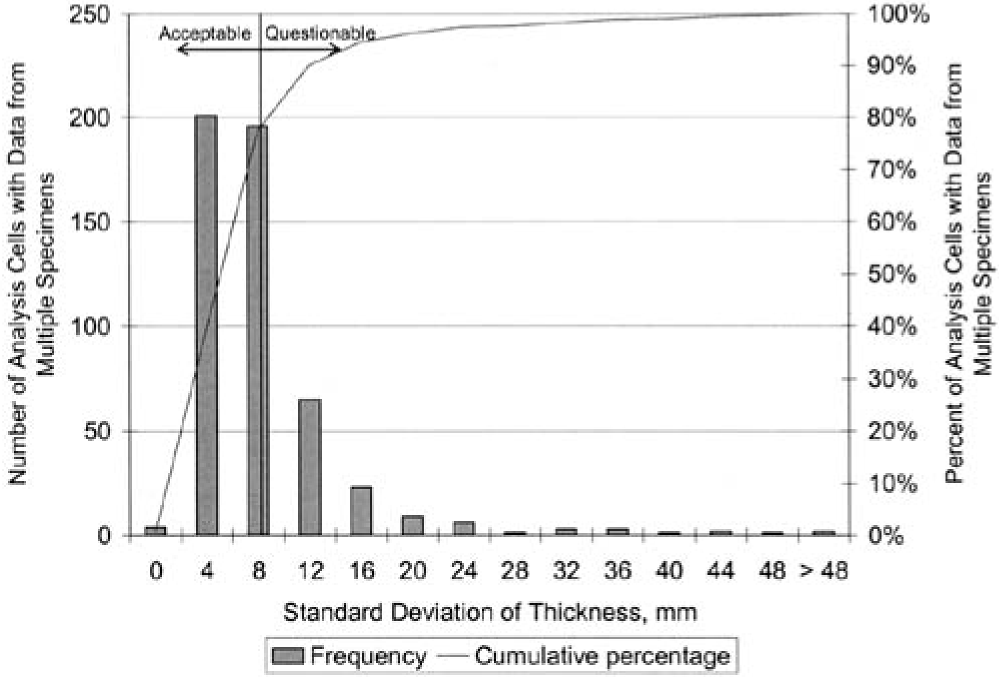

Figure 39. Distribution of standard deviation for pavement test sections thickness with complete testing.

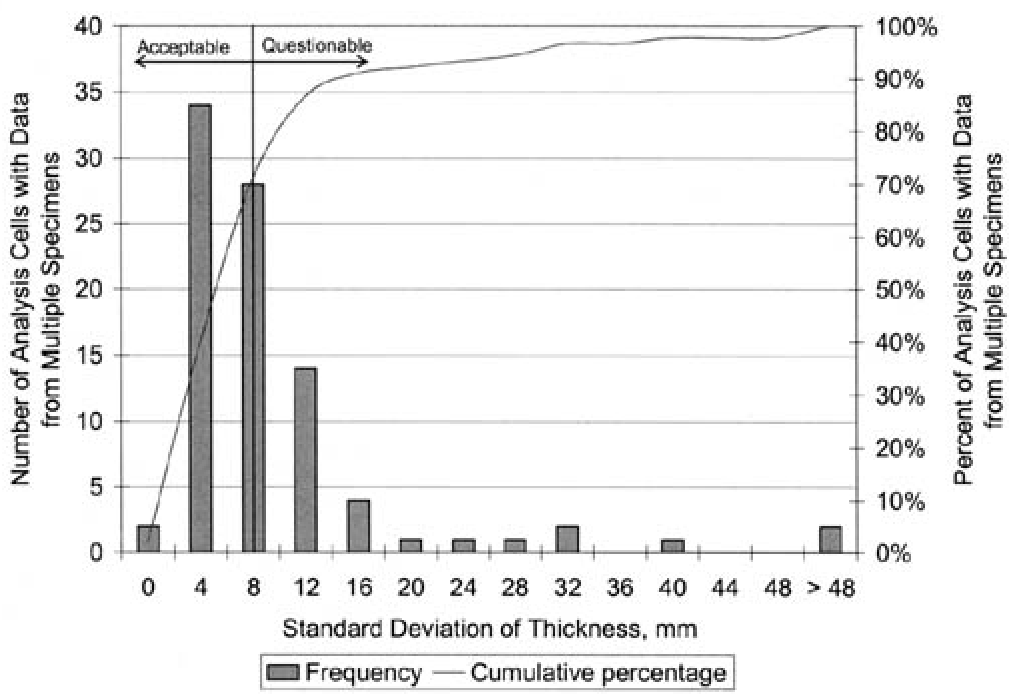

Figure 40. Distribution of standard deviation for pavement section thickness with incomplete testing.

These figures show that 78 percent of the test data from cells with complete testing and 71 percent of the test data from cells with incomplete testing had standard deviations less than the typical value of 8 mm. Thus, inadequate testing did not seem to affect the variability of thickness data from multiple specimens within an analysis cell. The data from the analysis cells that showed more than typical variability were considered anomalous, and a more detailed examination of these data was performed to determine the reasons for the high variability.

Visual Examination Data Quality Evaluation

Visual examination was performed to determine the condition of the cores retrieved from the GPS and SPS experiments. Of the 4,209 core specimens at level E, 604 had no visual examination results and, hence, could not be evaluated. The remainder of the data was split into various categories and summarized based on the comment codes noted in each of the visual examination fields in the test table. A description of the comment codes entered in the TST_PC06 table is presented in table 46. The following categories were used in summarizing the information:

- Category 1: No visual examination data available.
- Category 2: Intact cores denoted by comment code 51. This code represents that the cores are in excellent condition and are suitable for testing.
- Category 3: Intact cores denoted by comment codes 52, 53, 55, 56, and 65 through 76, in addition to comment code 51. These cores are also in excellent condition and suitable for testing but may contain some surface defects, such as voids in the matrix, uneven bottom, or segregation. Although these defects do not affect thickness measurement, they will need to be considered carefully if further testing is performed on these cores.
- Category 4: These cores have hairline cracks, either on the surface or on the sides. These cores are in good condition otherwise and are suitable for testing. These cores have a comment code 52, in addition to other visual examination codes.
- Category 5: Cores with comment codes 54, 57, or 64, which indicate badly damaged cores unsuitable for testing.
- Category 6: Skewed cores indicated by comment code 82.
- Category 7: All cores that do not fall in any of the six categories.

Figure 41 presents a piechart with the total number of records in each category expressed as a percentage of the total number of records considered in the analysis.

Approximately 78 percent of the cores are in categories 2, 3, and 4, indicating that they are suitable for testing. Note that "suitable for testing" does not necessarily mean that the core will provide consistent results when used in material characterization tests. The presence of hairline cracks, voids in the matrix, uneven core bottom, and material segregation each have an effect on material characterization. The degree to which these irregularities affect material characterization results varies, based on the sensitivity of the testing to these parameters. Therefore, it is important to consider the visual examination results appropriately when analyzing data from individual material characterization tests.

Fourteen percent of the records in the database were missing visual examination results, and 6 percent had comment code entries that were in the "miscellaneous" category. All the cores in the miscellaneous category were also suitable for testing based on the comment code entries, with the exception of four cores that showed signs of durability problems. Only 1 percent of the cores are unsuitable for testing due to damaged specimens, and an additional 1 percent are skewed cores.

Any data anomalies in the form of conflicting observations, such as describing cores as intact and in excellent condition, yet at the same time describing them as somehow cracked or damaged, were also checked. Only three core specimens from two different GPS sections had such conflicting visual examination results.

These specimens belong to a companion set of six specimens cored from each of these locations, and their thickness measurements were consistent with the other specimens. Hence, no remedial action was pursued. Further, considering that the numbers of specimens with such anomalies are in a minority, they are not expected to affect other material characterization results significantly.

Table 46. Description of visual survey codes.

Code	Description
51	Intact core; excellent condition; suitable for testing
52	Hairline cracks on the surface of the core; suitable for testing
53	Cracks or voids visible along the side of the core; suitable for testing
54	Badly cracked or damaged core; unsuitable for testing
55	Ridges on the sides of the cores (identified by placing a straight edge along the side of the core when the distance between the straight edge and core face is 1.6 mm or greater); such a condition should be recorded if the core is used for any other test
56	Very rough and uneven bottom surface of the core (identified with this code when less than75 percent of the surface area is in contact with a level surface when the core is perpendicular to the surface)
57	Core extremely damaged from sampling, shipping, or laboratory handling; unsuitable for testing
58	Core was sawed in the laboratory to remove the core from the underlying bonded layer ofbase, subbase, or AC
59	Core consisted of two or more PCC layers; core was sawed in the laboratory and appropriate layer numbers were assigned to each PCC layer
60	One or more PCC layers have become separated; appropriate layer numbers were assigned toeach PCC layer
61	Segregation of coarse and fine aggregate is observed over 25 percent or more of the surface area of the core
62	Voids in the matrix of the PCC mixture are observed along the sides of the core
63	Voids due to loss of coarse and fine aggregate are observed along the sides of the core
64	Core is missing significant portions and cannot be considered a coherent cylindrical core;unsuitable for testing
65	Coarse aggregate along the face of the core contains 50 percent or more of crushed materials with fractured faces
66	Coarse aggregate along the face of the core is a mixture of uncrushed gravel and crushedgravel or stone
67	The exposed aggregates along the face of the core are lightweight aggregate
68	More than 10 percent of the surface area of the core contains soft and deleterious aggregateparticles or clay balls (soft aggregates are defined as those aggregates that can be easilyscratched with a knife)
69	Cracks are generally across or through the coarse aggregate
70	Cracks are generally around the periphery of the coarse aggregate

71	Cracks are associated with embedded steel
72	Rims are observed on aggregate
73	Fine aggregate is natural sand
74	Fine aggregate is manufactured sand
75	Fine aggregate is a mixture of natural and manufactured sand
76	Steel is present in the core (give type size and location of steel in a separate note)
77	Steel is corroded
78	Core indicates D-cracking (a series of closely spaced crescent-shaped hairline cracks that appear at a PCC pavement surface at longitudinal joints/cracks and transverse joints/cracks)
79	Core indicates deterioration due to freeze-thaw cycles
80	Core indicates sulfate attack
81	Core indicates alkali silica reactivity (expansion of reactive aggregates)
82	Skewed core (when either end of the core departs from perpendicularity to the axis by more than 0.5 degrees or 3 mm in 300 mm, as tested by placing the core on a level surface)
99	Other comment (describe in a note)

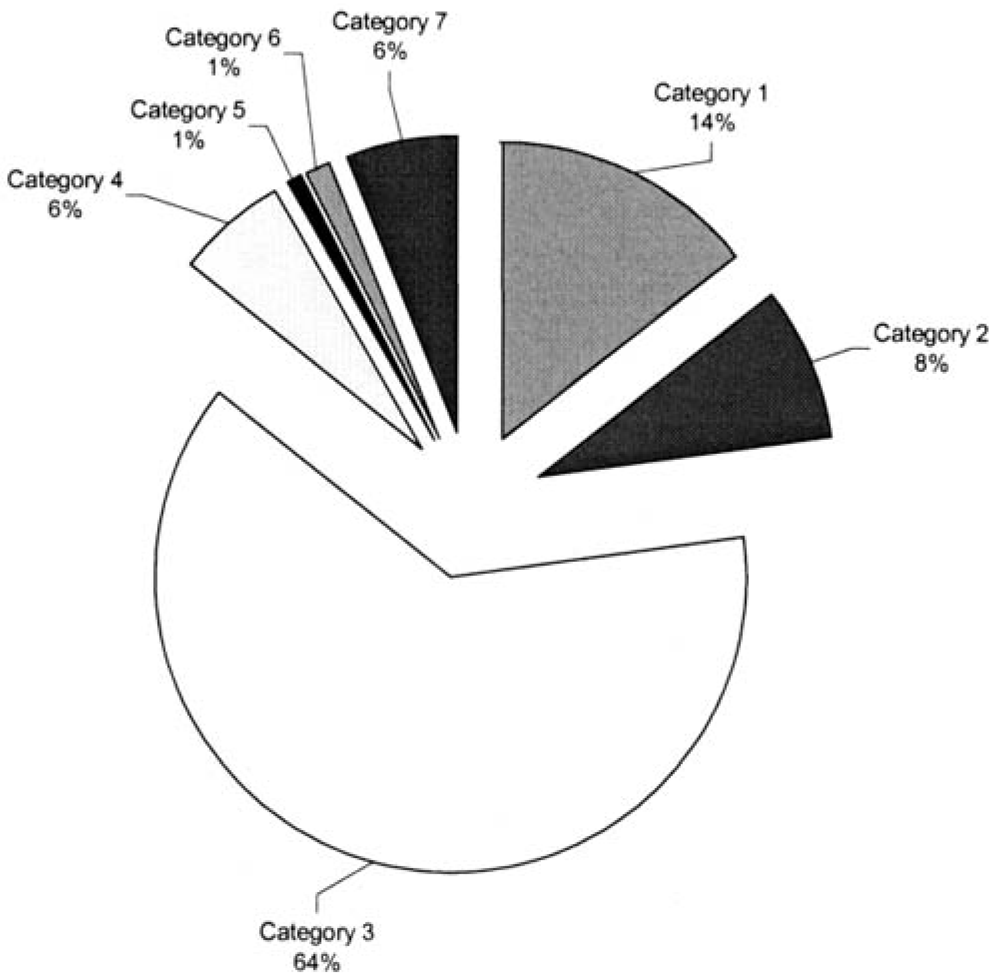

Figure 41. Summary of visual examination comments for all core specimens.

Identification of Anomalous Data

The anomalies noted during the various analyses are described below, along with a discussion of potential causes for their occurrence. Where possible, corrective or remedial actions were undertaken to address the anomalous data. It should be noted that excessive variability in the thickness values from multiple specimens belonging to the same analysis cell was the primary factor used in identifying anomalous data.

Anomaly 1: Mismatch in Target versus Actual Thicknesses

The reasonableness of experiments without a target project thickness value was ascertained by verifying whether the range of thicknesses found match that commonly encountered in practice. Where target thicknesses were available, reasonableness was ascertained by comparing the mean and standard deviation of the thickness information in the test table with the target values. Although data from SPS-2 and SPS-8 experiments were reasonable, the mean thickness and range of thicknesses from the various projects within the SPS-7 experiment were not consistent with the target values. Upon further analysis, it was revealed that the cause for this anomaly was the presence of "broken cores" and the fact that one of the States constructed overlays thicker than specified.

All "broken" or short cores leading to thickness data variability or bias were not used in further analysis. Removal of such data from further analysis meant that they were not included in developing the representative test tables. Because constructing a thicker-than-specified overlay is not an anomaly in itself, no remedial action is suggested for such data. However, the user should pay particular attention to this set of data if target thickness is a parameter of interest in the analysis under consideration.

Anomaly 2: Single Test Values

Eight analysis cells contained data from only a single test specimen. A single test value could result from inadequate sampling, discarded cores due to excessive damage, or a combination thereof. It is, therefore, not a testing anomaly. Nevertheless, the absence of duplicate test values to corroborate the measurements makes it difficult to characterize PCC layer thickness with a great degree of confidence.

To verify the accuracy of the single point thickness measurements, they were compared with corresponding TST_L05B representative layer thickness information in the LTPP database. The TST_L05B table uses more than one source (e.g., elevation information, thickness data from cores, bulk samples, test pits) while assigning representative layer thicknesses. The comparisons revealed that thickness data from six analysis cells matched the TST_L05B information. These data were, therefore, retained in the database, with an appropriate comment denoting that these are single test values. The TST_L05B table did not contain releasable data for the remaining two analysis cells, so the validity of these data could not be verified. Pending forensic testing to validate these thicknesses, these data were also retained in the database with an appropriate comment. The comment will inform users that the representative PCC layer thickness value assigned was from a single test.

Anomaly 3: Excessive Variability

Analysis cells with complete testing and incomplete testing were combined for the purposes of this evaluation. From a total of 607 analysis cells, 142 cells with multiple test values showed excessive within-cell variabilities (greater than 8 mm standard deviation). This constitutes approximately 23 percent of the total cells in the database considered for analysis. A careful review of the various data fields, including the comment fields, was performed to understand the reasons for the high within-cell variabilities. Based on this evaluation, the excess within-cell variability was attributed to the following causes:

- Presence of broken or short cores with significantly different core thicknesses than the companion specimens
- Presence of outliers

Data from broken or short cores were not used in developing the representative test values. Representative statistics computed without such data were compared with the original computed variability to observe the effect of removal of these data from the analysis. The 19 records from broken or short cores all belong to test sections within the SPS-7 experiment. They affected a total of eight analysis cells.

Standard deviations computed for seven of the affected eight cells without the affected test data were less than the typical value. For the remaining analysis cell, the recomputed standard deviation was only about 1.5 mm higher than the typical value. The computed representative test values and associated statistics were included into the representative data table with comments indicating the presence of the anomaly, the type of remedial action performed, and the effect the remedial action had on reducing the within-cell variability.

The 135 remaining analysis cells with excess variability were examined statistically to determine any outlying observations or outliers because the excessive variability could not be attributed to any physical causes. The ASTM E178 procedure entitled *Standard Practice for Dealing with Outlying Observations* was used for outlier identification (assuming a significance level of 0.05).(3)

Using the procedure outlined in ASTM E 178, a total of 22 analysis cells were detected as having outlier entries. The core thicknesses deemed as outliers were removed from the affected analysis cells, and the representative statistics were recomputed. This resulted in acceptable thickness variabilities for 20 of the 22 analysis cells. The two cells that did not meet the criteria had variabilities only slightly in excess of the acceptable 8 mm. The recomputed statistics were entered into the representative data set with comments indicating the presence of outliers, the type of remedial action performed, and the effect the remedial action had on reducing the within-cell variability.

Remedial Action--Summary

After taking appropriate remedial actions to account for inaccurate thickness data entries caused by broken or short cores and removal of outlier data entries, 27 of the 142 analysis cells originally exhibiting excessive variability were found to have acceptable within-cell thickness variability. For the remaining 115 analysis cells, no plausible explanation was found for the high within-cell thickness data variability. These data were retained in the representative data set with an appropriate comment code indicating the presence of excess variability.

Schema for Table TST_PC06_REP--Representative Length Measurements for PCC and LCB Cores

Representative length measurements for PCC and LCB cores for each analysis cell were computed along with related statistics and recommended for inclusion into the LTPP database. The schema developed for the representative thickness data table is presented in the next section. Note that this table summarizes essentially only the core thickness information. Summarizing visual examination information on an analysis cell basis was impractical.

However, as indicated earlier, the visual examination data revealed very few anomalies in the data, which was considered in developing the representative test values for each analysis cell. Also, the visual examination results showed that most of the cores were suitable for additional laboratory testing (e.g., compressive strength testing). The following data are maintained in the thickness data set:

1. Experiment type.
2. Experiment number.
3. SHRP identification number.
4. State code.
5. Construction number.
6. Layer number.
7. Material code.
8. Number of specimens tested.
9. Mean thickness.
10. Maximum thickness.
11. Minimum thickness.
12. COV of thickness data.
13. Standard deviation of thickness data.
14. Data source.
15. QA_Comment_1.
16. QA_Comment_2.
17. QA_Comment_3.
18. QA_Comment_4.

19. QA_Comment_5.
20. QA_Comment_6.
21. QA_Comment_Other.
22. Record status.

The first seven fields in the schema define the analysis cell. Field 8 presents the number of test specimens with thickness data within each analysis cell. The representative test value (mean thickness), along with the range of the thicknesses (max and min), COV, and standard deviation on an analysis cell basis are presented in fields 9 through 13. Field 14 describes the source of the data (all the values reported are original test values, i.e, no data were calculated).

Finally, comments are provided in fields 15 through 21 to describe the quality status of the data (e.g., excessive within-cell variability, incomplete sampling), based on the QA testing performed as part of this discussion to guide the user in selecting data for analysis and evaluation. The last field describes the record status.

10. DETERMINATION OF COMPRESSIVE STRENGTH OF PORTLAND CEMENT CONCRETE CORES

Introduction

The compressive strength of PCC is one of the most important properties widely used for design, research, and QC during construction. It is an indicator of the stress required to cause failure of a test specimen. A higher compressive strength indicates a stronger material. In addition to being an indicator of load-carrying ability, compressive strength also indicates, either directly or indirectly, resistance to wear, permeability, and durability. Because compressive strength testing can be performed with relative ease, its results are often used in QA/QC and to estimate concrete properties such as the flexural strength, elastic modulus, and tensile strength.

The determination of the compressive strength of PCC materials under the LTPP program covers jointed plain, jointed reinforced, and continuously reinforced concrete pavements, as well as concrete overlays and LCB's (from the SPS-2 experiment). Specimens are tested in accordance with SHRP protocol P61, which is based on the test standard AASHTO T22-88 (ASTM C39).

The test results are stored in the LTPP database after undergoing several levels of QA/QC checks that ensure a reasonable quality of data. Data that are of acceptable quality after the final series of QA/QC checks are classified as level E and are stored in table TST_PC01 in the LTPP database. Information maintained under this table for each specimen tested includes:

1. SHRP identification number.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.
8. Sample number.
9. Laboratory code.
10. Sample area number.
11. Test date.
12. Diameter.
13. Original length.
14. Capped length.
15. Length/diameter (L/D) ratio.
16. Cross-section area.
17. Compressive strength.
18. Maximum load.
19. Compressive strength fracture type code.
20. Compressive strength fracture type (other).
21. Comment codes for testing (seven fields).
22. Record status.

Material Sampling for Compressive Strength Testing

Test samples or specimens used for compressive strength testing consist of either cylinders cast from samples taken during construction or cores drilled from in-place PCC slabs. After the samples were procured from the field, they are carefully packaged, labeled, and shipped for testing, following the procedures outlined in the SHRP P61 protocol.

In general, two samples (one from either end of the test section but outside the monitoring area) were cored for GPS experiments for compressive strength testing. For SPS projects, the sampling plan was experiment-specific and often involved collecting samples from either end of test sections within a given experiment. Because some of the SPS experiments involve new construction or overlay construction (new pavement or overlays), fresh concrete cylinder specimens were also obtained during construction from test sections within these experiments. A detailed overview of the sampling locations for each SPS experiment is provided in the SPS Experimental Design and Research Plan documents developed by SHRP. (See references 17, 18, and 19 through 23.)

PCC compressive strength test data within the LTPP database table TST_PC01 pertain to GPS experiments 3, 4, 5, 7, and 9 and SPS experiments 2, 6, 7, and 8. Testing was performed on core specimens from all GPS and SPS-6 sections, in addition to cored samples from original pavement sections within the SPS-7 experiment. For SPS-2, SPS-7, and SPS-8 new and overlay test sections, testing was performed on both cylinders (fresh concrete) molded during construction for the newly placed concrete layers and cores taken after construction. Further, for the SPS-2 sections, cylinders and cores were obtained for both the PCC surface and LCB layers.

Table 47 presents the sampling program to determine the compressive strength of PCC materials. The table indicates the minimum number of tests required for each layer type for the relevant LTPP experiments, along with the sample locations. For GPS experiments, the number of tests required is strictly based on layer type, whereas for SPS-2, 7, and 8 experiments, it is also based on the target strength, specimen age, and specimen type (cylinder or core). This presents some unique challenges in the definition of analysis cells and the analysis of data in TST_PC01.

Table 47. Sampling requirements for determination of compressive strength of PCC materials.

Expt. Type	Layer Type	Test Type	LTPP Designation	LTPP Protocol	Min. No. of Tests per Layer	Designated Sampling Locations
GPS-3, 4, 5, and 9	PCC	Comp. strength	PC01	P61	2	C2 C8
GPS-7	PCC	Comp. strength	PC01	P61	2	C8 C20
SPS-2	PCC	Comp. strength (14 day, 3.8 MPa)	PC01	P61	3 (cylinder)	B21-B23
SPS-2	PCC	Comp. strength (14 day, 3.8 MPa)	PC01	P61	6 (core)	C1 C10 C18 C26 C34 C43
SPS-2	PCC	Comp. strength (14 day, 6.2 MPa)	PC01	P61	3 (cylinder)	B24-B26
SPS-2	PCC	Comp. strength	PC01	P61	6 (core)	C51 C59 C67 C75 C83 C91

		(14 day, 6.2 MPa)				
SPS-2	PCC	Comp. strength (28 day, 3.8 MPa)	PC01	P61	3 (cylinder)	B21-B23
SPS-2	PCC	Comp. strength (28 day, 3.8 MPa)	PC01	P61	6 (core)	C2 C11 C19 C27 C35 C44
SPS-2	PCC	Comp. strength (28 day, 6.2 MPa)	PC01	P61	3 (cylinder)	B24-B26
SPS-2	PCC	Comp. strength (28 day, 6.2 MPa)	PC01	P61	6 (core)	C52 C60 C68 C76 C84 C92
SPS-2	PCC	Comp. strength (1 year, 3.8 MPa)	PC01	P61	3 (cylinder)	B21-B23
SPS-2	PCC	Comp. strength (1 year, 3.8 MPa)	PC01	P61	6 (core)	C3 C12 C20 C28 C36 C45
SPS-2	PCC	Comp. strength (1 year, 6.2 MPa)	PC01	P61	3 (cylinder)	B24-B26
SPS-2	PCC	Comp. strength (1 year, 6.2 MPa)	PC01	P61	6 (core)	C53 C61 C69 C77 C85 C93
SPS-2	LCB	7 day	PC01	P61	6 (cylinder)	B19 B20
SPS-2	LCB	14 day	PC01	P61	8 (core)	C18 C22 C26 C30 C67 C70 C75 C79
SPS-2	LCB	28 day	PC01	P61	6 (cylinder)	B19 B20
SPS-2	LCB	28 day	PC01	P61	8 (core)	C19 C23 C27 C31 C68 C71 C76 C80
SPS-2	LCB	1 year	PC01	P61	6 (cylinder)	B19 B20
SPS-2	LCB	1 year	PC01	P61	8 (core)	C20 C24 C28 C32 C69 C72 C77 C81
SPS-6	PCC (cores)	Comp. strength	PC01	P61	10	C1 C3 C5 C7 C9 C11 C13 C15 C17 C19
SPS-7	PCC--Overlay (Postconstruction cores)	Comp. strength 14 day	PC01	P61	4	C12 C15 C17 C19

SPS-7	PCC--Overlay (Postconstruction cores)	Comp. strength 28 day	PC01	P61	4	C43 C50 C57 C64
SPS-7	PCC--Overlay (Postconstruction cores)	Comp. strength 365 day	PC01	P61	4	C86 C93 C100 C107
SPS-7	PCC--Overlay (During construction cylinders)	Comp. strength 14 day	PC01	P61	6	FC1 FC2 FC3 (75-mm cores)
SPS-7	PCC--Overlay (During construction cylinders)	Comp. strength 14 day	PC01	P61	6	FC4 FC5 FC6 (125-mm cores)
SPS-7	PCC--Overlay (During construction cylinders)	Comp. strength 14 day	PC01	P61	6	FC1 FC2 FC3 (75-mm cores)
SPS-7	PCC--Overlay (During construction cylinders)	Comp. strength 28 day	PC01	P61	6	FC4 FC5 FC6 (125-mm cores)
SPS-7	PCC--Overlay (During construction cylinders)	Comp. strength 365 day	PC01	P61	6	FC1 FC2 FC3 (75-mm cores)
SPS-7	PCC--Overlay (During construction cylinders)	Comp. strength 365 day	PC01	P61	6	FC4 FC5 FC6 (125-mm cores)
SPS-7	PCC--Original layer (cores)	Comp. strength	PC01	P61	9	C21 C25 C29 C33 C37 C44 C51 C58
SPS-8	PCC ("as-delivered" cylinders)	Comp. strength 14 day	PC01	P61	3	FC1 FC2 FC3
SPS-8	PCC ("as-delivered" cylinders)	Comp. strength 28 day	PC01	P61	3	FC1 FC2 FC3
SPS-8	PCC ("as-delivered" cylinders)	Comp. strength 365 day	PC01	P61	3	FC1 FC2 FC3
SPS-8	PCC ("as-placed" cores)	Comp. strength 14 day	PC01	P61	3	C1 C10 C20
SPS-8	PCC ("as-placed" cores)	Comp. strength 28 day	PC01	P61	3	C2 C11 C21
SPS-8	PCC ("as-placed" cores)	Comp. strength 365 day	PC01	P61	3	C4 C13 C22

Compressive Strength Data Completeness

The first step in assessing data completeness was to link the compressive strength data in TST_PC01 (January 2000 release) to tables TST_L05B and EXPERIMENT_SECTION for cross-referencing of layer information, experiment type, and other important data elements. Data extraction and assembly were described in detail in the introductory chapters of this report. Subsequently, data completeness was evaluated at two levels. The details of the data completeness assessment are provided below.

Level 1 Compressive Strength Data Completeness

A summary of the visual examination and thickness data collected for all GPS and SPS experiments at all record status levels (A to E) is presented in table 48. Almost all the experiments (with the exception of GPS-9) had sublevel E test data. Sublevel E data fell outside the scope of this study and were kept out of all further analysis. Also, not all the test records available at level E were usable because they had wrong material type descriptions or layer assignments, no compressive strength information, or they did not contain corroborating information from the TST_L05B and EXPERIMENT_SECTION LTPP database.

Table 48. Summary of compressive strength data in table TST_PC01 in the LTPP database.

Expt. Type	Expt. No.	Total No. of Records at Levels A to E	Total No. of Records at Level E	No. of Usable Records at Level E	Percent Usable Records at Level E	Total No. of Analysis Cells Represented at Level E
GPS	3	226	225	225	100	113
GPS	4	120	117	117	98	59
GPS	5	158	157	157	99	79
GPS	7A	65	64	64	98	33
GPS	7B	18	15	13[1]	72	7
GPS	9	94	94	89[2]	95	45
SPS	1	21	0	0	0	N/A
SPS	2	1334	1091	1008[3]	76	75--PCC 44--LCB
SPS	6	96	71	62[4]	65	9
SPS	7	236	182	178[5]	75	3--Original 12--Overlay
SPS	8	24	23	23	96	9
Unclassified[6]	N/A	4	4	N/A	N/A	N/A

[1]Two records with AC material type assigned to them.
[2]Three records with suspicious layer numbering; two records with no corresponding TST_L05B information required to verify layer type.
[3]Eighteen records with wrong material type assignment; four records with no compressive strength data; 61 records with no TST_L05B information.
[4]Nine records with no compressive strength data.
[5]Four records with no compressive strength data.
[6]These records could not be identified with any LTPP experiment.

Notes explaining the reasons for nonusable data at level E are provided in table 48 on a case-by-case basis. SPS experiments 2, 6, 7, and 8 had significantly lower percentages of usable records at level E than did the GPS experiments.

Definition of Analysis Cells

Also presented in table 48 is the total number of analysis cells in each experiment represented by the data at level E. Analysis cells formed the basis for level 2 data completeness analysis, because the number of test specimens per analysis cell in the test table is compared with the corresponding minimum required tests specified in the sampling program (see table 47). Within the context of this table, analysis cells were defined as follows:

- For data from GPS experiments: An analysis cell is the same as a layer of a given material type, within a monitoring test section, for which testing data are available. In analyzing the GPS data contained in TST_PC01, it was observed that analysis cells are the same as individual monitoring test sections because testing was done on only one layer type (PCC layers).
- For SPS experiments: An analysis cell is defined by layer type, target flexural strength (for SPS-2 data), specimen age (for SPS-2, SPS-7 time-dependent, and SPS-8 data), and specimen type (for SPS-2, SPS-7, and SPS-8 experiments). The sampling plan for most of the SPS experiments called for samples to be collected over various test sections within a given experiment. Therefore, an analysis cell for this test table typically spans the entire length of the experiments.

From the analysis cell definitions above, the fields required to define an analysis cell for SPS experiments are not uniform across all the experiments. For clarity, a list of fields that make up TST_PC01 analysis cells for the various LTPP experiments is presented in table 49. Note that, for SPS data, the SHRP_ID field is not used in defining the analysis cells.

Table 49. Analysis cell definitions for test table TST_PC01.

Key Fields	GPS Experiments (all)	SPS-2	SPS-6	SPS-7	SPS-8
Experiment type	X	X	X	X	X
Experiment number	X	X	X	X	X
SHRP_ID	X	--	--	--	--
State code	X	X	X	X	X
Layer number	X	--	X	X	X
Material code	X	X	X	X	X
Construction number	X	X	X	X	X
Target strength	--	X	--	--	--
Specimen type	--	X	--	X	X
Specimen age	--	X	--	X	X

Level 2 Compressive Strength Data Completeness

Level 2 data completeness evaluation consisted of a check on whether the analysis cells in the test table TST_PC01 satisfied the minimum number per layer requirement specified in the LTPP sampling and testing program.

GPS Data

A total of 665 usable records at level E were present in table TST_PC01 for GPS sections. These data represent 336 analysis cells. A level 2 data completeness analysis was performed on the data to determine sampling and testing adequacy. The first step in determining sampling adequacy was to compute the number of test samples collected and tested within each analysis cell. This was then compared with the minimum number of tests required for each layer, according to the SHRP P61 protocol (reported in table 47). Test sections that satisfied the minimum sampling requirements were categorized as complete, whereas those with less than the minimum are categorized as incomplete. Table 50 presents a summary of level 2 data completeness check for all the GPS experiments. Recall that the minimum sampling requirement for GPS experiments is two cores per PCC layer in a test section.

It is clear from table 50 that almost all the GPS sections met the minimum tests per layer requirement for compressive strength testing. This indicates that both ends of the test section were sampled and, thus, the test data available should provide a reasonable indication the entire test section compressive strength, eliminating any bias associated with sampling.

Table 50. Summary of level 2 data completeness analysis of data from TST_PC01 for GPS experiment sections.

Experiment Type	Total Number of Analysis Cells Represented at Level E	Number with Less than Minimum Samples	Percent Layers with Less than Minimum Samples
GPS-3	113	1	1
GPS-4	59	1	2
GPS-5	79	1	4
GPS-7A	33	2	6
GPS-7B	7	1	14
GPS-9	45	1	2

A total of 7 of the 336 cells from GPS experiments did not meet the sampling requirements. These cells contained only one test value reported at level E. Single test values may not be representative of the entire test section and were considered anomalous until a check was performed to ascertain the reasonableness of such data. Anomaly identification and remedial actions are discussed later in this chapter.

SPS-2 Data

A total of 1,008 level E records were usable from table TST_PC01 for the SPS-2 experiment. Of these, 311 records pertain to LCB, and 697 records pertain to PCC. The data were accordingly divided into these two material types. Further, because the sampling plan shown in table 47 indicates that the required number of tests per layer is grouped on the basis of target flexural strength, age of test specimen, and type of test specimen (cylinder or core), an attempt was made to formulate analysis cells in this manner. However, a major hurdle was encountered in achieving this task. The specimen age at testing was not recorded in table TST_PC06; only test date is provided. Therefore, specimen age at testing was computed by subtracting the test date from the construction completion date. Construction completion date from table SPS2_PCC_PLACEMENT for cored samples and from table TST_PCC_FRESH molded cylinder samples. Both the SPS2_PCC_PLACEMENT and TST_FRESH_PCC tables are available in the LTPP database. The determination of sample type was made from the sample number information provided within the TST_PC01 table. The following anomalies were observed in the various tables required for assessing both compressive test results and relevant testing information:

1. Missing sampling or placement dates from TST_PCC_FRESH and SPS2_PCC_PLACEMENT tables, respectively--21 PCC records and six LCB records. The specimen age at testing for these samples could not be computed.
2. The sample number information and the material type information did not match in a few samples (e.g., sample number CXXX stands for a PCC core sample but it is assigned to a material code 334 in the database, which stands for an LCB core sample)--40 PCC records and seven LCB records. This situation led to an ambiguity in data classification.
3. Negative specimen age at testing obtained after subtraction of PCC placement/sampling date from specimen test date--36 PCC records and six LCB records. A majority of these records did not contain specimen testing date, resulting in the negative specimen age at testing.
4. Nonstandard specimen ages (i.e., testing ages that were not in the original plan of study)--four PCC records and 21 LCB records. In making a determination of nonstandard age, the following criteria were adopted:

- While grouping specimens for 7-day strength analysis: Calculated specimen age outside a range of 7 ± 2 days.
- While grouping specimens for 14-day strength analysis: Calculated specimen age outside a range of 14 ± 3 days.
- While grouping specimens for 28-day strength analysis: Calculated specimen age outside a range of 28 ± 3 days.
- While grouping specimens for 365-day strength analysis: Calculated specimen age between 200 and 450 days.

The criteria are based on the assumption that a difference in specimen age of 2 to 3 days will not significantly affect the strength of specimens between 7 and 30 days old, and there will be no significant difference in strength for specimens with age ranging from 200 to 450 days. None of the anomalous data were considered in further analysis (i.e., development of representative test tables). As a result, 141 "usable" records at level E were not used in further analysis. This further reduced the total number of usable records for this experiment from 1,008 to 867. Of these, 596 pertained to PCC materials, and 271 pertain to LCB.

The remaining data were then grouped into analysis cells based on State code, layer number, construction number, target flexural strength (for PCC), specimen age, and specimen type. The SHRP_ID field was intentionally kept out of the grouping because sampling in the SPS experiments is done over all test sections within a given experiment. Summaries of the level 2 data completeness analyses are provided in table 51 for LCB sections and table 52 for PCC sections.

Each row in tables 51 and 52 represents an analysis cell. Information from multiple specimens is grouped under each analysis cell and is used in determining level 2 data completeness and for computing representative test values and other basic statistics. Also, data pertaining to multiple samples within an analysis cell were checked for within-cell variability, which is discussed later in this section. In reviewing the data presented in tables 51 and 52, the following observations were made:

- Approximately 43 percent of LCB cells and 38 percent of PCC cells were classified as complete.
- Approximately 47 percent of the LCB cells and 52 percent of the PCC cells were classified as incomplete (incomplete implies that cells had no testing information or some testing information but did not satisfy the minimum tests per analysis cell requirement).

The summary of the level 2 data completeness shows that a majority of the cells do not have the minimum number of tests performed. Twenty-four percent of the data was still undergoing LTPP database sublevel E data quality checks, and about 14 percent of the data at level E could not be considered, due to discrepancies in specimen ages at testing, material type definitions, and so on. These percentages will likely change as the LTPP quality checks are completed and some of the issues raised in this report are addressed by the FHWA.

The data presented showed that the LTPP sampling and testing plan was not always adhered to. For example, LCB cores were tested at 7 days for the testing conducted on samples from State 4; however, the sampling plan specifies that cores should be tested only at 14, 28, and 365 days. Nevertheless, this information was retained in the database, because it is a useful input for estimating the 14-day strength values through interpolation, as required by the test protocol.

SPS-6 Data

A total of 62 records belonging to the SPS-6 experiment were present at level E in table TST_PC01. According to the sampling plan for this experiment, 10 cores were required to be collected and tested for the PCC layer within the experiment at locations indicated in table 47.

Table 51. Summary of SPS-2 level 2 data completeness analysis for LCB layers.

State Code	Specimen Type	Specimen Age	Min. Samples Required	Samples Tested	Sampling Plan Satisfied?
4	Core	7 days	--[1]	6	N/A
4	Core	28 days	8	6	No
4	Core	365 days	8	6	No
4	Cylinder	7 days	6	6	Yes
4	Cylinder	28 days	6	5	No
4	Cylinder	365 days	6	2	No
10	Core	14 days	8	9	Yes
10	Core	28 days	8	0	No
10	Core	365 days	8	11	Yes
10	Cylinder	7 days	6	0	No
10	Cylinder	14 days	--[1]	2	N/A
10	Cylinder	28 days	6	2	No
10	Cylinder	365 days	6	2	No
19	Core	7 days	--[1]	8	N/A
19	Core	28 days	8	3	No
19	Core	365 days	8	8	Yes
19	Cylinder	7 days	6	3	No
19	Cylinder	28 days	6	3	No

19	Cylinder	365 days	6	3	No
20	Core	14 days	8	0	No
20	Core	28 days	8	0	No
20	Core	365 days	8	0	No
20	Cylinder	7 days	6	3	No
20	Cylinder	14 days	--[1]	3	N/A
20	Cylinder	28 days	6	7	Yes
20	Cylinder	365 days	6	6	Yes
26	Core	14 days	8	0	No
26	Core	28 days	8	0	No
26	Core	365 days	8	7	No
26	Cylinder	7 days	6	9	Yes
26	Cylinder	28 days	6	9	Yes
26	Cylinder	365 days	6	8	Yes
32	Core	14 days	8	8	Yes
32	Core	28 days	8	8	Yes
32	Core	365 days	8	8	Yes
32	Cylinder	7 days	6	7	Yes
32	Cylinder	28 days	6	8	Yes
32	Cylinder	365 days	6	8	Yes
38	Core	14 days	8	0	No
38	Core	28 days	8	1	No
38	Core	365 days	8	4	No
38	Cylinder	7 days	6	0	No
38	Cylinder	28 days	6	0	No
38	Cylinder	365 days	6	0	No
39	Core	7 days	--[1]	4	N/A
39	Core	14 days	8	0	No
39	Core	28 days	8	8	Yes
39	Core	365 days	8	8	Yes
39	Cylinder	7 days	6	3	No
39	Cylinder	28 days	6	6	Yes
39	Cylinder	365 days	6	6	Yes
53	Core	14 days	8	8	Yes
53	Core	28 days	8	8	Yes
53	Core	365 days	8	8	Yes
53	Cylinder	7 days	6	8	Yes
53	Cylinder	28 days	6	8	Yes
53	Cylinder	365 days	6	7	Yes

[1]The sampling plan did not prescribe this test.

Table 52. Summary of SPS-2 level 2 data completeness analysis for PCC layers.

State Code	Target Strength, MPa	Specimen Type	Specimen Age	Min. Samples Required	Samples Tested	Sampling Plan Satisfied?
4	3.8	Core	14 days	6	10	Yes
4	3.8	Core	28 days	6	9	Yes
4	3.8	Core	365 days	6	9	Yes
4	3.8	Cylinder	14 days	3	0	No
4	3.8	Cylinder	28 days	3	0	No
4	3.8	Cylinder	365 days	3	0	No
4	6.2	Core	14 days	6	8	Yes
4	6.2	Core	28 days	6	8	Yes
4	6.2	Core	365 days	6	9	Yes
4	6.2	Cylinder	14 days	3	0	No
4	6.2	Cylinder	28 days	3	0	No
4	6.2	Cylinder	365 days	3	0	No
5	3.8	Core	14 days	6	0	No
5	3.8	Core	28 days	6	0	No
5	3.8	Core	365 days	6	19	Yes
5	3.8	Cylinder	14 days	3	0	No
5	3.8	Cylinder	28 days	3	0	No
5	3.8	Cylinder	365 days	3	1[1]	No
5	6.2	Core	14 days	6	0	No
5	6.2	Core	28 days	6	0	No
5	6.2	Core	365 days	6	18	Yes
5	6.2	Cylinder	14 days	3	0	No
5	6.2	Cylinder	28 days	3	0	No
5	6.2	Cylinder	365 days	3	0	No
8	3.8	Core	14 days	6	18	Yes
8	3.8	Core	28 days	6	16	Yes
8	3.8	Core	365 days	6	20	Yes
8	3.8	Cylinder	14 days	3	0	No
8	3.8	Cylinder	28 days	3	0	No
8	3.8	Cylinder	365 days	3	0	No
8	6.2	Core	14 days	6	15	Yes
8	6.2	Core	28 days	6	18	Yes
8	6.2	Core	365 days	6	20	Yes
8	6.2	Cylinder	14 days	3	0	No
8	6.2	Cylinder	28 days	3	6	Yes

8	6.2	Cylinder	365 days	3	6	Yes
10	3.8	Core	14 days	6	13	Yes
10	3.8	Core	28 days	6	6	Yes
10	3.8	Core	365 days	6	9	Yes
10	3.8	Cylinder	14 days	3	0	No
10	3.8	Cylinder	28 days	3	0	No
10	3.8	Cylinder	365 days	3	0	No
10	6.2	Core	14 days	6	7	Yes
10	6.2	Core	28 days	6	5	No
10	6.2	Core	365 days	6	7	Yes
10	6.2	Cylinder	14 days	3	0	No
10	6.2	Cylinder	28 days	3	0	No
10	6.2	Cylinder	365 days	3	0	No
19	3.8	Core	14 days	6	7	Yes
19	3.8	Core	28 days	6	8	Yes
19	3.8	Core	365 days	6	6	Yes
19	3.8	Cylinder	14 days	3	0	No
19	3.8	Cylinder	28 days	3	0	No
19	3.8	Cylinder	365 days	3	0	No
19	6.2	Core	14 days	6	7	Yes
19	6.2	Core	28 days	6	8	Yes
19	6.2	Core	365 days	6	9	Yes
19	6.2	Cylinder	14 days	3	0	No
19	6.2	Cylinder	28 days	3	0	No
19	6.2	Cylinder	365 days	3	0	No
20	3.8	Core	14 days	6	8	Yes
20	3.8	Core	28 days	6	7	Yes
20	3.8	Core	365 days	6	7	Yes
20	3.8	Cylinder	14 days	3	0	No
20	3.8	Cylinder	28 days	3	0	No
20	3.8	Cylinder	365 days	3	0	No
20	6.2	Core	14 days	6	4	No
20	6.2	Core	28 days	6	5	No
20	6.2	Core	365 days	6	3	No
20	6.2	Cylinder	14 days	3	0	No
20	6.2	Cylinder	28 days	3	0	No
20	6.2	Cylinder	365 days	3	0	No
26	3.8	Core	14 days	6	8	Yes
26	3.8	Core	28 days	6	6	Yes
26	3.8	Core	365 days	6	9	Yes

26	3.8	Cylinder	14 days	3	0	No
26	3.8	Cylinder	28 days	3	0	No
26	3.8	Cylinder	365 days	3	0	No
26	6.2	Core	14 days	6	4	No
26	6.2	Core	28 days	6	6	Yes
26	6.2	Core	365 days	6	7	Yes
26	6.2	Cylinder	14 days	3	0	No
26	6.2	Cylinder	28 days	3	0	No
26	6.2	Cylinder	365 days	3	0	No
32	3.8	Core	14 days	6	9	Yes
32	3.8	Core	28 days	6	10	Yes
32	3.8	Core	365 days	6	10	Yes
32	3.8	Cylinder	14 days	3	0	No
32	3.8	Cylinder	28 days	3	0	No
32	3.8	Cylinder	365 days	3	0	No
32	6.2	Core	14 days	6	8	Yes
32	6.2	Core	28 days	6	7	Yes
32	6.2	Core	365 days	6	7	Yes
32	6.2	Cylinder	14 days	3	0	No
32	6.2	Cylinder	28 days	3	0	No
32	6.2	Cylinder	365 days	3	0	No
37	3.8	Core	14 days	6	3	No
37	3.8	Core	28 days	6	3	No
37	3.8	Core	365 days	6	2	No
37	3.8	Cylinder	14 days	3	0	No
37	3.8	Cylinder	28 days	3	1[1]	No
37	3.8	Cylinder	365 days	3	0	No
37	6.2	Core	14 days	6	2	No
37	6.2	Core	28 days	6	3	No
37	6.2	Core	365 days	6	4	No
37	6.2	Cylinder	14 days	3	4	Yes
37	6.2	Cylinder	28 days	3	4	Yes
37	6.2	Cylinder	365 days	3	2	No
38	3.8	Core	14 days	6	5	No
38	3.8	Core	28 days	6	3	No
38	3.8	Core	365 days	6	15	Yes
38	3.8	Cylinder	14 days	3	0	No
38	3.8	Cylinder	28 days	3	0	No
38	3.8	Cylinder	365 days	3	0	No
38	6.2	Core	14 days	6	4	No

38	6.2	Core	28 days	6	1[1]	No
38	6.2	Core	365 days	6	16	Yes
38	6.2	Cylinder	14 days	3	0	No
38	6.2	Cylinder	28 days	3	0	No
38	6.2	Cylinder	365 days	3	0	No
39	3.8	Core	14 days	6	9	Yes
39	3.8	Core	28 days	6	11	Yes
39	3.8	Core	365 days	6	7	Yes
39	3.8	Cylinder	14 days	3	0	No
39	3.8	Cylinder	28 days	3	0	No
39	3.8	Cylinder	365 days	3	0	No
39	6.2	Core	14 days	6	7	Yes
39	6.2	Core	28 days	6	5	No
39	6.2	Core	365 days	6	4	No
39	6.2	Cylinder	14 days	3	0	No
39	6.2	Cylinder	28 days	3	0	No
39	6.2	Cylinder	365 days	3	0	No
53	3.8	Core	14 days	6	12	Yes
53	3.8	Core	28 days	6	12	Yes
53	3.8	Core	365 days	6	11	Yes
53	3.8	Cylinder	14 days	3	0	No
53	3.8	Cylinder	28 days	3	0	No
53	3.8	Cylinder	365 days	3	0	No
53	6.2	Core	14 days	6	6	Yes
53	6.2	Core	28 days	6	6	Yes
53	6.2	Core	365 days	6	7	Yes
53	6.2	Cylinder	14 days	3	0	No
53	6.2	Cylinder	28 days	3	0	No
53	6.2	Cylinder	365 days	3	0	No

[1]Single test value.

Table 53 presents a comparison of the sampling plan with actual data available at level E. It must be reiterated that core test results belonging to various SPS-6 test sections within a given experiment were considered to pertain to one analysis cell to be consistent with the prescribed sampling requirements (table 47). Each row in table 53 is an analysis cell. Three of the six States for which data were available either met or exceeded the sampling requirement, and the other two had "incomplete" data; however, they had adequate specimens to represent the analysis cell fully.

Table 53. Summary of SPS-6 level 2 data completeness analysis.

State Code	Min. Samples Required	Samples Tested	Sampling Plan Satisfied?
4	10	9	No
17	10	8	No
26	10	18	Yes
29	10	11	Yes
40	10	10	Yes
42	10	6	No

SPS-7 Data

Sampling for compressive strength testing under this experiment involved both cores extracted from existing pavement test sections and cylinders formed from bulk samples of fresh concrete obtained during construction of the bonded overlays. The concrete cylinders were tested at 14, 28, and 365 days.

A total of 178 usable records were present at level E in table TST_PC01 for SPS-7 experiments. As with the SPS-2 data, the specimen age at testing had to be computed by subtracting the sampling or coring date of each sample from the testing date available in the TST_PC01 table. The sampling date for bulk samples was obtained from the TST_FRESH_PCC table and that for the cored samples was obtained from the SPS7_PCC_OVERLAY table. The following problems were noted upon completion of the specimen age calculation:

- Four specimens had negative specimen age at testing.
- Sixty-seven specimens had nonstandard specimen ages at testing (39 samples with 0-day, 24 with 1-day, and four with 2-day ages at testing). The same criteria used for analyzing nonstandard specimens of the SPS-2 data were used here.

These problem data were not used in the analysis and will need to be examined when more accurate specimen age information is available. Therefore, only 107 records were considered in the level 2 data completeness analysis, reducing the number of usable records at level E from 75 to 45 percent of the total number of records in the database.

Table 54 presents a comparison of the anticipated testing plan versus what is reflected in TST_PC01 (i.e., level 2 data completeness analysis). Only 36 percent of the data was "complete" at level 2. As with the SPS-2 data, a significant portion of the SPS-7 data was either not at level E or has not been included in the analysis due to the various reasons previously covered. This could be the cause for the high percentage of incomplete data.

Table 54. Summary of SPS-7 level 2 data completeness analysis.

State Code	Layer Type	Specimen Type	Specimen Age	Min. Samples Required	Samples Tested	Sampling Plan Satisfied?
19	Existing PCC	Core	N/A	9	6	No
19	PCC Overlay (during construction)	Cylinder	14 days	6	0	No
19	PCC Overlay (during construction)	Cylinder	28 days	6	0	No
19	PCC Overlay (during construction)	Cylinder	365 days	6	0	No
19	PCC Overlay (postconstruction)	Core	14 days	4	3	No
19	PCC Overlay (postconstruction)	Core	28 days	4	3	No
19	PCC Overlay (postconstruction)	Core	365 days	4	4	Yes
22	Existing PCC	Core	N/A	9	7	No
22	PCC Overlay (during construction)	Cylinder	14 days	6	4	No
22	PCC Overlay (during construction)	Cylinder	28 days	6	8	Yes
22	PCC Overlay (during construction)	Cylinder	365 days	6	0	No
22	PCC Overlay (postconstruction)	Core	14 days	4	4	Yes
22	PCC Overlay (postconstruction)	Core	28 days	4	4	Yes
22	PCC Overlay (postconstruction)	Core	365 days	4	4	Yes
27	Existing PCC	Core	N/A	9	0	No
27	PCC Overlay (during construction)	Cylinder	14 days	6	0	No
27	PCC Overlay (during construction)	Cylinder	28 days	6	0	No
27	PCC Overlay (during construction)	Cylinder	365 days	6	0	No

27	PCC Overlay (postconstruction)	Core	14 days	4	0	No
27	PCC Overlay (postconstruction)	Core	28 days	4	0	No
27	PCC Overlay (postconstruction)	Core	365 days	4	3	No
29	Existing PCC	Core	N/A	9	22	Yes
29	PCC Overlay (during construction)	Cylinder	14 days	6	2	Yes
29	PCC Overlay (during construction)	Cylinder	28 days	6	28	Yes
29	PCC Overlay (during construction)	Cylinder	365 days	6	0	No
29	PCC Overlay (post construction)	Core	14 days	4	0	No
29	PCC Overlay (post construction)	Core	28 days	4	0	No
29	PCC Overlay (post construction)	Core	365 days	4	4	Yes

SPS-8 Data

The SPS-8 experiment involves the study of environmental effects in the absence of heavy loads. It involves both flexible and rigid pavement sections; however, only the latter is relevant for discussion here. Compressive strength testing was performed on both freshly delivered concrete (cylinders) and "as-placed" concrete (cores) as part of the sampling and testing program for this experiment.

Only 23 records of data pertaining to two experiments located in two different States were available in test table TST_PC01. The specimen age at testing for the SPS-8 data was computed by subtracting the test dates provided in the TST_PC01 table from the PCC placement dates in the SPS8_PCC_PLACEMENT_DATA table for core samples and from the sampling dates provided in the TST_FRESH_PCC table for bulk (cylinder) samples. No major problems were found in determining the specimen age at testing for the SPS-8 data. The 23 records were grouped under nine analysis cells. Level 2 data completeness analysis was then performed on the data, and a summary of the findings is presented in table 55. A majority of the cells met the minimum sampling requirement.

Table 55. Summary of SPS-8 level 2 data completeness analysis.

State Code	Layer Type	Specimen Type	Specimen Age	Min. Samples Required	Samples Tested	Sampling Plan Satisfied?
8	PCC Overlay (during construction)	Cylinder	14 days	3	3	Yes
8	PCC Overlay (during construction)	Cylinder	28 days	3	3	Yes
8	PCC Overlay (during construction)	Cylinder	365 days	3	0	No
8	PCC Overlay (postconstruction)	Core	14 days	3	3	Yes
8	PCC Overlay (postconstruction)	Core	28 days	3	3	Yes
8	PCC Overlay (postconstruction)	Core	365 days	3	0	No
39	PCC Overlay (during construction)	Cylinder	14 days	3	3	Yes
39	PCC Overlay (during construction)	Cylinder	28 days	3	3	Yes
39	PCC Overlay (during construction)	Cylinder	365 days	3	0	No
39	PCC Overlay (postconstruction)	Core	14 days	3	2	No
39	PCC Overlay (postconstruction)	Core	28 days	3	3	Yes
39	PCC Overlay (postconstruction)	Core	365 days	3	0	No

Compressive Strength Data Quality

Data quality was evaluated for all the analysis cells summarized in tables 51 through 55. (Data that were found to be problematic during the level 2 data completeness analysis were excluded from further analysis.) Data quality checks were performed at three levels: data reasonableness assessment, compliance with test protocol, and data variability analysis. The tasks undertaken under each of these checks are elaborated below.

Data reasonableness assessment included comparing the magnitudes of the compressive strength test results with typical strength values found in literature for similar materials.(13) For time-dependent strength data, another important reasonableness check was observing the time-series trends. Protocol compliance verification involved evaluation of various data fields for each test record found in TST_PC01 to check for compliance with test standards and protocols. Finally, within-cell variability was checked for all analysis cells with compressive strength data available. This was done to determine cells with excessive variability.

Compressive Strength Data Reasonableness

Long-Term Strength: GPS, SPS-6, and SPS-7 Data

Long-term strength compressive strength data from all the GPS, SPS-6, and SPS-7 (only data pertaining to original layers) experiments were plotted together in figure 42. The mean of the long-term compressive strength data is approximately 51 MPa, which is in reasonable agreement with published values for normal (ASTM Type I) cement. The standard deviation is approximately 10.5 MPa, and the COV is around 20 percent. Considering the geographical distribution of projects, along with associated construction and testing variability, the spread in compressive strength test data seems reasonable. In fact, a majority of values lie between 40 and 70 MPa, with only about 10 percent of the data below 40 MPa, and 4 percent above 70 MPa. The range of long-term compressive strength was between 22 and 90 MPa.

Time-Series Plots--SPS-2 Data

Figures 43 through 50 present time-series plots of LCB compressive strength for which strength data are available in the database. Figures 51 through 61 present similar plots for PCC sections. LCB strength data from the SPS-2 experiments located in State 38 and PCC strength data from SPS-2 experiments in State 5 were not plotted, due to lack of time-series information.

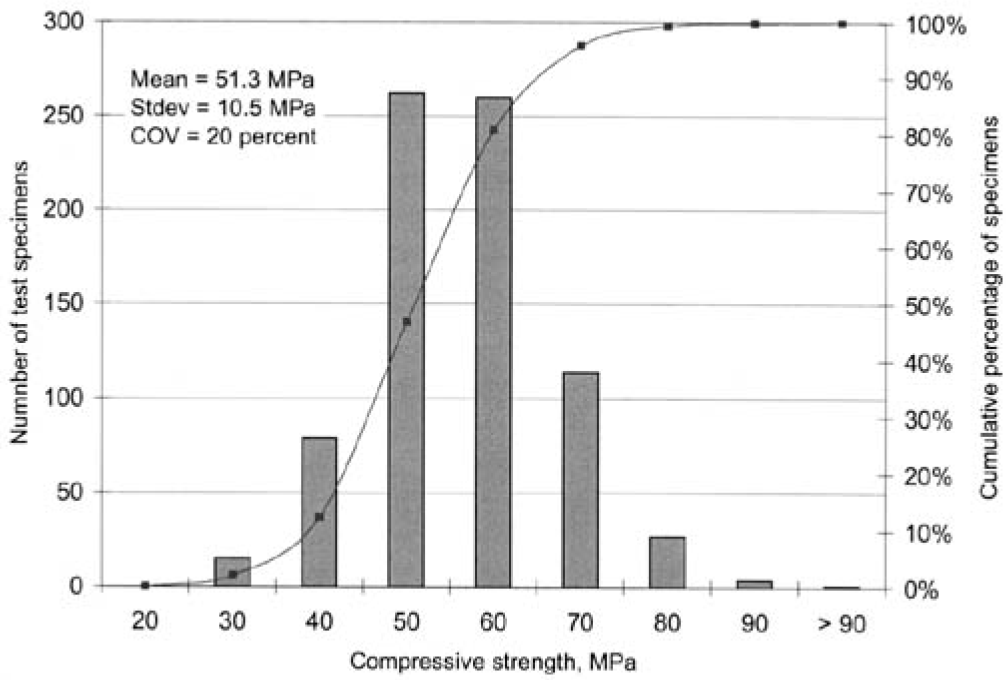

Figure 42. Long-term compressive strength data from GPS, SPS-6, and SPS-7.

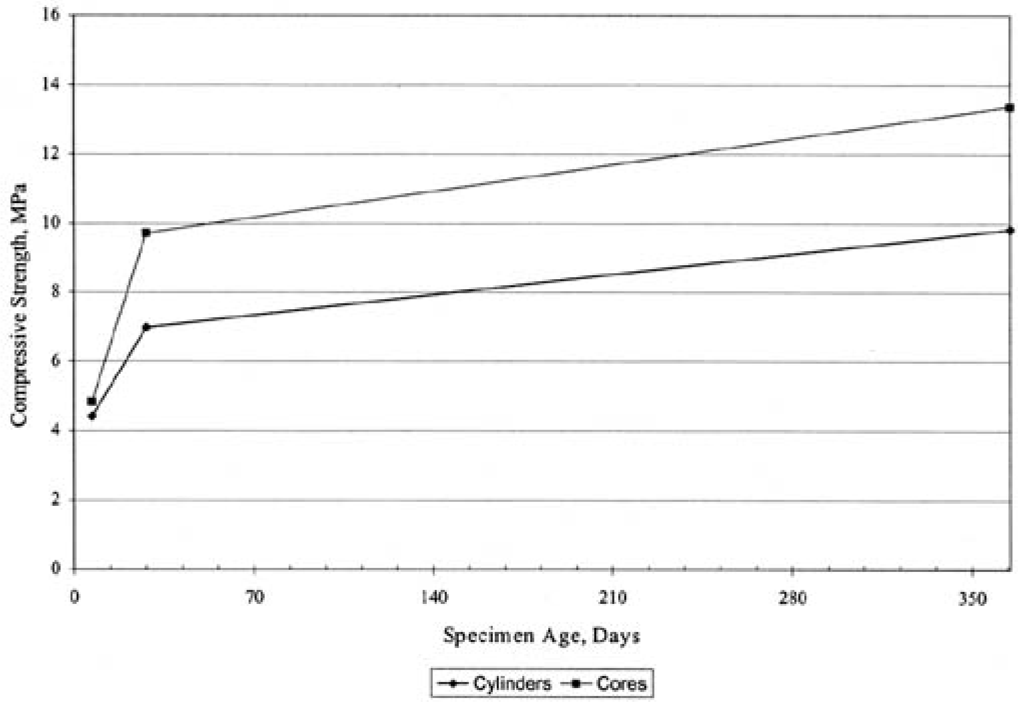

Figure 43. Time-series plots of SPS-2 LCB compressive strength data for State 4.

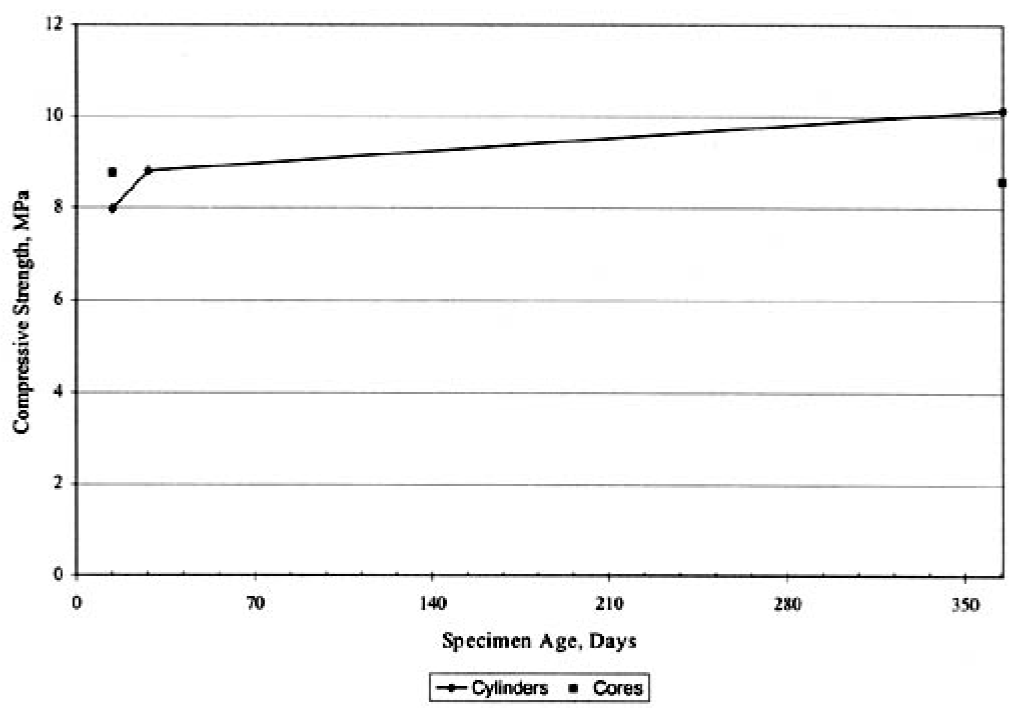

Figure 44. Time-series plots of SPS-2 LCB compressive strength data for State 10.

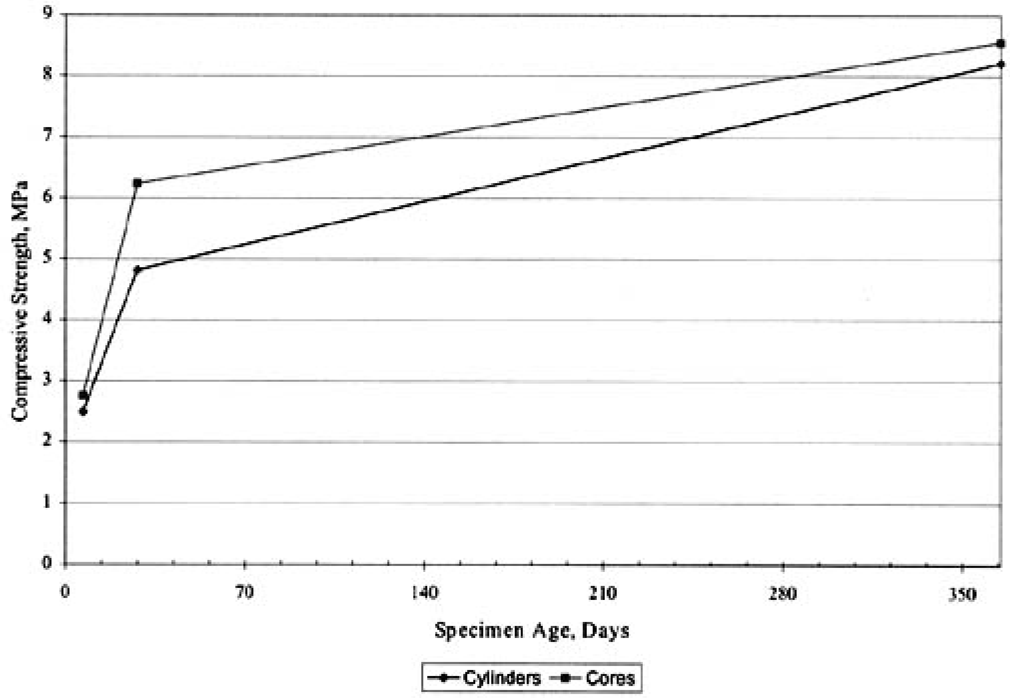

Figure 45. Time-series plots of SPS-2 LCB compressive strength data for State 19.

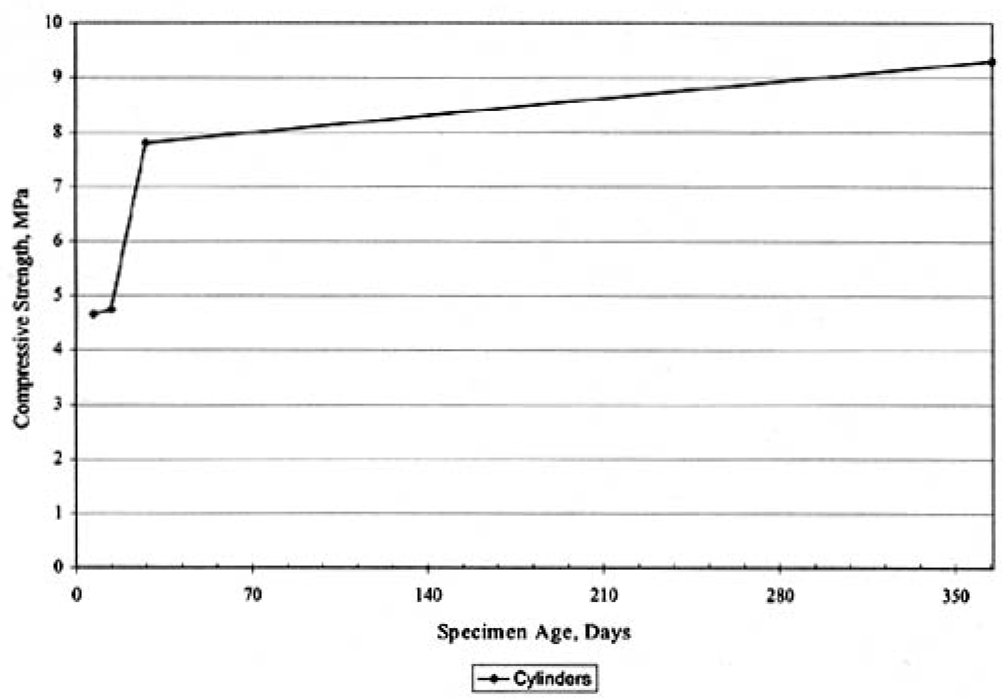

Figure 46. Time-series plots of SPS-2 LCB compressive strength data for State 20.

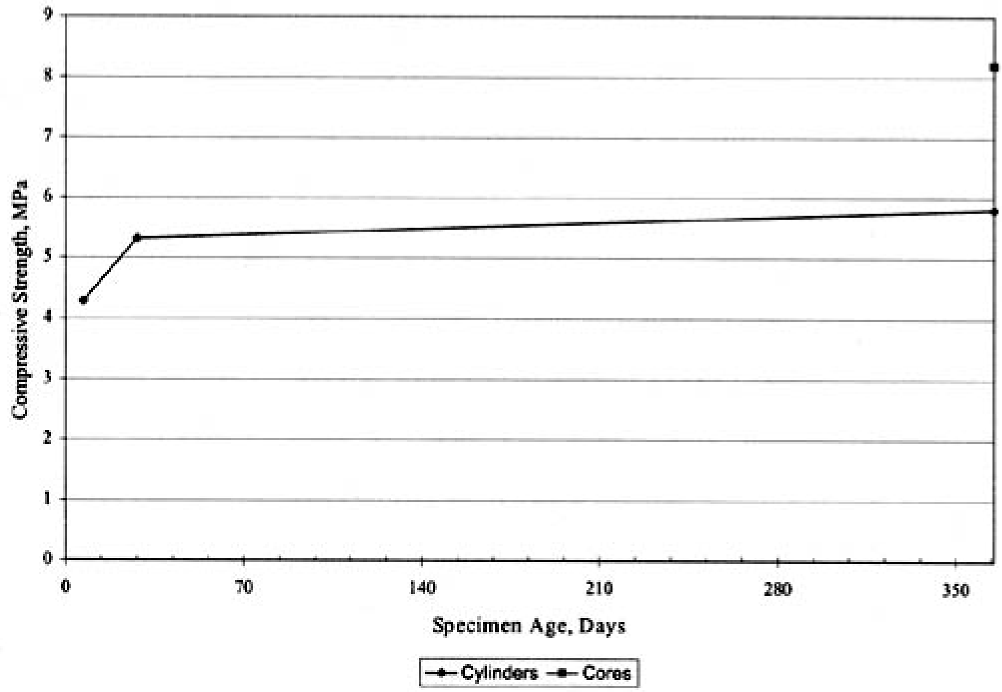

Figure 47. Time-series plots of SPS-2 LCB compressive strength data for State 26.

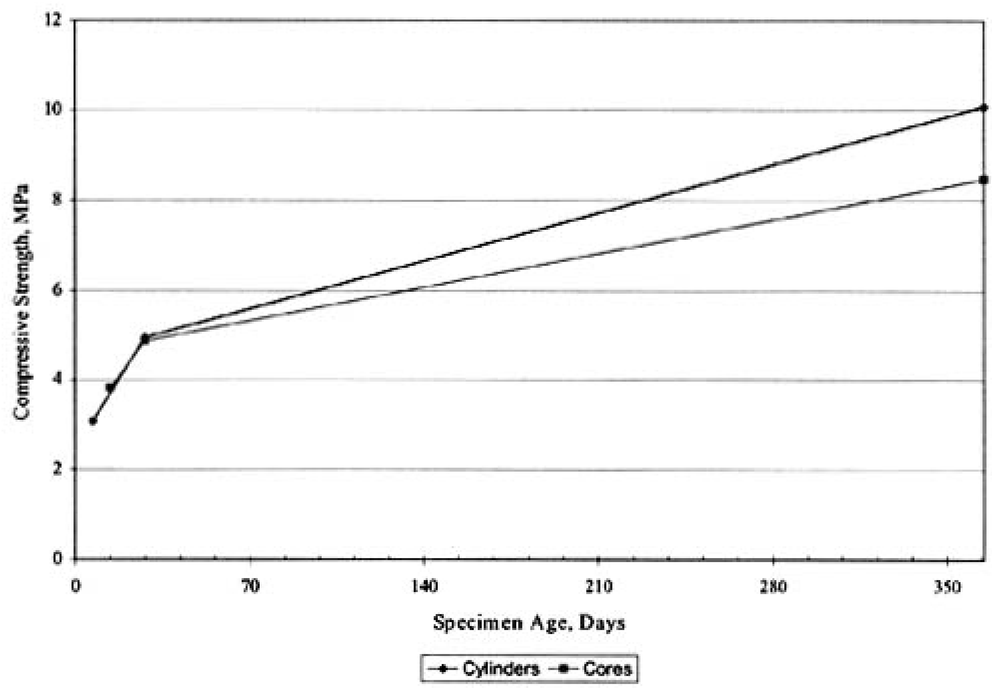

Figure 48. Time-series plots of SPS-2 LCB compressive strength data for State 32.

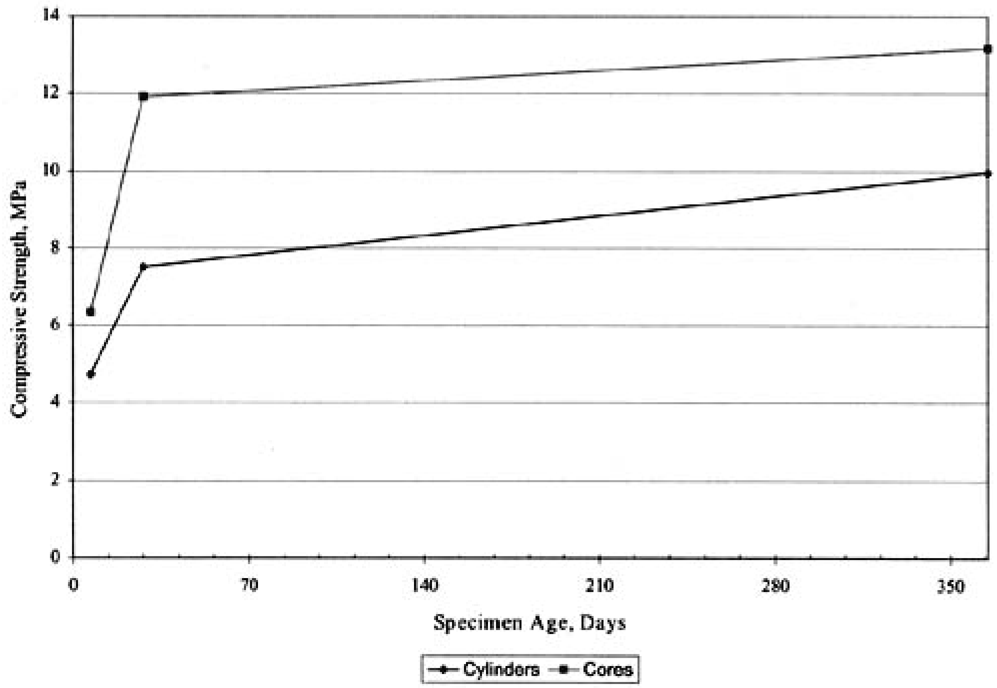

Figure 49. Time-series plots of SPS-2 LCB compressive strength data for State 39.

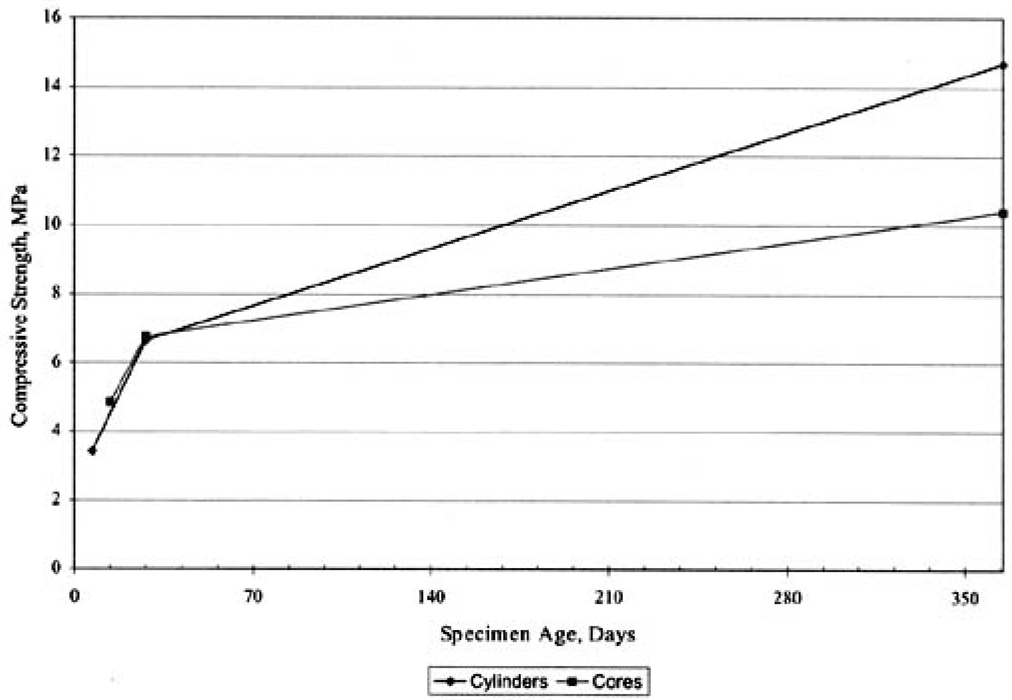

Figure 50. Time-series plots of SPS-2 LCB compressive strength data for State 53.

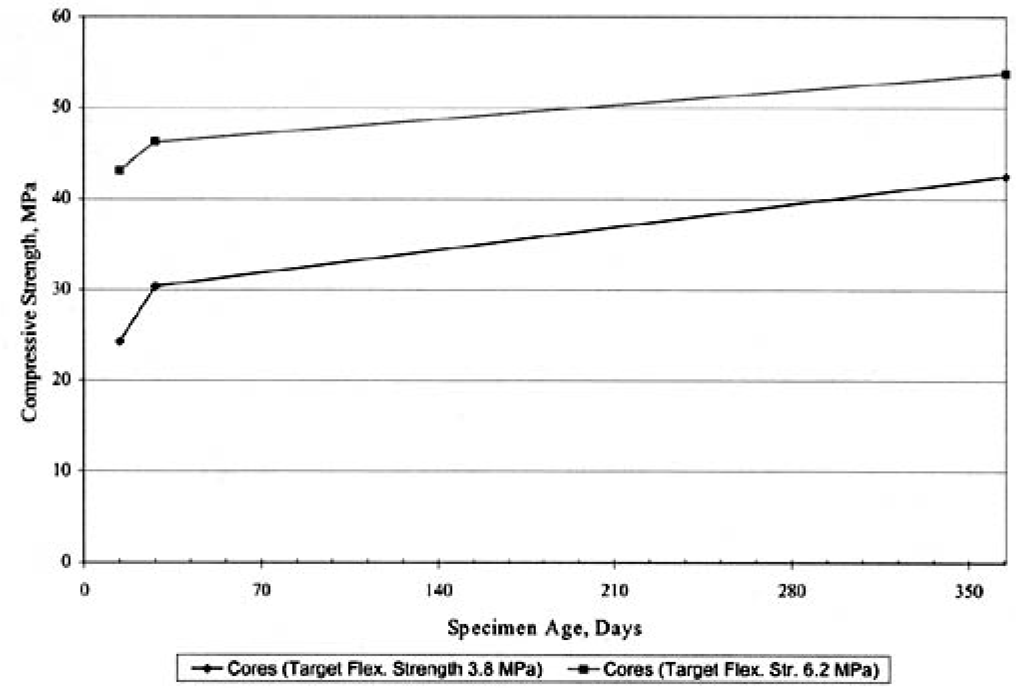

Figure 51. Time-series plots of SPS-2 PCC compressive strength data for State 4.

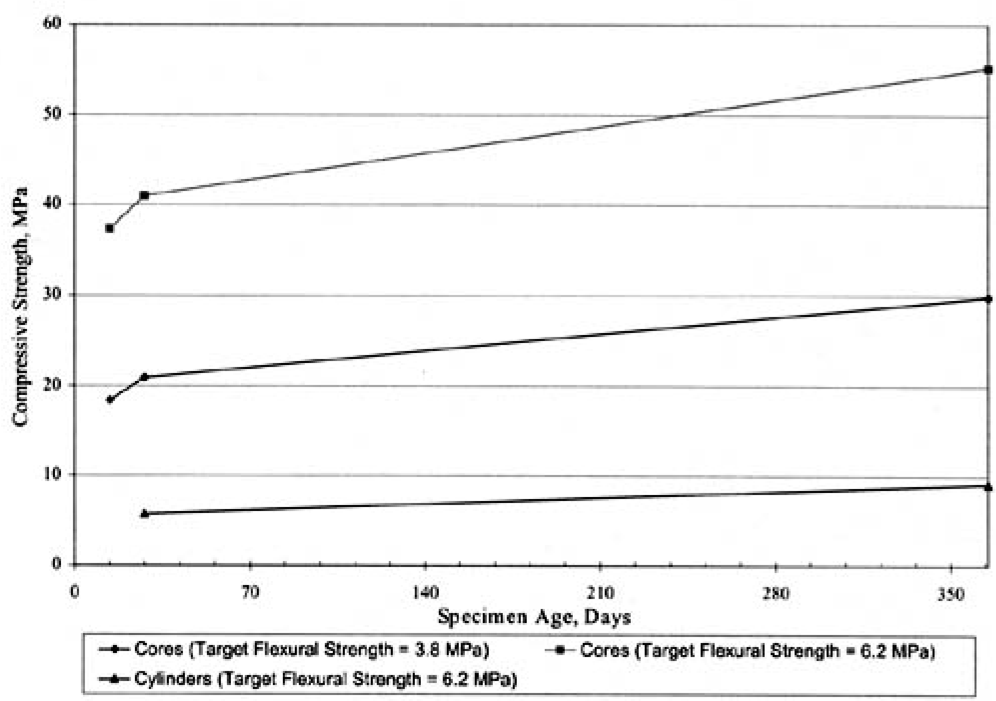

Figure 52. Time-series plots of SPS-2 PCC compressive strength data for State 8.

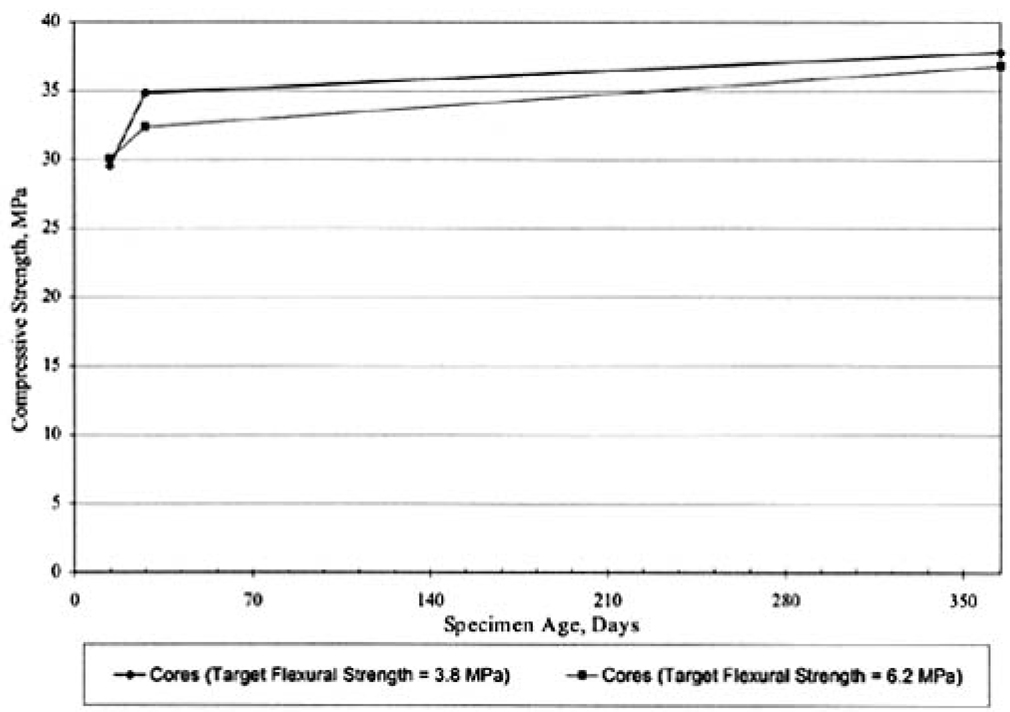

Figure 53. Time-series plots of SPS-2 PCC compressive strength data for State 10.

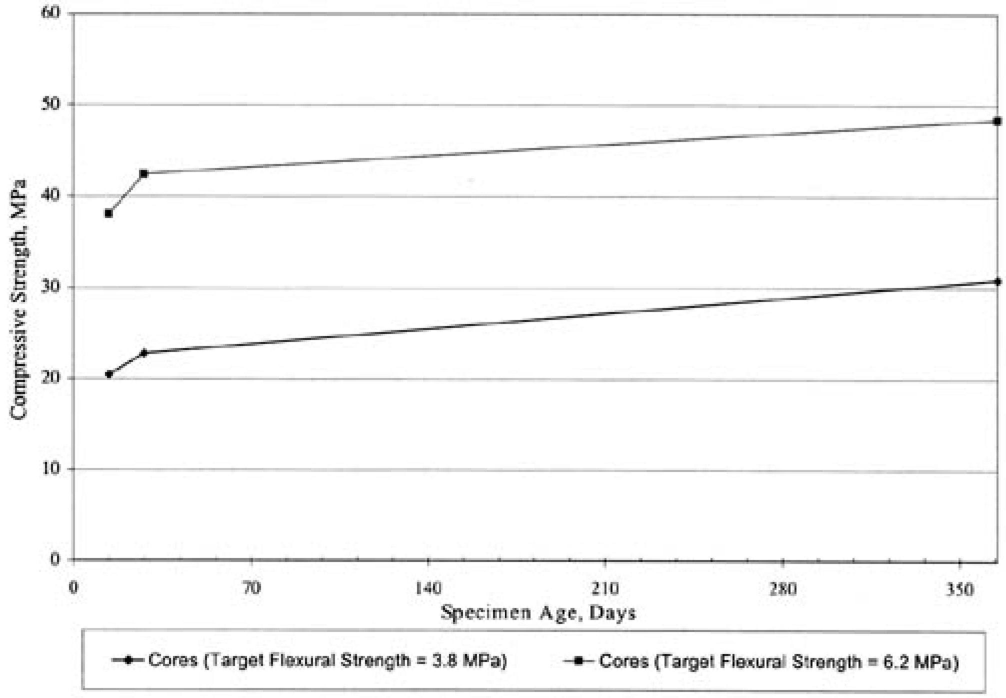

Figure 54. Time-series plots of SPS-2 PCC compressive strength data for State 19.

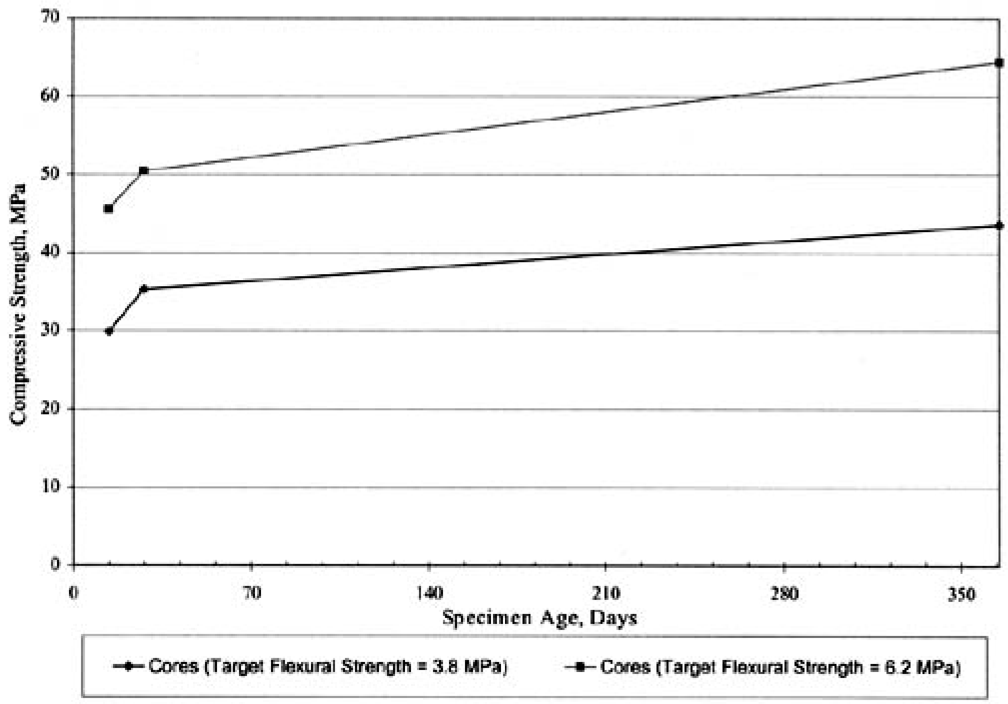

Figure 55. Time-series plots of SPS-2 PCC compressive strength data for State 20.

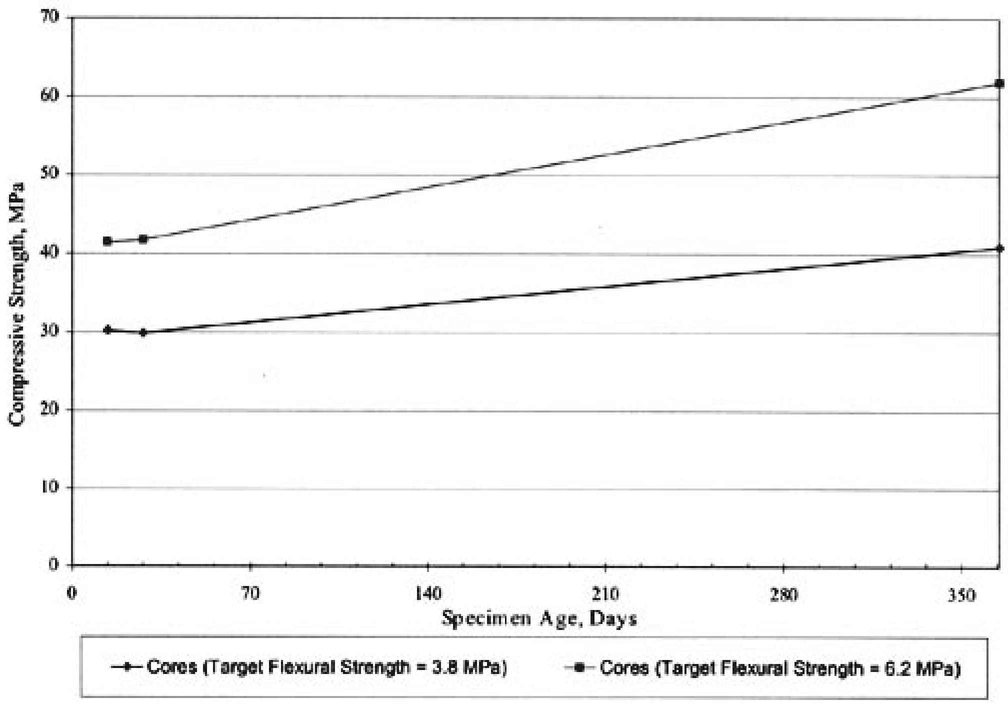

Figure 56. Time-series plots of SPS-2 PCC compressive strength data for State 26.

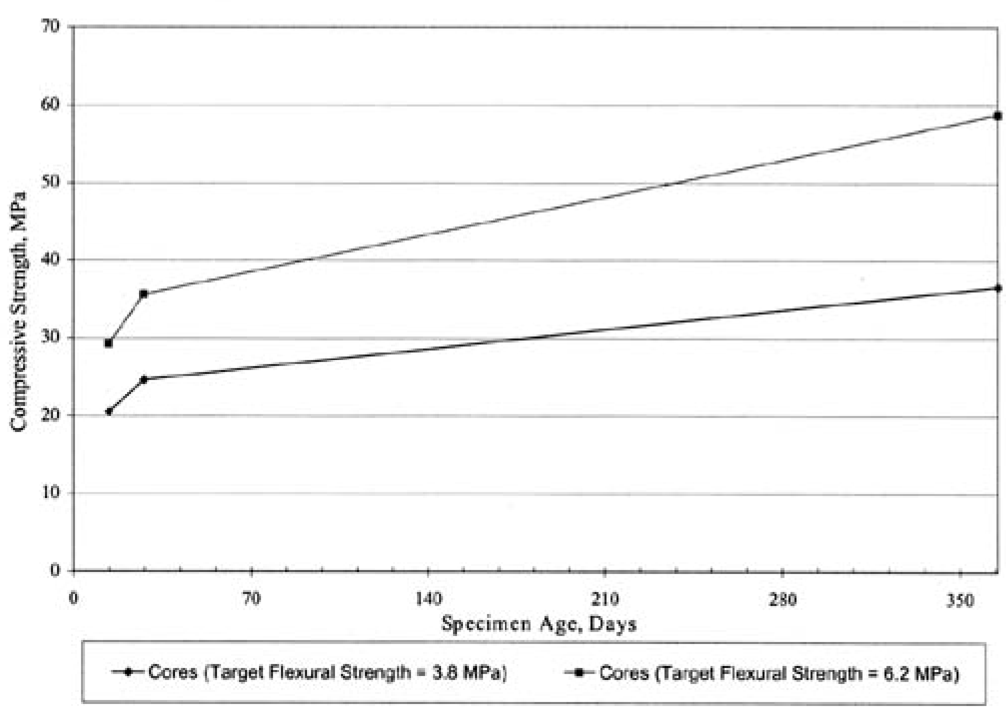

Figure 57. Time-series plots of SPS-2 PCC compressive strength data for State 32.

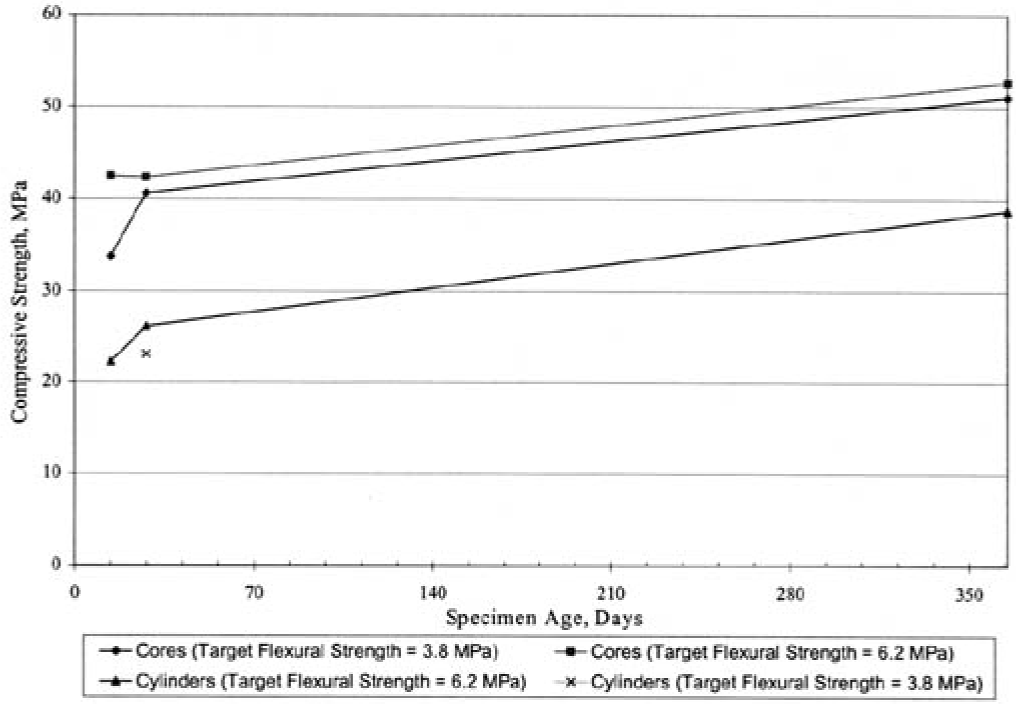

Figure 58. Time-series plots of SPS-2 PCC compressive strength data for State 37.

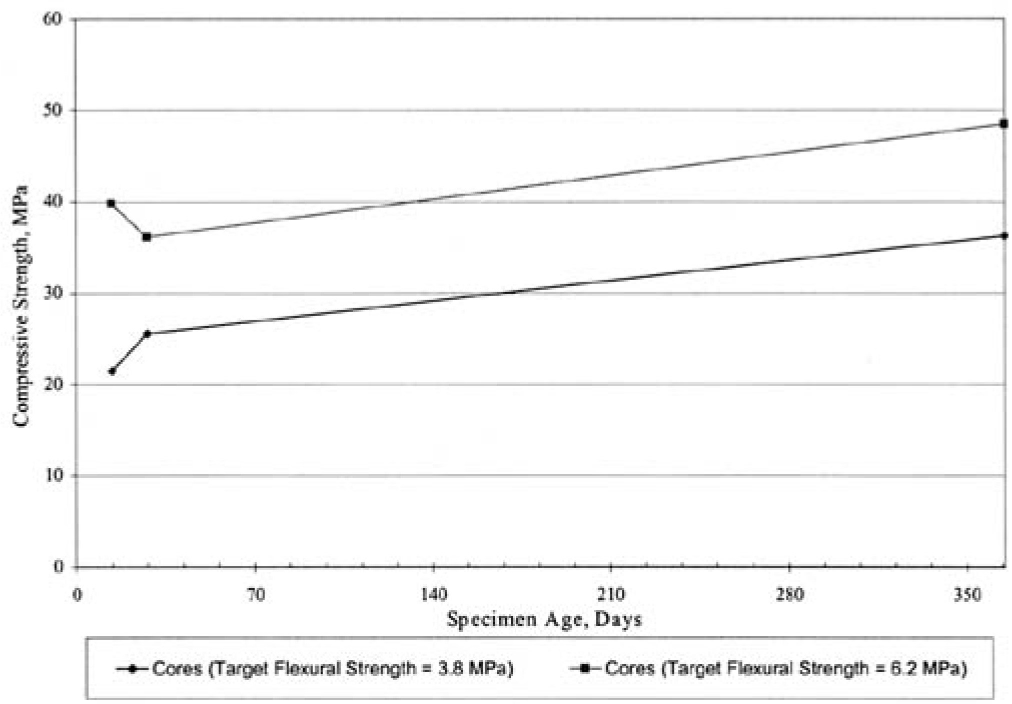

Figure 59. Time-series plots of SPS-2 PCC compressive strength data for State 38.

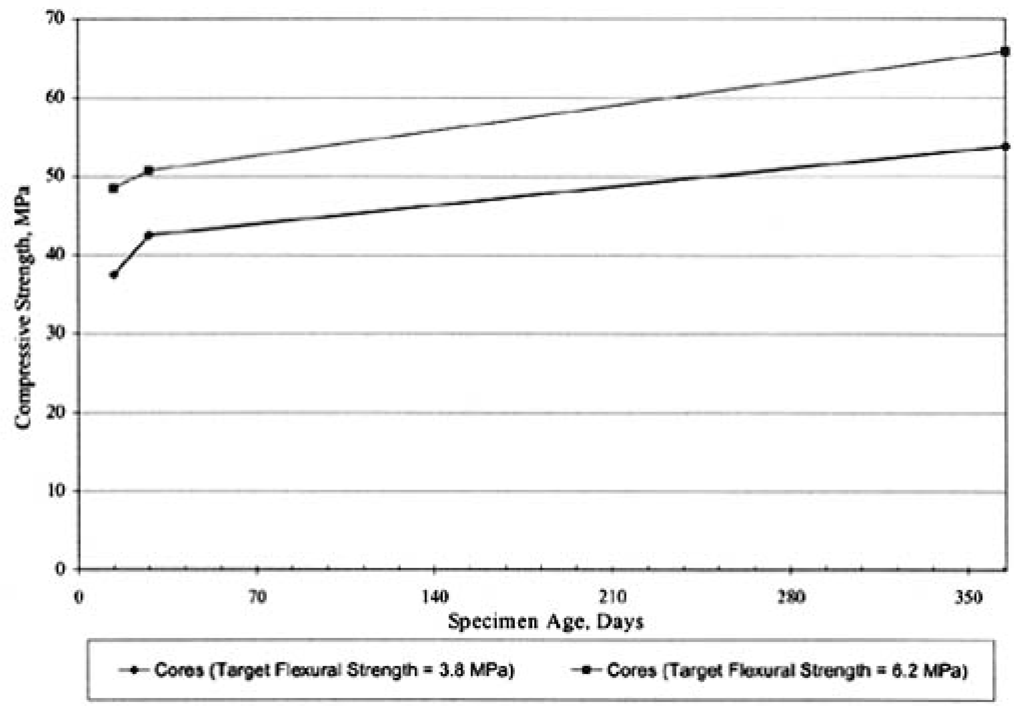

Figure 60. Time-series plots of SPS-2 PCC compressive strength data for State 39.

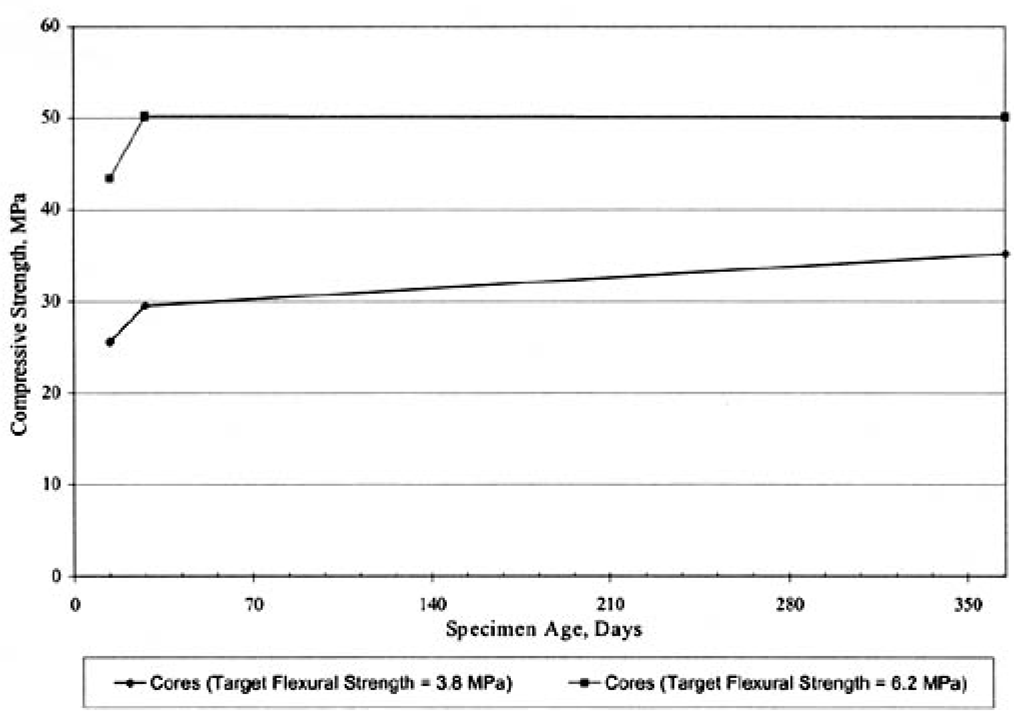

Figure 61. Time-series plots of SPS-2 PCC compressive strength data for State 53.

Each point on the plots shown in figures 43 through 61 represents an analysis cell, and strengths reported are the mean values of strength data from specimens contained within that analysis cell. Most of the test sections have a good representation of time history data. Figures 44, 52, and 58 are the examples of charts where some of the time-series data are missing. These analysis cells are prime candidates for forecasting or backcasting of strength values.

The following observations can be made from figures 43 through 61:

- As expected, the compressive strengths of the PCC layers are much higher than the LCB layers.
- Compressive strength increases with time in most cases. However, in States 37 and 38, some inconsistencies in the time series trends are apparent.
- The rate of increase and magnitudes of compressive strength with time appear reasonable.
- As expected, for PCC layers the compressive strengths for the higher target flexural strength are higher than those for lower target flexural strength, with one exception (State 10).

Time-Series Data: SPS-7 and SPS-8 Data

Figures 62 through 64 present the time-series information of the compressive strength data from three of four SPS-7 projects for which information is available in the LTPP database. Data from one of the projects (located in State 27) could not be plotted because only one of the analysis cells had data, which is inadequate to describe a trend. It can be noted from the figures that the compressive strength increased with time in all cases, suggesting a satisfactory trend.

Figures 63 and 64 had missing time-series information for one of the three analysis cells. Such information can be obtained by extrapolating from trends observed from the existing data.

Considering that very limited information is available for the SPS-7 and SPS-8 experiments, broad-based conclusions on data reasonableness could not be drawn.

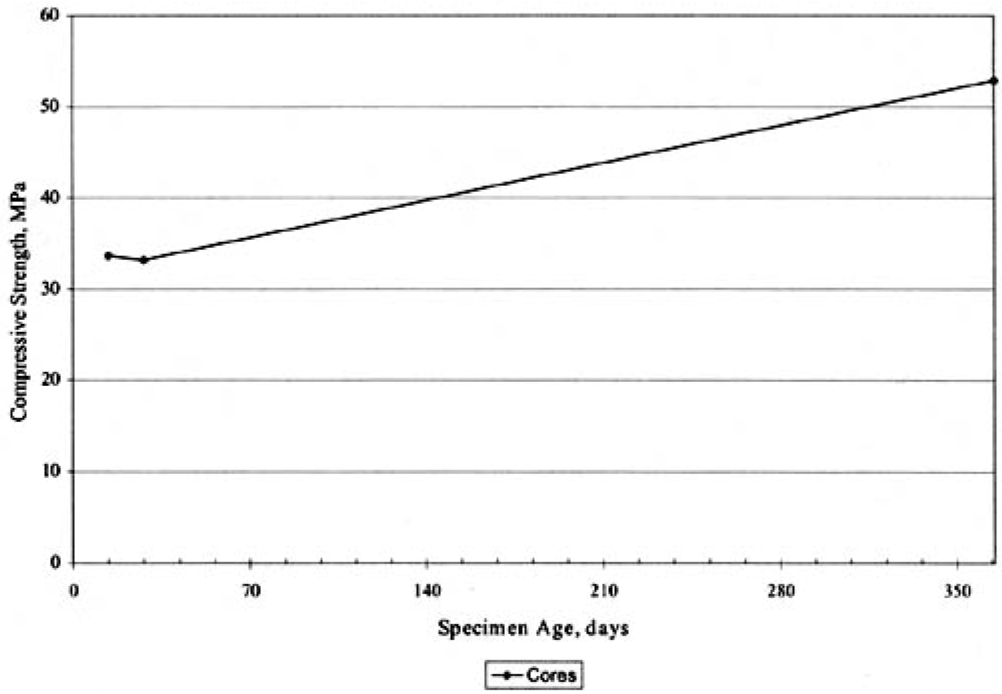

Figure 62. Time-series plots of SPS-7 PCC compressive strength data for State 19.

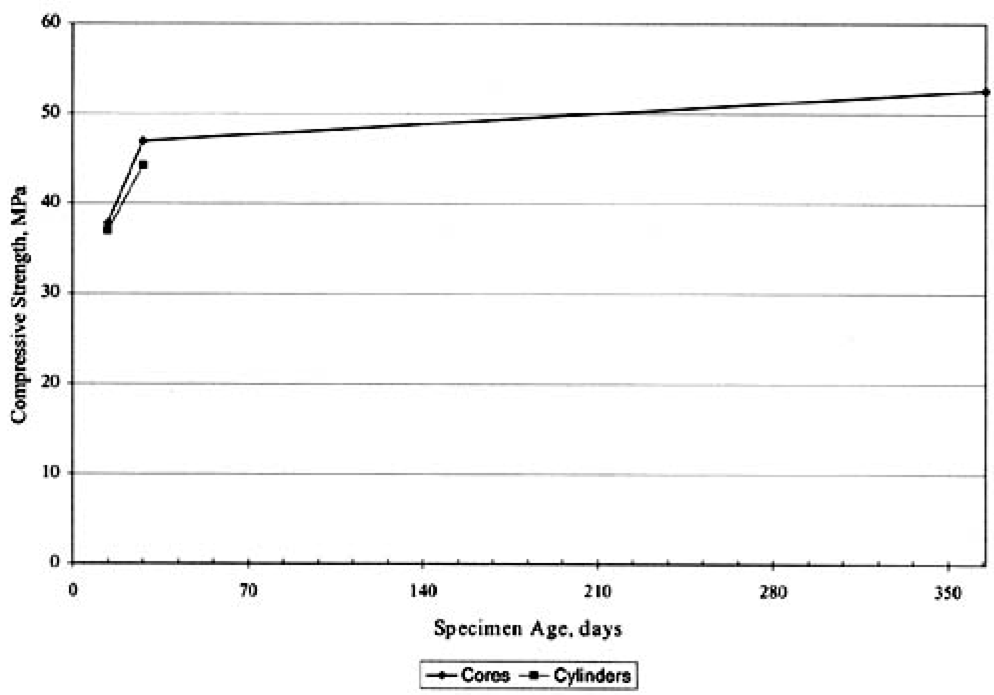

Figure 63. Time-series plots of SPS-7 PCC compressive strength data for State 22.

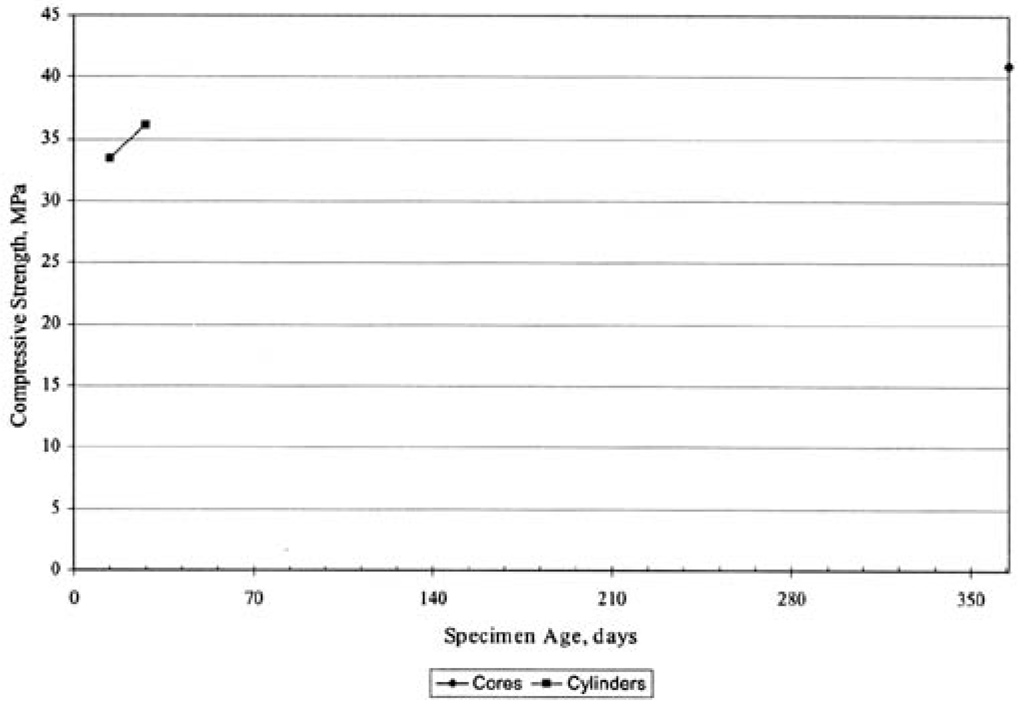

Figure 64. Time-series plots of SPS-7 PCC compressive strength data for State 29.

Compliance with Test Procedure

L/D Ratio

The SHRP P61 protocol suggests that the desirable L/D ratio for the concrete test specimens should be between 1.94 and 2.10, except for thin PCC overlays (e.g., SPS-7 specimens) and specimens sawed off to remove embedded steel. Because the L/D ratio has a significant impact on the measured compressive strength, the protocol specifies correction factors to adjust the measured strength between L/D ratios of 1.0 and 1.8. The protocol also requires the L/D ratio to be kept above 1.0, where possible. If this ratio is less than 1.0, a special comment field is supposed to be added to the TST_PC01 table and a special correction factor applied to the compressive strength data obtained. To examine the range of L/D ratios in TST_PC01 computed L/D ratio data from all records were plotted in figure 65. A majority of the specimens have L/D ratios around 2.0. Further, only one specimen had an L/D ratio less than 1.0. This shows that the testing was performed in accordance with the protocol.

Variability in Compressive Strength Data

Considering that the basis for the SHRP P61 protocol is the AASHTO T22 (ASTM C39) test standard, the latter was consulted to determine estimates on precision of compressive strength data obtained from multiple specimens of the same material. According to ASTM C39 for a well-mixed sample of concrete made under normal laboratory conditions, the maximum COV of compressive strength data obtained from multiple samples should not exceed 2.87 percent, for a single operator test.(3) However, the COV of test results obtained by testing specimens from various locations along a project (field data) is expected to be higher than 2.87 percent due to the added effects of sampling error, the material's natural variability, and within-lot construction variability.

Several studies conducted to estimate the overall variability of 28-day concrete compressive strength results along a given project are summarized in table 56. It can be observed from the table that the COV for PCC 28-day compressive strength test data (obtained from field specimens) ranges from 5 to 18.95 percent. However, a COV of 15 percent, which represents the 90th percentile value of the various COV's summarized in table 56, was adopted conservatively as the typical within-cell variability. In other words, specimens within an analysis cell with computed compressive strength COV of 15 percent or less were not considered anomalous.

Prior to performing within-cell variability analysis, the data pertaining to LCB from the SPS-2 experiment were separated from the data for PCC layers.

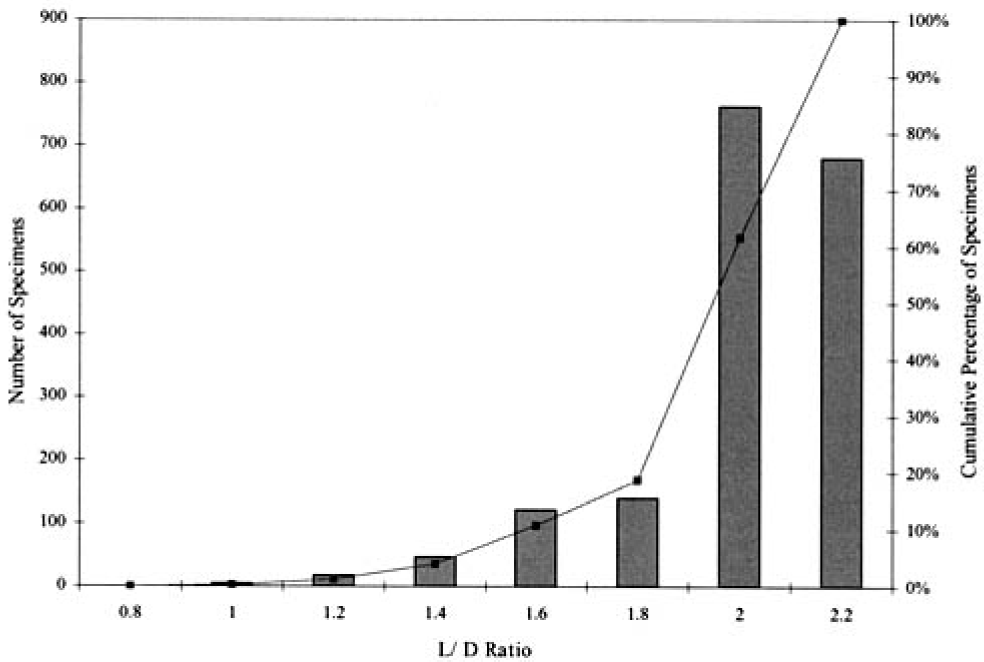

Figure 65. L/D ratio representation in table TST_PC01 (all experiments).

Table 56. Typical variability for 28-day compressive strength data.

Reference	Specimen Type	COV, percent	Standard Deviation
Bartlett et al., 1995[33]	28-day Core	12 to 13	--
Hughes, 1996[13]	28-day Core	17	--
Demos et al., 1995	28-day Cylinders	12.9	--
Darter, 1972[27]	28-day Specimens	9.8 to 16.5	--
Di Cocco, 1973[36]	28-day Cylinders	--	4.98 MPa
Neaman et al., 1967[29]	28-day Cylinder	18.95	--
ACPA, 1995[37]	28-day Specimens	Ready mix 7 to 13 Central mix 5 to 12	--
McMahon et al., 1990[30]	28-day Specimen	--	3.2 to 4.57 MPa

Steele et al., 1966[38]	28-day Cylinders	8 to 15	--
Hughes et al., 1998[31]	28-day Cores 28-day Cylinders	13.410.4	--

Further, only those analysis cells within each material type having multiple specimens were used for analysis; hence, cells with single test values were considered in this analysis.

Figure 66 presents the within-cell COV of compressive strength data from PCC layers. In all, 432 analysis cells with multiple test data were considered. Approximately 81 percent of the analysis cells have within-cell COV at or below the typical 15 percent and were considered acceptable; the remaining data were classified as questionable. The analysis cells with high within-cell COV were marked as anomalous, and the reasons for this variation were investigated.

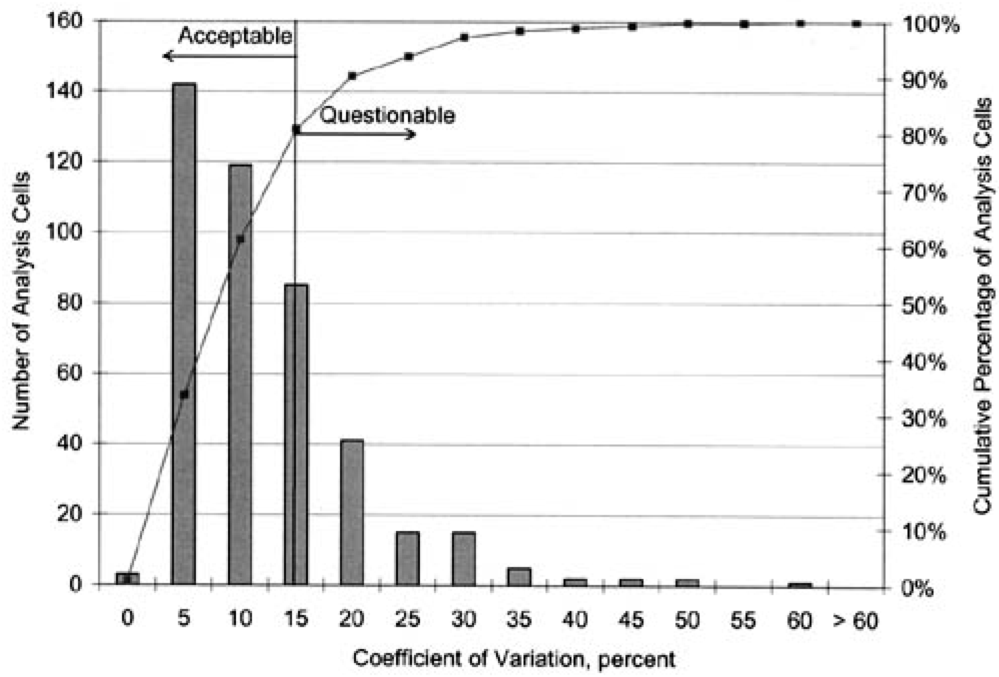

Figure 66. Intersample variability of PCC compressive strength data (all experiments).

Figure 67 presents a similar analysis for the LCB layers from the SPS-2 experiment. In all, 44 cells with multiple samples were available for the analysis. It can be inferred from the figure that about 60 percent of the data satisfy the typical within-cell COV criterion of 15 percent. The remainder of the data was questionable and had to be examined further to identify possible sources of variability.

Identification of Anomalous Data

The discussion presented so far has focused on assessing data availability and quality. Data availability was assessed at two levels. Data quality checks were subsequently performed to verify data reasonableness, protocol compliance, and the reasonableness of within-cell variability. The anomalies in the data noted during the various analyses are described below, along with a discussion of potential causes for their occurrence. The corrective or remedial actions implemented to address some of the anomalous data are also described.

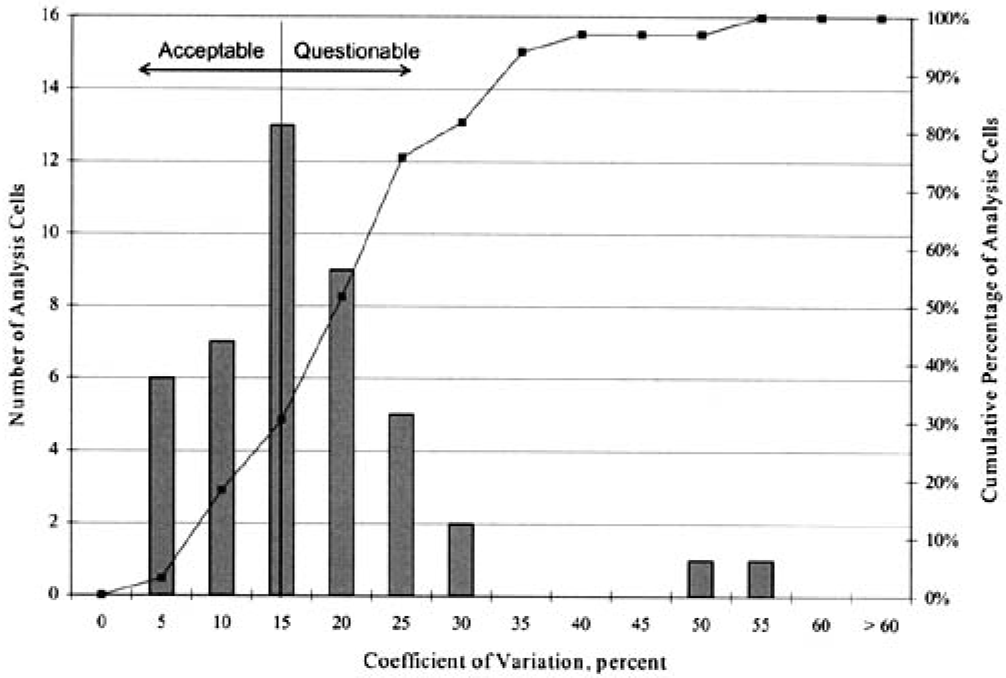

Figure 67. Intersample variability of LCB compressive strength data (SPS-2).

Anomaly 1: Discrepancies in Material Type Descriptions

For 47 records from the SPS-2 experiment, the material type description information in table TST_PC01 did not correspond to that in table TST_L05B. This discrepancy could be the result of an error in either data table. Relevant information about this anomaly was submitted to the FHWA for further investigation and correction. The data in its present state was not included in the development of the representative test values.

Anomaly 2: Single Test Values

Long-Term Strength Data

In analyzing the long-term compressive strength data represented by the GPS, SPS-6, and SPS-7 (original layers) data, seven analysis cells with single test values were found. Further, one analysis cell pertaining to the SPS-2 experiment also had a single estimate of the long-term (365-day) strength (the corresponding time-series strength information, i.e, 14-day and 28-day strength values, for this cell were missing). Although single test values by themselves do not constitute an anomaly, it is questionable whether the results obtained from testing a single specimen can adequately represent the entire test section or experiment.

The single test values were checked for reasonableness by comparing their magnitudes with strength data from similar SPS experiments (see figure 42), and all 10 cells analyzed were found to have reasonable long-term compressive strength data.

Compressive Strength Time-Series Data

When time-series information is available, the reasonableness of an individual analysis cell with single test values was judged by comparing the trend of the data contained in the cell with those from the companion cells making up the time-series plot. Only two such analysis cells were found in the database. Based on a time-series evaluation, only one of the cells was deemed to represent the analysis cell under consideration adequately.

The data deemed fit from the reasonableness evaluation were retained in the representative data table. Data found unreasonable were also retained in the representative data table; however, appropriate comments were applied to such data to alert uses of possible anomalies.

Anomaly 3: Erroneous Specimen Ages

The erroneous specimen ages fell under two categories: negative ages and nonstandard specimen ages. Recall that specimen ages were computed by subtracting the date of testing from the date of sampling (for bulk samples) or date of PCC placement completion (for core samples). A total of 138 records from the SPS-2 and SPS-7 experiments were affected by this anomaly.

Relevant information about this anomaly was submitted to the FHWA for further investigation and correction. The data in its present state were not included in the development of the representative test values.

Anomaly 4: Missing Time-Series Data

It can be observed from tables 51, 52, 54, and 55 that there are gaps in the time-series compressive strength data in some projects (analysis cells with zero specimens tested). An example of such data would be that, for projects with time-series strength data (e.g., 14-, 28-, and 365-day compressive strength), the 28-day and 365- strength data are available but the 14-day value is missing.

A total of 25 analysis cells had missing time-series information. This information pertained to SPS-2, 7, and 8 experiments.

Missing strength time-series data was computed by either forecasting or backcasting from known strength-age relationships. For example, in the example cited above, the 14-day strength can be estimated by extrapolation if either the 28-day or the 365-day strength values are available and their relationships to the 14-day strength is known. For the purposes of this study, compressive strength-age relationships presented in table 57 were used for interpolating or extrapolating the test results.

The age-strength relationships in the table are expressed as normalized ratios with respect to the 28-day value and were developed from analyzing 5,000 concrete prisms and 1,500 concrete cylinders representing nearly 300 combinations of cement type, mix proportions, and curing conditions.[39] In the referenced study, strength ratios were developed for a number of cement types and curing conditions; however, ratios developed for Type I cement (which is the most commonly used cement type) for curing conditions marked "outdoor exposure" and "moist curing" in table 57 were used for computing the missing test values. Note that 14-day strength ratios, not reported in table 57, were linearly interpolated from the 7- and 28-day ratios. The strength ratios for the "outdoor exposure" curing conditions were used for core specimens, and those for "moist curing" were used for cylinder specimens because these curing conditions closely mimic the curing conditions to which the core and specimen samples were subjected.

Table 57. Variation of concrete compressive strength with age and curing conditions.(39)

Age at Test	Strength Ratio for Moist Curing[1]	Strength Ratio for Outdoor Exposure[1]
1 day	0.18	--
3 days	0.46	0.53
7 days	0.70	0.78
28 days	1.00	1
3 months	1.14	1.09
1 year	1.22	1.19
5 years	1.33	1.37
10 years	1.33	1.39
20+ years	1.44	1.42

[1]Ratios based on the testing of several cubes and prisms with varying aspect ratios.

Anomaly 5: High Intersample Variability

About 19 percent of the PCC specimens (81 analysis cells) and 40 percent of the LCB specimens (18 analysis cells) showed higher than typical within-cell variabilities (COV greater than the typical 15 percent).

A closer examination of the protocol compliance, visual examination results, and comments fields of the affected specimens was conducted to determine the causes for the high variability in test results. The following observations were made based on this examination.

- Fifteen of the 81 PCC and five of the 18 LCB analysis cells reported to have excessive COV were within 2 percent of the allowable value of 15 percent.
- Examination of the data for each of the affected specimens did not reveal any obvious testing or sampling anomalies.
- For GPS analysis cells with excessive variability, samples from test number 1 always yielded lower strength values than did the samples from test number 2 for these cells.
- An outlier analysis performed according to ASTM E178 revealed the presence of outliers in six analysis cells.

Based on these observations, the following actions were taken:

- Where no apparent reason for excessive variability could be found, the analysis cell was suitably commented in the representative data set to alert the user.
- Where there is a consistent pattern of data from one test number being greater than the other, comments were provided to indicate the same.
- Where outliers were detected, they were removed from the analysis cells, and the representative test value (mean) and the basic statistics were recomputed. Comments were provided to indicate to the user of the removal of outliers and the outcome of this action on the within-cell variability.

Schema for Representative PCC Compressive Strength Data Table (TST_PC01_REP)

The representative PCC compressive strength data table (TST_PC01_REP) was recommended for inclusion in the LTPP database. The schema for table (TST_PC01_REP) are presented below:

1. Experiment type.
2. Experiment number.
3. SHRP identification number/SPS cell identification number.
4. State code.
5. Layer number.
6. Material code.
7. Construction number.
8. Target strength.
9. Specimen type (cylinder or core).
10. Age of specimen.
11. Number of test results.
12. Mean compressive strength.
13. Maximum compressive strength.
14. Minimum compressive strength.
15. COV.
16. Standard deviation.
17. Source of data.
18. QA_Comment_1.
19. QA_Comment_2.
20. QA_Comment_3.
21. QA_Comment_4.
22. QA_Comment_5.
23. QA_Comment_6.
24. QA_Comment_Other.
25. Record status.

The first seven fields in the schema define the analysis cell used in computing the mean, maximum, and minimum test results for all GPS, SPS-6, and original SPS-7 layers. Fields 8 through 10 are used in addition to these fields to qualify further time-dependent SPS-2, SPS-7, and SPS-8 analysis cells. These results are presented along with other basic statistics, such as number of test data, COV, and standard deviation in fields 11 through 16. Field 17 describes the source of the data (whether the representative test values were computed from original test data from TST_PC06 table or extrapolated using the strength ratios presented in table 57). Finally, comments are provided in fields 18 through 24 to describe the status of the data (e.g., excessive variability, incomplete sampling) based on the QA testing performed. The comments are intended to guide the user in selecting data for analysis and evaluation. The remaining field describes the record status.

11. DETERMINATION OF THE COEFFICIENT OF THERMAL EXPANSION OF PORTLAND CEMENT CONCRETE

Introduction

The CTE is the change in unit length per degree of temperature change. PCC CTE is a very important parameter in concrete pavement analysis because the magnitude of the slab curling stress is directly proportional to this value. Although a value of 9.9x10-6/°C is commonly used in design, the CTE can vary widely as a function of aggregate type and concrete mix design properties, such as the water/cement ratio.

The CTE of PCC is determined using LTPP protocol P63, which provided the basis for AASHTO TP60-00.(2) This protocol is based on a test method and apparatus recently developed by the FHWA. The test is performed either on test cores (obtained in accordance with ASTM C42 or AASHTO T24) or test cylinders (obtained in accordance with ASTM C31/C192 or AASHTO T23/T126).(3, 4)

The referenced test standards and protocols provide guidance on all aspects of material sampling, preparation, testing, computation of test results, and presentation. The test results are stored in the LTPP database after undergoing several levels of QA/QC checks that ensure a reasonable quality of data. Data that were of acceptable quality after the final series of QA/QC checks were classified as level E and were stored in table TST_PC03 in the LTPP database. The following information is maintained under this table:

1. SHRP_ID.
2. State code.
3. Layer number.
4. Test number.
5. Field set.
6. Location number.
7. Sample number.
8. Construction number.
9. Record status.
10. Laboratory code.
11. Sample area number.
12. Thickness, mm.
13. Diameter, mm.
14. CTE, mm/mm/°C.
15. PCC aggregate type.
16. Comment_other.

Material Sampling for the Determination of CTE

Table 58 presents the sampling requirements for PCC CTE testing. It is clear from table 58 that CTE testing was performed on cores obtained primarily from the GPS and SPS-2, SPS-6, SPS-7, and SPS-8 experiments. The table also indicates the minimum number of samples required per layer for the various LTPP SPS experiments, along with the sample locations. For detailed information on sample locations, the appropriate SHRP Experiment Design and Research Plan documents can be consulted. (See references 7, 18 through 20, and 32.) At the present time, there is no information on the minimum number of tests required per layer or sampling location for GPS experiments. However, based on an examination of the data available in TST_PC03, it was observed that only one core specimen was tested for each of the GPS test sections.

Table 58. Sampling for determination of CTE of PCC.

Experiment Type	Layer Type	Test Type	LTPP Designation	LTPP Protocol	Min No. of Tests per Layer	Designated Sampling Location
GPS 1-7 and 9	PCC	CTE	PC03	P63	--	--
SPS-2	PCC	CTE	PC03	P63	2	C42, C99
SPS-6	PCC	CTE	PC03	P63	3	A1 A2 A3
SPS-7	PCC overlay (postconstruction)	CTE (14 day)	PC03	P63	1	C11
SPS-7	PCC overlay (preconstruction)	CTE	PC03	P63	1	C11
SPS-8	PCC	CTE	PC03	P63	1	C18

Sampling information for the GPS sections is unavailable at the present time.

CTE Data Completeness

The first step in assessing data completeness was to link the CTE and related data in TST_PC03 (January 2000 release) in the LTPP database to tables TST_L05B and EXPERIMENT_SECTION for cross-referencing of layer information, experiment type, and other related data. (Data extraction and assembly was described in detail in the introductory chapters of this report.) Subsequently, data completeness was evaluated at two levels. The details of the data completeness assessment are provided below.

Level 1 CTE Data Completeness

Level 1 data completeness evaluation involves determining the amount of CTE data collected at level E (and, therefore, in table TST_PC03) as a percentage of the total amount of data collected at all levels. The findings of this assessment are tabulated in table 59. It is evident from table 59 that all the data currently in the LTPP database table TST_PC03 pertain to GPS sections. The data available in the table at the present time represent 100 percent of the total data collected at all levels.

Table 59. Summary of PCC CTE data available in test table TST_PC03.

Expt.Type	Expt. No.	Total No. of Records at All Levels	Total No. of Records at Level E	No. of Usable Records at Level E	Percent Usable Records at Level E	Total No. of Analysis Cells Represented
GPS	3	67	67	67	100	67
GPS	4	48	48	48	100	48
GPS	5	54	54	54	100	54
GPS	7B	4	4	4	100	4

Definition of Analysis Cells

Also shown in table 59 is the number of analysis cells represented by the data within each GPS experiment. The following fields make up an analysis cell for the data reported from GPS experiment test sections in TST_PC03:

- GPS_SPS.
- EXPERIMENT_NO.
- SHRP_ID.
- STATE_CODE.
- LAYER_NO.
- CONSTRUCTION_NO.

Note that the total number of analysis cells in table 59 equals the total number of records because only one specimen was collected per test section.

Level 2 CTE Data Completeness

Level 2 data completeness evaluation consisted of a check on an analysis cell basis to determine whether the data in test table TST_PC03 satisfied the minimum number of test samples for each layer, as specified in the LTPP sampling and testing program (see table 58). However, this could not be accomplished because the sampling and testing plan for GPS experiments is not specified in the LTPP material sampling and testing program; all the data in the test table currently is from GPS test sections.

CTE Data Quality

Data quality was evaluated for all analysis cells summarized in table 59. The data were initially evaluated for reasonableness by comparing the data with typical values found in the literature. Subsequently, the data were checked for compliance with certain key parameters specified in the test protocol. Details of the data quality evaluation are presented below. A check on intersample variability could not be accomplished for this test type because, as mentioned previously, only one sample was tested per layer.

CTE Data Reasonableness

The reasonableness of the data in the analysis cell was checked by analyzing the magnitudes of the CTE from each individual test. Subsequently, the mean CTE value and standard deviation were computed for subsets of the data grouped according to aggregate material type (e.g., core specimens with limestone or granite as coarse aggregates).

Figure 68 presents a histogram of the distribution of CTE values for all samples in the database. The figure shows that the CTE data range from $7.4*10^{-6}$ to $1.34*10^{-5}$ mm/mm/°C, with a mean value of $1.06*10^{-5}$ mm/mm/°C and a standard deviation of $1.25*10^{-6}$ mm/mm/°C. The data appear to fall within a tight band, as indicated by the COV of 11.8 percent. This is perhaps due to the fact that all the testing for this data element was performed by a single laboratory (the FHWA materials testing laboratory).

A CTE value of $9.9*10^{-6}$ mm/mm/°C is typically used in PCC pavement analysis. When grouped according to coarse aggregate type and concrete mix properties, typical CTE ranges from 7.4 to $13* 10^{-6}$ mm/mm/°C.(11) Both the typical mean value (for all aggregate types grouped together) and range of typical values based on coarse aggregate type and concrete mix properties agree well with the observed values in figure 68. This comparison, along with the fact that the data in the test table exhibit a low COV, implies that the testing was performed in a consistent manner and that the data are reasonable.

Because aggregate type is one of the primary factors affecting the CTE value, an attempt was made to classify the information in table TST_PC03 using this parameter to ascertain data reasonableness further. However, only 56 of 170 records considered had information on aggregate type of the test specimen. Further, five different aggregate types were represented in the 56 records, leaving very little data available for meaningful comparisons of mean values for each aggregate type. Therefore, this analysis was not pursued.

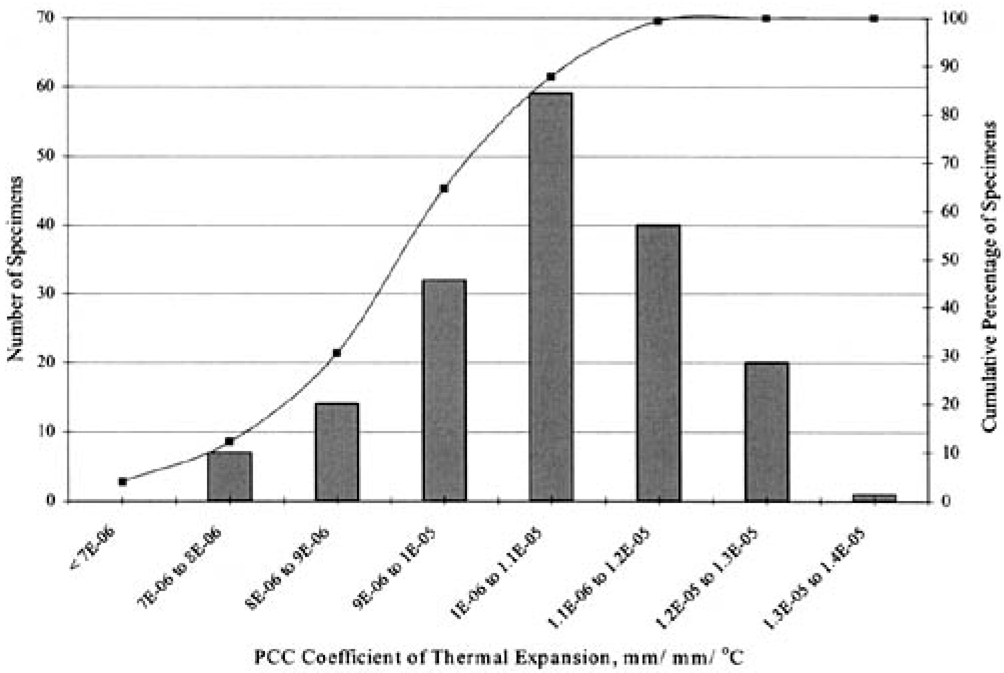

Figure 68. Scatter plot of CTE data for all PCC sections in table TST_PC03.

Compliance with Test Procedure

Minimum Specimen Thickness Requirement

The SHRP P63 protocol states that a length of 180 ± 2 mm is acceptable for CTE testing. Figure 69 presents a scatter plot of the sample thicknesses for all the records in the database. Approximately 50 percent of the specimens satisfy the protocol. Although none of the specimens exceed the upper bound thickness specification of 182 mm, approximately 50 percent of them fall below the lower bound value of 178 mm.

Identification of Anomalies

Data Anomaly: Noncompliance with Protocol

Approximately 50 percent of the specimens did not satisfy the thickness requirement of the protocol. Because this is a new protocol, the impact of nonconformance of the specimen thickness is not well documented. The protocol does not have estimates on precision and bias developed as yet.

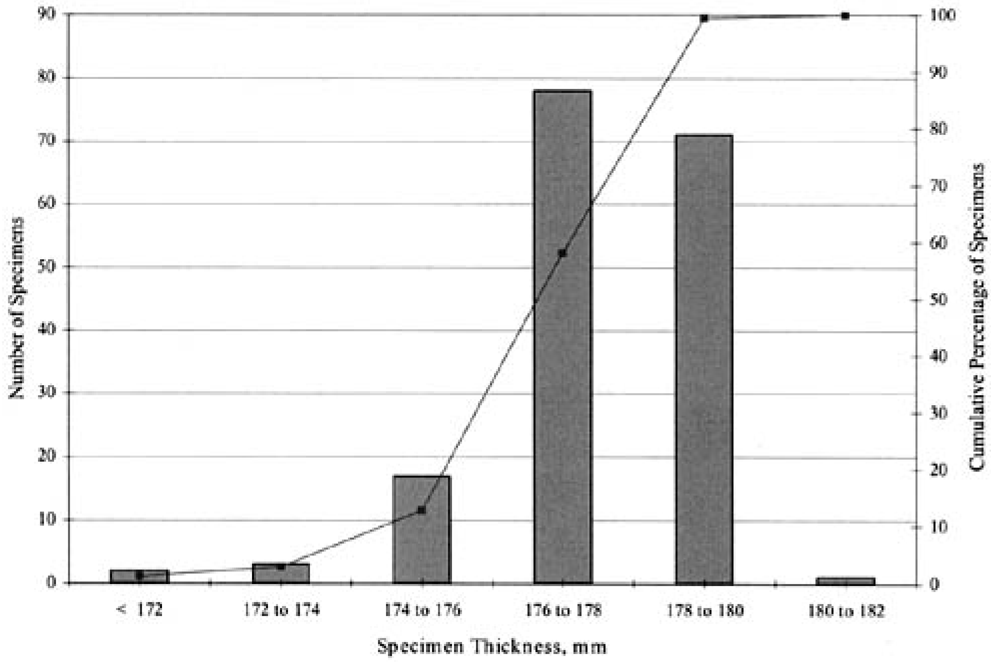

Figure 69. Sample thickness variability for all records in TST_PC03.

Remedial Action

Because the overall quality of the data analyzed appears to be reasonable in terms of magnitude and range of values, it is presumed that the influence is not significant. However, a comment code alerting the user of this deviation from the protocol was included in the representative test table.

Schema for the Representative PCC CTE Data Table (TST_PC03_REP)

A representative PCC CTE data table (TST_PC03_REP) was developed and recommended for inclusion into the LTPP database. Data in table TST_PC03_REP were arranged by analysis cells, with appropriate comments provided to describe the anomalies observed on a cell-by-cell basis. Unlike the other test tables analyzed in this study, the representative data table for TST_PC03 did not contain any basic statistics data, such as standard deviation or COV. These parameters could not be computed because only one test value existed per analysis cell. Nevertheless, the schema provide for such data to be included in table TST_PC03_REP when available, making TST_PC03_REP consistent with the other representative tables developed in this study. The schema for table TST_PC03_REP are presented below:

1. GPS_SPS.
2. Experiment number.
3. SHRP identification number.
4. State code.
5. Layer number.
6. Number of test results.
7. Mean CTE.
8. Maximum CTE.

9. Minimum CTE.
10. COV.
11. Standard deviation.
12. Source of data.
13. QA_Comment_1.
14. QA_Comment_2.
15. QA_Comment_3.
16. QA_Comment_4.
17. QA_Comment_5.
18. QA_Comment_6.
19. QA_Comment_Other.
20. Record status.

The first five fields in the schema define the analysis cell. Fields 6 through 11 present the number of test specimens in the analysis cell, the representative test values (mean), and other basic statistics. Field 12 describes whether the representative test values reported were computed from test data in TST_PC03 or estimated from models. Finally, comments are provided in fields 13 through 19 to describe the quality status of the data (e.g., excessive variability, incomplete sampling, etc.), based on the quality assurance testing performed. The comments are intended to guide the user in selecting data for analysis and evaluation. The final field describes the record status.

12. FLEXURAL STRENGTH OF PORTLAND CEMENT CONCRETE

Introduction

The flexural strength test was performed on PCC concrete beams molded from fresh concrete samples taken during construction. This method of obtaining specimens therefore limited sampling to only newly constructed PCC layers in the SPS experiments. The SHRP test protocol for the determination of PCC flexural strength is SHRP P69, *Flexural Strength of Concrete Using Simple Beam with Third-Point Loading*.[2] It covers the test method for determining the flexural strength of concrete by the use of a simple beam with third-point loading. SHRP P69 is based on ASTM C78, *Standard Test Method for Flexural Strength of Concrete* (Using Simple Beam and Third-Point Loading).[3, 4]

PCC flexural strength results are stored in table TST_PC09 in the LTPP database after undergoing basic QC checks to ensure that common anomalies are identified and corrected or flagged out. Data that were of acceptable quality after the QC checks were classified as level E and are stored in table TST_PC09. The following fields are maintained in table TST_PC09:

1. SHRP_ID.
2. State code.
3. Construction number.
4. Layer number.
5. Field set.
6. Test number.
7. Location number.
8. Sample number.
9. Sample area number.
10. Laboratory code.
11. Test date.
12. Average width.
13. Average depth.
14. Span length.
15. Details of curing history.
16. Moisture condition.
17. Specimen age.
18. Maximum applied load.
19. Modulus of rupture (flexural strength).
20. Comments 1.
21. Comments 2.
22. Comments 3.
23. Comments 4.
24. Comments 5.
25. Comments 6.
26. Comments other.
27. Record status.

Material Sampling for Flexural Strength Testing

Beam specimens were molded from fresh concrete during pavement construction, as directed by the SHRP P69 protocols and the SPS Construction Guidelines.[18,19,23] Sampling for the SPS experiments was dependent on both the experiment type and individual test section characteristics. Some of the individual test section characteristics included target flexural strength and layer thickness. The molded specimens were prepared according to procedures outlined in SHRP P69 and ASTM C78 (e.g., curing, sample identification marking) before being shipped to certified laboratories for testing.(2,3,4) Specimen preparation consisted of taking fresh PCC samples at designated locations within the monitoring sections along the entire SPS experiment (which consist of several adjacent SPS test sections) and molding them into beams to be tested. For each "bulk" fresh concrete sample taken, nine beams were molded in the field to determine (using three specimens each) 14-day, 28-day, and 1-year PCC flexural strength.

Full details of the sampling plans, material preparation, and testing are presented in the relevant SHRP protocols, AASHTO test procedures, and the SPS Data Collection Guidelines.(18,19,23)

Flexural Strength Data Completeness

The first step in assessing data completeness was to extract and assemble the flexural strength data available in table TST_PC09. This process was described in detail in the introductory chapters of this report.(37) Table TST_PC09 contained data from only the SPS experiments. The January 2000 release of table TST_PC09 was used for analyses.

Level 1--Flexural Strength Data Completeness

A summary of all the flexural strength test data available in the LTPP database is presented in table 60. Flexural strength data were not required (and, therefore, not collected) for SPS-4 and SPS-5 pavements. The LTPP database has no flexural strength information for GPS experiments. Flexural strength data that were collected but not currently at level E either failed the QA/QC checks or are in the process of QA/QC and were classified as levels A to D. Table 60 shows that the level E data available represented 28 analysis cells. A histogram of data availability for the SPS experiments is shown as figure 70.

Table 60. Summary of flexural strength data available in LTPP database table TST_PC09.

Experiment Type	Experiment Number	Total Number of Specimens at All Levels	Total Number of Specimens at Level E	Percentage of Specimens at Level E	Total Number of PCC Layers Represented[1]
SPS	1	12	0	0	--
SPS	2	282	274	97	23
SPS	2S[2]	80	0	0	--
SPS	7	36	28	77	3
SPS	7S[2]	6	0	0	--
SPS	8	11	10	91	2

[1]SPS-2 experiments sections with different target strengths and SPS-7 sections with different target thicknesses were considered as different layers. SPS-2 and SPS-7 sections, therefore, had two PCC layers per experiment, whereas SPS-8 experiments had one. The total number of analysis cells represented by these layers was 90.
[2]Supplementary test sections.

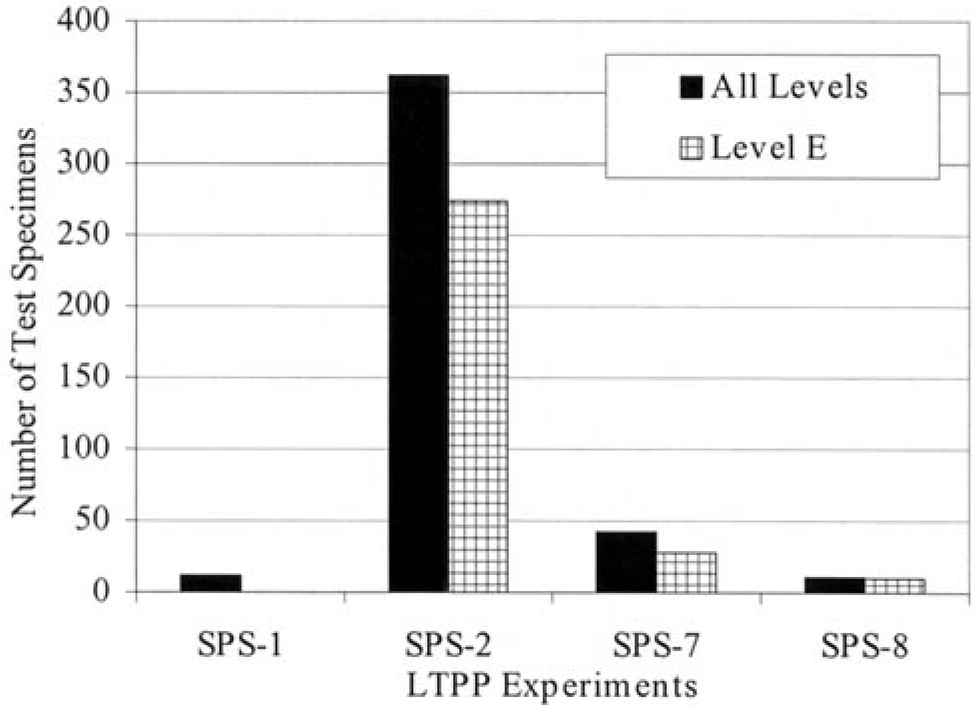

Figure 70. Histogram of flexural strength data availability for SPS pavement sections.

Analysis cells were defined based on the sampling requirements described in relevant SHRP documents. The parameters used to define analysis cells included layer description (PCC), specimen age at testing (14- or 28-day), target strength, and target thickness. For the LTPP SPS experiments with flexural strength data evaluated, analysis cell was defined as follows:(2)

- SPS-2 experiments.
  - Test sections with target PCC flexural strength of 3.8 MPa and target age 14 days.
  - Test sections with target PCC flexural strength of 3.8 MPa and target age 28 days.
  - Test sections with target PCC flexural strength of 3.8 MPa and target age 365 days.
  - Test sections with target PCC flexural strength of 6.2 MPa and target age 14 days.
  - Test sections with target PCC flexural strength of 6.2 MPa and target age 28 days.
  - Test sections with target PCC flexural strength of 6.2 MPa and target age 365 days.
- SPS-7 experiments.
  - Test sections with target PCC thickness of 75 mm and target age 14 days.
  - Test sections with target PCC thickness of 75 mm and target age 28 days.
  - Test sections with target PCC thickness of 75 mm and target age 365 days.
  - Test sections with target PCC thickness of 125 mm and target age 14 days.
  - Test sections with target PCC thickness of 125 mm and target age 28 days.
  - Test sections with target PCC thickness of 125 mm and target age 365 days.
- SPS-8 experiments.
  - Test sections with target age 14 days.
  - Test sections with target age 28 days.
  - Test sections with target age 365 days.

Level 2--Flexural Strength Data Completeness

Level 2 data completeness consisted of checking each analysis cell with flexural strength data to determine whether the minimum number of required tests were performed and reported in the LTPP database at level E. This check will identify test sections with possible sampling bias, because the LTPP material sampling guide recommends taking random samples at predetermined locations within the test section to obtain representative test results. The method for determining level 2 data completeness was as follows:

1. Compute the number of test specimens molded and tested for each cell with results reported at level E.
2. Compare the number of test specimens molded and tested for each cell to the minimum number of tests required.
3. Cells with the minimum number of tests performed and reported at level E are categorized as complete, whereas those with less than the minimum were classified as incomplete.

Table 61 presents a summary of the minimum number of tests required for each cell. The recommended minimum number of tests is given according to specimen target strength or thickness and age at testing for SPS experiments (analysis cell). A summary of level 2 data completeness for flexural strength data reported in table TST_PC09 is presented in table 62.

Table 62 shows a total of 72 analysis cells representing 12 SPS-2 experiments with flexural strength data. Three of the 12 experiments did not have data representing all possible analysis cells based on sampling requirements. For the individual analysis cells within the experiments, 76 percent (55 of 72) had complete data. Table 62 shows that two SPS-7 experiments had flexural strength data; five of the 12 possible analysis cells within the SPS-7 experiments had complete data. Two SPS-8 experiments had test data, and three of the six possible analysis cells with data within the SPS-8 experiment were classified as complete. It must be noted that analysis cells with insufficient or incomplete sampling data may have a potential sampling bias that could skew average test results and make them unrepresentative of the test sections or analysis cells as a whole.

Summary of Flexural Strength Data Availability

The focus of this section was to evaluate flexural strength data availability in table TST_PC09 in the LTPP database. The first task was to access the LTPP database to obtain information on all PCC flexural strength data available. The next step was to determine how many of the test results had successfully passed QA/QC checks and were at level E. The level E data were further examined to determine whether the minimum number of tests required for each analysis cell was performed and reported at level E.

Of the 427 molded specimens tested from various SPS experiments, 73 percent passed QA/QC and are present in the table TST_PC09 (level E data). The 312 specimens at level E represented 90 analysis cells. However, only 71 cells from the different test sections within the SPS experiments had some or all the test data required. Of the 71 cells with flexural test results, 84 percent (62 of 74) had the required minimum number of 3 specimens tested and reported. The statistics presented do not include test results from SPS supplementary experiments.

Table 61. Sampling for determination of in-place concrete flexural strength.(18,19,23)

Experiment Type	Layer Material Type	Target Age, days	Target Compressive Strength, MPa	Target Thickness, mm	LTPP Designation	SHRP Test Protocol	Minimum Number of Tests	Minimum Number of Tests per Cell	Sampling Location[1]
SPS-2	PCC	14	3.8	--	PC09	P69	3	3	B21-B23
SPS-2	PCC	28	3.8	--	PC09	P69	3	3	B21-B23
SPS-2	PCC	365	3.8	--	PC09	P69	3	3	B21-B23
SPS-2	PCC	14	6.2	--	PC09	P69	3	3	B24-B26
SPS-2	PCC	28	6.2	--	PC09	P69	3	3	B24-B26
SPS-2	PCC	365	6.2	--	PC09	P69	3	3	B24-B26
SPS-7	PCC	14	--	75	PC09	P69	3	3	FC1 FC2 FC3
SPS-7	PCC	28	--	75	PC09	P69	3	3	FC1 FC2 FC3
SPS-7	PCC	365	--	75	PC09	P69	3	3	FC1 FC2 FC3
SPS-7	PCC	14	--	125	PC09	P69	3	3	FC4 FC5 FC6
SPS-7	PCC	28	--	125	PC09	P69	3	3	FC4 FC5 FC6
SPS-7	PCC	365	--	125	PC09	P69	3	3	FC4 FC5 FC6
SPS-8	PCC	14	--	--	PC09	P69	3	3	FC1 FC2 FC3
SPS-8	PCC	28	--	--	PC09	P69	3	3	FC1 FC2 FC3
SPS-8	PCC	365	--	--	PC09	P69	3	3	FC1 FC2 FC3

[1]No test data were reported for GPS experiments. Full details of sampling locations can be obtained from references 18, 19, and 23.

Table 62. Summary of flexural strength data available for SPS experiments.

State Code	SPS Experiment Type	SPS-2 Target Strength, MPa	SPS-7 Target Thickness, mm	Specimen Age, days	Number of Specimens Tested	Target Minimum	Minimum Satisfied?
4	SPS-2	3.8	--	14	3	3	Yes
4	SPS-2	3.8	--	28	3	3	Yes
4	SPS-2	3.8	--	365	3	3	Yes
4	SPS-2	6.2	--	14	6	3	Yes
4	SPS-2	6.2	--	28	6	3	Yes
4	SPS-2	6.2	--	365	6	3	Yes
5	SPS-2	3.8	--	14	5	3	Yes
5	SPS-2	3.8	--	28	5	3	Yes
5	SPS-2	3.8	--	365	5	3	Yes
5	SPS-2	6.2	--	14	2	3	No
5	SPS-2	6.2	--	28	2	3	No
5	SPS-2	6.2	--	365	2	3	No
8	SPS-2	3.8	--	14	9	3	Yes
8	SPS-2	3.8	--	28	9	3	Yes
8	SPS-2	3.8	--	365	7	3	Yes
8	SPS-2	6.2	--	14	9	3	Yes
8	SPS-2	6.2	--	28	9	3	Yes
8	SPS-2	6.2	--	365	9	3	Yes
10	SPS-2	3.8	--	14	3	3	Yes
10	SPS-2	3.8	--	28	3	3	Yes
10	SPS-2	3.8	--	365	3	3	Yes
10	SPS-2	6.2	--	14	3	3	Yes
10	SPS-2	6.2	--	28	2	3	No
10	SPS-2	6.2	--	365	2	3	No
19	SPS-2	3.8	--	14	3	3	Yes
19	SPS-2	3.8	--	28	3	3	Yes
19	SPS-2	3.8	--	365	3	3	Yes
19	SPS-2	6.2	--	14	3	3	Yes
19	SPS-2	6.2	--	28	3	3	Yes
19	SPS-2	6.2	--	365	3	3	Yes
20	SPS-2	3.8	--	14	7	3	Yes
20	SPS-2	3.8	--	28	7	3	Yes
20	SPS-2	3.8	--	365	7	3	Yes

20	SPS-2	6.2	--	14	6	3	Yes
20	SPS-2	6.2	--	28	5	3	Yes
20	SPS-2	6.2	--	365	4	3	Yes
26	SPS-2	3.8	--	14	0	3	No
26	SPS-2	3.8	--	28	0	3	No
26	SPS-2	3.8	--	365	3	3	Yes
26	SPS-2	6.2	--	14	0	3	No
26	SPS-2	6.2	--	28	0	3	No
26	SPS-2	6.2	--	365	3	3	Yes
32	SPS-2	3.8	--	14	3	3	Yes
32	SPS-2	3.8	--	28	3	3	Yes
32	SPS-2	3.8	--	365	3	3	Yes
32	SPS-2	6.2	--	14	3	3	Yes
32	SPS-2	6.2	--	28	3	3	Yes
32	SPS-2	6.2	--	365	3	3	Yes
37	SPS-2	3.8	--	14	0	3	No
37	SPS-2	3.8	--	28	0	3	No
37	SPS-2	3.8	--	365	2	3	No
37	SPS-2	6.2	--	14	0	3	No
37	SPS-2	6.2	--	28	0	3	No
37	SPS-2	6.2	--	365	0	3	No
39	SPS-2	3.8	--	14	3	3	Yes
39	SPS-2	3.8	--	28	3	3	Yes
39	SPS-2	3.8	--	365	3	3	Yes
39	SPS-2	6.2	--	14	3	3	Yes
39	SPS-2	6.2	--	28	3	3	Yes
39	SPS-2	6.2	--	365	3	3	Yes
53	SPS-2	3.8	--	14	4	3	Yes
53	SPS-2	3.8	--	28	4	3	Yes
53	SPS-2	3.8	--	365	4	3	Yes
53	SPS-2	6.2	--	14	3	3	Yes
53	SPS-2	6.2	--	28	3	3	Yes
53	SPS-2	6.2	--	365	3	3	Yes
55	SPS-2	3.8	--	14	3	3	Yes
55	SPS-2	3.8	--	28	3	3	Yes
55	SPS-2	3.8	--	365	0	3	No
55	SPS-2	6.2	--	14	4	3	Yes
55	SPS-2	6.2	--	28	2	3	No
55	SPS-2	6.2	--	365	0	3	No
22	SPS-7	--	75	14	4	3	Yes

22	SPS-7	--	75	28	2	3	No
22	SPS-7	--	75	365	0	3	No
22	SPS-7	--	125	14	3	3	Yes
22	SPS-7	--	125	28	3	3	Yes
22	SPS-7	--	125	365	0	3	No
29	SPS-7	--	75	14	0	3	No
29	SPS-7	--	75	28	8	3	Yes
29	SPS-7	--	75	365	0	3	No
29	SPS-7	--	125	14	0	3	No
29	SPS-7	--	125	28	8	3	Yes
29	SPS-7	--	125	365	0	3	No
8	SPS-8	--	--	14	3	3	Yes
8	SPS-8	--	--	28	3	3	Yes
8	SPS-8	--	--	365	0	3	No
39	SPS-8	--	--	14	3	3	Yes
39	SPS-8	--	--	28	1	3	No
39	SPS-8	--	--	365	0	3	No

Flexural Strength Data Quality

Data quality evaluation consisted of a determination of whether the test results were reasonable and assessing whether there was variability within each analysis cell. Results of the evaluation are discussed in the next few sections.

Data Reasonableness

Data reasonableness was assessed by observing trends in time-series plots (flexural strength vs. specimen age). The observed trends were evaluated to determine whether they were in agreement with engineering and analytical expectations. Figures 71 through 77 present examples of time-series plots for SPS-2, SPS-7, and SPS-8 experiments. The plots are grouped according to experiment type and PCC target flexural strength or thickness, where relevant.

All the plots except figure 71 show expected trends (increasing modulus of rupture [flexural strength] with age). Even though the 365-day flexural strength value for figure 71 is less than the 28-day values, the actual difference in magnitude was not significant (approximately 4 percent difference). Plots for some PCC layers in SPS-2 experiments for States 26 and 37 and SPS-7 experiments in State 29 were not presented because they had no data at all or single data points (a data point for these plots represents the mean test value of a given analysis cell).

Data from analysis cells with less than the required number of test results were included in the plots presented. The aim was to determine whether representative values from such cells showed any bias or unexpected test values. The plots show that the data in such cells were reasonable and as expected.

Flexural Strength Data Variability

Analysis cells were classified as acceptable or questionable, based on whether the level of variability within such cells was typical or excessive. Typical variability was determined by: 1) reviewing the test protocols and standards for recommended precision and 2) reviewing typical variability as reported in the literature.

ASTM C78 recommends the following testing precision or variability:[3]

The coefficient of variation of test results has been observed to be dependent on the strength levels of the beams. The single operator coefficient of variability has been found to be 5.7 percent. The multilaboratory coefficient of variability has been found to be 7.0 percent.

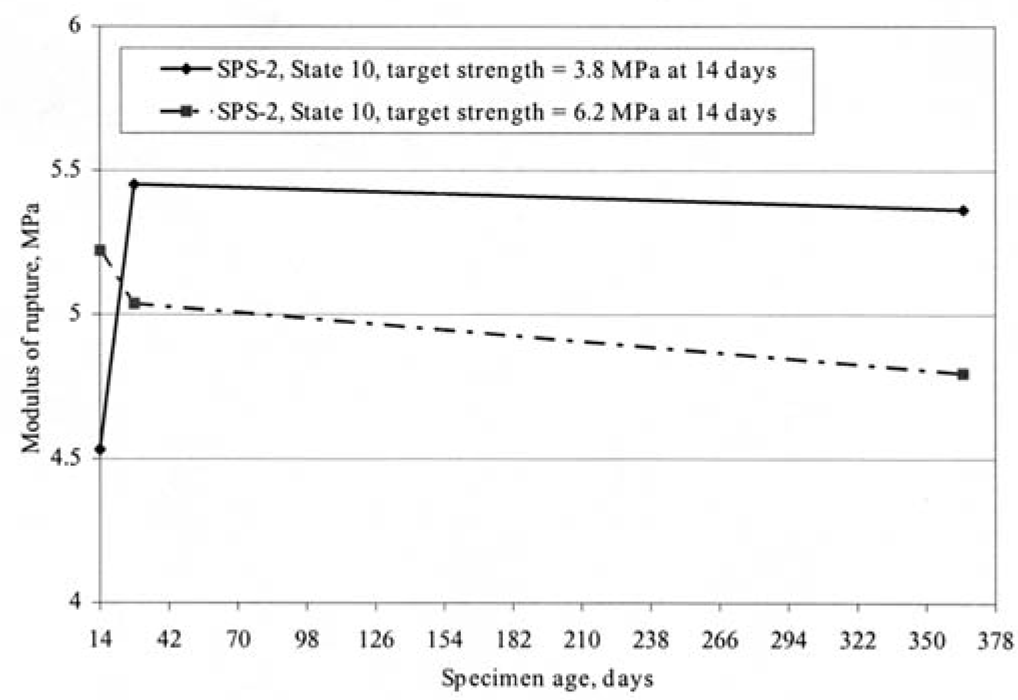

Figure 71. Time-series plot of modulus of rupture versus specimen age for SPS-2 experiments in State 10.

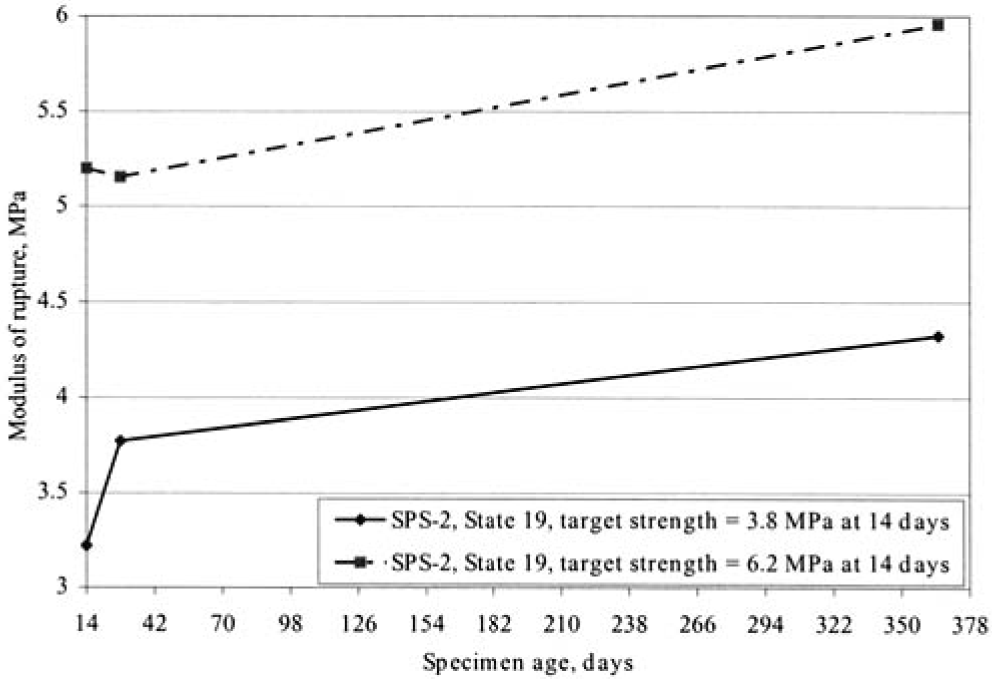

Figure 72. Time-series plot of modulus of rupture versus specimen age for SPS-2 experiments in State 19.

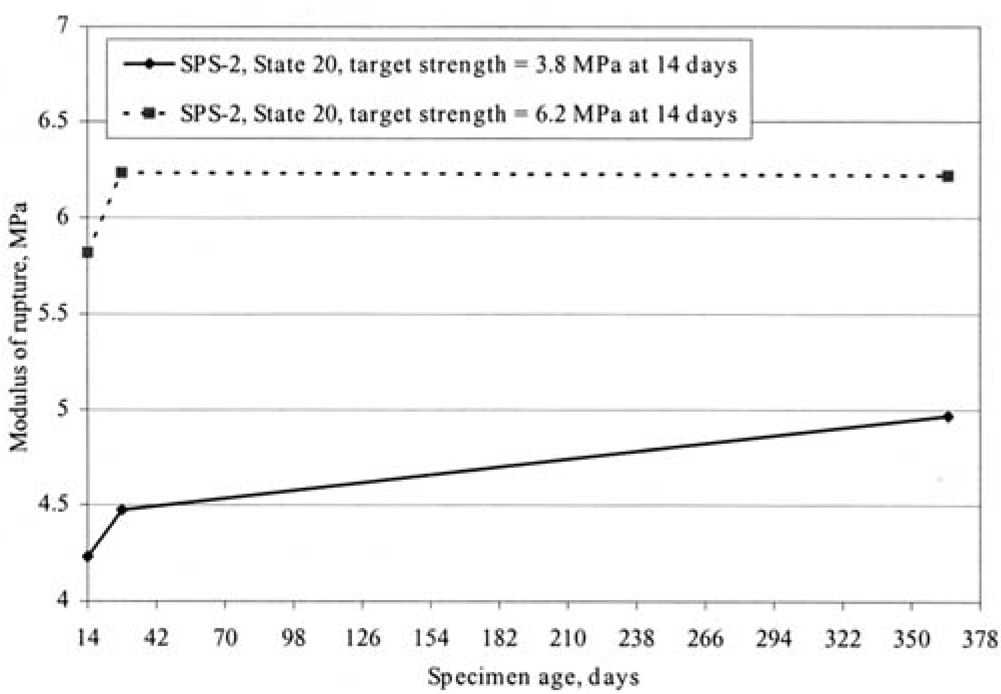

Figure 73. Time-series plot of modulus of rupture versus specimen age for SPS-2 experiments in State 20.

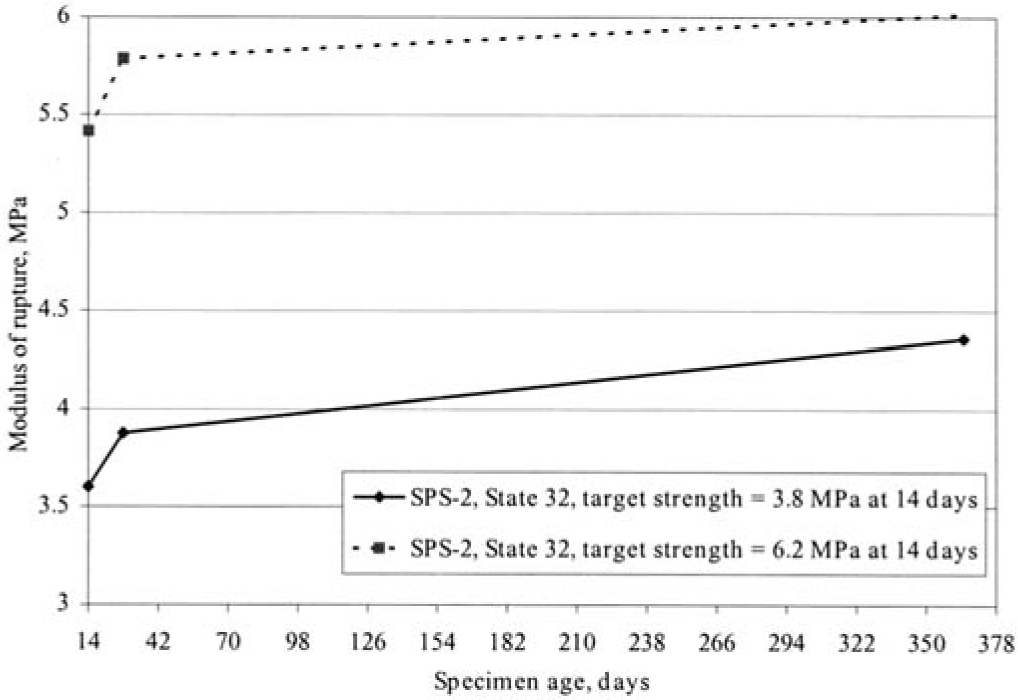

Figure 74. Time-series plot of modulus of rupture versus specimen age for SPS-2 experiments in State 32.

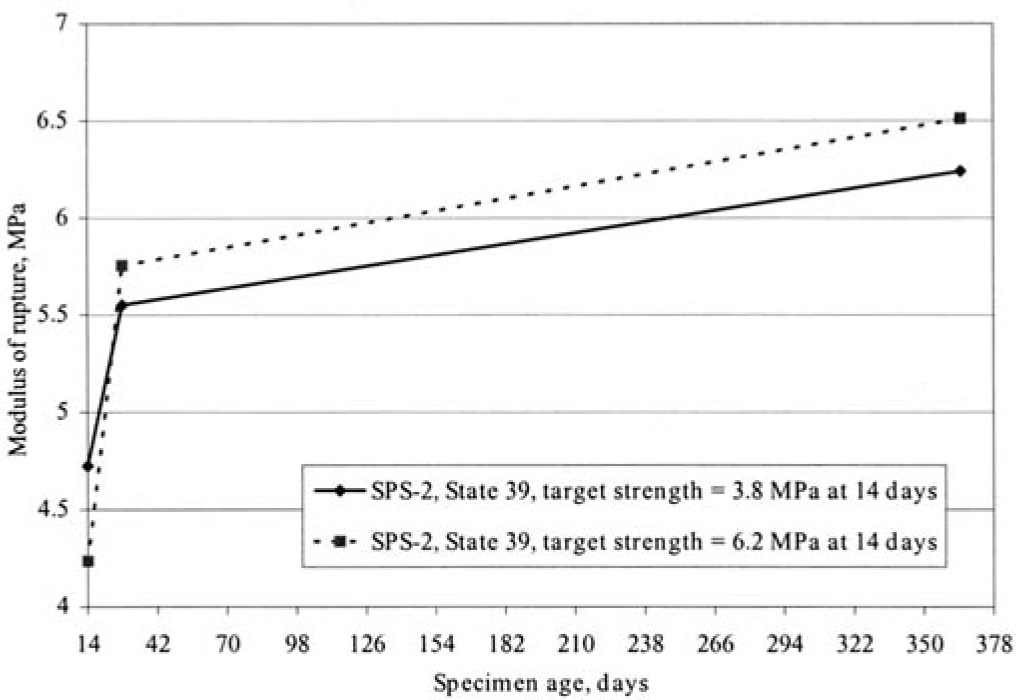

Figure 75. Time-series plot of modulus of rupture versus specimen age for SPS-2 experiments in State 39.

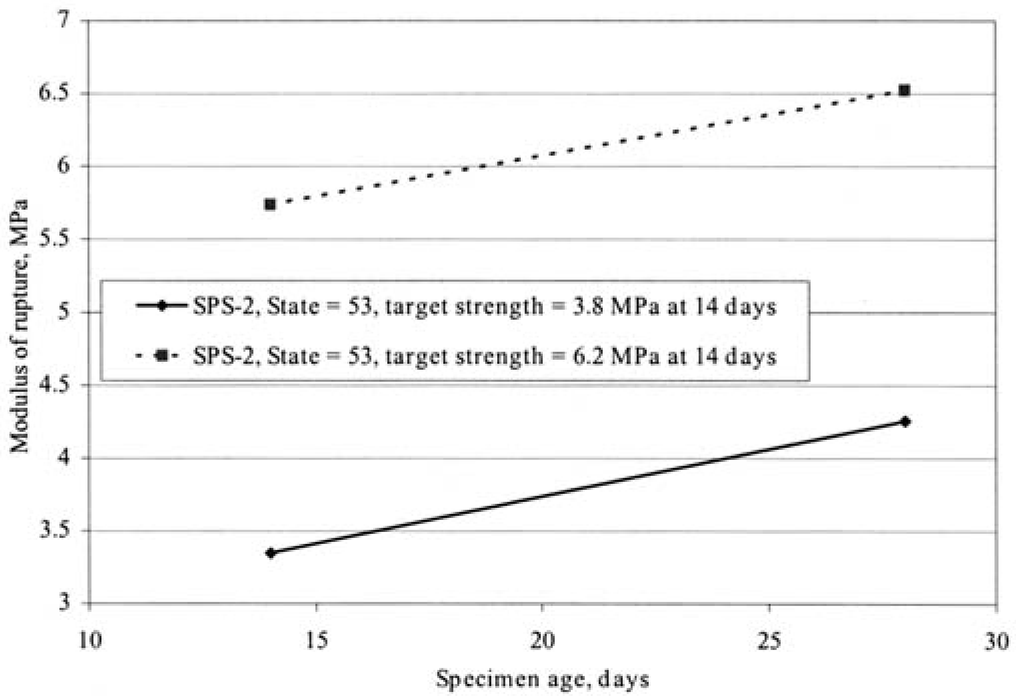

Figure 76. Time-series plot of modulus of rupture versus specimen age for SPS-2 experiments in State 53.

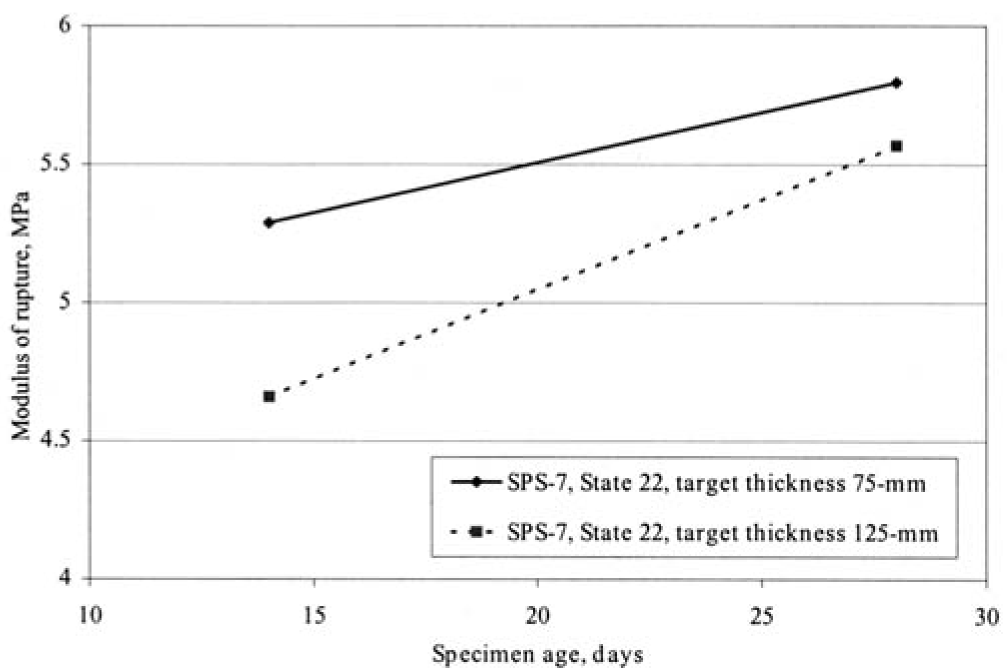

Figure 77. Time-series plot of modulus of rupture versus specimen age for SPS-7 experiment in State 22.

This implies that the PCC material's natural variability and testing and sampling (very controlled sampling in the laboratory) can be expected to be as high as 7 percent COV. The 7 percent COV recommended will definitely be increased when the sampling and QC methods during field construction of PCC pavements are factored into determining the typical variability expected from field samples. Several studies have reported typical variability (from field tests) in flexural strength test results ranging from 5 to 12.7 percent, as summarized in table 63.

Table 63. Typical allowable variability for flexural strength.

Data Element	Reference	Coefficient of Variation, percent
Flexural Strength	Demos et al.(35)	8.1
Flexural Strength	Darter(27)	7.6 to 9.7
Flexural Strength	Hughes et al. 1998(31)	10.4 to 12.7
Flexural Strength	Indiana Contractors QC(31)	5
Flexural Strength	Lytton and Zollinger(32)	8 to 10
Flexural Strength	Indiana DOT QC(31)	5.8

For this study, a COV of 12 percent was adopted and used in defining acceptable and questionable data. Twelve percent corresponds to the 90th percentile of the range of COV from 7 to 12.7 percent. The 90th percentile is conservative and incorporates all reasonable estimates of COV, while eliminating possible outliers. Figure 78 shows the distribution of estimated COV for all PCC layer combinations with multiple flexural strength data. Approximately 87 percent of the data had acceptable variability. Analysis cells with excessive variability were further evaluated to determine the reasons for excessive variability and to rectify possible anomalies, where feasible.

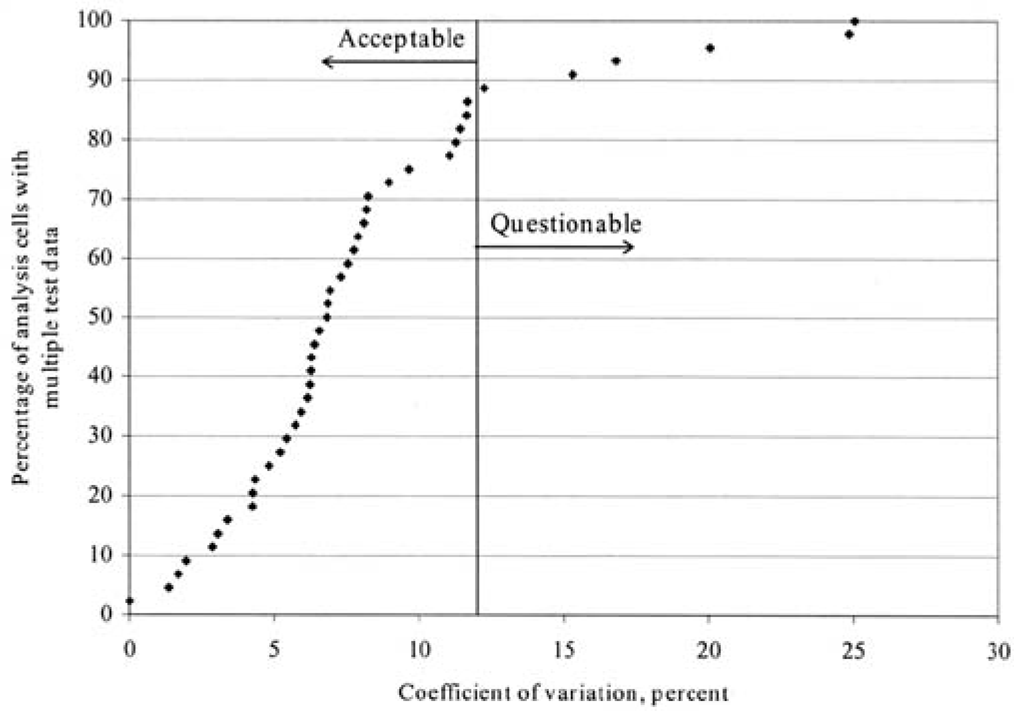

Figure 78. Distribution of within-cell COV for PCC flexural strength data..

Summary of Flexural Strength Data Evaluation

Data quality was evaluated by computing the within-cell COV for each of the analysis cells with multiple test data and comparing it with the typical values expected (12 percent). Analysis cells with a COV of less than 12 percent were classified as acceptable, whereas those with greater than 12 percent were classified as questionable. The following is a summary of the state of the flexural strength data in LTPP database table TST_PC09:

- The 312 specimens at level E in table TST_PC09 represented 90 analysis cells from different SPS experiments.
    - Nineteen analysis cells had no data at level E.
    - Nine analysis cells had two or fewer test results at level E.
    - Sixty-two analysis cells had three or more test results at level E.
- Eighty-seven percent (62 of 71) of the cells with two or more test specimens had acceptable variability (COV < 12 percent).

Identification of Anomalous Data

Two general types of anomalies were identified: excessive variability and insufficient/no test data. They are presented and discussed in the next few sections.

Anomaly 1: Analysis Cells with Excessive Variability

There are various causes of excessive variability in test data. Some of the common causes include the following:

1. Erroneous test results due to defects in the test specimen or testing process.
2. Erroneous test data caused by incorrect data entries.
3. Variability in construction and mix preparation along the test section.
4. Outlier present for no apparent reason.

Erroneous Test Results due to Defects in Test Specimen or Testing Process

The test specimens used for flexural strength testing were molded from PCC samples taken during construction. This ensured that there was almost no occurrence of common defects observed from PCC cores such as cracking, voids, uneven surface, and aggregate segregation. However, some of the test specimens' dimensions were smaller than recommended. Testing specimen beams with relatively small dimensions could result in a mode of fracture not representative of a beam loaded in flexure, as required by ASTM C78[3]. Figure 79 shows a diagram of the flexural test of concrete using the third-point loading method, as directed by ASTM C78.[11]

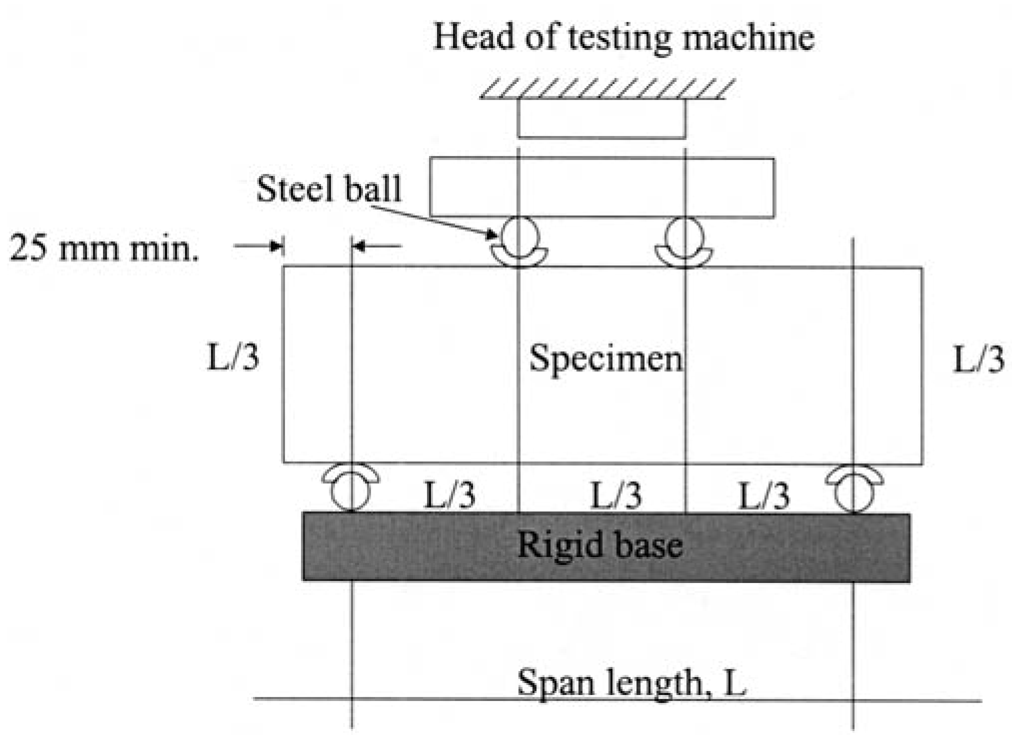

Figure 79. Diagram of the flexural test of concrete using the third-point loading method (ASTM C78).[11]

For a PCC test specimen tested as shown in figure 79, the theoretical maximum flexural strength (modulus of rupture) is calculated from the simple beam-bending formula for third-point loading:

$$M_R = \frac{PL}{bd^2} \qquad (9)$$

where

M_R = flexural strength
P = maximum load applied, MPa
L = specimen span length
b = specimen width
d = specimen depth

However, equation 9 holds only if the specimen breaks in between the two interior loading points (middle third of the beam). If the beam breaks outside these points by not more than 5 percent of the span length, equation 9 is replaced by:

$$M_R = \frac{3Pa}{bd^2} \qquad (10)$$

where **a** is the average distance between the point of fracture and nearest support. The results of tests where failure occurs even closer to the supports must be discarded. Even though concrete has a nonlinear stress-strain relationship, equation 9 assumes a linear relationship, as shown in figure 80. The assumed linear stress-strain state is true for the middle third of the test specimen. However, the difference between actual and assumed stress increases exponentially for stresses measured out of the middle third of the specimen and toward the end supports. Specimens that are fractured outside of the middle third of the beam will, therefore, yield erroneous test results. This will result in increased variability when such test results are evaluated with results from beams with fracture within the middle third of the beam.

Erroneous Test Data Caused by Incorrect Data Entries

Erroneous test results may be entered into table TST_PC09, thereby contributing to excessive variability. Such data will most likely not be typical and would have been detected when the data were evaluated for reasonableness.

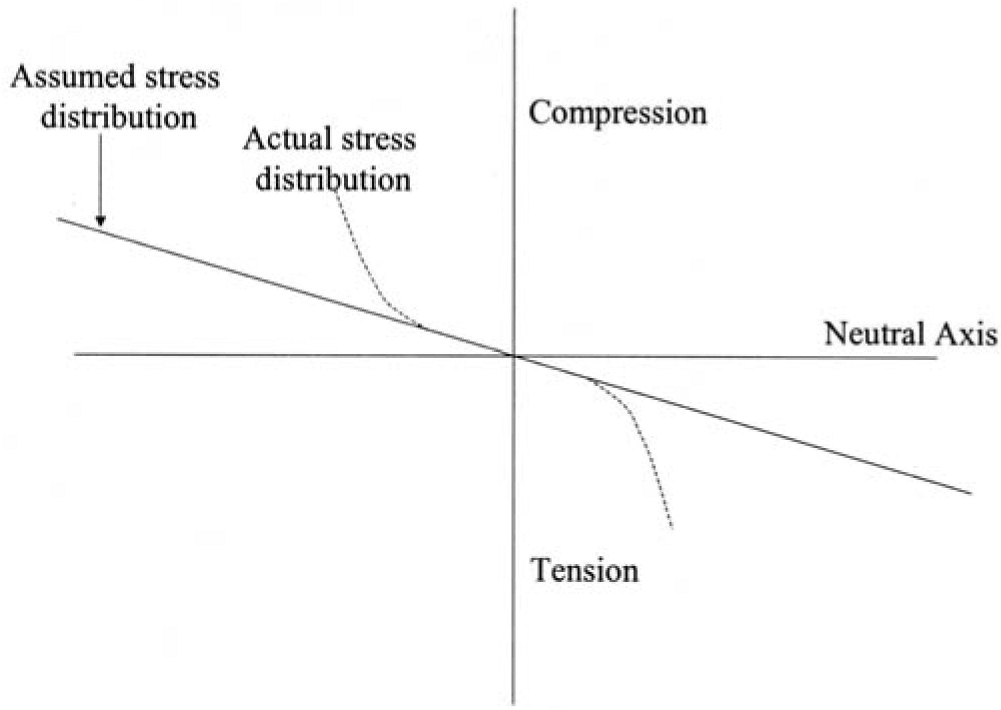

Figure 80. Stress distribution across the depth of a concrete specimen in flexure.

Variability Due to Material and Construction

Excessive variability may also be caused by material and construction variability. This type of variability is difficult to detect and most likely will pass through QA/QC. Excessive variability caused by obvious documented defects in test procedures, test specimens, or data entry and processing was identified and rectified by not using the affected data in developing representative test tables. Analysis cells with unexplained excessive variability were flagged with appropriate comments to alert data users.

Anomaly 2: Insufficient Test Data

Another common anomaly identified was insufficient (or no) test results for the various analysis cells. The reasons for insufficient or no data include the following:

1. Test data are still undergoing QA/QC and are not yet at level E (data reported in LTPP database as levels A to D).
2. Sampling, preparation, or testing is still in progress.
3. Test specimens were not suitable for testing and were, therefore, rejected (no testing performed).

No remedial action was taken for case 1. This was because the test data had not been rejected, and it would, therefore, be premature to take any corrective remedial action.

For cases 2 and 3, a feedback report was sent to the FHWA to obtain additional information about the status of the data. Appropriate remedial action will be implemented by the FHWA, based on the following scenarios.

Missing Data Cannot Be Recovered in Any Shape or Form

If it is determined that the missing data will not be available (e.g., tests were performed at a different reference age or the test results have been rejected), the missing flexural strength data will be estimated by any of the following methods:

1. Interpolating or extrapolation by using correction factors obtained from published literature to adjust flexural strength of a given reference age to obtain missing values of other reference ages.
2. Using empirical and analytical models to compute flexural strength from available PCC compressive strength data. This method will be used only if all the flexural strength data (i.e., for all three reference ages) are missing.

The recommended remedial action will be to estimate the missing data through interpolation or extrapolation. This is because the estimated test data will be based on test data that were obtained under similar conditions (e.g., curing, testing, construction, concrete mix proportions) as that of the missing data. However, interpolation or extrapolation is only possible for situations where other strength data (e.g., 28-day or 365-day flexural strength) are available for the given experiment.

For situations where the experiment has all of its flexural strength data missing, reasonable estimates of flexural strength can be computed only from other test data. The test data recommended are PCC compressive strength data, even though other strength parameters, such as PCC elastic modulus and PCC tensile strength, if available, can also be used.

Interpolation or Extrapolation

The following equation, developed during the Zero Maintenance study, was adopted for use in developing strength ratios between the 28-day flexural strength and flexural strength at all other ages.(40)

$$STRRATIO = 1.22 + 0.17\log_{10}(AGE) - 0.05[\log_{10}(AGE)]^2 \qquad (11)$$

where

STRRATIO = ratio of M_R at a given age to M_R at 28 days
AGE = specimen age in years

Figure 81 is a plot showing the relationship between strength ratio and specimen age in days. Table 64 presents the normalized 14-, 28-, and 365-day flexural strengths estimated using equation 11.

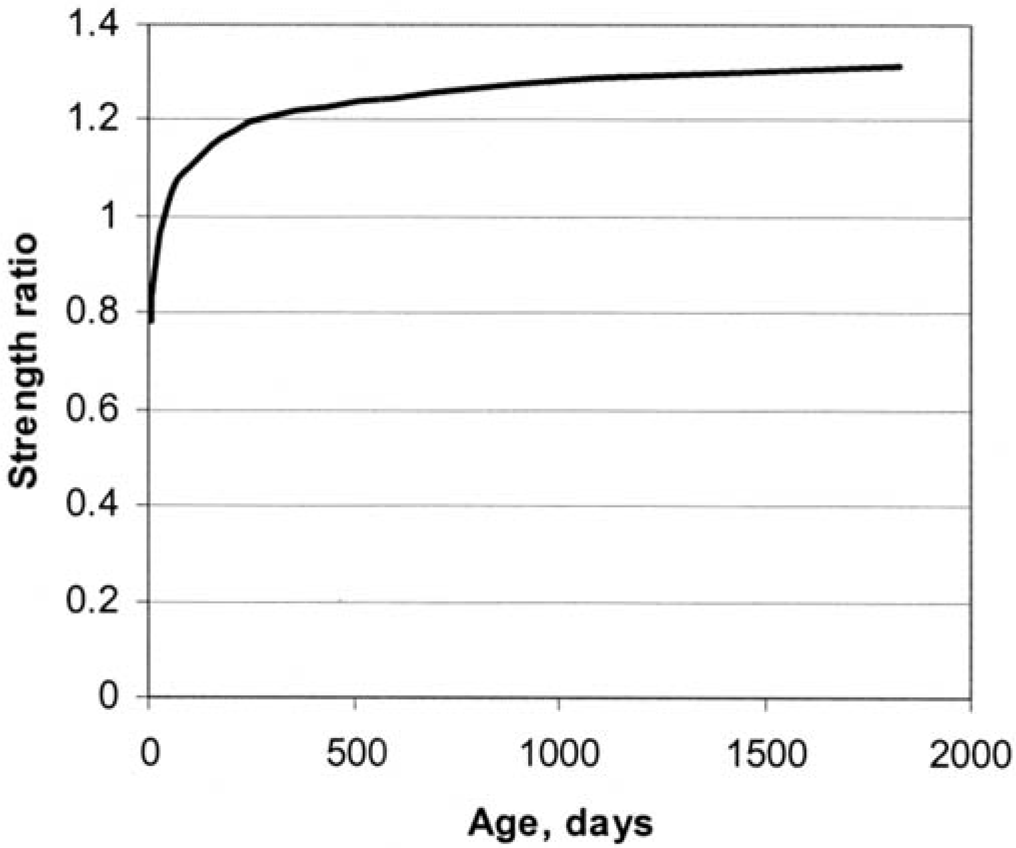

Figure 81. Plot showing the relationship between strength ratio and specimen age in days.

Table 64. Normalized 14-, 28-, and 365-day flexural strengths estimated using equation 11.

Specimen Age, days	Strength Ratio
14	0.91
28	1.00
365	1.26

Computing Flexural Strength Using Models

Several models have been developed that relate flexural strength to compressive strength (see table 65). As noted, the models in table 65 are recommended only in the extreme situations where there are no flexural strength data available at any reference age (14, 28, 365 days), making interpolation or extrapolation impossible. This is because the models available do not consider all the factors that must be included in a relationship between flexural and compressive strength. Some of the factors not considered include the following:

- Coarse aggregate type--Crushed aggregates have a different effect on flexural and compressive strength of PCC. Crushed aggregates seem to improve flexural strength more than compressive strength.[41]
- Curing method--Some research studies have reported that, compared with moist curing, air curing reduces tensile strength more than it does compressive strength. Therefore, the M_R/sigma$_c$ ratio is less for air cured than it is for moist-cured concretes.[11, 41]
- Incomplete compaction and air entrainment--These factors affect compressive strength more than flexural strength because the presence of air lowers compressive strength more than flexural strength, especially in rich and strong mixes.[41]
- Specimen age--The influence of age on the ratio M_R/sigma$_c$ differs with increasing age. Beyond 28 days, flexural strength increases more slowly than does compressive strength.[41]

The American Concrete Institute (ACI) model in table 65 was adopted for use in this study because the model was developed using data characterizing a wide range of PCC compressive strength and other concrete properties, making it one of the most reliable.[42]

Table 65. Models for relating compressive to flexural strength. (See references 38 through 42.)

Model	Source
M_R = 0.62 (sigma$_c$)$^{0.5}$ (stress in MPa)	Price (American Concrete Institute, [ACI])[42]
M_R = k$_2$(sigma$_c$)^{k_1}(k$_2$ ranges from 3 to 6, k$_1$ from 0.3 to 0.8, stress in psi)	Neville[43]
M_R = 8.3 (sigma$_c$)$^{0.5}$ (stress in psi)	Teychenne[44]
M_R = 8.3 / (4 + 12000/sigma$_c$) (stress in psi)	Sozen[45]
M_R = 9.5 (sigma$_c$)0.5 (stress in psi)	Comite Europeen du Beton[43]

Sampling, Preparation, or Testing in Progress

No remedial action is proposed for this situation because the test data would be collected and will eventually be placed in the LTPP database after going through the normal QA/QC procedures.

Implementation of Remedial Action to Correct Identified Anomalies

The identified anomalies were corrected, where feasible, using the remedial actions proposed. For the analysis cells with excessive variability, the remedial action did not always reduce variability to within the acceptable limits. For such situations, excessive variability may be assumed to be due to other sources, such as the material and construction.

Schema for the Representative PCC Flexural Strength Data Table (TST_PC09_REP)

A representative PCC flexural strength data table (TST_PC09_REP) was developed and recommended for inclusion into the LTPP database. Data in table TST_PC09_REP were arranged by analysis cells with appropriate comments provided to describe the anomalies observed on a cell-by-cell basis. The table also contained basic statistics, such as standard deviation and coefficient of variation. The schema for table TST_PC09_REP are presented below:

1. Experiment type.
2. Experiment number.
3. SHRP identification number.
4. State code.
5. Construction number.
6. Target strength.
7. Target thickness.
8. Specimen age.
9. Number of specimens tested.
10. Mean moduli of rupture (flexural strength).
11. Maximum moduli of rupture.
12. Minimum moduli of rupture.
13. COV.
14. Standard deviation.
15. Source of data.
16. Comments.
17. Record status.

The first seven fields in table TST_PC09_REP define the analysis cell used in computing mean, maximum, and minimum test results. Basic statistics-such as the number of test data, COV, and standard deviation-were also computed for the each analysis cell. Codes describing the source of the data (e.g., from laboratory testing or obtained through models and equations) were also presented. Finally, comments were provided to describe the state of the data (e.g., excessive variability or incomplete sampling) to guide the user in selecting data for analysis and evaluation. The final field describes the record status.

13. COMPRESSIVE STRENGTH OF OTHER THAN ASPHALT TREATED BASE AND SUBBASE MATERIALS

Introduction

The LTPP describes lean concrete, cement aggregate mixture (CAM), econocrete, and soils treated with cement, lime, cement- or lime-flyash, and other chemical products as "other than asphalt-treated bases," or OTBs.(2) Treated layers are often used under pavement surface layers to provide uniform support and to reduce the potential for moisture- and fatigue-related pavement distresses. The compressive strength of a treated base is an important parameter in characterizing the material. Its primary use is in model development, in which performance characteristics are related to strength parameters, and for quality control during construction. It is also an indirect indicator of the durability of the material. Testing for compressive strength of OTB specimens in good condition is based on ASTM C39-86, as modified by SHRP protocol P32--Method A.(2,3) Testing of weak and crumbly specimens is based on ASTM D2166-85, as modified by SHRP protocol P32--Method B.(2,3)

The test protocols provide guidance on all aspects of material sampling, preparation, testing, computation of test results, and presentation. The test results are stored in the LTPP database after undergoing several levels of quality checks. Data that are acceptable after the final series of quality checks are classified as level E and are stored in table TST_TB02. A total of 37 fields of information, identified below, are maintained under this table:

1. SHRP_ID.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.
8. Laboratory code.
9. Sample area number.
10. Sample number.
11. Diameter.
12. P32 method (A or B).
13. Graph (yes or no).
14. Original length.
15. Capped length.
16. L/D (length to diameter) ratio.
17. Cross-section area.
18. Maximum load.
19. Compressive strength fracture type code.
20. Compressive strength fracture type (other).
21. Compressive strength.
22. Visual exam comment codes (seven fields).
23. Comments codes for testing (seven fields).
24. Test date.
25. Record status.

Material Sampling for OTB Compressive Strength Determination

Material samples are collected as directed by the SHRP P32 protocol.(2) A representative sample can be a core, block (undisturbed sample 0.33 m^2), chunk (large pieces), small pieces, bulk (0.33-m-diameter borehole), thin-walled tube, or jar sample. Methods used in retrieving material from the pavement layers include:(2)

- Coring.
- Excavating test pits.
- Digging boreholes.

The excavated material is packaged, labeled, and shipped for testing, following the procedures outlined in the SHRP P32 protocol.(2) Test specimens (100-mm-diameter cores with a length equal to or less than the layer thickness) are prepared from the sampled material in accordance with the protocol.(2)

Because the sampling involves excavating materials (a destructive process), the boreholes and test pits were located outside the distress monitoring sections. For GPS experiments, materials were excavated from either end of the test sections, as indicated by the numbered boxes in the figure. For SPS experiments, materials were excavated at designated locations from several adjacent SPS test sections. Detailed information on sample locations for SPS experiments is available in the appropriate SHRP Experiment Design and Research Plan documents.(18, 19, 20)

Table 66 presents the LTPP sampling requirements for compressive strength testing of OTB layers. The table indicates the minimum number of specimens required per layer for the various LTPP experiments, along with the sampling locations. It is clear from the table that testing for this particular data element is performed on in-service pavements, which primarily consist of pavements from the GPS experiments and from SPS-5, SPS-6, and SPS-7 experiments. Although there are pavement sections with LCB's in the SPS-2 experiment, they were not included in table TST_TB02 because the SPS-2 LCB cores were tested in accordance with the SHRP P61 protocol and, therefore, the test results were stored table TST_PC01 in the LTPP database.

Experiment Type

Table 66. Sampling requirements for the determination of compressive strength of OTB materials.(See references 7, 16, 17, and 18.)

Experiment Type	Layer Type	Test Type	LTPP Designation	LTPP Protocol	Minimum Number of Tests per Layer	Designated Sampling Location[1]
GPS 2, 6 and 7	Treated base/subbase and subgrade	Unconfined compressive strength	TB02	P32	2	C10 and C22 or one from (C7, C8, C9) and (C19, C20, C21)
GPS 3, 4, 5 and 9	Treated base/subbase and subgrade	Unconfined compressive strength	TB02	P32	2	C4 and C10 or one from (C1, C2, C3) and (C7, C8, C9)
SPS 5	Treated base/subbase and subgrade	Unconfined compressive strength	TB02	P32	3	[C4-C5] [C15 C16] [C23 C24]

SPS 6	Treated base/subbase and subgrade	Unconfined compressive strength	TB02	P32	3	C5 C11 C19
SPS 7	Treated base/subbase and subgrade	Unconfined compressive strength	TB02	P32	3	C1 C4 C7

[1]For a detailed schematic diagram of the sampling locations, the appropriate data collection guides must be consulted.[(7,16,17,18)]

OTB Compressive Strength Data Completeness

Discussed below are the results of data completeness analyses for table TST_TB02. The January 2000 release to the LTPP database was used in determining the data completeness and other analyses described.

Level 1 Data Completeness

The first step in assessing data completeness was to extract and assemble the OTB compressive strength data available in table TST_TB02 in the LTPP database. This table was then linked to tables TST_L05B and EXPERIMENT_SECTION, also in the LTPP database, for accurate cross-referencing of layer information, experiment type, and other important data elements. The extracted data were examined for completeness at level 1. The findings of this assessment are tabulated in table 67.

Table 67. Summary of level 1 data completeness analysis for TST_TB02.

Expt. Type	Expt. No.	No. of Records at Levels A to E	No. of Records at Level E	No. of Usable Records at Level E	Percent Usable Records at Level E	Total Number of Analysis Cells Represented
GPS	2	70	68	68	97	34
GPS	3	66	66	65[1]	98	34
GPS	4	13	11	11	85	7
GPS	5	32	32	32	100	17
GPS	6B	7	7	7	100	4
GPS	7A	6	6	6	100	3
GPS	9	6	6	6	100	3
SPS	2	7	7	0[2]	0	N/A
SPS	5	2	2	0[3]	0	N/A
SPS	6	5	5	5	100	2

[1]One record did not have compressive strength data.
[2]Seven records belong to the TST_PC01 table.
[3]Two records belong to supplemental sections.

Most of the data in table TST_TB02 were at level E. However, not all the records present at level E could be used in the data analysis. For example, table 67 suggests the presence of 7 SPS-2 data test records pertaining to LCB layers at level E. This is erroneous, because LCB layers from the SPS-2 experiment were supposed to be tested for compressive strength using the P61 protocol and recorded in the TST_PC01 table. Also not considered in further analysis were the two SPS-5 records, because they belonged to supplemental sections that are outside the scope of this study, and one GPS-3 record, because it did not contain any strength data.

Definition of Analysis Cell

Also presented in table 67 is the total number of analysis cells represented by the data at level E. A total of 104 analysis cells were represented by the level E data in the test table TST_TB02. In the context of this data table, an analysis cell was defined as follows:

- For GPS experiments: It is the same as a given OTB layer within a test section for which testing data are available.
- For SPS experiments: It is the same as a given OTB layer within an entire experiment for which testing data are available.

Table 68 presents a list of fields that defines analysis cells for the various LTPP experiments with data table TST_TB02. Note that the SHRP_ID field is not a part of the analysis cell definition for the SPS experiments because sampling and testing requirements for SPS experiments (see table 66) are assessed on an experiment-wide basis (which could consist of several test sections) instead of on a test section basis.

Table 68. Analysis cell definitions for test table TST_TB02.

Key Fields	GPS Experiments (All)	SPS Experiments (All)
Experiment type	X	X
Experiment number	X	X
SHRP_ID	X	--
SPS cell identification number	--	X
State code	X	X
Layer number	X	--
Material code	X	X
Construction number	X	X

Level 2 Data Completeness

The required level 2 data completeness evaluation consisted of determining whether the analysis cell contains the minimum number of tests required, as specified in the LTPP sampling and testing program.[(2)] To accomplish this, the data in table TST_TB02 were grouped according to analysis cells. The number of test results within each cell was then compared with the minimum number of tests required (see table 66). Pavement sections that satisfied the minimum testing requirements were categorized as complete, whereas those with less than the minimum were categorized as incomplete. Table 69 presents a summary of level 2 completeness of the test data reported in table TST_TB02. Of the 106 analysis cells with compressive strength data at level E in TST_TB02, 10 cells did not meet the minimum sampling and testing requirement. The cells that did not meet the minimum requirement contained one test value each.

Table 69. Summary of level 2 data completeness analysis for TST_TB02.

Experiment Type	No. of Analysis Cells with Data at Level E	No. with Less than Minimum Required Samples	Percent Cells with Less than Min. Required Samples
GPS-2	34	0	0
GPS-3	34	3	9
GPS-4	7	3	43
GPS-5	17	2	12
GPS-6B	4	1	25
GPS-7A	3	0	0
GPS-9	3	0	0
SPS-6	2	1	50

OTB Compressive Strength Data Quality

Data quality was evaluated for all analysis cells summarized in table 69. The data were evaluated initially for reasonableness by comparing the magnitudes of the test values with typical values reported in the literature.[13] Subsequently, the data were evaluated for compliance with test standards and protocols. Finally, within-cell variability was computed for each analysis cell and evaluated for reasonableness. Details of the data quality evaluation are presented below.

Data Reasonableness

The reasonableness of the data in the test table was checked by analyzing the magnitudes of compressive strength from each strength test. The data were first grouped on the basis of material type. Five different material types were represented: including CAM, lean concrete, econocrete, soil cement, and cement-treated soil. The mean and standard deviation of the compressive strength for each material type were determined for all the projects. However, only two material types--CAM and LCB--had substantial information (123 and 51 test results, respectively) in the database. On the other hand, there were only 18 soil cement, six econocrete, and two cement-treated soil test results. Test results from the cement-treated soil were combined with soil cement for simplification of analysis. The mean and standard deviation of strength results for soil cement and econocrete are reported; however, the accuracy of these results is limited, due to the small amount of data available.

Figure 82 presents a histogram showing the distribution of compressive strength for all CAM specimens in the database. The mean value of the cement aggregate compressive strength is approximately 14.6 MPa. It can be seen in the figure that a majority of the data is between 5 and 20 MPa (approximately 78 percent of the compressive strength data for cement aggregate bases lie between 5 and 20 MPa, 3 percent of the data are below 5 MPa, and 19 percent are above 20 MPa).

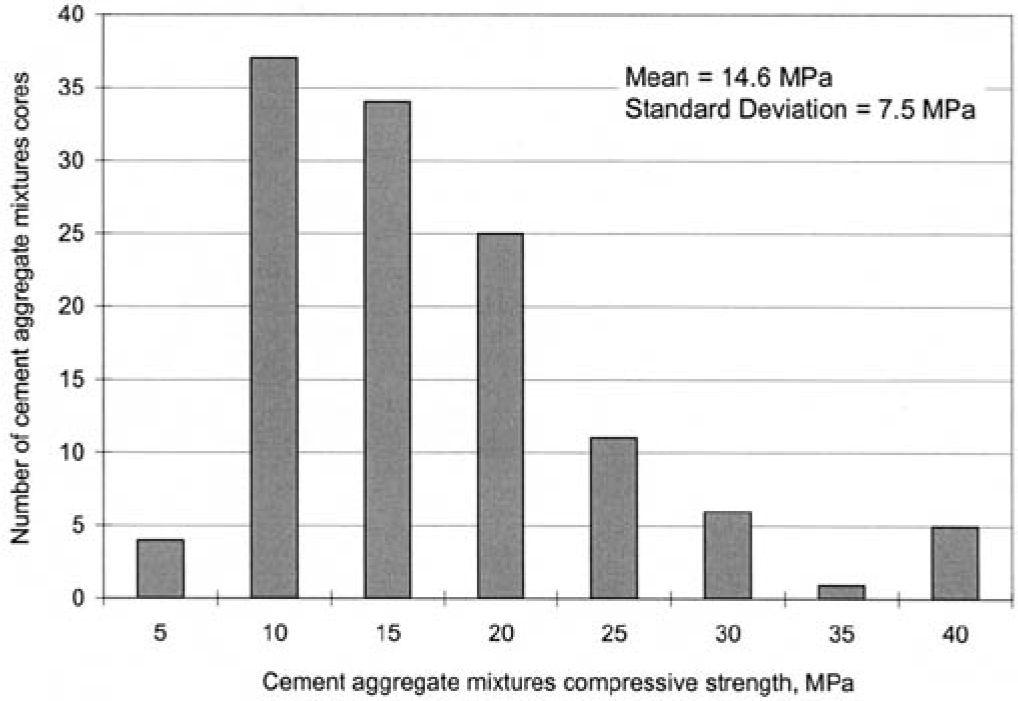

Figure 82. Scatter plot of compressive strength data for all cement aggregate specimens in TST_TB02.

Based on this information, the data seem reasonably representative of this material type.

A similar analysis for the LCB specimens in the database, presented in figure 83, shows that approximately 90 percent of the compressive strength data for LCB's is between 7.5 MPa and 25 MPa. Approximately 2 percent of the data are below 7.5 MPa, and 8 percent are above 25 MPa. The mean value of the lean concrete compressive strength is approximately 16.8 MPa. The mean and standard deviation of the compressive strength for econocrete analysis cells were calculated as 27.8 MPa and 13 MPa, respectively. For soil cement cells, the mean and standard deviation for the compressive strength test results were 11.2 MPa and 5.7 MPa, respectively.

Arranging the various materials in TST_TB02 from the highest to lowest based on the mean strength results in the following sequence: econocrete, lean concrete, CAM's, and soil cement. Although this trend agrees well with engineering intuition and published literature,[46, 47] it needs to be reconfirmed when more data become available for the econocrete and soil cement layers.

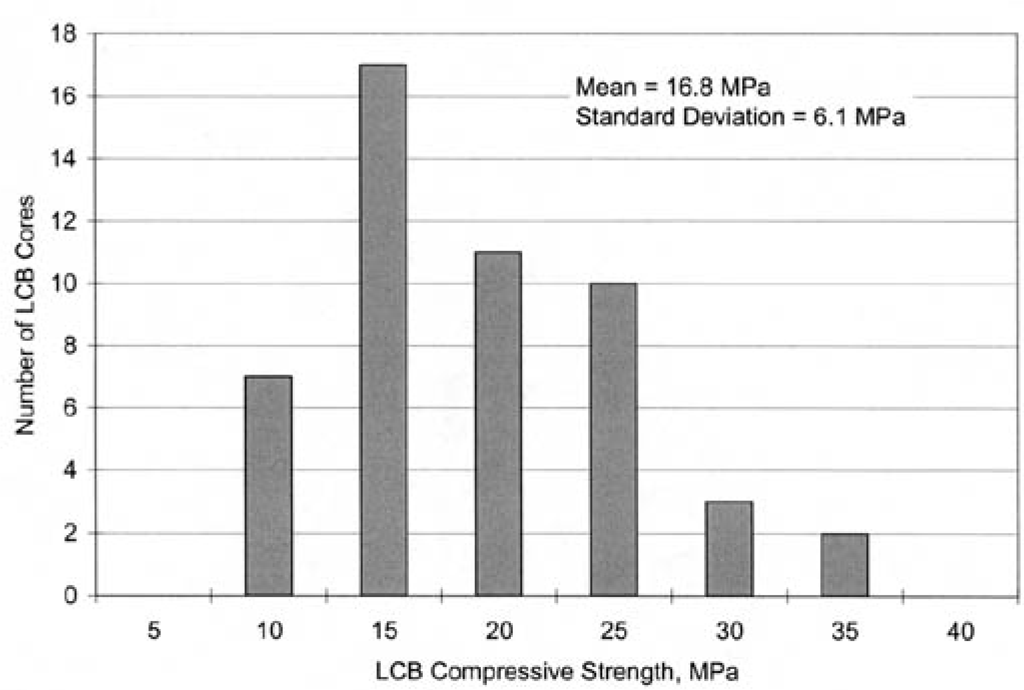

Figure 83. Scatter plot of compressive strength data for all lean concrete specimens in TST_TB02.

Compliance with Test Procedure

Noncompliance with the testing protocol can introduce errors into the test values and contribute to the overall variability of the data. A key element in data evaluation was to determine whether key requirements in the protocols and standards were adhered to. Some of the key issues evaluated included specimen thickness and L/D ratio.

Minimum Specimen Thickness Requirement

In the SHRP P32 protocol, two methods are suggested for handling test samples--Method A for intact samples and Method B for cracked and soft samples. The P32_METHOD field in TST_TB02 suggests that all the specimens were tested with Method A, which implies that all the specimens were in good condition prior to testing. It is also specified in the protocol that all the treated layer specimens should be at least 75 mm thick or greater. Figure 84 presents the thickness information of all but one of the records, due to lack of thickness information for that record. It can be observed from the figure that all the specimens plotted meet the minimum thickness requirement.

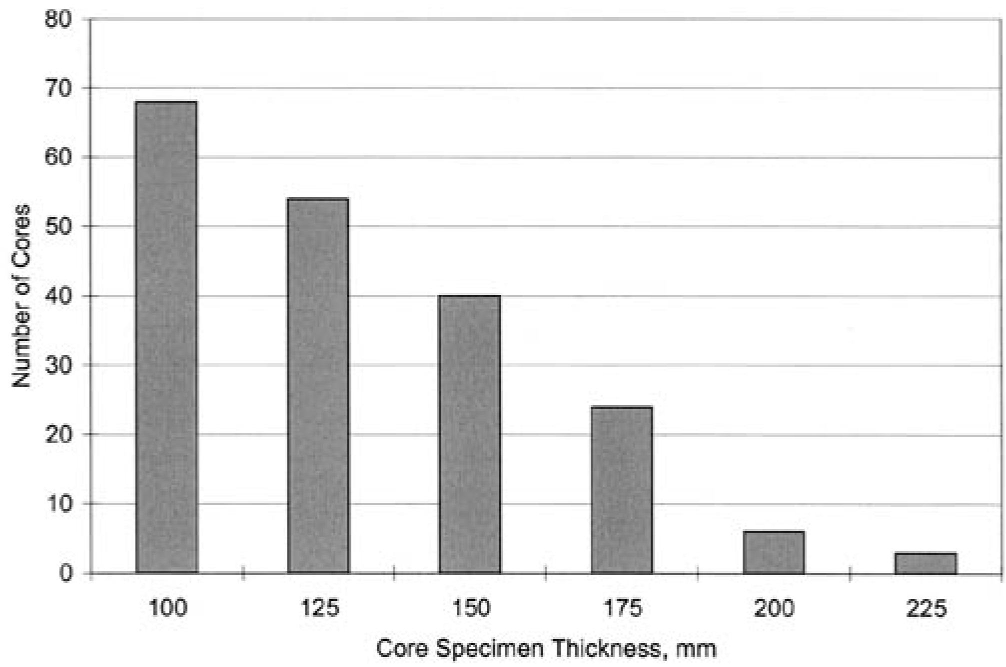

Figure 84. Sample thickness variability for all records in TST_TB02.

L/D Ratio

The protocol also requires the L/D ratio to be kept above 1.0, where possible. If this ratio is less than 1.0, a special comment field is to be added to the TST_TB02 table and a special correction factor applied to the compressive strength data obtained. On examination of the data in the table, it was found that about 28 percent of the records (57 of 211 records) had L/D ratios less than 1.0. This is shown graphically in figure 85. The protocol recommends the same correction factor for all specimens with L/D ratios less than 1.0. This could lead to significant problems, especially if only a few of the specimens from a given section have these low ratios. The effect of L/D ratio on compressive strength will be elaborated on later in this chapter.

Variability of OTB Strength Data

The analysis cells were checked to determine whether within-cell variability was excessive. Excessive variability was defined as having a variability level greater than typical. Considering that the basis for the SHRP P32 protocol is the AASHTO T22 standard (ASTM C39), the latter was consulted to estimate the precision of compressive strength data obtained from multiple specimens of the same material.

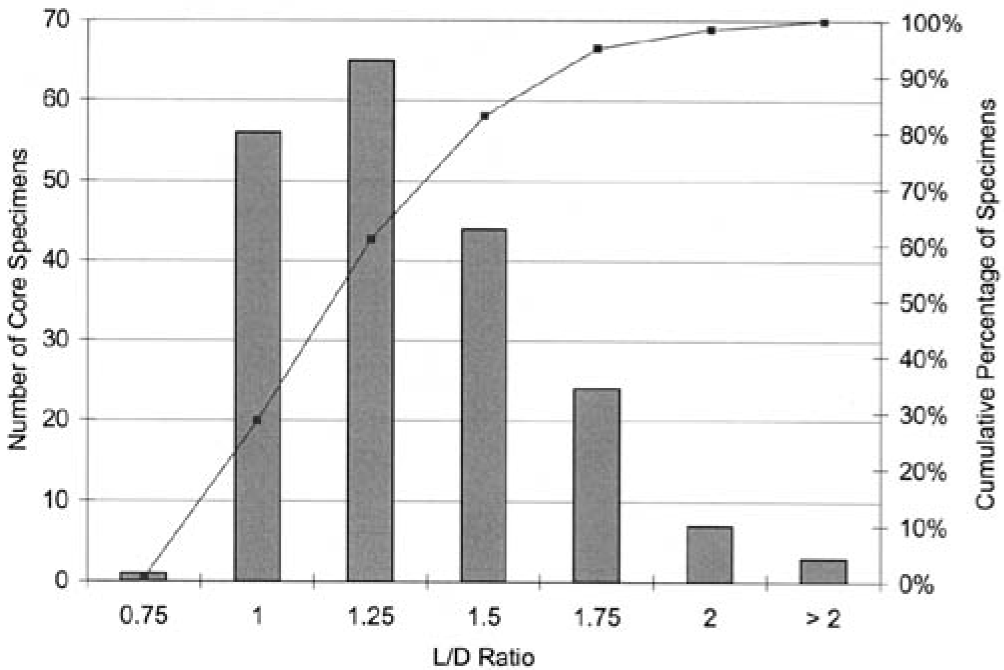

Figure 85. Sample L/D ratio variability for all records in TST_TB02.

According to ASTM C39, for a well-mixed sample of concrete made under normal field conditions, the maximum COV of compressive strength data obtained from multiple samples should not exceed 2.87 percent for a single operator test.

However, variability in the test results obtained by testing specimens from various locations along a project (within-cell variability) is expected to be higher than the ASTM recommended because additional sources of variability is expected from sampling, the material's natural variability, and within-lot construction variability.

In the absence of substantial information on typical "within-cell" variability in compressive strength of the various cement-treated materials for which data is available in table TST_TB02, the 15 percent COV value previously established for PCC materials (see chapter 10) was adopted. In fact, the "within-cell" compressive strengths of OTB materials can be expected to vary by a greater degree than for PCC materials because they have lower cement contents and their properties are controlled to a greater extent by the fine and coarse aggregates. Therefore, the COV value adopted is more stringent and, consequently, more conservative.

Prior to performing the variability analysis, the data in test table TST_TB02 were grouped into analysis cells. Although the TST_TB02 table was supposed to contain information on all treated base/subbase and subgrade layers, it was found that a majority of the data pertained to treated base layers. There were only two records for soil cement-treated subbases. The treated bases were cement aggregate, lean concrete, econocrete, or soil cement mixtures. Details of the variability evaluation are presented in the following sections.

Cement Aggregate and Lean Concrete Bases

There were a total of 57 cement aggregate base analysis cells and 24 LCB analysis cells with multiple samples in the database. The within-cell COV for each of these layer types is plotted in figure 86. Both of these material types exhibit a similar distribution of COV. Considering that these materials are more or less alike, this is not surprising. Based on the adopted standard of 15 percent for typical intersample COV, it can be inferred from figure 86 that approximately 79 percent of cement aggregate and 75 percent of lean concrete analysis cells have acceptable within-cell variability. The remaining data are questionable and required further investigation.

Econocrete Bases

There were only three econocrete analysis cells in the test table. An analysis of these cells yielded intersample COV's of 4.6, 19.2, and 51.1 percent, respectively. These values suggest excessive variability in two of the cells.

Soil Cement Bases/Subbases

There are nine soil cement base analysis cells in the test table. Analysis suggests within-cell COV values in excess of 15 percent for at least five of the cells. For the one soil cement subbase analysis cell in the database, the intersample COV was 22.1 percent, which is also quite high.

In summary, the within-cell variability for the cement aggregate and lean concrete layers seems to be reasonable. The same cannot be said, however, for the econocrete and soil cement layers, however.

Identification of Anomalous Data

The discussion presented so far has focused on assessing data availability and quality. Data availability was assessed at two levels. Data quality checks were subsequently performed to verify data reasonableness, protocol compliance, and variability. The anomalies in the data noted during the various analyses are described below, along with a discussion of potential causes for their occurrence. Where possible, corrective or remedial actions were implemented to address the anomalies.

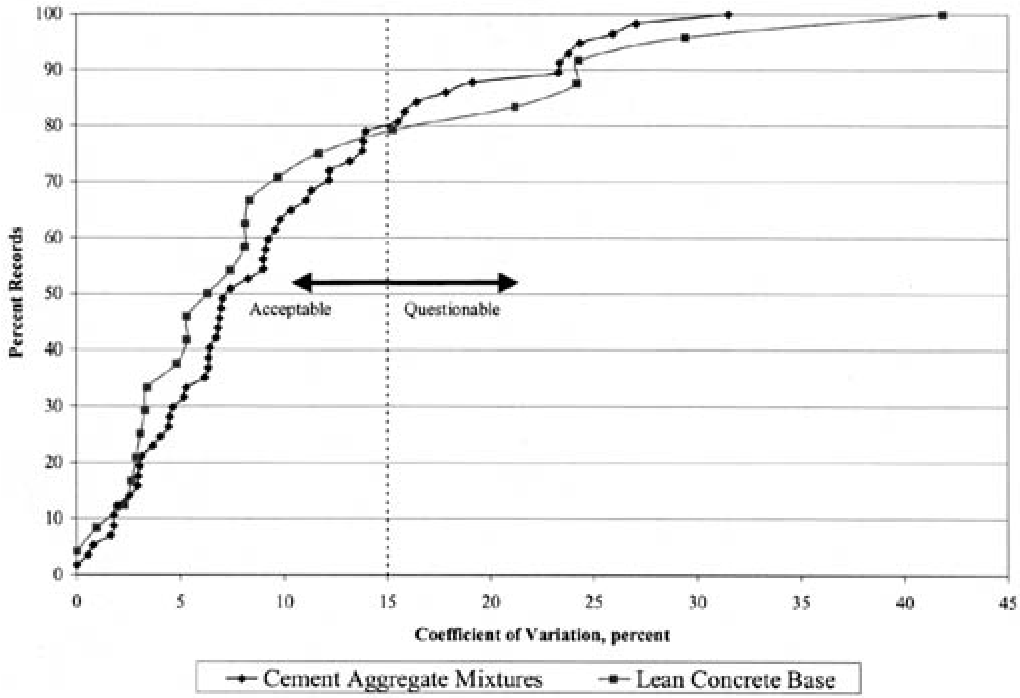

Figure 86. Intersample variability for cement aggregate and LCB compressive strength data.

Anomaly 1: Erroneous Data Entry (SPS-2 LCB Compressive Strength Data)

During the course of linking the layer information from the TST_TB02 table with material information from the TST_L05B table, it was found that seven LCB records pertaining to the SPS-2 experiment were included in this table erroneously. The prescribed protocol for testing LCB cores drawn from projects under SPS-2 experiment for compressive strength is the P61 protocol. The data tested according SHRP P61 was supposed to be stored in the LTPP database table TST_PC06.

The LCB records pertaining to SPS-2 experiments were removed from further analysis. A feedback report was sent to the FHWA. Appropriate remedial action will be implemented by the FHWA.

Anomaly 2: Single Test Values (STV's)

A total of 10 analysis cells contained single compressive strength test data (obtained from test specimens taken from either end of the test section). Although this by itself does not constitute a testing anomaly, it is an anomaly in sampling. Single test results could introduce bias into computed representative test values and reduce the accuracy of the data.

All the single-point compressive strength test results pertaining to a given material type were compared with typical values for that material to ascertain their reasonableness. They were found to be within acceptable ranges for compressive strength of the respective material types. Therefore, these values were assessed as adequately representing the properties of their respective pavement test sections and analysis cells, and were used in developing the representative test table.

Anomaly 3: Excessive Variability

A total of 25 analysis cells with multiple test values showed excessive within-cell variabilities (greater than 15 percent COV). This constitutes approximately 24 percent of the total number of cells in table TST_TB02. Twelve of these cells belonged to cement aggregate layers, six to lean concrete layers, two to econocrete layers, and five to soil cement layers. A careful review of the various data fields, including the core visual examination and comment fields, was performed for specimens in the affected cells to establish reasons for the high within-cell variabilities. Although no plausible explanation could be offered for a majority of the cases, six analysis cells had test specimens with L/D ratios that were less than 1.0. There were also considerable differences in the L/D ratios (>/= 10 percent) between the specimens in those cells.

Effect of L/D Ratio

According the ASTM C39 standard, on which SHRP protocol P32 is based, the ideal L/D ratio for compressive strength testing should be between 1.8 and 2.2. Whereas L/D ratios greater than 2.2 might not have a great influence on the compressive strength, L/D ratios less than 1.8 could have a significant impact on the strength result obtained. Specimens with smaller L/D ratios tend to overestimate compressive strength. The ASTM standard gives correction factors to account for smaller-than-desirable L/D ratios; however, these factors were developed for normal concrete and not for the materials under consideration in TST_TB02. Research conducted by Murdoch and Kesler[48] suggests that the effect of lower L/D ratios on strength determination is greater in concrete materials of lower strength. Most of the materials tested using SHRP protocol P32 fall under this category.

Figure 87 presents a plot of the influence of the L/D ratio on the apparent compressive strength of a cylinder for different strength levels. As the L/D ratio falls below 1.0, the effect on compressive strength is highly nonlinear, especially for the low-strength materials. It may be recalled that several specimens in the test table had L/D ratios less than 1.0. A constant correction factor is specified in the SHRP protocol to adjust the compressive strengths determined from such specimens.

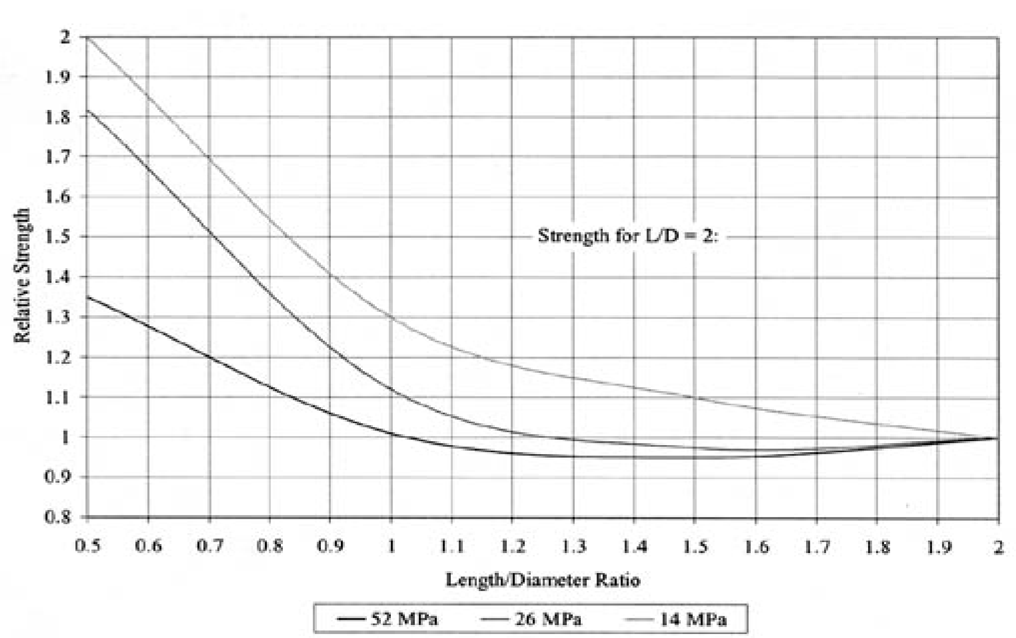

Figure 87. Influence of the L/D ratio on the apparent strength of a cylinder for different strength levels.[48]

Because of the nonlinear effect that an L/D ratio less than 1.0 has on compressive strength, applying a constant correction factor could lead to discrepancies in test results, further increasing variability. In light of this, it is possible that two specimens with L/D ratios in the vicinity of 1.0 that differ considerably might exhibit a COV greater than 15 percent.

Based on the discussion on possible sources of anomalies in test data presented in the preceding sections, the following remedial actions were applied:

- *Analysis cells with no plausible explanation for high COV:* All the test results were retained and used in developing the representative data table. A suitable comment alerting the user to the high variability was provided in the test table.
- *For analysis cells with high variability introduced by L/D ratio discrepancies:* To resolve the problem conclusively, resampling and testing of specimens from the affected locations is recommended. Although this is a time-consuming and expensive proposition, it is essential to enhance the quality of the data in the database. Until the test results from new cores are available, it is recommended that the affected data be retained in the current form with appropriate comments to alert the user to the high variability.

Schema for the Representative OTB Compressive Strength Data Table (TST_TB02_REP)

A representative OTB compressive strength data table (TST_TB02_REP) was developed and recommended for inclusion into the LTPP database. Data in table TST_TB02_REP were arranged by analysis cells, with appropriate comments provided to describe the anomalies observed on a cell-by-cell basis. The table also contained basic statistics, such as standard deviation and COV. The schema for table TST_TB02_REP are presented below:

- Experiment type.
- Experiment number.
- SHRP identification number.
- State code.
- Layer number.
- Material code.
- Number of test results.
- Construction number.
- Mean compressive strength.
- Maximum compressive strength.
- Minimum compressive strength.
- COV.
- Standard deviation.
- Source of data.
- QA_Comment_1.
- QA_Comment_2.
- QA_Comment_3.
- QA_Comment_4.
- QA_Comment_5.
- QA_Comment_6.
- QA_Comment_Other.
- Record status.

The first eight fields in the schema define the analysis cell used in computing the mean, maximum, and minimum test results. These results are presented along with other basic statistics, such as number of test results, COV, and standard deviation, in fields 9 through 13. Field 14 is a code that describes the source of the data (whether the data was computed from test values reported in the original table TST_TB02 or extrapolated using models). Finally, comments are provided in fields 15 through 21 to describe the status of the data (e.g., excessive variability, incomplete sampling, etc.), based on the QA testing performed as part of this discussion, to guide the user in selecting data for analysis and evaluation. The final field describes the record status.

14. ATTERBERG LIMITS OF SUBGRADE SOILS

Introduction

Atterberg limits describe the liquid limit, plastic limit, and Plasticity Index of a soil. Liquid limit is the water content corresponding to an arbitrary limit between the liquid and plastic states of consistency of a soil; the plastic limit is the water content, corresponding to an arbitrary limit between the plastic and the semisolid states of consistence of a soil. Plasticity Index is the range of water content within which the material is in a plastic state (i.e., the numerical difference between the liquid limit and plastic limit).

The most important use of Atterberg limits is in the classification of soils. As part of the LTPP material characterization program, Atterberg limits were determined for all unbound paving materials. Testing was done using the following testing protocols and standards:

- SHRP P43--*Determination of Atterberg Limits of Unbound Granular Base and Subbase Materials and Subgrade Soils.*
- AASHTO T89--*Determining the Liquid Limit of the Soils--Method B.*
- AASHTO T90--*Determining the Plastic Limit and Plasticity Index of Soils.*

Also, SHRP P43, AASHTO T89, and AASHTO T90 provided guidance on material sampling, preparation of test specimens, testing of specimens, computation of test results, and presentation of results. The test results were stored in table TST_UU04_SS03 in the LTPP database after undergoing of quality checks A to E. Table TST_UU04_SS03 has the following 22 fields of information:

1. SHRP_ID.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.
8. Lab code.
9. Sample number.
10. QA_Comment_1.
11. QA_Comment_2.
12. QA_Comment_3.
13. QA_Comment_4.
14. QA_Comment_5.
15. QA_Comment_6.
16. QA_Comment_Other.
17. Liquid limit.
18. Plastic limit.
19. Plasticity Index.
20. Sample number.
21. Test date.
22. Record status.

Material Sampling for Determining Atterberg Limits of Subgrade Soils

The SHRP *Interim Guide for Laboratory Materials Handling and Testing* and other publications provide detailed information about subgrade material sampling. (See references 2, 15, 16 through 20, and 23.)

For GPS experiments, bulk samples of materials were sampled from boreholes and test pits at the approach and leave ends of the test pavement. For SPS projects, materials are excavated at designated locations at the approach and leave ends of adjacent SPS test sections within the SPS experiment. Because of the destructive nature of sampling and excavating materials, the boreholes and test pits were located outside the distress-monitoring sections of the test pavements. The test samples were packaged, labeled, and shipped for testing to the designated laboratories, according to the procedures described in the SHRP P43 protocol.

The sampling and testing requirements of the various LTPP test sections for the determination of Atterberg limits are presented in table 70. Sampling and testing were required only for subgrade and embankment soils.

Table 70. Sampling and testing requirements for Atterberg limits of subgrade soils.

Expt. Type	Layer Type	LTPP Designation	SHRP Protocol	Minimum Number of Tests per Layer	Sampling Location
All GPS experiments	Subgrade	SS03	P43	2	TP, BA1-BA3
SPS-1	Subgrade	SS03	P43	6	B1-B6
SPS-1	Embankment	SS03	P43	3	B7-B12
SPS-2	Embankment	SS03	P43	3	B7-B12
SPS-5	Subgrade	SS03	P43	3	BA1-3, TP, BA4-6
SPS-6	Subgrade	SS03	P43	3	TP1, BA1-3, TP2
SPS-8	Subgrade	SS03	P43	3	B1-B3

Data Completeness for Atterberg Limits of Subgrade Soils

Data completeness was evaluated at two levels. Level 1 data completeness consisted of determining the total number of test records in table TST_UU04_SS03, the percentage at level E, and the number of analysis cells represented by the data at level E. Level 2 data completeness consisted of determining whether the analysis cells had the required number of test results present. The January 2000 release of table TST_UU04_SS03 was used in data analysis.

Level 1 Data Completeness

The data in table TST_UG04_SS03 were extracted from the LTPP database and merged with TST_ LO5B, EXPERIMENT_SECTION, and other relevant data tables. The assembly of data from the different tables made it possible to evaluate the accuracy of material and layer description information in table TST_UG04_SS03. Cross-referencing the data from the different tables made it possible to check for anomalies in material description, layer type, and layer number information in the table TST_UG04_SS03. The test records with anomalies in the material and layer descriptions were not used in further analysis.

Table TST_UG04_SS03 contained a total of 3,431 records, of which 94 percent (3,227 of 3,431 records) were at level E. The table also contained 118 records from SPS supplementary sections. The data from

SPS supplemental sections were not used in further analysis because they fall out of the scope of this study. The data at level E represented 1,506 analysis cells. For this data table, *analysis cell* was defined as follows:

- For GPS experiments, every layer in a test section is considered an analysis cell. Therefore, an analysis cell is defined as a unique combination of State_code, SHRP_ID, and Layer_No.
- For SPS experiments, an analysis cell is defined as a unique combination of State_code, SHRP_ID, Material_Code, and Layer_Type.

Table 71 presents the fields used for defining analysis cells for pavement test sections within the GPS and SPS experiments. Table 72 presents a summary of level 1 data availability for table TST_UG04_SS03.

Table 71. Fields used in defining analysis cells for table TST_ UG04_SS03 data evaluation.

Field Names	GPS 1 through 9	SPS-1	SPS-2	SPS-5	SPS-6	SPS-8	SPS-9
State Code	X	X	X	X	X	X	X
SHRP_ID	X	X	X	X	X	X	X
Construction Number	X	X	X	X	X	X	X
Layer Number	X						
Material Code		X	X	X	X	X	X
Layer type		X	X	X	X	X	X

Table 72. Level 1 data completeness for table TST_UG04_SS03.

Experiment Type	Experiment Number	Total Number of Records at All Levels	Total Number of Records at Level E	Percentage of Records at Level E	Number of Analysis Cells Represented at Level E
GPS	1	940	940	100	488
GPS	3	419	419	100	217
GPS	3	447	446	99.8	232
GPS	4	217	217	100	111
GPS	5	239	239	100	121
GPS	6	246	246	100	129
GPS	6	59	59	100	33
GPS	7	122	122	100	62
GPS	7	23	23	100	12
GPS	9	81	81	100	41
SPS	1	136	114	83.8	26
SPS	2	120	96	80.0	21
SPS	5	99	81	81.8	22

SPS	6	55	42	76.4	14
SPS	8	81	75	92.6	23
SPS	9	29	27	93.1	17

There were an additional 118 records from SPS supplementary sections.

Level 2 Data Completeness

Level 2 data completeness was determined by comparing the actual number of test data present in each analysis cell to what was required. The analysis cells containing less than the amount of data required were classified as incomplete, and those with at least the minimum required data were classified as complete. Approximately 79 percent of the analysis cells were classified as complete. Table 73 presents the results of the level 2 data completeness analysis.

Table 73. Summary of level 2 data completeness evaluation for table TST_UG04_SS03.

Experiment Type	Number of Analysis Cells with Data and Material Information	Min. Number of Test Results Required	Analysis Cells with Minimum Number of Test Results	Percent Analysis Cells with Minimum Test Results
GPS-1	480	2	444	92.5
GPS-2	216	2	201	93.1
GPS-3	225	2	208	92.4
GPS-4	110	2	105	95.5
GPS-5	120	2	116	96.7
GPS-6A	129	2	117	90.7
GPS-6B	32	2	25	78.1
GPS-7A	60	2	58	96.7
GPS-7B	12	2	11	91.7
GPS-9	40	2	39	97.5
SPS-1	31	6/3[1]	23	74.2
SPS-2	7	6/3[1]	6	85.7
SPS-5	36	3	11	30.6
SPS-6	3	3	1	33.3
SPS-8	5	3	2	40.0

[1]For SPS-1 and SPS-2 projects, six tests are required for the subgrade, and three tests are required for the embankment layer.

Atterberg Limits of Subgrade Soils Data Quality Assessment

Table TST_UG04_SS03 data quality evaluation was as follows:

1. Evaluate test results for reasonableness by comparing the test data with typical values reported in the literature.

2. Compare within-cell variability with typical variability.

Individual test results that fell out of the typical range of values were examined in greater detail to identify potential anomalies or error. Analysis cells with excessive variability (variability greater than the typical value) were classified as questionable, and the potential causes of the excessive variability were investigated. A detailed summary of the evaluation of data reasonableness and variability is presented in the next few sections.

Data Reasonableness

The liquid and plastic limits of soils are influence by several properties, including:

- Clay content or fraction.
- Percentage passing the 0.075-mm sieve.
- Mineralogy of the clay fraction (percentage passing 0.002-mm sieve size).

Because these properties vary in naturally occurring soils (subgrades), the liquid and plastic limits vary widely across the United States. The liquid and plastic limits of various soils are summarized in table 74 and summarized as follows.

- Plastic limit ranges from 1 to 92 percent.
- Liquid limit ranges from 18 to 130 percent.

Based on this information, the following typical values were adopted for data reasonableness evaluation:

- Plastic limit--0 to 50 percent.
- Liquid limit--0 to 100 percent.

Values outside of this range may not necessarily be erroneous but were investigated further to establish whether they are outliers or erroneous entries. The distribution of liquid limit values for fine-grained soils from test sections within the GPS experiments is presented in figure 88. Figure 88 shows clearly that all of the test results fell within the typical range of 0 to 100 percent. Liquid limit tests were also performed on the finer fraction of coarse-grained soils (passing the 0.425-mm sieve). For coarse-grained soils in GPS experiments, the distribution of liquid limit values is plotted in figure 89. All test results fell within the typical range of 0 to 100 percent. Figures 90 and 91 present the distribution of liquid limit values from test sections within SPS experiments for fine- and coarse-grained soils, respectively. All of the test values fell within the typical values.

Figures 92 and 93 present the distribution of plastic limit values for fine- and coarse-grained soils from test sections within GPS experiments, and figures 94 and 95 present the distribution of plastic limit values for fine- and coarse-grained soils from test sections within SPS experiments. The ranges of plastic limit test values for the plots are as follows:

- Plastic limit for fine-grained soils ranged from 10 to 30 percent.
- Plastic limit for coarse-grained soils ranged from 0 to 30 percent.

The ranges presented fall within the typical range of plastic limit for fine and coarse materials, so the data are reasonable.

Table 74. Liquid and plastic limits of various soils.[47]

Soil Description	Place of Origin	Plastic Limit	Liquid Limit	Plasticity Index
Bryce B	Illinois	24	53	29
Cisne B	Illinois	20	59	39
Cowden B	Illinois	21	54	33
Drummer B	Illinois	23	54	31
Elliot B	Illinois	25	53	28
Fayette B	Illinois	21	50	29
Hosmer B2	Illinois	24	41	17
AASHO Road Test	Illinois	14	25	11
Huey B	Illinois	17	46	29
Sable B	Illinois	27	51	24
Limestone[1]	Texas	10	21	11
Iron ore gravel[1]	Texas	1	18	17
Sandy gravel[1]	Texas	7	20	13
Caliche[1]	Texas	15	33	18
Silt	Texas	6	23	17
Lean Clay	Texas	10	28	18
Fat Clay	Texas	21	35	14
Lias Clay	England	24	60	36
Weald clay	England	25	68	43
Oxford clay	England	24	72	48
London Clay	England	26	78	52
Silty clay	England	24	43	19
Sandy clay	England	19	27	8
Clay silt	England	19	33	14
Bearpaw(Cret.)	Nebraska	90	130	40
Pepper (Cret.)	Waco, Texas	58	80	22
Bearpaw (Cert.)	Saskatchewan	92	115	23

[1]Coarse-grained materials.

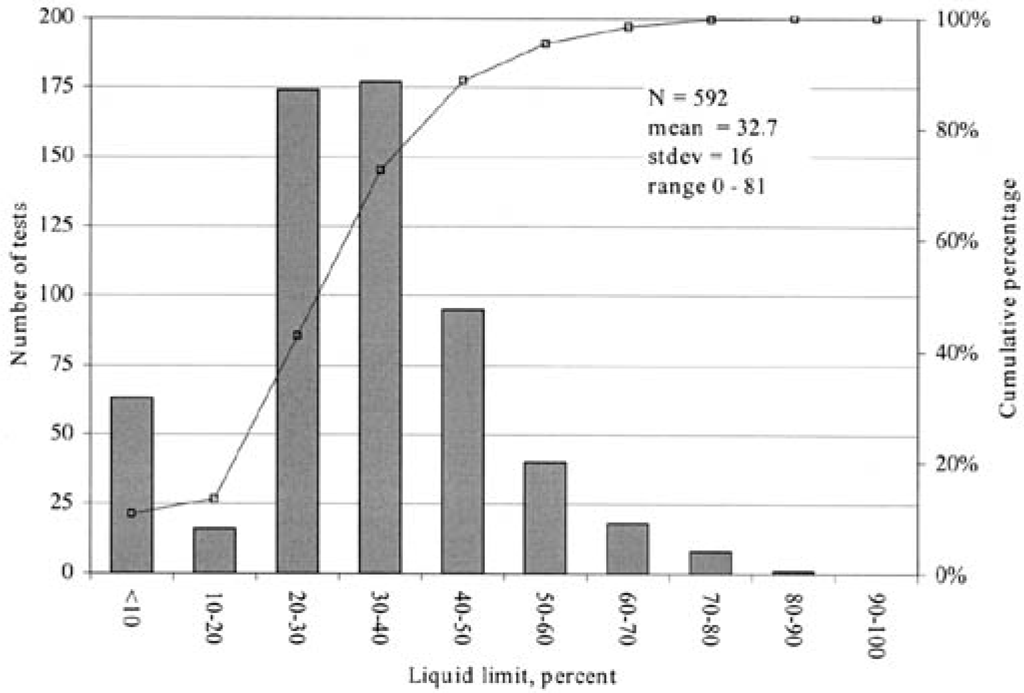

Figure 88. Distribution of liquid limit measurements for fine-grained soils (GPS experiments).

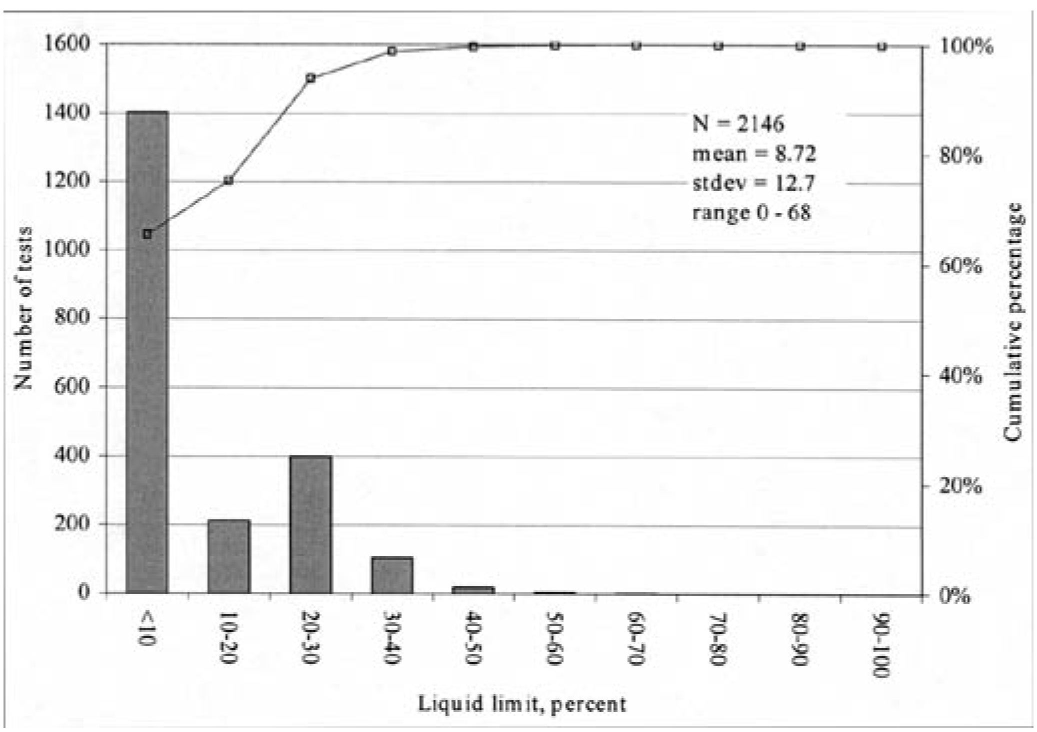

Figure 89. Distribution of liquid limit measurements for coarse-grained soils (GPS experiments).

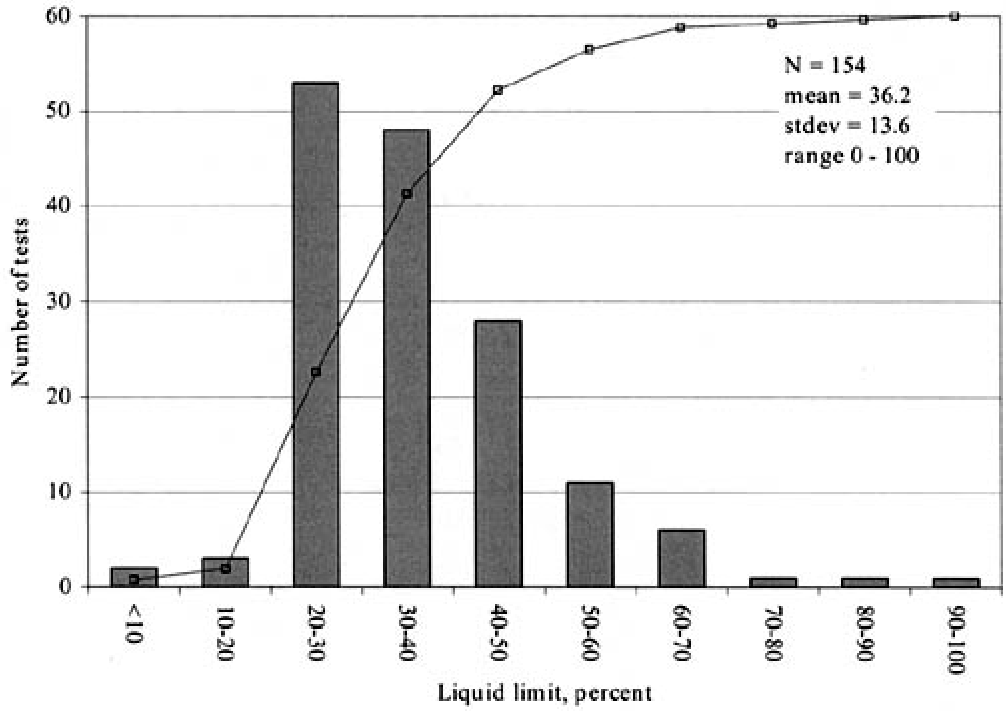

Figure 90. Distribution of liquid limit measurements for fine-grained soils (SPS experiments).

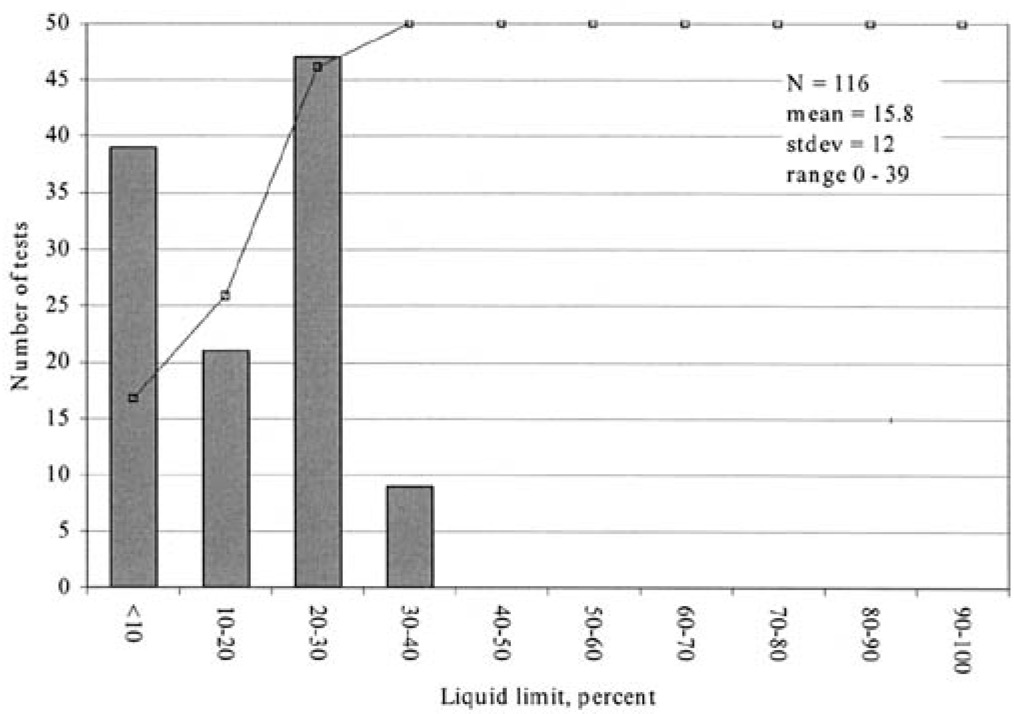

Figure 91. Distribution of liquid limit measurements for coarse-grained soils (SPS experiments).

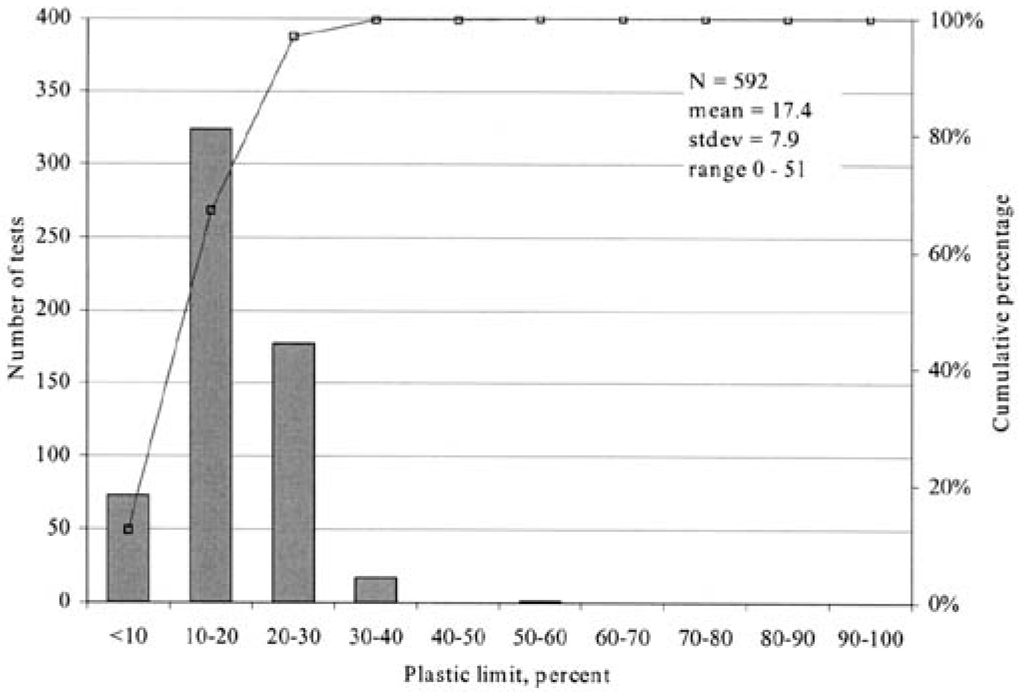

Figure 92. Distribution of plastic limit measurements for fine-grained soils (GPS experiments).

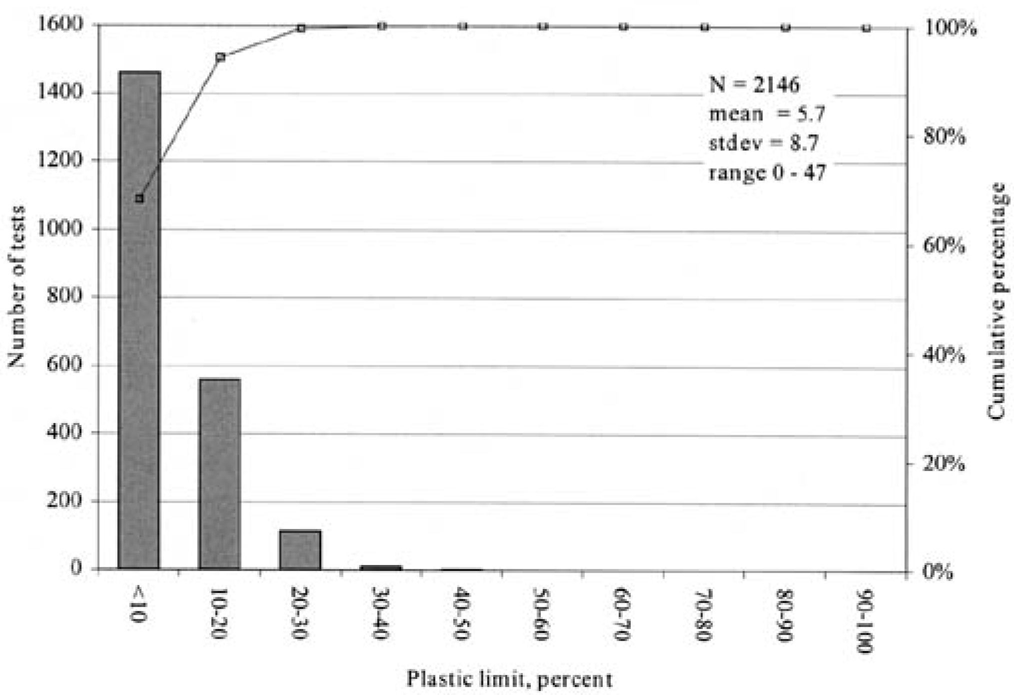

Figure 93. Distribution of plastic limit measurements for coarse-grained soils (GPS experiments).

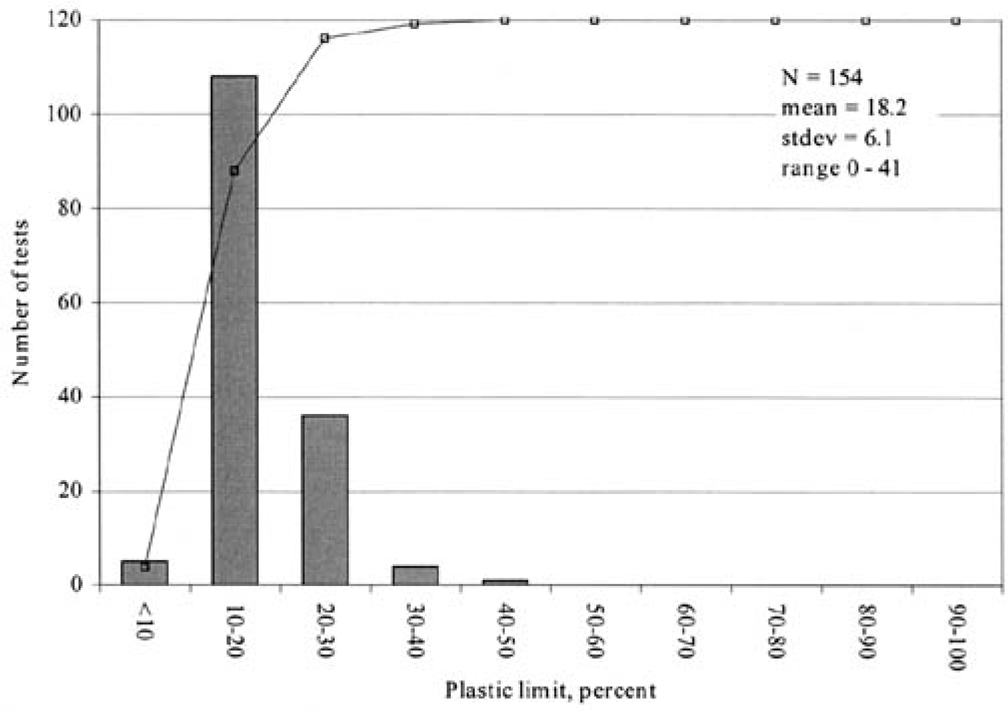

Figure 94. Distribution of plastic limit measurements for fine-grained soils (SPS experiments).

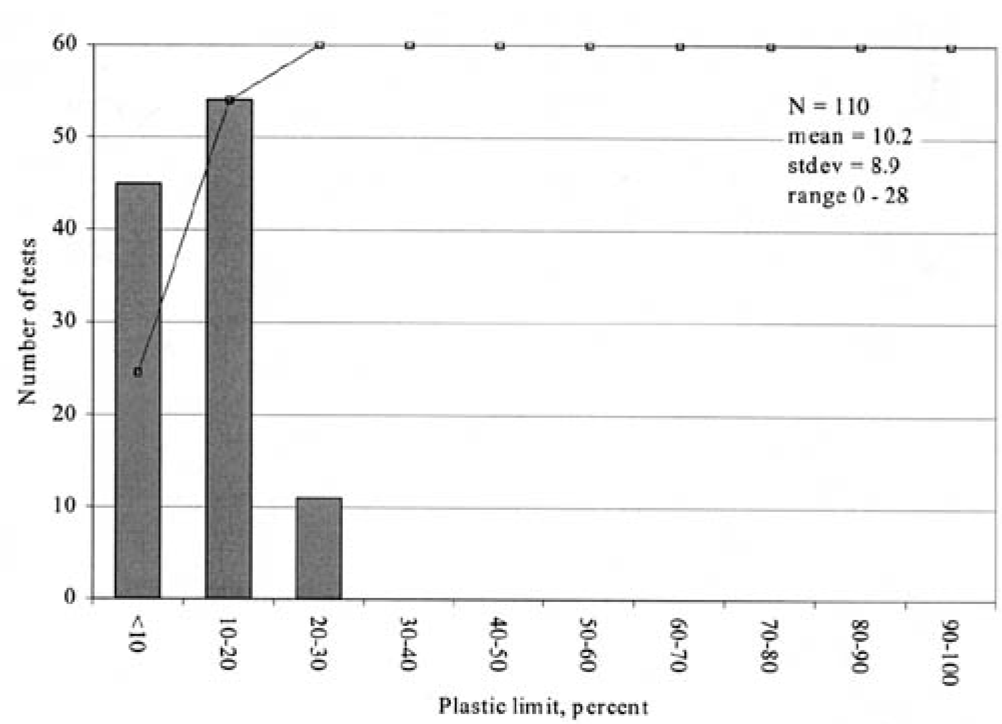

Figure 95. Distribution of plastic limit measurements for coarse-grained soils (SPS experiments).

Atterberg Limits Data Quality

Data quality assessment began with determining the appropriate typical variability expected for test data obtained from samples with similar properties and characteristics. Typical variability as defined in preceding chapters consists of testing, material, sampling, and construction variability. Recommended testing variability from AASHTO T89 and T90 is summarized in table 74.

The precision presented in table 75 constitutes only variability due to testing.[3, 4] Typical variability, therefore, must be greater than the testing variability that matches the test conditions under which LTPP tests are performed-multioperators, multilaboratories. Table 76 presents a summary of typical variability observed in the field and published in the literature.[47]

Table 75. Recommended variability for liquid and plastic limit test results.[3, 4]

Condition of Test	Liquid Limit Acceptable Range of Two Results	Plastic Limit Acceptable Range of Two Results
Single operator, single laboratory using the same apparatus, and on different days	Less than 7 percent of mean value	Less than 10 percent of mean value
Multioperators, multilaboratories	Less than 13 percent of mean value	Less than 18 percent of mean value

Table 76. Summary of typical variability within liquid and plastic limit test results.[47]

Testing Condition	Test Property	No. of Soils	No. of Operators	No. of Tests per Operator	No. of Labs	Avg. Standard Deviation, %	Standard Deviation Range, %	Avg. COV, %	COV Range, %
Within operator	LL	3	2	10	1	0.70	0.56-0.85	2.0	1.5-2.5
Within operator	PL	3	2	10	1	0.72	0.64-0.88	3.6	3.0-4.0
Within operator	PI	3	2	10	1	0.84	0.64-0.99	6.0	3.7-8.7
Between operator	LL	9	5	1	1	1.10	0.44-2.14	4.0	1.7-7.7
Between operator	PL	9	5	1	1	1.03	0.37-2.20	6.5	2.3-13.2
Between operator	PI	9	5	1	1	1.53	0.94-2.54	14.6	6.7-33.8
Between Laboratory	LL	3	1	1	99	3.20	1.7-5.4	7.8	6.2-9.9
Between Laboratory	PL	3	1	1	99	2.80	2.1-3.5	12.3	9.1-15.5
Between Laboratory	PI	3	1	1	99	3.90	2.4-5.7	43.5	17.8-78.0

Based on the information in table 76, a COV of 15 percent was adopted for both liquid limit and plastic limit as the typical variability to be expected and was used as the threshold value for classifying the analysis cells evaluated as acceptable or questionable. Analysis cells classified as questionable were further evaluated to determine possible sources of variability and to implement remedial action, where possible, to correct identified anomalies.

The distribution of COV for liquid limit data for analysis cells from GPS experiments are presented in figure 96. Approximately 82 percent of the analysis cells had acceptable within-cell variability (COV less than 15 percent). Figure 97 presents the distribution of COV for liquid limit data for analysis cells from SPS experiments.

Figure 97 shows that approximately 71 percent of the analysis cells had acceptable within-cell variability. Similar plots were generated for the distribution of COV for plastic limit data for analysis cells obtained from GPS and SPS experiments (see figures 98 and 99). Approximately 86 percent of the analysis cells from the GPS experiments and 77 percent of the analysis cells from the SPS experiments had acceptable variability.

Identification of Anomalous Data

Several anomalies were found in the data during evaluation. The anomalies found, the possible causes of the anomalies, and corrective or remedial measures taken or recommended to address the anomalies are discussed in the next few sections.

Anomaly 1: Erroneous Data Entry

Two analysis cells in table TST_UG4_SS03 had Atterberg limits test results for non-subgrade layers. These are erroneous data entries that do not belong to this table. One of these cells is from SHRP_ID 087776 for treated base material, and the other is from SHRP_ID 040600 for treated base material. Atterberg limits tests are not required for treated base layers. The records were retained in the database with a comment code assigned to them. A feedback report was generated for these records and sent to the FHWA. No further action was taken. Possible remedial action will be taken by the FHWA after the investigation is completed.

Anomaly 2: Liquid Limit Excessive Variability

Excessive variability (COV greater than 15 percent) was observed in 260 of the 1,534 analysis cells with multiple test data. This constitutes about 17 percent of the total number of analysis cells with multiple test results. Various data fields were carefully reviewed for the records belonging to analysis cells with high variability to determine possible causes of the excessive variability. The following was determined:

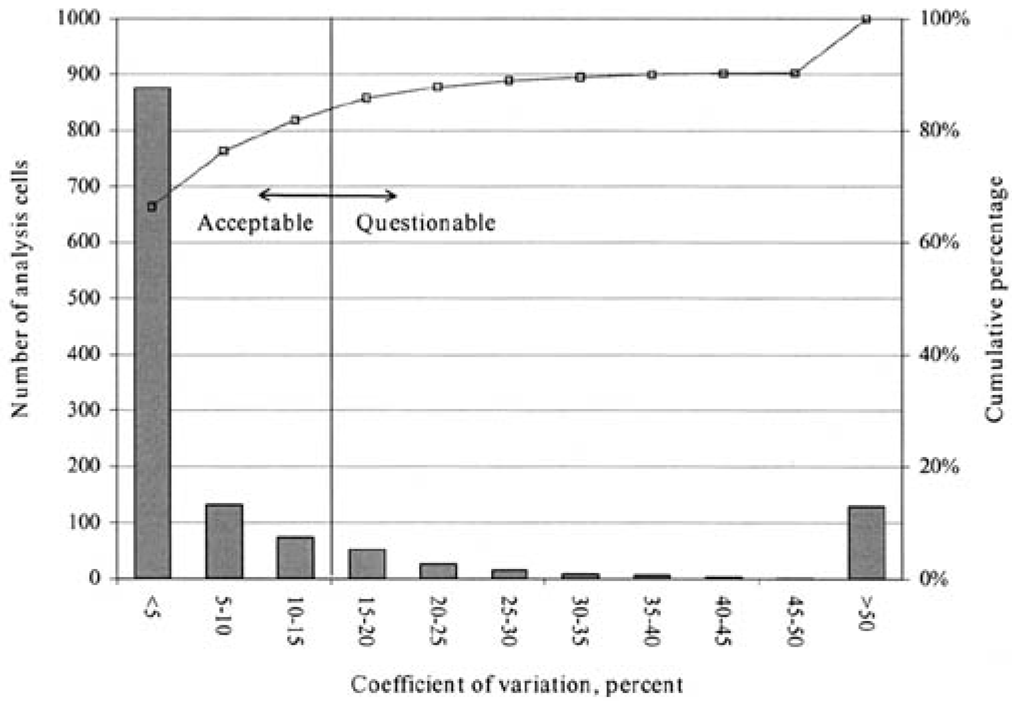

Figure 96. Distribution of COV for liquid limit analysis cell from GPS experiments.

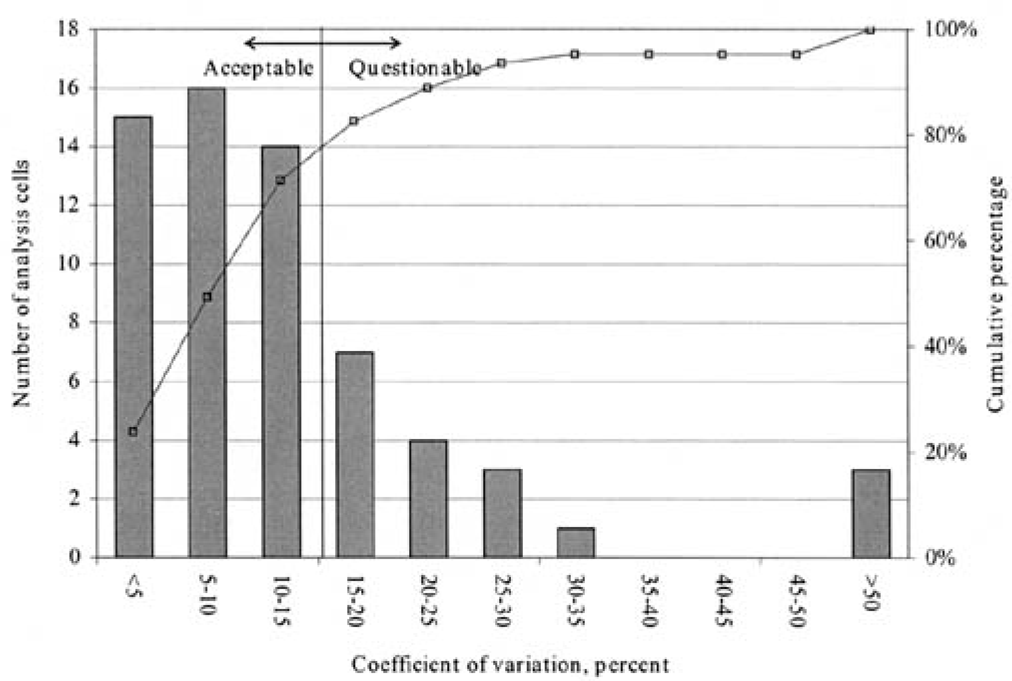

Figure 97. Distribution of COV for liquid limit analysis cell from SPS experiments.

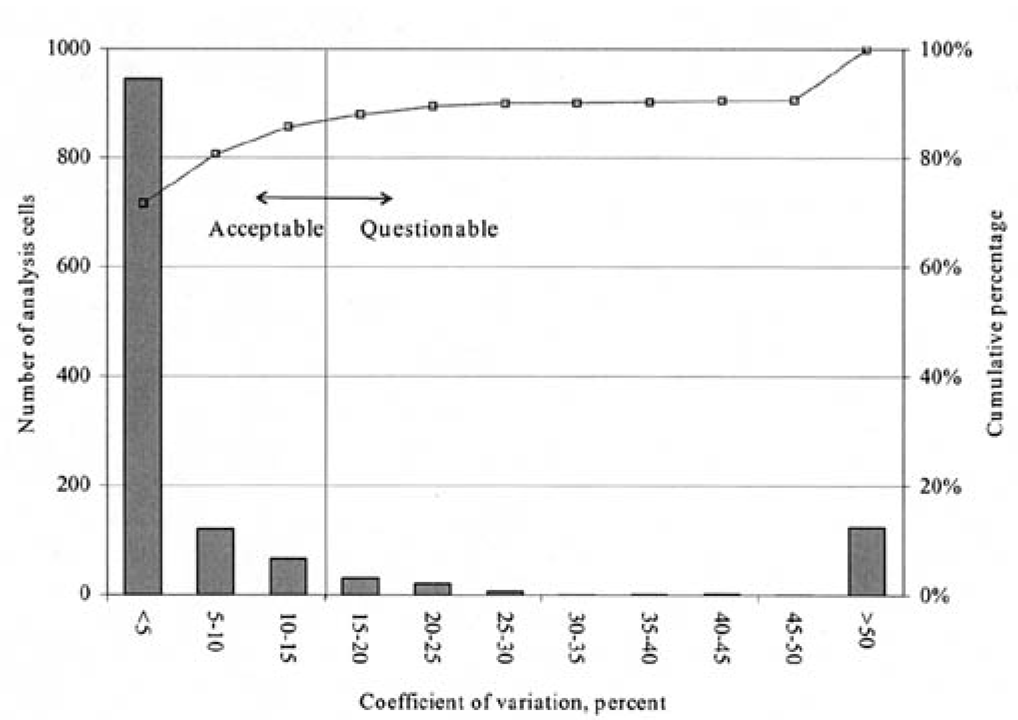

Figure 98. Distribution of COV for plastic limit analysis cell from GPS experiments.

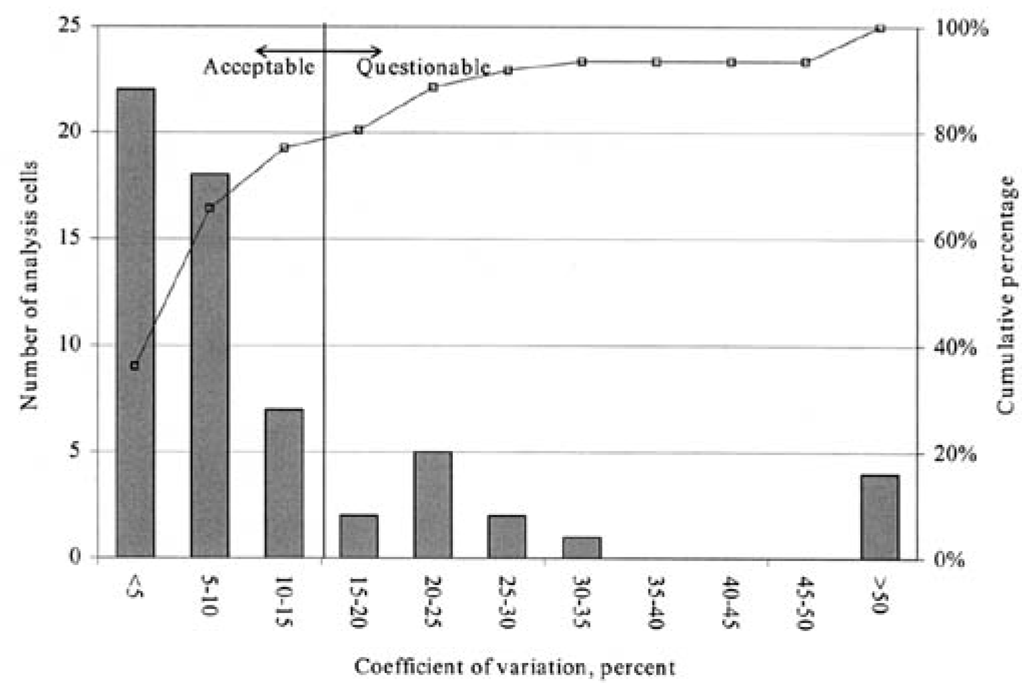

Figure 99. Distribution of COV for plastic limit analysis cell from SPS experiments

- Approximately 50 percent of the 260 cells with excessive variability (131 of 260 cells [128 from GPS experiments and 3 from SPS experiments]) had duplicate samples with a zero and nonzero liquid limit. This result is contradictory and results in extremely high variability.
- Two SPS analysis cells contained outliers (i.e., test data outside mean ± 4 standard deviations).
- The remaining 127 cells had no apparent reason for the excessive variability.

All the data with excessive variability were retained and used in developing the representative data tables. Appropriate comment codes were assigned to explain the possible reasons for the excessive variability. Outliers (i.e., test data outside ± 4 standard deviations of the mean) were not used in developing the representative data tables.

Anomaly 3: Plastic Limit Excessive Variability

Excessive variability (COV greater than 15 percent) was observed in 204 of the 1,534 analysis cells having multiple test results. This constitutes approximately 9 percent of the total number of analysis cells with multiple test results. Various data fields were carefully reviewed for the test records within the analysis cells with excessive variability. The following were observed:

- Of 134 cells with excessive variability, 127 (123 from GPS experiments and 4 from SPS experiments) had duplicate test results with zero and nonzero values. This result is contradictory and results in extremely high variability.
- One SPS cell contained outliers (i.e., test data outside mean ± 4 standard deviations).
- The remaining 76 cells had no apparent reason for the excessive variability.

Most of the data with excessive variability were retained and used in developing the representative data tables. Appropriate comment codes were assigned to explain the possible reasons for the excessive variability. Outliers (i.e., test data outside ± 4 standard deviations of the mean) were not used in developing the representative data tables.

Schema for the Representative Atterberg Limits Data Tables (TST_ UG04_SS03_REP_GPS and TST_ UG04_SS03_REP_SPS)

Two representative Atterberg limits data tables TST_ UG04_SS03_REP_GPS and TST_ UG04_SS03_REP_SPS were developed and recommended for inclusion into the LTPP database. Data in the table were arranged on an analysis cell basis, with appropriate comments provided to describe the anomalies observed on a cell-by-cell basis. The tables also contained basic statistics, such as standard deviation and COV. The schema for tables TST_ UG04_SS03_REP_GPS and TST_ UG04_SS03_REP_SPS are presented in table 77.

The first four fields in the GPS schema and first six fields in SPS schema define the analysis cell used in computing representative test values and other summary statistics of the measured Atterberg limits test data. Fields 5 to 20 and 7 to 22 present the representative test values and basic statistics for the GPS and SPS data, respectively. This is followed by QA comment fields that describe the quality status of the data (e.g., excessive variability and incomplete sampling) based on the QA testing performed. The final field describes the record status.

Table 77. Fields in the representative Atterberg limits data tables TST_ UG04_SS03_REP_GPS and TST_ UG04_SS03_REP_SPS.

Code Number	TST_ UG04_SS03_REP_GPS	TST_ UG04_SS03_REP_SPS
1	State code	State code
2	SHRP identification number	SPS cell identification number
3	Layer number	Description of the layer
4	Construction number	Material code of the layer
5	Number of specimen tested	Construction number
6	Mean LL	Number of specimen tested
7	Maximum LL	Mean LL
8	Minimum LL	Maximum LL
9	Mean PL	Minimum LL
10	Maximum PL	Mean PL
11	Minimum PL	Maximum PL
12	Mean PI	Minimum PL
13	Maximum PI	Mean PI
14	Minimum PI	Maximum PI
15	Standard deviation of LL	Minimum PI
16	Coefficient of variation of LL	Standard deviation of LL
17	Standard deviation of PL	Coefficient of variation of LL
18	Coefficient of variation of PL	Standard deviation of PL
19	Standard deviation of PI	Coefficient of variation of PL
20	Coefficient of variation of PI	Standard deviation of PI
21	QA_Comment_1	Coefficient of variation of PI
22	QA_Comment_2	QA_Comment_1
23	QA_Comment_3	QA_Comment_2
24	QA_Comment_4	QA_Comment_3
25	QA_Comment_5	QA_Comment_4
26	QA_Comment_6	QA_Comment_5
27	QA_Comment_Other	QA_Comment_6
28	Record status	QA_Comment_Other
29		Record status

PL = plastic limit; LL = liquid limit.

15. UNCONFINED COMPRESSIVE STRENGTH OF SUBGRADE SOILS

Introduction

Soils are highly variable materials because of the complex interrelationship between properties such as texture, density, and moisture content. The unconfined compressive strength of soils is determined as part of the LTPP material characterization program. It provides an approximate value of the strength of cohesive soils, which is a very important input for pavement design and analysis. Unconfined compressive strength (q_u) is defined as the compressive stress at which an unconfined cylindrical specimen of soil fails in a simple compression test. Failure is defined as the maximum load per unit area that can be applied to the test specimen or load per unit area at which 15 percent axial strain is achieved (whichever comes first during testing).

For LTPP material characterization, testing is performed using the guidelines provided in SHRP protocol P54--*Unconfined Compressive Strength of Subgrade Soils* and the test standard AASHTO T208--*Unconfined Compressive Strength of Cohesive Soils* (ASTM D2166--*Standard Test Method for Unconfined Compressive Strength of Cohesive Soils*).[2, 3, 4] The test results are stored in the LTPP database in table TST_SS10 after undergoing several levels of quality checks (levels A to E). Table TST_SS10 has the following fields of information:

1. SHRP_ID.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.
8. Lab code.
9. Sample area number.
10. Test date.
11. Specimen height.
12. Specimen diameter.
13. Average cross-section.
14. Moisture content.
15. Dry density.
16. Unconfined compressive strength.
17. L/D ratio.
18. Average failure strain.
19. Average rate of strain.
20. QA Comment 1.
21. QA Comment 2.
22. QA Comment 3.
23. QA Comment 4.
24. QA Comment 5.
25. QA Comment 6.
26. QA Comment others.
27. Record status.

Material Sampling for Unconfined Compressive Strength Testing of Subgrade Soils

Unconfined compressive strength tests were performed on only the subgrade and embankment layers of pavement test sections in various SPS experiments. SHRP and LTPP documents, including the SHRP *Interim Guide for Laboratory Materials Handling and Testing* and the *SPS Guidelines for Nomination and Evaluation of Candidate Projects*, provide detailed information about material sampling and testing procedures for this test.[1-8] Sampling is done at designated locations between adjacent sections within the entire SPS experiment site. SHRP P54 states that tests must be performed only on undisturbed materials sampled using a thin-walled tube.[15, 19, 23] Table 78 presents a summary of the sampling and testing recommended by SHRP for this test.

Table 78. Sampling and testing requirements for unconfined compressive strength of subgrade soils.

Expt Type	Layer Type	LTPP Designation	LTPP Protocol	Minimum Number of Tests per Layer	Sampling Location
SPS-1	Subgrade	SS10	P54	6	A1-A18
SPS-1	Embankment	SS10	P54	6	A1-A18 (if available)
SPS-2	Subgrade	SS10	P54	6	A1, A4, A8, A10, A13, A16
SPS-2	Embankment	SS10	P54	6	A1, A4, A8, A10, A13, A16
SPS-8	Subgrade	SS10	P54	2	A2, A4

Data Completeness for Unconfined Compressive Strength

The data in table TST_SS10 were evaluated for completeness at two levels. Level 1 data completeness consisted of determining the total number of tests records (at all levels A to E) in the data table, the percentage of the data at level E, and the number of analysis cells represented by the data at level E. Level 2 data completeness evaluation consisted of checking each analysis cell to determine whether the required number of tests had been performed with the test data at level E. Results of levels 1 and 2 data completeness are presented and discussed in the next few sections. The January 2000 release of table TST_SS10 was used for data evaluation. Analysis cells were defined using the fields presented in table 79.

Table 79. Fields used in defining analysis cells for table TST_ UG04_SS03 data evaluation.

Field Names	GPS 1 through 9	SPS 1	SPS 2	SPS 5	SPS 6	SPS 8	SPS 9
State Code	X	X	X	X	X	X	X
SHRP ID	X	X	X	X	X	X	X
Construction Number	X	X	X	X	X	X	X
Layer Number	X						
Material Code		X	X	X	X	X	X
Layer Type		X	X	X	X	X	X

Level 1 Data Completeness

The first step in assessing level 1 data completeness was the extraction and assembly of all unconfined compressive strength and related data from the LTPP database. The layer and material description information in table TST_SS10 was cross-referenced with similar information in other LTPP database tables, such as table TST_ LO5B and table EXPERIMENT_SECTION, by combining these tables with TST_SS10. Cross-referencing the data made it possible to check for anomalies in material description, layer type, and layer number information in table TST_SS10. Test results or records with anomalies in material and layer information were not used in further evaluation.

The results of the level 1 data completeness analysis are presented in table 80. Table TST_SS10 had a total of 108 records. Approximately 73 percent (69 of 94) of the records were at level E. Eleven records were test results from supplementary SPS experiments. Test data from SPS supplementary sections were excluded from further analysis because they fall out of the scope of this study.

Table 80. Level 1 completeness for table TST_SS10.

Expt. Type	Expt. No.	Total Number of Records at all Levels	Total Number of Records at Level E	Percentage of Records at Level E	Number of Analysis Cells Represented at Level E
SPS	1	54	40	74.1	7
SPS	2	29	19	65.5	6
SPS	8	11	10	90.9	4

There were 11 records from SPS supplemental sections.

Level 2 Data Completeness

The analysis cells were further evaluated to determine whether the minimum number of tests required by the test protocols had been performed and reported at level E. This was done by checking the amount of test results or records available in each analysis cell and comparing it with the sampling and testing requirements presented in the SHRP guidelines. Analysis cells with at least the minimum number of test records required were categorized as complete, and analysis cells with less than the minimum required test results at level E were classified incomplete. Results of the level 2 data completeness analysis are presented in table 81.

Of the 16 analysis cells with data in table TST_SS10, 44 percent (7 of 16) were classified as complete. The remaining 9 analysis cells were incomplete. The analysis cells with incomplete data were analyzed further to determine the reasons for having incomplete data and the effect of the incomplete data on computing representative test values. The outcome of this evaluation is presented throughout the remaining portions of this chapter.

Table 81. Level 2 data completeness evaluation for table TST_SS10.

Experiment Type	Number of Analysis Cells with Data and Material Information	Min. Number of Test Results Required	Number of Analysis Cells with Min. Number of Test Results	Percent Analysis Cells with Minimum Test Results
SPS-1	7	6	3	43
SPS-2	5	6	1	20
SPS-8	4	2	3	75

Quality Assessment of Unconfined Compressive Strength of Subgrade Soils

Data quality was evaluated as follows for the unconfined compressive strength data in table TST_SS10:

1. Evaluate data for reasonableness.
2. Determine compliance to test protocols and standards.
3. Check analysis cells for excessive variability.

Data Reasonableness

Subgrade soils are quite variable because they are naturally occurring material. Table 82 presents a summary of typical unconfined compressive strength of clayey subgrade soils from published literature.(22)

Table 82. Summary of unconfined compressive strength of clayey soils (fine-grained) from published literature.(22)

Consistency of Soil	Unconfined Compressive Strength, kPa
Very soft	<25
Soft	25-50
Medium	50-100
Stiff	100-200
Very Stiff	200-400
Hard	>400

The information presented in table 82 shows that typical unconfined compressive strength of fine-grained subgrade soils range from less than 25 kPa to more than 400 kPa. Unconfined compressive strength of fine and coarse mixtures is influenced significantly by the percentage of fines in the mixture.

The unconfined compressive strength values in table TST_SS10 ranged from 41 to 682 kPa for fine-grained subgrade soils and from 21 to 205 kPa for coarse-grained mixtures. Even though coarse-grained soils are expected to exhibit higher strength levels than fine-grained materials, both ranges were in agreement with the typical results presented in published literature. The distributions of unconfined compressive strength values for fine-grained and coarse-grained soils are presented in figures 100 and 101.

Compliance with Test Protocols and Standards

The test data in table TST_SS10 were further evaluated to determine whether testing was done according to recommended guidelines and procedures. The checks were done only for situations where testing conditions had been documented (e.g., L/D ratio and specimen length). The results are presented in the next few sections.

Specimen Diameter

AASHTO T208 recommends a minimum specimen diameter of 30 mm. All the specimens with test results in table TST_SS10 had a diameter of 30 mm or greater. They were, therefore, in compliance.

Specimen L/D Ratio

AASHTO T208 recommends an L/D ratio of 2 to 2.5. All the specimens with test results in table TST_SS10 had an L/D ratio between 2 and 2.5. They were, therefore, in compliance.

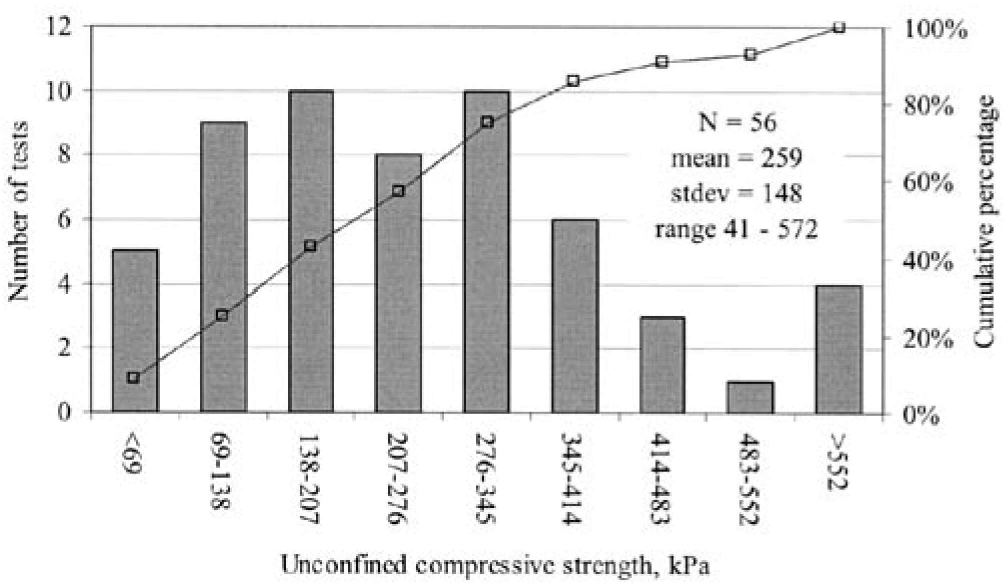

Figure 100. Distribution of unconfined compressive strength values for fine-grained subgrade soils.

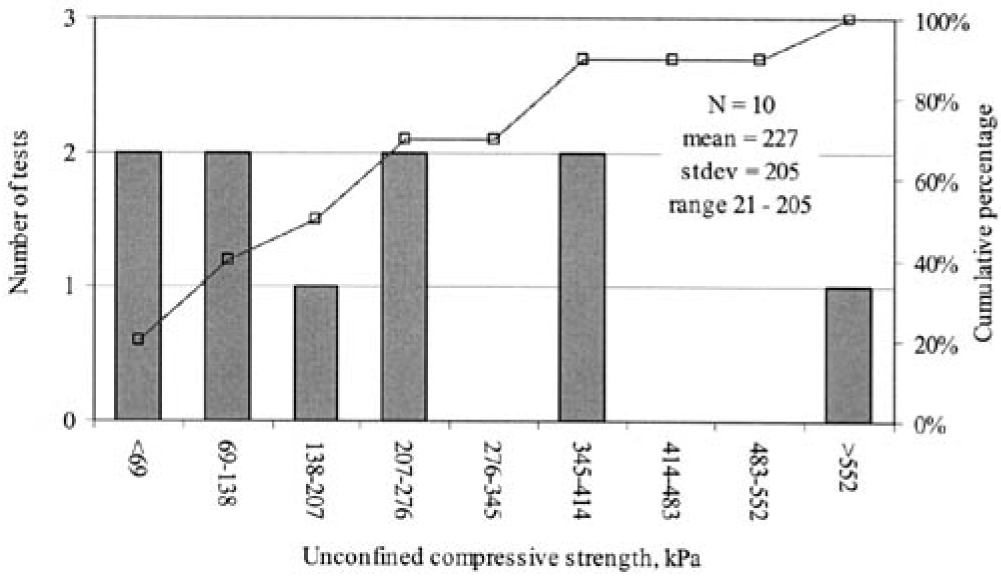

Figure 101. Distribution of unconfined compressive strength values for coarse-grained subgrade soils.

Testing Strain Rate

AASHTO T208 states that the rate of strain during testing must range between 0.5 and 2.0 percent. All the tests reported in table TST_SS10 were in compliance with this recommendation except one (SHRP_ID 200208 [SPS-2 State 20]), which had a strain rate of 2.4 percent.

Failure Strain

AASHTO defines unconfined compressive strength as the stress at which the maximum load is obtained or at which specimen strain reaches 15 percent. All the test data had information on the maximum strain, with the exception of the record for SHRP_ID 200112. The records show that the tests were in compliance with the test standards and protocols.

Assessing Unconfined Compressive Strength Data Quality

The first step in assessing data quality was to determine typical variability expected for test results belonging to the same analysis cell. This was done by reviewing typical variability measured as standard deviation or COV in published literature.[26] The AASHTO T208 test standard provides no recommendations on testing variability. However, AASHTO T208 recognizes the natural variability of subgrade materials and states that "undisturbed soils specimens from apparently homogeneous soil deposits at the same location often exhibit significantly different strength and stress strain properties."[4]

Typical variability from unconfined compressive testing available in published literature is summarized in table 82. Typical standard deviation could range from 1.5 to 49.2, and typical COV ranges from 1.6 to 26.8 percent. The variability presented in table 83 includes sampling, testing, material, and construction variability.

Table 83. Typical variability for unconfined compressive strength testing.

Data Source	Soil Type	Number of Tests	Specimens per Test	Avg. Standard Deviation	Standard Deviation Range	Avg. COV, %	COV Range, %
Yoder and Witzak[26]	Fine-grained	40	8	5	1.5-10	8.4	1.6-26.1
Yoder and Witzak[26]	Coarse-grained	12	5	21	1.7-49.2	11.2	2.6-26.8

Based on information in table 82 and the expected high variability exhibited by natural subgrade materials, a COV of 50 percent was adopted as typical variability. The COV of unconfined compressive strength data in table TST_SS10 ranged from 17 to 65 percent, which is very high but as expected. This high variability may be due to material variability within an SPS experiment.

Of the 16 analysis cells, two had single test values; therefore, variability could not be computed. Figure 102 shows the distribution of COV for the remaining 14 analysis cells. Nine of the 14 cells (64 percent) had acceptable variability.

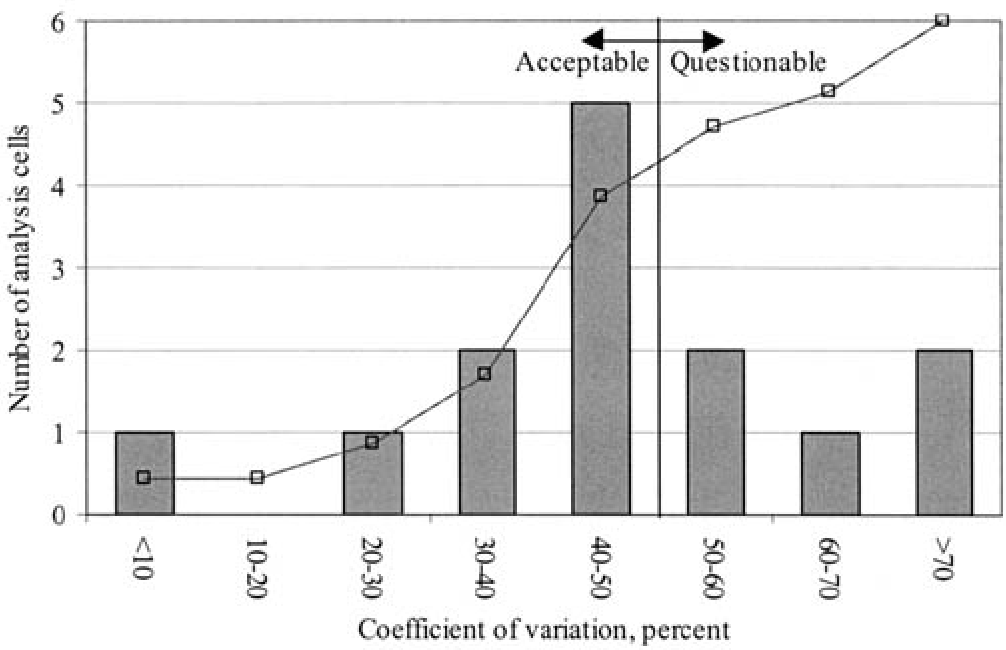

Figure 102. Distribution of COV for analysis cells in table TST_SS10.

Identification of Anomalous Data

Table TST_SS10 had 65 records and 16 analysis cells. Very few anomalies were identified. The analysis cells with excessive variability were checked to determine whether the variability was caused by test results obtained without strict adherence to test protocols and standards. This proved negative, and no plausible reasons were assigned for the high variability observed. Therefore, all the data were used in developing the representative data table TST_SS10_REP.

Schema for the Representative Unconfined Compressive Strength Data Table (TST_SS10_REP)

A representative unconfined compressive strength data table (TST_TB02_REP) was developed and recommended for inclusion into the LTPP database. Data in table TST_SS10_REP were arranged by analysis cells, with appropriate comments provided to describe the anomalies observed on a cell-by-cell basis. The table also contained basic statistics, such as standard deviation and COV. The following are the fields in the table (TST_TB02_REP):

1. State code.
2. SHRP identification number.
3. Description of layer.
4. Material code for the layer.
5. Construction number.
6. Number of specimen tested.
7. Mean unconfined compressive strength.
8. Maximum unconfined compressive strength.
9. Minimum unconfined compressive strength.
10. COV of unconfined compressive strength.
11. Standard deviation of unconfined compressive strength.
12. QA_Comment_1.
13. QA_Comment_2.
14. QA_Comment_3.
15. QA_Comment_4.
16. QA_Comment_5.
17. QA_Comment_6.
18. QA_Comment_Other.
19. Record status.

For table TST_TB02_REP, the first six fields in the schema define the analysis cell used in computing mean, maximum, and minimum test results. Quality assurance comment fields are included to describe the quality status of the data (e.g., excessive variability, incomplete sampling), based on the quality assurance analysis performed as part of this study to guide the user in selecting data for analysis and evaluation. The final field describes the record status.

16. PARTICLE SIZE ANALYSIS OF UNBOUND BASE, SUBBASE, EMBANKMENT, AND SUBGRADE MATERIALS

Introduction

Particle size distribution (gradation) is performed on all unbound base, subbase, and subgrade materials as part of the LTPP material characterization program. The SHRP test protocols for performing particle size analysis are SHRP P41, *Gradation of Unbound Base/Subbase Materials* and SHRP P51, *Gradation of Unbound Subgrade Materials*. SHRP P41 and P51 are based on AASHTO T27 (ASTM C136) *Sieve Analysis of Fine and Coarse Aggregates*.(2, 3, 4)

The test protocols and standards provide guidance on all aspects of material sampling, preparation, testing, computation of test results, and presentation on test results. Test results are stored in the LTPP database after undergoing QA/QC checks. Test results that are at QA/QC levels A to E are stored in table TST_SS01_UG01_UG02 in the LTPP database. The following data are maintained in table TST_SS01_UG01_UG02:

1. SHRP_ID.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. SHRP test.
7. Location number.
8. Construction number.
9. Laboratory code.
10. Sample area number.
11. Sample number.
12. Test date.
13. Percent passing 75-mm sieve.
14. Percent passing 50-mm sieve.
15. Percent passing 37.5-mm sieve.
16. Percent passing 25.4-mm sieve.
17. Percent passing 19.5-mm sieve.
18. Percent passing 12.5-mm sieve.
19. Percent passing 9.5-mm sieve.
20. Percent passing 4.75-mm sieve.
21. Percent passing 2.0-mm sieve.
22. Percent passing 0.425-mm sieve.
23. Percent passing 0.2-mm sieve.
24. Percent passing 0.075-mm sieve.
25. Percent washing through 0.075-mm sieve.
26. QA Comment 1.
27. QA Comment 2.
28. QA Comment 3.
29. QA Comment 4.
30. QA Comment 5.
31. QA Comment 6.
32. QA Comment Other.
33. Sample weight.
34. Moisture content.
35. Record status.

Material Sampling for Particle Size Analysis

Gradation tests were performed on material samples obtained from bulk samples retrieved from the unbound base, subbase, or subgrade layers of GPS and SPS experiments. The bulk samples were obtained by excavating 300-mm diameter boreholes and test pits. The bulk samples from boreholes were combined and prepared in accordance with AASHTO T87-86 and reduced to a representative test size in accordance with AASHTO T248-83.(2) Only material samples taken from the same sampling location and pavement layer were combined. The natural moisture content of the bulk samples was also determined.

For GPS experiments, materials for gradation testing were excavated from boreholes and test pits (located at both the approach and leave ends of the pavement test section). The boreholes and test pits were sited outside the pavement distress monitoring section. For SPS experiments, materials were excavated at designated locations along the different test sections within the SPS experiment.

Details of the sampling plans showing the approximate locations where sample materials were obtained from test pits and boreholes for gradation testing (for GPS experiments and SPS projects) are presented in the LTPP Data Collection Guidelines for GPS and SPS Experiments.(2, 27-32) Details of the procedures used for material preparation and testing are presented in the relevant SHRP protocols and AASHTO test procedures.(2, 27-32)

Material sampling for gradation testing is performed once--just after construction for newly constructed pavements or several years after construction for in-service pavements. The number of samples taken for testing depends on the LTPP experiment. Sampling materials for gradation testing is very comprehensive for SPS experiments because the SPS projects were designed to have a diverse matrix of site and design features and, therefore, layer types and material properties vary along the experiment.

Also, the different SPS projects consist of both newly constructed and in-service pavements that have undergone minor or major rehabilitation. Samples are, therefore, obtained pre- and postconstruction or during construction, as appropriate, based on experiment type.

Gradation Data Completeness

Data completeness was evaluated at two levels after data extraction and assembly. Procedures for data extraction and assembly were described in the introductory chapters. Level 1 data completeness consisted of the determination of the total number of material samples collected, tested, and with test results reported in the LTPP database at all QC quality levels (A to E). This was used to determine the percentage of all test results at level E.

The data at level E were grouped into analysis cells, and the number of analysis cells represented by the test results at level E was determined. An analysis cell was broadly defined as that part of the pavement produced with similar material and placed with similar equipment and techniques. For the gradation test results of unbound base, subbase, and subgrade materials, analysis cells for were defined as follows:

- For GPS experiments--analysis cells generally consist of a layer within the pavement structure, where the material can be assumed to be homogeneous.
- For SPS experiments--analysis cells generally consist of layers with similar properties from the individual test pavements (e.g., 201, 202, …., 224) within a given experiment.

Table 84 is a summary of the fields that define analysis cells for GPS and SPS test sections. Level 2 data completeness consisted of assessing the test data for each analysis cell to determine whether the minimum number of tests required by the LTPP had been performed and reported at level E.

Table 84. Data fields used for defining analysis cells for gradation of unbound base, subbase, and subgrade materials.

Data Fields	GPS	SPS[1]
State code	X	X
SHRP_ID	X	X
Layer number	X	X
Layer type	X	X
Material code	X	X
Construction number	X	X

[1]SPS-1, -2, -5, -6, -7, -8, and -9A.

The next few sections of this chapter describes level 1 and 2 data availability for unbound base, subbase, and subgrade gradation test results available in the LTPP database.

Level 1--Data Completeness

The gradation tests available in the LTPP database at all the different levels of QC (levels A to E) are presented in table 85. Histograms showing the total number of samples tested, as compared with the number of samples that have successfully completed QA/QC and are at level E for each experiment type, are shown as figures 103 and 104 for GPS and SPS experiments, respectively.

Level 2--Data Completeness

Level 2 data completeness evaluation consisted of checking each analysis cell with gradation test results at level E to determine whether the minimum required number of tests had been conducted and, hence, test results reported at level E. Table 86 is a summary of the minimum number of gradation tests required for each analysis cell for the different LTPP experiments. Inadequate sampling may introduce bias into computed representative test results and other descriptive statistics. Bias generally leads to test results that may be unrepresentative of the gradation properties of the entire pavement test section or analysis cell.

The first step in assessing level 2 data completeness was to compute the number of test results reported at level E for each analysis cell. The computed values were then compared with the minimum number of tests required. Analysis cells with the minimum number of test results were categorized as complete, and those with less than the minimum were classified as incomplete. Tables 87 and 88 present a summary of level 2 data completeness for GPS and SPS experiments. There were a total of 486 analysis cells for GPS-1 pavement sections. Of these, 8.4 percent of the analysis cells had less than the required minimum number of tests reported at level E. For GPS-2 experiments, 7.4 percent of the analysis cells had less than the required minimum number of test results reported at level E. Of the 233 GPS-3 analysis cells, approximately 11 percent had less than the minimum required number of test results reported at level E.

A summary of the remaining analysis cells is as follows:

- GPS-4--4.6 percent.
- GPS-5--4.2 percent.

- GPS-6A--9.2 percent.
- GPS-6B--22.9 percent.
- GPS-7A--4.8 percent.

Table 85. Summary of level 1 data completeness for TST_ SS01_UG01_UG02.

Experiment Type	Experiment Number	Total Number of Samples Tested (All QC Levels A to E)	Total Number of Samples atLevel E	Percent Samples at Level E	Total Number of Analysis Cells Represented
GPS	1	941	935	99.4	486
GPS	2	422	419	99.3	216
GPS	3	449	441	98.2	233
GPS	4	218	213	97.7	109
GPS	5	238	236	99.2	120
GPS	6A	248	248	100.0	130
GPS	6B	59	58	98.3	35
GPS	7A	124	122	98.4	62
GPS	7B	23	22	95.7	12
GPS	9	81	76	93.8	39
SPS	1	150	128	85.3	26
SPS	2	137	102	74.5	21
SPS	5	121	78	64.5	23
SPS	6	65	34	52.3	13
SPS	7	18	18	100.0	6
SPS	8	100	82	82.0	24
SPS	9	63	4	6.3	2

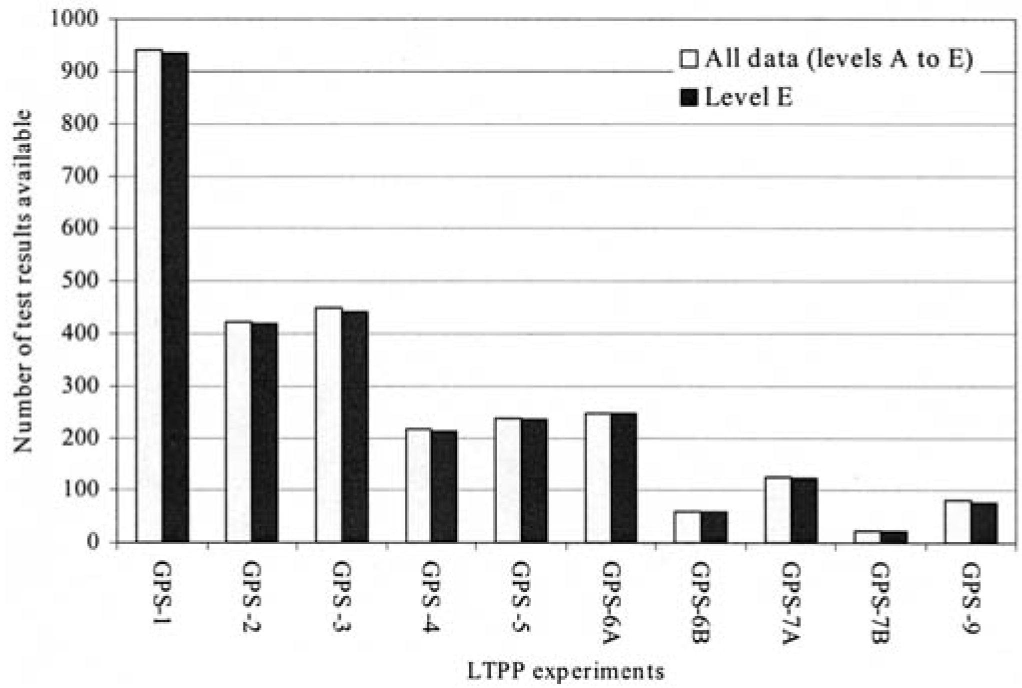

Figure 103. Histograms showing gradation data availability for GPS experiments.

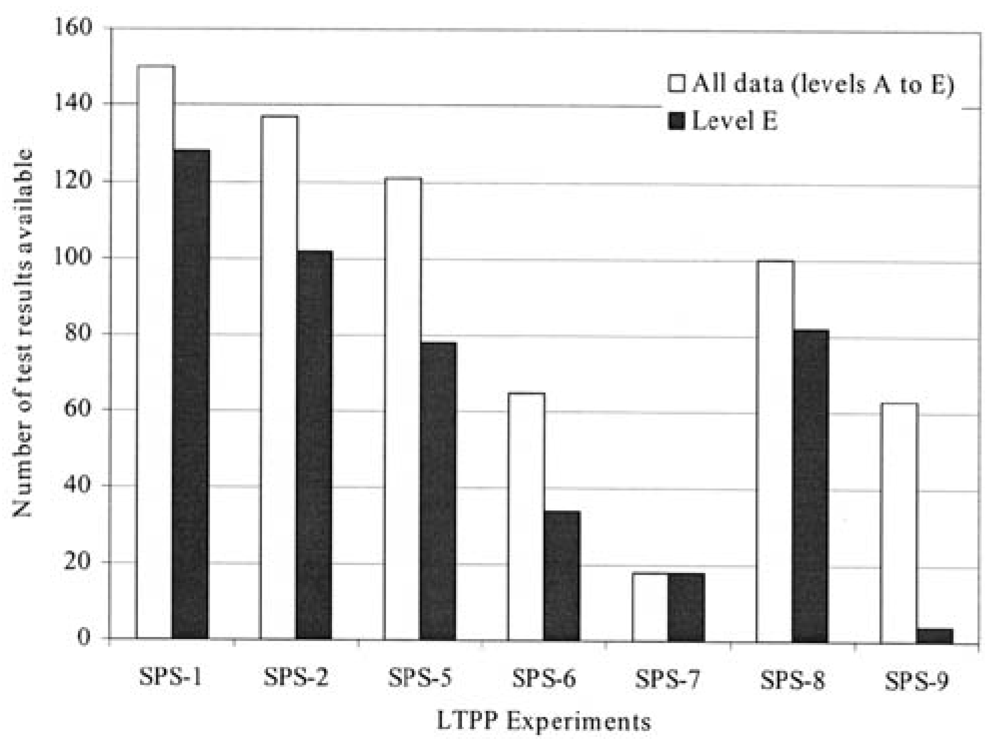

Figure 104. Histogram showing gradation data availability for SPS experiments.

- GPS-7B--16.7 percent.
- GPS--9-5.1 percent.

For SPS-1 experiments, 26 analysis cells had some gradation test results available at level E. Approximately 69 percent of the analysis cells with gradation data had the required minimum number of test results (as recommended by the SHRP protocols) reported at level E. The remaining 31 percent had less than the required minimum test results reported at level E. For SPS-2 experiments, the total number of analysis cells with gradation test data was 21. Fifty-seven percent of these had the required minimum number of test results reported at level E. The remaining 43 percent had less than the required minimum.

Gradation testing was not required for SPS-3 and SPS-4 experiments. For SPS-5 experiments, the total number of analysis cells with available test data was 23. Sixty-one percent of the analysis cells had the required minimum number of test results reported at level E.

SPS-6 experiments had 12 or 13 analysis cells with gradation test data at level E. Fifty-nine percent had the required minimum number of tests results reported. Approximately 67 percent of the analysis cells from SPS-7 experiments with gradation test data had the required minimum number of results reported.

Table 86. Sampling for determination of particle size analysis of granular base/subbase and subgrade materials.

Experiment Type[1]	Layer Type	Test Type	LTPP Designation	LTPP Protocol	Minimum Number of Tests per Layer	Sampling Location
GPS 1 - 7 and 9	Base	Sieve analysis	UG01, UG02	P41	2	Approach end, BA, Leave end, TP1
GPS 1 - 7 and 9	Subgrade	Sieve analysis	SS01	P51	2	Approach end, BA, Leave end, TP1
SPS-1	Subgrade (with embankment >/= 1.2 m)	No test	--	--	--	--
SPS-1	Subgrade (with embankment < 1.2 m)	Sieve analysis	SS01	P51	6	B1-B6
SPS-1	Embankment (< 1.2 m thick)	Sieve analysis	SS01	P51	6	B7-B12
SPS-1	Embankment (>/= 1.2 m thick)	Sieve analysis	SS01	P51	6	B1-B6
SPS-1	Unbound granular base/subbase	Particle size analysis	UG01, UG02	P41	3	B13-B15

SPS-1	Unbound granular base/subbase	Sieve analysis (washed)	UG01, UG02	P41	3	B13-B15
SPS-2	Subgrade (with embankment >/= 1.2 m)	No test	--	--	--	--
SPS-2	Subgrade (with embankment < 1.2 m)	Sieve analysis	SS01	P51	6	B1-B6
SPS-2	Embankment (< 1.2 m thick)	Sieve analysis	SS01	P51	6	B7-B12
SPS-2	Embankment (>/= 1.2 m thick)	Sieve analysis	SS01	P51	6	B1-B6
SPS-2	Unbound granular base/subbase	Particle size analysis	UG01, UG02	P41	3	B13-B15
SPS-2	Unbound granular base/subbase	Sieve analysis (washed)	UG01, UG02	P41	3	B13-B15
SPS-5	Subgrade	Sieve analysis	SS01	P51	3	[BA1-3] [TP] [BA4-6]
SPS-5	Unbound granular base/subbase	Particle size analysis	UG01	P41	3	[BA1-3] [TP] [BA4-6]
SPS-5	Unbound granular base/subbase	Sieve analysis (washed)	UG01	P41	3	[BA1-3] [TP] [BA4-6]
SPS-6	Subgrade	Sieve analysis	SS01	P51	3	TP1 [BA1-3] TP2
SPS-6	Unbound granular base/subbase	Particle size analysis	UG01	P41	3	TP1 [BA1-3] TP2
SPS-6	Unbound granular base/subbase	Sieve analysis (washed)	UG01	P41	3	TP1 [BA1-3] TP2
SPS-7	Subgrade	Sieve analysis	SS01	P51	3	TP1 [BA1-3] TP2
SPS-7	Unbound granular base/subbase	Particle size analysis	UG01	P41	3	TP1 [BA1-3] TP2
SPS-7	Unbound granular base/subbase	Sieve analysis (washed)	UG01	P41	3	TP1 [BA1-3] TP2
SPS-8	Subgrade	Sieve analysis	SS01	P51	3	B1-B3
SPS-8	Unbound granular base/subbase	Particle size analysis	UG01	P41	3	B4-B6

SPS-8	Unbound granular base/subbase	Sieve analysis (washed)	UG01	P41	3	B4-B6
SPS 9 (new construction)	Subgrade	Sieve analysis	SS01	P51	3	B01A01, B01A02, B01A03
SPS 9 (new construction)	Unbound granular base/subbase	Particle size analysis	UG01	P41	3	B02A01, B02A02, B02A03
SPS 9 (existing construction-overlay)	Subgrade	Sieve analysis	SS01	P51	3	A01A01, A01A02, A01A03
SPS 9 (existing construction--overlay)	Unbound granular base/subbase	Particle size analysis	--	--	--	--

[1]No gradation tests for SPS-3 and SPS-4 experiments.

Table 87. Summary of level 2 dta completeness for TST_SS01_UG01_UG02.

Experiment Type	Total Number of Analysis Cells (Layers) Represented	Number of Layers/Cells with Less Than Minimum No. of Tests	Percent Layers/Cells with Incomplete Data
GPS-1	486	41	8.4
GPS-2	216	16	7.4
GPS-3	233	25	10.7
GPS-4	109	5	4.6
GPS-5	120	5	4.2
GPS-6A	130	12	9.2
GPS-6B	35	8	22.9
GPS-7A	62	3	4.8
GPS-7B	12	2	16.7
GPS-9	39	2	5.1

Table 88. Summary of particle size analysis data available for SPS experiments.

Expt. Type	Expt. Number	State Code	SHRP ID	Construction Number	Layer No.	Cell/Layer Description	Number of Samples	Minimum No. of Samples	Minimum Satisfied?
S	1	1	100	1	2	Base	3	3	Yes
S	1	1	100	1	1	Subgrade	6	7	Yes
S	1	4	100	1	2	Base	3	4	Yes
S	1	4	100	1	1	Subgrade	6	12	Yes
S	1	5	100	1	1	Subgrade	6	5	No

S	1	12	100	1	2	Base	3	1	No
S	1	12	100	1	1	Subgrade	6	5	No
S	1	19	100	1	3	Base	3	3	Yes
S	1	19	100	1	2	Embankment	6	7	Yes
S	1	22	100	1	2	Embankment	6	6	Yes
S	1	22	100	1	1	Subgrade	6	6	Yes
S	1	26	100	1	2	Base	3	2	No
S	1	26	100	1	1	Subgrade	6	2	No
S	1	30	100	1	1	Subgrade	6	10	Yes
S	1	31	100	1	2	Embankment	6	3	No
S	1	31	100	1	1	Subgrade	6	5	No
S	1	32	100	1	4	Base	3	3	Yes
S	1	32	100	1	3	Embankment	6	6	Yes
S	1	32	100	1	1	Subgrade	6	6	Yes
S	1	35	100	1	1	Subgrade	6	6	Yes
S	1	40	100	1	3	Base	3	3	Yes
S	1	40	100	1	1	Subgrade	6	6	Yes
S	1	48	100	1	3	Base	3	3	Yes
S	1	48	100	1	1	Subgrade	6	6	Yes
S	1	51	100	1	3	Base	3	3	Yes
S	1	51	100	1	1	Subgrade	6	5	No
S	2	4	200	1	2	Base	3	4	Yes
S	2	4	200	1	1	Subgrade	6	9	Yes
S	2	5	200	1	2	Base	3	3	Yes
S	2	5	200	1	1	Subgrade	6	6	Yes
S	2	8	200	1	2	Base	3	3	Yes
S	2	8	200	1	1	Subgrade	6	7	Yes
S	2	10	200	1	3	Base	3	2	No
S	2	10	200	1	2	Embankment	6	5	No
S	2	10	200	1	1	Subgrade	6	16	Yes
S	2	19	200	1	3	Base	3	3	Yes
S	2	19	200	1	1	Subgrade	6	6	Yes
S	2	26	200	1	3	Base	3	3	Yes
S	2	26	200	1	2	Embankment	6	5	No
S	2	26	200	1	1	Subgrade	6	5	No
S	2	37	200	1	3	Base	3	2	No
S	2	37	200	1	2	Embankment	6	2	No
S	2	37	200	1	1	Subgrade	6	5	No
S	2	38	200	1	3	Base	3	2	No
S	2	53	200	1	4	Base	3	3	Yes

S	2	53	200	1	3	Embankment	6	9	Yes
S	2	53	200	1	2	Embankment	6	1	No
S	5	1	500	1	3	Base	3	1	No
S	5	1	500	1	1	Subgrade	3	7	Yes
S	5	4	500	1	2	Base	3	5	Yes
S	5	4	500	1	1	Subgrade	3	5	Yes
S	5	8	500	1	1	Subgrade	3	3	Yes
S	5	12	500	1	3	Base	3	1	No
S	5	13	500	1	2	Embankment	3	2	No
S	5	13	500	1	1	Subgrade	3	2	No
S	5	23	500	1	3	Base	3	7	Yes
S	5	23	500	1	2	Embankment	3	4	Yes
S	5	23	500	1	1	Subgrade	3	1	No
S	5	28	500	1, 2	1	Subgrade	3	8	Yes
S	5	30	500	1	3	Base	3	2	No
S	5	30	500	1	2	Embankment	3	2	No
S	5	30	500	1	1	Subgrade	3	2	No
S	5	34	500	1	4	Base	3	2	No
S	5	34	500	1	2	Embankment	3	3	Yes
S	5	34	500	1	1	Subgrade	3	2	No
S	5	81	500	1	2	Embankment	3	3	Yes
S	5	81	500	1	1	Subgrade	3	3	Yes
S	5	83	500	2	3	Base	3	5	Yes
S	5	83	500	2	2	Embankment	3	4	Yes
S	5	83	500	2	1	Subgrade	3	4	Yes
S	6	4	600	1	3	Treated base	3	2	No
S	6	4	600	1	2	Embankment	3	1	No
S	6	4	600	1	1	Subgrade	3	2	No
S	6	19	600	1	2	Base	3	3	Yes
S	6	19	600	1	1	Subgrade	3	3	Yes
S	6	26	600	1, 2	3	Base	3	3	Yes
S	6	29	600	1	2	Base	3	5	Yes
S	6	29	600	1	1	Subgrade	3	2	No
S	6	40	600	1	2	Base	3	3	Yes
S	6	40	600	1	1	Subgrade	3	3	Yes
S	6	42	600	2	2	Base	3	2	No
S	6	42	600	2	1	Subgrade	3	2	No
S	6	47	600	1	1	Subgrade	3	3	Yes
S	7	19	700	1, 2	3	Base	3	3	Yes
S	7	19	700	1, 2	2	Embankment	3	3	Yes

S	7	19	700	1, 2	1	Subgrade	3	3	Yes
S	7	22	700	1, 2	1	Subgrade	3	5	Yes
S	7	29	700	1, 2	2	Base	3	2	No
S	7	29	700	1, 2	1	Subgrade	3	2	No
S	8	5	800	1	3	Base	3	4	Yes
S	8	5	800	1	1	Subgrade	3	6	Yes
S	8	8	800	1	2	Base	3	3	Yes
S	8	8	800	1	1	Subgrade	3	5	Yes
S	8	30	800	1	2	Base	3	3	Yes
S	8	30	800	1	1	Subgrade	3	3	Yes
S	8	34	800	1	2	Base	3	1	No
S	8	34	800	1	1	Subgrade	3	3	Yes
S	8	36	800	1	2	Base	3	2	No
S	8	36	800	1	1	Subgrade	3	2	No
S	8	37	800	1	2	Base	3	2	No
S	8	37	800	1	1	Subgrade	3	2	No
S	8	39	800	1	3	Base	3	3	Yes
S	8	39	800	1	2	Subgrade	3	2	No
S	8	39	800	1	1	Subgrade	3	5	Yes
S	8	48	800	1	3	Base	3	3	Yes
S	8	48	800	1	1	Subgrade	3	3	Yes
S	8	49	800	1	3	Base	3	3	Yes
S	8	49	800	1	2	Embankment	3	3	Yes
S	8	49	800	1	1	Subgrade	3	3	Yes
S	8	53	800	1	4	Base	3	6	Yes
S	8	53	800	1	3	Embankment	3	6	Yes
S	8	53	800	1	2	Embankment	3	6	Yes
S	8	53	800	1	1	Subgrade	3	3	Yes
S	9	4	900	1	2	Base	3	2	No
S	9	4	900	1	1	Subgrade	3	2	No

For SPS-8 experiments, the total number of analysis cells with test data available was 24. Seventy-five percent of the analysis cells had the required minimum number of test results reported. Finally, there were two analysis cells with test data available for SPS-9 experiments, and both had less than the required minimum number of test results reported at level E.

Summary of Gradation Data Availability

The focus of this section was to summarize gradation data available in the LTPP database. The first task was to evaluate the LTPP database to obtain all gradation test results (levels A to E) available. This was followed by determining how much of the test data had successfully passed QA/QC and was at level E. The number of analysis cells represented by the level E data was estimated, and this was used to determine whether the minimum number of test results required for material characterization was available to the LTPP data user. The following is a summary of data availability for gradation test data:

- The LTPP database contains 3,457 records of gradation test results at various quality levels (A to E) representing individual tests performed on 3,457 aggregate samples.
- Of the 3,457 test results, 95 percent (3,215 of 3,457) are at quality level E.
- The 3,215 test results at level E represent 1,557 analysis cells.
- Eighty-nine percent of the analysis cells (1,395 of 1,557) had the required minimum number of test results reported.

Gradation of Unbound Base, Subbase, and Subgrade Test Data Quality

Data quality was evaluated in two parts. All individual test results reported at level E in the LTPP database were evaluated for reasonableness. Reasonableness was assessed in terms of whether the test results followed expected trends and whether the test protocols and procedure (such as minimum sample size required for testing) had been adhered to. Test results grouped into analysis cells were then checked for homogeneity or whether they belong to the same population of results. The statistic used to assess whether the results were homogeneous was standard deviation. Details of the data quality evaluation are presented in the following sections of this chapter.

Evaluation of Trends in Gradation Test Results

Gradation test results for all the samples in the LTPP database (level E) were checked for reasonableness by plotting sieve size against the percent passing by weight. All the plots showed reasonable trends. Figure 105 shows an example of the plots used in assessing the reasonableness of the gradation data.

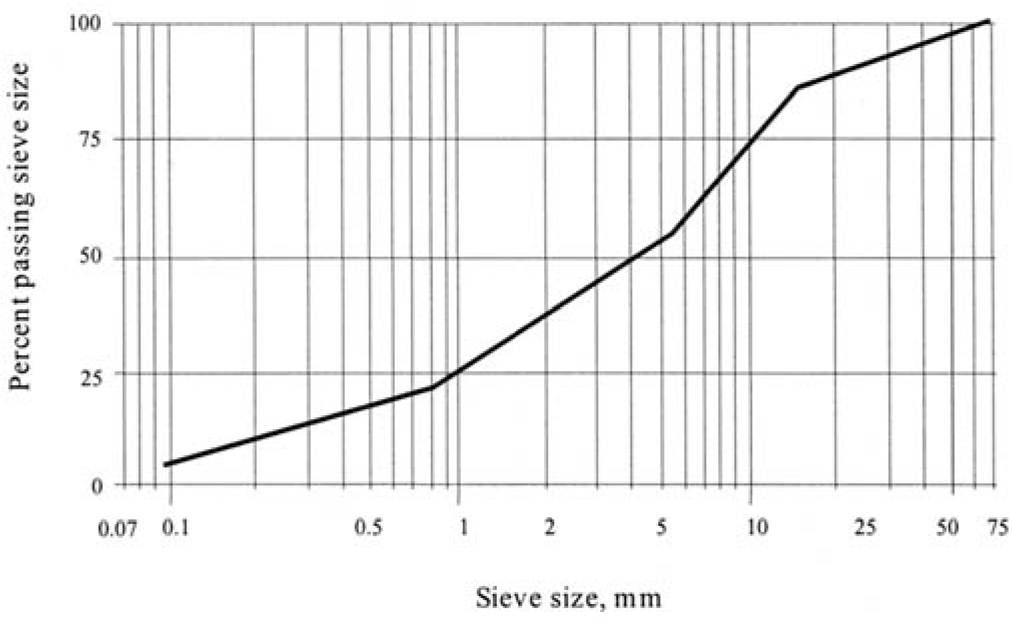

Figure 105. Example of plots used in assessing the gradation data reasonableness.

Identification of Analysis Cells with Inadequate Number of Test Results

The LTPP material characterization program was designed to ensure that representative test values could be obtained for a given test section without bias. This can be achieved only if adequate numbers of test samples are taken and tested for each experiment type, according to the LTPP sampling and testing guidelines. Inadequate sampling and testing could potentially result in biased computed representative test values for the entire pavement section.

The SHRP P41 and P51 test protocols and SPS Pavement Construction and Material Sampling Guidelines recommend both the minimum number and location of sample materials to be tested for gradation. Strict adherence to these guidelines will minimize the potential for bias in computed representative test results. Analysis cells with less than the required number of sampling and tests performed or single test values have a high potential for bias. Table 89 is a summary of the percentage of analysis cells with less than the required test results reported at level E in the LTPP database.

Table 89. Percentage of analysis cells with potentially biased results due to inadequate sampling.

Experiment Type	Total Number of Analysis Cells	Number of Analysis Cells with Minimum Number of Tests	Percent Analysis Cells with Complete Testing	Percent Analysis Cells with Potential Sampling Bias
GPS-1	486	445	91.6	8.4
GPS-2	216	200	92.6	7.4
GPS-3	233	208	89.3	10.7
GPS-4	109	104	95.4	4.6
GPS-5	120	115	95.8	4.2
GPS-6A	130	118	90.8	9.2
GPS-6B	35	27	77.1	22.9
GPS-7A	62	59	95.2	4.8
GPS-7B	12	10	83.3	16.7
GPS-9	39	37	94.9	5.1
All SPS	115	72	62.6	37.4
Total	1557	1395	89.6	10.4

Identification of Test Samples with Inadequate Sample Size

Bias in test results could also be introduced into the sampling and testing process through any of the following:

- Collecting undersized test samples for testing. This is irrespective of whether the required number of test samples were collected at a given pavement section or for a given analysis cell.
- Using noncalibrated equipment for testing.
- Not complying with test procedure or protocols
- Using untrained technicians for testing.

AASHTO T27 provides no guidelines for assessing testing bias during the actual testing process. Because LTPP samples were tested only in designated laboratories with certified equipment and personnel, it is not likely that bias was introduced into the test results from any of the following sources:

- Use of noncalibrated equipment for testing.
- Noncompliance with test procedures or protocols.
- Use of untrained technicians for testing.

Nevertheless, bias may be introduced by testing undersized samples. AASHTO T27 provides recommendations on the minimum size of test samples to minimize the potential for bias. The minimum sample weight is determined from the nominal aggregate size of the test material. Using test samples with the minimum recommended weight ensures that the presence or absence of one or two of the largest particles in the sample does not distort the gradation test results.[20]

For the LTPP material characterization program, aggregate nominal size was defined as the smallest sieve opening through which at least 95 percent of the aggregate passes.[2] For coarse aggregates or coarse/fine aggregate mixtures, SHRP P41 states that recommendations for test sample size in AASHTO T27 should be applied only for aggregates with nominal size 50.8 mm or less and for bulk samples weighing 68 kg or more.[2] For aggregates with nominal size greater than 50.8 mm, the approximate weight of the test sample shall not exceed 22.5 kg. However, the approximate weight of the test sample shall not exceed 18 kg if the total bulk sample weighs between 48 and 68 kg. Table 90 is a summary of recommended test sample weight from AASHTO T27 for coarse and coarse/fine aggregate mixtures.[2, 4]

Table 90. Summary of recommended test sample weight for gradation testing.

Nominal Maximum Size(based on square openings), mm[1]	Minimum Weight of TestSample, kg
9.5	1
12.5	2
19.0	5
25.0	10
37.5	15
50	20

[1]The nominal maximum aggregate size is defined as the smallest sieve size opening through which at least 95 percent of the aggregate passes.

Test sample sizes for fine aggregates are determined as follows:

- For aggregates with at least 95 percent passing the 2.36-mm sieve size, the minimum sample weight will be 0.1 kg.
- For aggregates with at least 85 percent passing the 4.75-mm sieve with more than 5 percent retained on the 2.36-mm sieve, the minimum sample weight will be 0.45 kg.

Coarse aggregate is generally defined as materials retained on the 4.75-mm sieve, and fine aggregate is considered to be any material that passes the 9.5-mm sieve and essentially all material that passes the 4.75-mm sieve.[2, 4] Thirty-three percent of the test samples were classified as fine aggregates, and the remaining 67 percent were classified as coarse/fine aggregates mixtures. Figures 106 and 107 show histograms of the difference in required sample size and actual sample size for the 3,457 test samples evaluated.

Approximately 46 percent of the coarse/fine aggregate test samples were undersized, and less than 1 percent of the fine aggregate test samples were undersized. The SHRP P41 test protocol allows tests to be performed on samples with less than the required sample size, as long as this information is reported as part of the test results.[(2)]

Determining Within-Cell Typical Variability

The final data quality check was to determine analysis cells with excessive variability (i.e., variability levels greater than what is typical for the testing conditions and material type under evaluation). Typical variability can be defined loosely as the variability expected for gradation test results when the normal procedures for materials selection, construction, sampling, and testing are applied to a pavement project. Typical variability reported in AASHTO T27 and other published literature is presented in the next few sections.

AASHTO T27

AASHTO T27 defines testing variability or precision for sieve analysis using both standard deviation and COV.(4) Precision recommendations were based on several tests conducted at the AASHTO Materials Reference Laboratory.[(12)] The recommended precision is based on aggregate size (i.e., coarse or fine) and whether testing was conducted by a single operator or multiple operators. Precision recommended by AASHTO T27 is summarized in tables 91 and 92 for coarse and fine aggregate fractions, respectively.

Tables 91 and 92 show that the appropriate level of precision must be selected based on several factors, including the conditions under which testing was performed (single operator vs. multilaboratory), the percentage of material retained on consecutive sieves, and the sieve size (coarse or fine fraction). For this study, only multilaboratory "reproducibility" precision values must be considered in determining typical variability because the LTPP gradation test data were obtained from multiple laboratories. Also, an evaluation of the gradation test data shows the following:

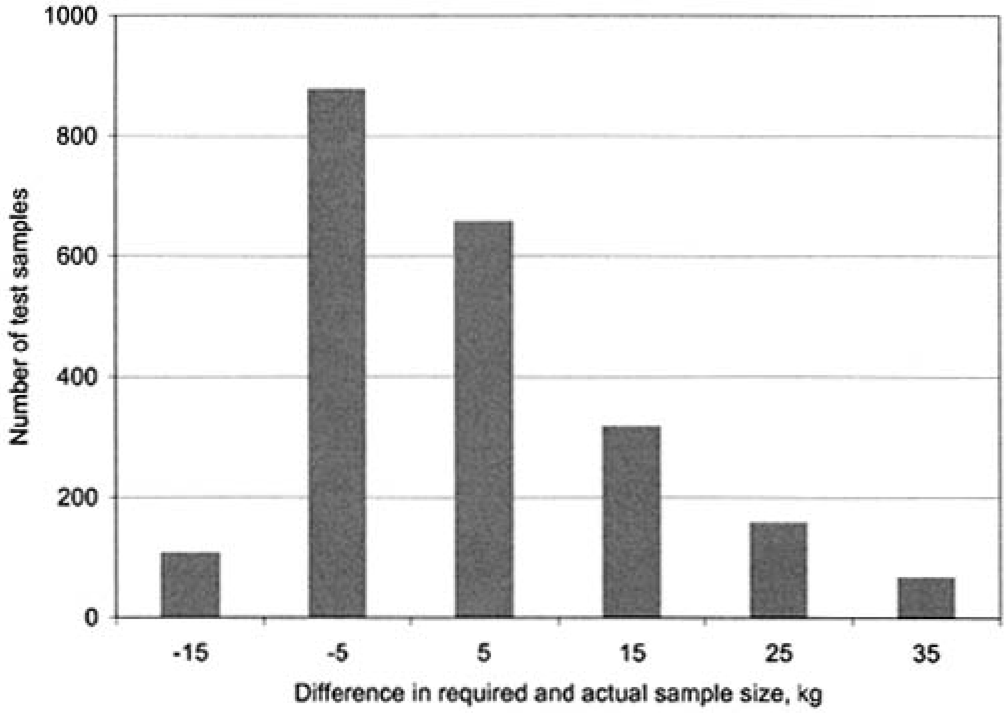

Figure 106. Distribution of difference in required and actual sample size for coarse/fine aggregate mixtures test samples analyzed.

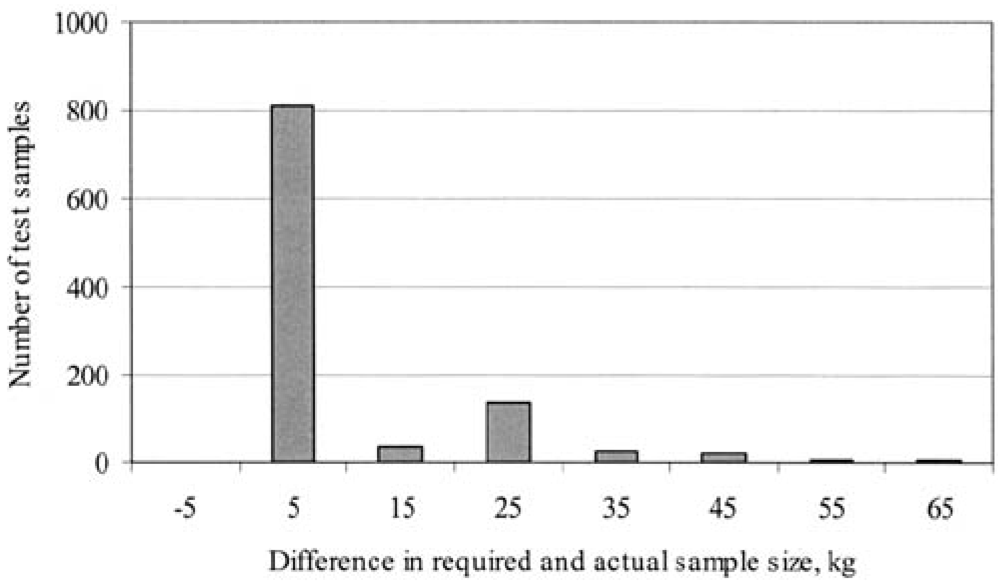

Figure 107. Distribution of difference in required and actual sample size for fine aggregate test samples analyzed.

Table 91. Precision for coarse aggregate fraction.(4)

Test Condition	Percent of Material between Consecutive Sieves	COV (1S), Percen[1, 2]	Standard Deviation(1S), Percent[1, 2]
Single Operator[3]	0 to 3	30[4]	--
Single Operator[3]	3 to 10	--	1.44
Single Operator[3]	10 to 20	--	0.95
Single Operator[3]	20 to 50	--	1.38
Multilaboratory	0 to 3	35[4]	--
Multilaboratory	3 to 10	--	1.06
Multilaboratory	10 to 20	--	1.66
Multilaboratory	20 to 30	--	2.01
Multilaboratory	30 to 40	--	2.44
Multilaboratory	40 to 50	--	3.18

[1]These numbers represent the (1S) limits described in ASTM C670.
[2]The precision estimates are based on coarse aggregates with nominal maximum size of 19.5 mm.
[3]These values are from precision indices first included in AASHTO T27.
[4]AASHTO T-27 defines coarse aggregates as the fraction of material passing through the 90-mm sieve to the 9.5-mm sieve. Fine aggregates are the fraction passing through the 4.75-mm sieve to the 0.075-mm sieve.

Table 92. Precision for fine aggregate particle size analysis.(4)

Test Condition	Percent of Material between Consecutive Sieves	COV (1S), Percent[1]	Standard Deviation(1S) Percent[1]
Single Operator	0 to 3	--	0.14
Single Operator	3 to 10	--	0.43
Single Operator	10 to 20	--	0.60
Single Operator	20 to 30	--	0.64
Single Operator	30 to 40	--	0.71
Single Operator	40 to 50	--	--
Multilaboratory	0 to 3	--	0.21
Multilaboratory	3 to 10	--	0.57

Multilaboratory	10 to 20	--	0.95
Multilaboratory	20 to 30	--	1.24
Multilaboratory	30 to 40	--	1.41
Multilaboratory	40 to 50	--	--

[1]These numbers represent the (1S) limits described in ASTM C670.

- The material retained between consecutive sieve sizes ranged between 0 and 30 percent for the coarse fractions and 0 and 60 percent for the fine fractions.
- For the coarse fraction of mixed coarse/fine aggregate materials, greater than 99 percent of the material retained between consecutive sieves had a value of less than 50 percent.
- For the fine fraction of mixed coarse/fine aggregate materials and fine aggregate materials, 96 percent of the material retained between consecutive sieves had a value less than 40 percent.

Using the information presented above, the appropriate within-analysis cell precision applicable to the LTPP gradation data to be evaluated was 3.18 and 1.41 percent for the coarse and fine fractions, respectively.

Hughes 1995

Typical variabilities reported from various pavement projects and research studies were synthesized and reported by Hughes.[13] A summary of the variability obtained from these studies is presented in table 93. Table 93 shows that typical gradation test variability ranges from 1.8 to 7.7 for coarse aggregates and from 0.9 to 3.7 for fine aggregates. Using the information presented in table 92 and the AASHTO guidelines for precision, the next step was to determine an appropriate typical variability level to be used for determining acceptable and questionable within-cell variability.

Table 93. Typical allowable variability for gradation of unbound materials.[13, 25]

Material Type	Sieve Size, mm	Pennsylvania Study	Virginia Study	Aggregate Producers	North Carolina Study	Virginia Producers
Coarse fraction	25.4	--	1.9	--	--	1.8 to 2.2
Coarse fraction	19.5	3.5 to 6.8	--	0.9 to 3.9	--	--
Coarse fraction	12.5	--	--	--	4.3	--
Coarse fraction	9.5	5.6 to 8.3	4.2	--	--	--
Coarse fraction	4.75	5.2 to 6.2	--	2.3 to 7.7	3.4 to 4.2	4.3 to 4.6
Fine fraction	2.36	--	--	1.7 to 3.7	--	--
Fine fraction	2.00	--	2.8	0.9 to 3.7	3 to 4.3	3 to 3.4

Fine fraction	1.18	3.4 to 3.6	--	--	--	--
Fine fraction	0.425	--	1.7	--	3.2 to 3.3	1.7 to 1.9
Fine fraction	0.250	--	--	1.0 to 3.1	--	--
Fine fraction	0.075	1.2 to 1.4	0.9	0.7 to 1.2	1 to 1.3	0.9 to 1.1

Variability is reported as standard deviation and is based on sieve size and aggregate type.

Typical variability was determined by setting the AASHTO-recommended precision or variability as the minimum end of the range of typical variability. The maximum typical variability was determined from the test results reported in table 93. This resulted in the following ranges of typical variability expected for fine and coarse aggregates:

- Coarse aggregate--standard deviation of 3.2 to 7.7 percent.
- Fine aggregate--standard deviation of 1.4 to 3.7 percent.

The 90th percentile of the range, which corresponded to 7.5 and 3.5 percent for coarse-and fine-grained aggregates, respectively, was adopted as the threshold variability between acceptable and questionable data.

Summary of Gradation Test Data Quality

A total of 1,557 analysis cells had some gradation test results reported in the LTPP database at level E. Of these, 126 analysis cells had single test results, so the standard deviation of the test results of those analyses could not be computed. Standard deviation was computed for analysis cells with multiple test results, then used to assess the data quality of the remaining 1,431 analysis cells by comparing typical and actual standard deviation. A summary of the results is presented in table 94.

Table 94. Summary of test data quality for LTPP table TST_SS01_UG01_UG_02.

Sieve Size, mm	Number of Analysis Cells with Acceptable Variability	Number of Analysis Cells with Excessive Variability	Number of Analysis Cells with Single Test Data	Total Number of Analysis Cells	Percent Analysis Cells with Acceptable Data
75	1412	19	126	1557	90.7
50	1392	39	126	1557	89.4
37.5	1357	74	126	1557	87.2
25	1325	106	126	1557	85.1
19	1274	157	126	1557	81.8
12.5	1215	216	126	1557	78.0
9.5	1192	239	126	1557	76.6
4.75	834	597	126	1557	53.6
2	776	655	126	1557	49.8

0.425	697	734	126	1557	44.8
No. 80	734	697	126	1557	47.1
0.075 (dry)	899	532	126	1557	57.7
0.075 (wash)	890	541	126	1557	57.2

Identification of Anomalous Data

Two general types of anomalies were identified: excessive variability and insufficient/missing test data. The procedures adopted for correcting these anomalies are presented in the next few sections.

Anomaly 1--Analysis Cells with Excessive Variability

There are various causes of excessive variability in test data. Some of the common causes include the following:

1. Erroneous test results due to insufficient sample size.
2. Erroneous test data caused by incorrect data entries.
3. Erroneous test data caused by a lack of adherence to test protocol and standards.

A detailed description of the causes of excessive variability and possible remedial action are presented as follows.

Erroneous Test Results Due to Insufficient Sample Size

AASHTO T27 recommends a minimum sample size to avoid introducing bias from the presence or absence of one or two of the largest particles in the sample. Undersized test sample could potentially introduce biased tests results, resulting in excessive within-analysis cell variability.

The SHRP P41 test protocols recommend that undersized test samples should not be eliminated from the pool of test data but should be identified using an appropriate comment code. Therefore, analysis cells with excessive variability and undersized test samples were identified and flagged. The data user will have the option of whether to include such data in analysis.

Erroneous Test Data Caused by Incorrect Data Entries

Erroneous test results may be entered by mistake into table TST_SS01_UG01_UG02, thereby contributing to excessive variability. Such data are most likely not typical and should have been detected when the data were evaluated for reasonableness.

V*ariability Due to Lack of Adherence to Test Protocols*

Excessive variability may be caused by the lack of adherence to test standards and protocols. This type of variability can be detected only if such deviations are noted with the test results.

Test data obtained through the use of procedures that contradict the recommended SHRP guidelines were not used in the development of the representative data table. Removing the erroneous data should rectify the excessive variability caused by obvious documented defects in testing.

There were some analysis cells with no obvious reasons for excessive variability. Such analysis cells were reported as part of the representative data table. The usefulness of such data will be evaluated ultimately by users.

Anomaly 2--Insufficient Test Data

Another common anomaly identified was insufficient (or missing) test results for the various analysis cells. The reasons for insufficient or missing data include the following:

1. Test data are still undergoing QA/QC and are not yet at level E.
2. Test is yet to be performed or is currently being performed.
3. Test samples were not found suitable for testing and were, therefore, rejected (no testing performed).
4. The data are simply missing.

For case 1, the test data were identified in the LTPP database as levels A to D data. No remedial action was taken because the data are still going through QA/QC. An assessment of the state of the data will be possible only after the QA/QC process is complete and the data are (or are not) available at level E.

For cases 2 and 3, there was no record of the data in the LTPP database. For these situations, a feedback report has been sent to the FHWA. Appropriate remedial action will be taken by the FHWA. For case 4, if it is determined that the missing data will not be available, the missing data will be estimated by interpolating or extrapolating existing test data.

Implementation of Remedial Action to Correct Identified Anomalies

The identified anomalies were corrected, where feasible, using the remedial actions outlines. For the analysis cells with excessive variability, the remedial action did not always reduce variability to within the acceptable limits. For such situations, excessive variability was assumed to be due to other sources, such as the material and construction. The analysis cells were still identified as having excessive variability in the representative data table.

Schema for the Representative Particle Size Analysis of Unbound Base, Subbase, Embankment, and Subgrade Materials Data Table (TST_ SS01_UG01_UG02_REP)

A representative particle size analysis of unbound base, subbase, embankment, and subgrade materials data table (TST_ SS01_UG01_UG02_REP) was developed and recommended for inclusion into the LTPP database. Data in TST_SS01_UG01_UG02_REP were arranged by analysis cells, with appropriate comments provided to describe the anomalies observed on a cell-by-cell basis. The table also contained basic statistics, such as standard deviation and COV. The schema for table TST_ SS01_UG01_UG02_REP is presented below:

1. Experiment type.
2. Experiment number.
3. State code.
4. SHRP identification number.
5. Construction number.
6. Layer number.
7. Test date.
8. Material code.
9. Layer type.
10. Number of test samples.
11. Mean percent passing X-mm sieve size.

12. Maximum percent passing X-mm sieve size.
13. Minimum percent passing X-mm sieve size.
14. COV.
15. Standard deviation.
16. Data source.
17. QA Comment 1.
18. QA Comment 2.
19. QA Comment 3.
20. QA Comment 4.
21. QA Comment 5.
22. QA Comment 6.
23. QA Comment Other.
24. Record status.

X is the sieve size in millimeters. The first seven fields in the schema define the analysis cell used in computing mean, maximum, and minimum test results. Basic statistics--such as the number of test data, COV, and standard deviation--are also computed for the given analysis cell. Codes describing the source of the data (e.g., from laboratory testing or obtained through interpolation or extrapolation) are also presented.

Comments are provided to describe the state of the data (e.g., excessive variability or incomplete sampling) to guide the user in selecting data for analysis and evaluation. The final field describes the record status.

17. GRADATION OF AGGREGATE EXTRACTED FROM ASPHALTIC CONCRETE

Introduction

Gradation of aggregate extracted from asphaltic concrete was determined for all asphaltic (bituminous) materials retrieved from GPS and SPS experiments as part of the LTPP material characterization program. Testing procedures were based on guidelines presented in the following SHRP test protocol and AASHTO test guide:[2, 4]

- SHRP P14--Gradation of Aggregate Extracted from Asphaltic Concrete.
- AASHTO T30--Mechanical Analysis of Extracted Aggregates.

The test protocol and standard provided guidance on all aspects of material sampling, preparation, testing, computation of test results, and presentation on test results. Test results were stored in the LTPP database after undergoing QA/QC checks to ensure that anomalies are identified, corrected, or identified with an appropriate comment code. Test results that are at various levels of QA/QC were stored in table TST_AG04 in the LTPP database. The following gradation data elements are maintained in table TST_AG04:

1. SHRP_ID.
2. State code.
3. Layer number.
4. Field set.
5. Test number.
6. Location number.
7. Construction number.
8. Laboratory code.
9. Sample area number.
10. Sample number.
11. Test date.
12. Percent passing 37.5-mm sieve.
13. Percent passing 25.4-mm sieve.
14. Percent passing 19.5-mm sieve.
15. Percent passing 12.5-mm sieve.
16. Percent passing 9.5-mm sieve.
17. Percent passing 4.75-mm sieve.
18. Percent passing 2.0-mm sieve.
19. Percent passing 0.425-mm sieve.
20. Percent passing 0.2-mm sieve.
21. Percent passing 0.075-mm sieve.
22. QA Comment 1.
23. QA Comment 2.
24. QA Comment 3.
25. QA Comment 4.
26. QA Comment 5.
27. QA Comment 6.
28. QA Comment Other.
29. Soil geology.
30. Geology code A.
31. Geology code B.
32. Record status.

Material Sampling

Gradation tests were performed on material samples obtained from 300-mm diameter asphaltic concrete cores retrieved (and separated from any other layers, if necessary) from the approach end of the GPS test pavements and block samples from test pits at the leave end. For SPS experiments, cores were obtained from designated locations (at the approach and leave ends of individual test sections) within the entire SPS experiment. The samples were prepared in accordance with AASHTO T164, *Quantitative Extraction of Bitumen from Bituminous Paving Mixtures*, and tested for AC content before being tested to determine the aggregate gradation.(4)

A sketch of the layout of the GPS and SPS test sections showing the approximate locations (where sample materials were obtained from test pits and boreholes) for gradation testing is presented in various LTPP documents. Full details of the sampling plans, material preparation, and testing are presented in the relevant SHRP protocols, AASHTO test procedures, and LTPP Data Collection Guidelines for GPS and SPS Experiments.(2,27, and 32)

Material sampling for gradation testing is performed once--just after construction for newly constructed pavements or several years after construction for in-service pavements. The number of samples taken for testing depended on the LTPP experiment type. Sampling materials for gradation testing was very comprehensive for SPS experiments because the SPS experiments were designed to have a diverse matrix of site and design features (such as different base and subbase types for adjacent test sections and subgrade conditions [pavements constructed over the natural subgrade or over an embankment]). Also, because the different SPS projects consisted of both newly constructed and in-service pavements, in some cases, samples from the same layers were collected both pre- and postconstruction or even during construction with different construction numbers).

Gradation Data Completeness

Data completeness was evaluated at two levels. Procedures for data extraction and assembly were described in the introductory chapters. Level 1 data completeness consisted of the determination of the total number of material samples collected, tested, and with test results reported in the LTPP database at all QC quality levels (A to E), the percentage of the test data at level E, and the number of analysis cells represented by the data at level E.

The analysis cells for GPS and SPS pavement test sections were defined as follows:

- For GPS experiments--A given AC or asphalt treated layer within the test section.
- For SPS experiments--Similar AC or asphalt-treated material located in the test sections within a given experiment. As an example, the asphalt-treated base layers located in relevant test sections throughout an SPS 1 experiment for one analysis cell.

Level 2 data completeness consisted of assessing the test data for each analysis cell to determine whether the minimum number of tests recommended in the SHRP protocols had been performed. The next few sections of this chapter describe level 1 and 2 data availability for gradation data of aggregates extracted from asphaltic concrete in table TST_AG04.

Level 1--Data Completeness

A summary of all gradation tests results available in table TST_AG04 at QC levels A to E is presented in table 95. Histograms showing the total number of test data as compared with the test data that have successfully completed QA/QC and are at level E for each experiment type are shown as figures 108 and 109.

Level 2--Data Completeness

Level 2 data completeness evaluation consisted of checking each analysis cell with gradation test results at level E to determine whether the recommended minimum number of tests had been conducted and the results reported at level E. Table 96 is a summary of the minimum number of gradation tests required for each AC layer or analysis cell. Inadequate sampling and testing may introduce bias into computed representative test results and other descriptive statistics. Bias generally leads to test results that may be unrepresentative of the gradation properties of the entire pavement test section.

Table 95. Summary of particle size analysis data available in LTPP database.

Expt. Type	Expt. Number	Total Number of Samples Tested (All QC Levels A to E)	Total Number of Samples at Level E	Total Number of Usable Samples at Level E[1]	Percent Usable Samples at Level E	Total Number of Analysis Cells Represented
GPS	1	627	624	559	89.2	288
GPS	2	473	471	459	97.0	204
GPS	3	5	5	5	100.0	3
GPS	4	2	2	0	0.0	0
GPS	6A	269	262	253	94.1	129
GPS	6B	187	184	177	94.7	80
GPS	6C	15	14	14	93.3	6
GPS	6D	4	3	3	75.0	2
GPS	6S	44	42	40	90.9	17
GPS	7A	93	92	84	90.3	44
GPS	7B	49	44	41	83.7	20
GPS	7C	2	2	2	100.0	1
GPS	7S	12	10	8	66.7	4
GPS	9	12	12	6	50.0	4
SPS	1	142	110	71	50.0	23
SPS	2	23	14	13	56.5	4
SPS	5	164	159	120	73.2	18
SPS	6	61	5	7	11.5	2
SPS	8	21	21	10	47.6	4
SPS	9	31	3	0	0.0	0

[1]Records with layer material descriptions available.

Notes:

Six records were removed because they had the wrong material descriptions.

Seventeen records from SPS-5 supplemental sections were removed. There were 141 records with material description information from table TST_LO5B at level A to D.

There were 74 test sections with no material description information from table TST_LO5B.

There were 237 records with gradation data at level A to D. This included 119 SPS supplemental sections.

There were 30 records classified at level A to D with no gradation information.

Of a total of 2,395 records in table TST_AG04, 405 were not used in any further analysis because of the reasons stated above. Statistics describing the remaining 1,990 remaining records are presented in the table.

Eighteen records at level E with materials description information had missing gradation data.

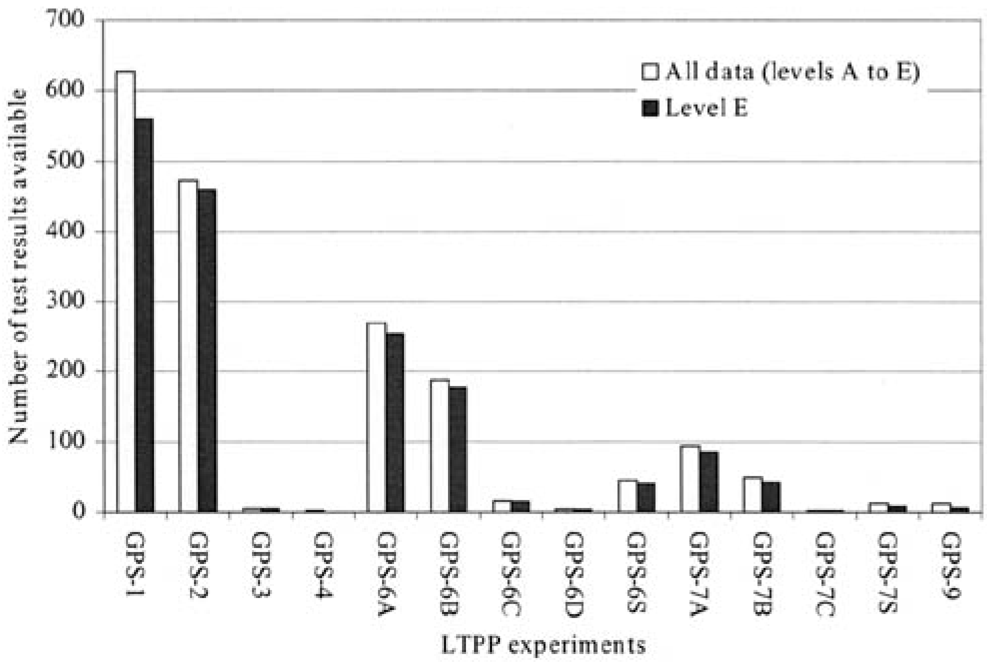

Figure 108. Histogram showing gradation data availability for GPS experiments.

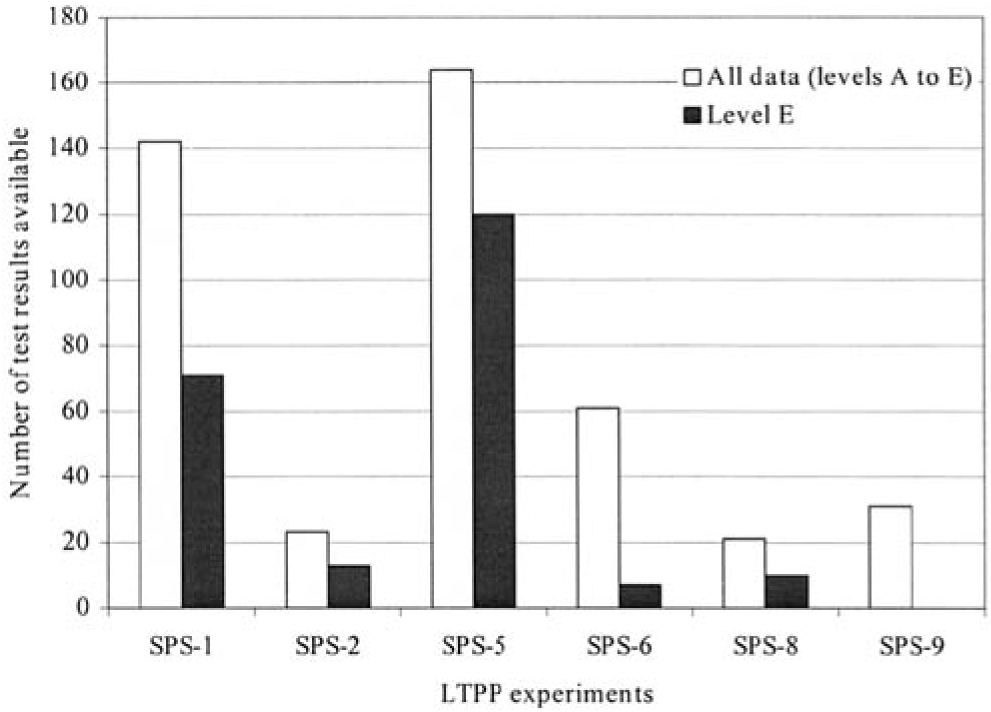

Figure 109. Histogram showing gradation data availability for SPS experiments.

Table 96. Sampling and testing requirements for gradation of extracted aggregates.

Experiment Type	Layer Type	LTPP Designation	SHRP Protocol	Minimum Number of Tests per Layer	Sampling Location
GPS-1, -2, -6, and -7	Asphalt Concrete	AG04	P14	2	TP, BA1
SPS-1	Asphalt-Treated Base	AG04	P14	3	B19, B20, B21 from paver
SPS-1	Asphalt Concrete Surface and Binder	AG04	P14	3	B25, B26, B27 from paver
SPS-5 Preconstruction	Asphalt Concrete	AG04	P14	3	BA1-3, TP, BA4-6
SPS-5 Postconstruction	Asphalt Concrete	AG04	P14	6	BV1, BV2, BV3, BR1, BR2, BR3
SPS-6	Asphalt Concrete	AG04	P14	3	BV1, BV2, BV3,
SPS-8	Asphalt Concrete	AG04	P14	3	BV-01, BV-02, BV-03,

The first step in assessing level 2 data completeness was to compute the number of test results reported at level E for each analysis cell. The computed values were then compared with the minimum number of tests required. Test sections with the minimum number of test results were classified as complete, and those with less than the minimum were classified as incomplete. Tables 97 and 98 present a summary of level 2 data completeness for GPS and SPS experiments.

There were a total of 288 analysis cells for GPS-1 pavement sections. Of these, 5.6 percent had less than the required minimum number of tests performed or reported at level E. For GPS-2 experiments, 3.9 percent of the analysis cells had less than the required minimum number of test results reported at level E. Of the three GPS-3 analysis cells, 33.3 percent had less than the minimum required number of test results reported at level E.

For SPS-1 experiments, 18 analysis cells had some gradation test results available at level E. Approximately 78 percent of the analysis cells with gradation data had the required minimum number of test results (as recommended by the SHRP protocols) reported at level E. The remaining 22 percent had less than the required minimum test results reported at level E. For SPS-2 experiments, three analysis cells had gradation test data, and two of those had the required minimum number of test results reported at level E.

Table 97. Summary of gradation data available for GPS sections.

Experiment Type	Total Number of Analysis Cells (Layers) Represented	Number of Layers/Cells with Less Than Minimum Number of Tests	Percent Layers/Cells with Incomplete Data
GPS-1	288	16	5.6
GPS-2	204	8	3.9
GPS-3	3	1	33.3
GPS-4	0	0	0.0
GPS-6A	129	5	3.9
GPS-6B	80	8	10.0
GPS-6C	6	1	16.7
GPS-6D	2	1	50.0
GPS-6S	17	0	0.0
GPS-7A	44	4	9.1
GPS-7B	20	1	5.0
GPS-7C	1	0	0.0
GPS-7S	4	0	0.0
GPS-9	4	2	50.0

Table 98. Summary of gradation data available for SPS experiments.

Expt. Type	Expt. Number	State Code	SHRP ID	Const. No.	Layer No.	Cell/Layer Material Description	No. of Samples	Minimum No. of Samples	Minimum Satisfied?
S	1	4	100	1	3	325	3	3	Yes
S	1	4	100	1	4	319	4	3	Yes
S	1	4	100	1	5	1	4	3	Yes
S	1	10	100	1	7	1	8	3	Yes
S	1	12	100	1	4	319	3	3	Yes
S	1	12	100	1	5	1	6	3	Yes
S	1	19	100	1	5	1	3	3	Yes
S	1	19	100	1	4	319	3	3	Yes
S	1	31	100	1	4	325	2	3	No
S	1	31	100	1	4	319	2	3	No
S	1	32	100	1	6	1	2	3	No
S	1	32	100	1	5	319	3	3	Yes
S	1	32	100	1	5	325	4	3	Yes
S	1	35	100	1	4	1	3	3	Yes
S	1	35	100	1	4	319	5	3	Yes
S	1	39	100	1	4	1	4	3	Yes
S	1	51	100	1	4	325	2	3	No
S	1	51	100	1	6	1	5	3	Yes
S	2	8	200	1	3	325	6	3	Yes
S	2	37	200	1	4	325	2	3	No
S	2	53	200	1	5	325	4	3	Yes
S	5	4	500	2	5	13	3	9	No
S	5	4	500	1, 2	3	1	8	9	No
S	5	8	500	2	5	13	3	9	No
S	5	8	500	1, 2	3	1	5	9	No
S	5	12	500	2	6	13	4	9	No
S	5	12	500	2	7	1	5	9	No
S	5	13	500	1	4	1	2	9	No
S	5	23	500	2	10	13	6	9	No
S	5	23	500	1, 2	6	1	26	9	Yes
S	5	24	500	1	7	2	9	9	Yes
S	5	24	500	1, 2	6	1	20	9	Yes
S	5	30	500	2	6	13	3	9	No
S	5	30	500	1, 2	4	1	5	9	No
S	5	34	500	2	8	1	3	9	No
S	5	34	500	2	8	13	9	9	Yes

S	5	81	500	2	7	13	3	9	No
S	5	81	500	1, 2	4	1	6	9	No
S	6	4	600	2	6	1	3	3	Yes
S	6	47	600	2	6	1	4	3	Yes
S	8	34	800	1	3	1	1	3	No
S	8	36	800	1	5	1	3	3	Yes
S	8	49	800	1	4	1	3	3	Yes
S	8	53	800	1	5	1	3	3	Yes

Gradation testing was not required for SPS-3 and -4 experiments. For SPS-5 experiments, the total number of analysis cells with available test data was 17. Twenty-four percent of the analysis cells had the required minimum number of test results reported at level E. Test results from samples obtained pre- and postconstruction (different construction numbers) were combined to form analysis cells. SPS-6 experiments had two analysis cells with gradation test data at level E. Both analysis cells had the required minimum number of tests results reported. Seventy-five percent of the analysis cells from SPS-8 experiments with gradation test data had the required minimum number of results reported. However, only a small number of analysis cells was represented.

Summary of Gradation Data Availability

The focus of the preceding sections of the chapter was to determine data availability for the gradation data in table TST_AG04. The first task was to evaluate the data in table TST_AG04 to determine all the gradation test results (levels A to E) available. This was followed by determining how much of the test data had successfully passed QA/QC and was at level E. The number of analysis cells represented by level E data was then estimated. The analysis cells were further evaluated to determine whether all the required number of test results were available. The following is a summary of levels 1 and 2 data availability for gradation test data in table TST_AG04:

- The LTPP database contains 2,395 records of gradation test results at various quality levels (A to E), representing individual tests performed on 2,395 aggregate samples.
    - Of the 2,395 records, 1,872 were evaluated and found to have both gradation and material description information available and at level E. The 1,872 records represented 853 analysis cells.
        - The 523 records were not suitable for further analysis because:
            - Six records were removed because they had the wrong material descriptions.
            - Seventeen records from SPS-5 supplemental sections were removed.
            - There were 141 records with material description information from table TST_LO5B at levels A to D.
            - There were 74 test sections with no material description information from table TST_LO5B.
            - There were 237 records with gradation data at levels A to D. This included 119 SPS supplemental section.
            - There were 30 records classified at levels A to D with no gradation information.
            - Eighteen records at level E with material description information had missing gradation data.

○

Gradation of Extracted Aggregate from Asphaltic Concrete Data Quality

Data quality was evaluated in two parts. All individual test results reported at level E in the LTPP database were evaluated for reasonableness. Reasonableness consisted of determining whether the test results followed expected trends and whether the test protocols and procedure (such as minimum sample size required for testing) had been adhered to. Test results grouped into analysis cells were then checked for homogeneity or whether they belong to the same population of results.

The statistic used to assess homogeneity was standard deviation. Details of the data quality evaluation are presented in the following sections of this chapter.

Evaluation of Trends in Gradation Test Results

Gradation test results for all the samples in the LTPP database (level E) were checked for reasonableness by plotting sieve size against the percent passing by weight. All the plots showed reasonable trends. Figure 110 shows examples of the plots used in assessing the reasonableness of the gradation data.

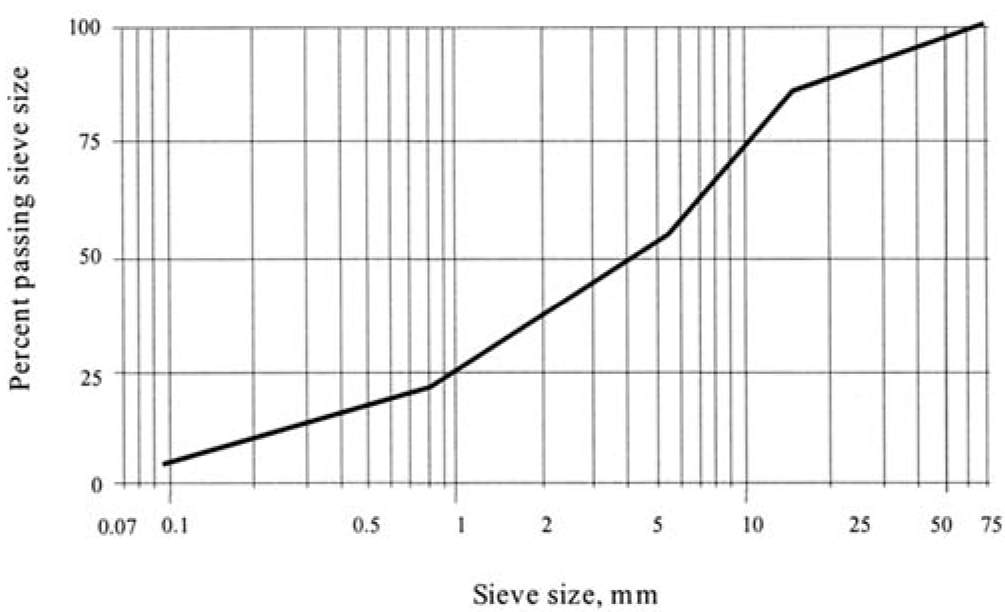

Figure 110. Examples of plots used in assessing the gradation data reasonableness.

Identification of Analysis Cells with Inadequate Number of Test Results

The LTPP material characterization program was designed to ensure that representative values of the various components of the pavement could be obtained without bias. This can only be achieved if adequate numbers of test samples are taken and tested for each experiment type, according to the LTPP sampling and testing guidelines. Inadequate sampling and testing could potentially result in biased computed representative test values for the entire pavement section.

The SHRP P14 test protocol and SPS Pavement Construction and Material Sampling Guidelines recommend both the minimum number and location of sample materials to be tested for gradation. Analysis cells with less than the required number of samples and tests performed will be prime candidates for bias. Table 99 is a summary of the percentage of analysis cells with less than the required test results reported at level E in the LTPP database.

Evaluation of Within-Cell Variability

The final data quality check was to determine analysis cells with excessive variability (i.e., variability levels greater than what is typical for the testing conditions and material type under evaluation). Typical variability can be loosely defined as the variability expected for gradation test results when the normal procedures for materials selection, construction, sampling, and testing are applied to a pavement project. The procedure for determining typical variability is presented in the following section.

Table 99. Percentage of analysis cells with potentially biased results due to inadequate sampling.

Experiment Type	Total Number of Analysis Cells	Number of Analysis Cells with Minimum Number of Tests	Percent Analysis Cells with Complete Testing	Percent Analysis Cells with Potential Sampling Bias
GPS-1	288	272	94.4	5.6
GPS-2	204	196	96.1	3.9
GPS-3	3	2	66.7	33.3
GPS-4	0	0	--	--
GPS-6A	129	124	96.1	3.9
GPS-6B	80	72	90.0	10.0
GPS-6C	6	5	83.3	16.7
GPS-6D	2	1	50.0	50.0
GPS-6S	17	17	100.0	0.0
GPS-7A	44	40	90.9	9.1
GPS-7B	20	19	95.0	5.0
GPS-7C	1	1	100.0	0.0
GPS-7S	4	4	100.0	0.0
GPS-9	4	2	50.0	50.0
All SPS	44	25	56.8	43.2
Total	846	780	92.2	7.8

Determination of Within-Cell Allowable Variability

Each analysis cell with multiple test data was assessed to determine the level of variability within the test results. AASHTO T30 defines test precision for sieve analysis, using either of the following statistics:(4)

- Standard deviation.
- Acceptable range of two results.

Precision recommendations were based on several tests conducted at the AASHTO Materials Reference Laboratory.(12) The precision statement is based on the total percentage of material passing a given sieve size and whether the tests were conducted by a single operator or multiple operators. Precision recommended by AASHTO T30 and used in estimating the typical variability for this study is summarized in table 100.

Table 100. Precision for coarse aggregate fraction.(4)

Test Condition	Total Percentage of Material Passing a Sieve	Standard Deviation (1S) Percent[1, 2]	Acceptable Range of Two Test Results--(D2S), Percent[1, 2]	
Single Operator	< 100	>/= 95	0.49	1.4
Single Operator	< 95	>/= 40	1.06	3.0
Single Operator	< 40	>/= 25	0.99	2.8
Single Operator	< 25	>/= 10	0.46	1.3
Single Operator	< 10	>/= 5	0.25	0.7
Single Operator	< 5	>/= 2	0.21	0.6
Single Operator	< 2	>/= 0	0.17	0.5
Multilaboratory	< 100	>/= 95	0.57	1.6
Multilaboratory	< 95	>/= 40	1.24	3.5
Multilaboratory	< 40	>/= 25	0.84	2.4
Multilaboratory	< 25	>/= 10	0.81	2.3
Multilaboratory	< 10	>/= 5	0.56	1.6
Multilaboratory	< 5	>/= 2	0.43	1.2
Multilaboratory	< 2	>/= 0	0.32	0.9

[1]These numbers represent the (1S) limits described in ASTM C670.
[2]The precision estimates are based on coarse aggregates with nominal maximum size of 19.5 mm.

The determination of the appropriate precision (a component of typical variability) to be applied in assessing data quality was based on:

- The conditions under which tests were performed (single operator vs. multilaboratory).
- The percentage of material passing on consecutive sieves.

The multilaboratory "reproducibility" precision values were considered in determining allowable variability because the LTPP gradation test data were obtained from multiple laboratories.

Gradation test results theoretically ranges from 0 to 100 percent for a given sieve size. An evaluation of the test data shows the following:

- The test results (percentage of material passing a given sieve size) in table TST_AG04 ranged from 0 to 100 percent.
- Approximately 31 percent of the test results had a value between 40 and 95 percent.
- Another 31 percent of the test results had a value between 95 and 100 percent.
- The remaining 38 percent of the test results had a value less than 40 percent.

Therefore, based on the AASHTO-recommended test precision values presented in table 100, a within-analysis cell test standard deviation (precision) of 1.24 was adopted.

The next step after determining test precision was to determine an appropriate allowable variability to be used for determining acceptable within-cell variability (based on field conditions). The precision values were a good guide because typical variability should always be greater than test precision since it has the added effects of sampling, material, and construction variability. Table 101 shows that typical gradation test standard deviation ranges from 1.7 to 4.9 percent for the 4.75- to 12.5-mm sieves and 0.4 to 2.8 percent for the 0.075- to 2.0-mm sieves.

For this study, variability measured as standard deviation from the testing component of allowable variability alone was 1.54 percent. Typical variability should, therefore, range from 1.54 to 4.9 and 1.54 to 2.8 percent for the 4.75- to 12.5-mm and 0.075- to 2.0-mm sieves, respectively. A 90th percentile of the range, which corresponded to 4.7 and 2.3 percent for the two sieve ranges, respectively, was adopted as the threshold typical variability between acceptable and questionable data.

Summary of Gradation Test Data Variability

A total of 853 analysis cells had some gradation test results reported in the database at level E. Of these, 68 analysis cells had single test results; therefore, the standard deviation of the test results of those analysis cells could not be computed. Within cell standard deviations were computed and used to assess the data quality of the remaining 785 analysis cells by comparing typical with actual standard deviation. A summary of the state of the quality of the test data is presented in table 102.

Identification of Anomalous Data

Two general types of anomalies were identified: excessive variability and insufficient/missing test data. The procedures adopted to correct the identified anomalies are presented in the next few sections.

Table 101. Typical allowable variability for gradation of extracted aggregates from asphaltic concrete.[13, 25]

	Sieve Size, mm	Standard Deviation Arkansas	Standard Deviation Washington	Standard Deviation Pennsylvania Study	Standard Deviation Bureau of Public Roads	Standard Deviation Virginia
Coarse Fraction	12.5 - 19	1.7	1.6	2.3	1.4	--
Coarse Fraction	9.5	2.6	2.5	4.4	2.5	1.9
Coarse Fraction	4.75 - 6.3	2.8	3	3.4	3.5	3.3
Fine Fraction	2 - 2.3	1.7	2.4	2.5	2.8	3.2
Fine Fraction	0.6 - 0.85	1.3	--	1.9	2.1	2.1
Fine Fraction	0.3 - .425	1.3	1.6	1.5	1.6	1.6
Fine Fraction	0.08 - 0.3	1.1	--	1.2	1.2	1.2
Fine Fraction	0.075	0.6	0.5	1	0.9	0.9

Variability is reported as standard deviation and is based on sieve size and aggregate type.

Table 102. Summary of test data quality for LTPP table TST_AG04.

Sieve Size, mm	Number of Analysis Cells with Acceptable Variability	Number of Analysis Cells with Excessive Variability	Number of Analysis Cells with Single Test Data	Total Number of Analysis Cells	Percent Analysis Cells with Acceptable Data
37.5	783	70	68	853	91.8
25	762	91	68	853	89.3
19	729	124	68	853	85.5
12.5	674	179	68	853	79.0
9.5	656	197	68	853	76.9
4.75	668	185	68	853	78.3
2	711	142	68	853	83.4
0.425	704	149	68	853	82.5
No. 80	744	109	68	853	87.2
0.075	764	89	68	853	89.6

Anomaly 1: Analysis Cells with Excessive Variability

There are various causes of excessive variability in test data. Some of the common causes include the following:

- Erroneous test results due to insufficient sample size.
- Erroneous test data caused by incorrect data entries.
- Variability in construction and mix preparation along the test section.
- Erroneous test data caused by a lack of adherence to test protocol and standards.

Detailed descriptions of the causes of excessive variability and possible remedial actions are presented as follows.

Erroneous Test Data Caused by Incorrect Data Entries

Erroneous test results may be entered into table TST_AG04, thereby contributing to excessive variability. Such data will most likely not be typical and should be detected when the data was evaluated for reasonableness.

Because no such anomaly was detected during the checks for data reasonableness, it was assumed that the data present at level E were the correct test results obtained from the laboratory.

Variability Due to Material and Construction

Excessive variability may also be caused by material and construction variability. This situation may be more prevalent for natural materials, especially subgrades, than for any other types of paving materials where the material sources are tightly controlled or manufactured.

This type of variability is difficult to detect and most likely will pass through QA/QC.

Variability Due to Lack of Adherence to Test Protocols

Excessive variability may be caused by the lack of adherence to test standards and protocols. This type of variability can be detected only if such deviations are noted with the test results.

Removing the erroneous data will rectify the excessive variability caused by obvious documented defects in testing.

There was some analysis cells with no obvious reasons for excessive variability. Such analysis cells were flagged with appropriate comments in the representative test table. The usefulness of such data will be evaluated ultimately by the users of the LTPP data.

Anomaly 2: Insufficient Test Data

Another common anomaly identified was insufficient (or missing) test results for the various analysis cells. This anomaly can be categorized at three levels:

1. There is no data for the entire analysis cell.
2. There is insufficient test data for a given analysis cell.
3. There are some sieve sizes for test data for a given test sample with data.

The reasons for insufficient or missing data include the following:

1. Test data are still undergoing QA/QC and are not yet at level E.
2. Test is yet to be performed or is currently being performed.
3. Test samples were not found suitable for testing and were, therefore, rejected (no testing performed).
4. The data are simply missing.

For case 1, the test data will be in the LTPP databse and will be identified as level A to D. No remedial action was taken because the data is still going through QA/QC. An assessment of the state of the data will be made only after the QA/QC process is complete and the data are (or are not) available at level E. For cases 2 and 3, there will be no record of the data in the LTPP database. For these situations, a feedback report was sent to the FHWA to obtain additional information about the status of the data.

Appropriate remedial action, such a interpolating or extrapolating the existing test data or conducting forensic testing to estimate the value of the missing data, is recommended once the status of the missing data is established as lost data.

For case 4, if it is determined that the missing data will not be available, the data will be estimated by interpolation or extrapolation.

Implementation of Remedial Action to Correct Anomalies

The identified anomalies were corrected, where feasible, using the remedial actions proposed. For the analysis cells with excessive variability, the remedial action did not always reduce variability to within the acceptable limits. For such situations, excessive variability was assumed to be due to other sources, such as the material and construction. The analysis cells were still identified as having excessive variability in the representative test table.

Schema for the Representative Gradation of Aggregate Extracted from Asphaltic Concrete Data Table (TST_AG04_REP)

A representative gradation of aggregate extracted from asphaltic concrete data table (TST_ SS01_UG01_UG02_REP) was developed and recommended for inclusion into the LTPP database. Data in table TST_ AG04 _REP were arranged by analysis cells, with appropriate comments provided to describe the anomalies observed on a cell-by-cell basis. The table also contained basic statistics, such as standard deviation and COV. The schema for table TST_AG04_REP are presented below:

1. Experiment type.
2. Experiment number.
3. State code.
4. SHRP identification number.
5. Construction number.
6. Layer number.
7. Test date.
8. Material code.
9. Layer type.
10. Number of test samples.
11. Mean percent passing X-mm sieve size.
12. Maximum percent passing X-mm sieve size.
13. Minimum percent passing X-mm sieve size.
14. COV.
15. Standard deviation.
16. Data source.
17. QA Comment 1.

18. QA Comment 2.
19. QA Comment 3.
20. QA Comment 4.
21. QA Comment 5.
22. QA Comment 6.
23. QA Comment Other.
24. Record status.

The first seven fields in the schema define the analysis cell used in computing mean, maximum, and minimum test results. Basic statistics--such as the number of test data, COV, and standard deviation--are also computed for the given analysis cell. Codes describing the source of the data (e.g., from laboratory testing or obtained through interpolation or extrapolation) are also presented. Comments are provided to describe the state of the data (e.g., excessive variability or incomplete sampling) to guide the user in selecting data for analysis and evaluation. The final field describes the record status.

18. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This report documents the procedures used for revising and improving the quality of selected material-related test data in the LTPP database and developing new representative data tables for pavement design, analysis, and research. The list of the existing data tables reviewed and the representative data tables developed and recommended for inclusion into the LTPP database are presented in table 103.

Table 103. Summary of existing and new tables developed.

Existing Table	Description	Representative Test Table
TST_AC_01	AC core examination and thickness	TST_AC01_REP
TST_AC_02	AC bulk specific gravity	TST_AC_02_REP_GPS TST_AC_02_REP_SPS
TST_AC_03	AC maximum specific gravity	TST_AC_03_REP_GPS TST_AC_03_REP_SPS
TST_AC_04	Asphalt content of asphaltic concrete	TST_AC_04_REP_GPS TST_AC_04_REP_SPS
TST_AC05	Moisture susceptibility	TST_AC05_REP
TST_AG_04	Gradation of extracted aggregate from asphaltic concrete	TST_AG_04_REP
TST_PC01	Determination of compressive strength of in-place concrete	TST_PC01_REP
TST_PC03	Coefficient of thermal expansion for PCC	TST_PC03_REP
TST_PC06	Visual examination and length measurement of PCC cores	TST_PC06_REP
TST_PC09	Flexural strength of concrete	TST_PC09_REP
TST_SS01_UG01_UG02	Particle size analysis of granular base/subbase	TST_SS01_UG01_UG02_REP
TST_UU04_SS03	Determination of Atterberg limits (subgrade)	TST_UU04_SS03_REP_GPS TST_UU04_SS03_REP_SPS
TST_SS10	Unconfined compressive strength of subgrade soils	TST_SS10_REP
TST_TB02	Unconfined compressive strength of treated base/subbase material	TST_TB02_REP

Important tasks undertaken as part of this study were as follows:

- Examined the selected material-related data tables to evaluate data availability.
- Identified missing or unavailable data.
- Evaluated data quality by identifying anomalous data.
- Examined and explained possible sources of anomalies and identified remedial actions, as appropriate.
- Provided recommendations to eliminate anomalies in future data collection and processing activities.
- Developed representative test values for multiple data from the same layers/analysis cells of a given test section and other relevant statistics, and used that information to develop representative data tables for inclusion into the LTPP database.

Data Availability

The availability of data in each test table was evaluated at two levels on an experiment-by-experiment basis:

- Level 1--determining the amount of data collected at level E as a percentage of the total amount of data collected at all levels (A to E).
- Level 2--determining the percentage of data at level E with the required minimum number of tests per layer.

The goal of the level 1 data availability analysis was to provide a snapshot of the data availability at level E at the time of this analysis. Obviously, this will change over time as more data are made available at level E in the LTPP database. On the other hand, the objective of level 2 data availability analysis was to determine whether the data at level E followed the prescribed sampling plan in the SHRP *Interim Guide for Laboratory Material Handling and Testing Guide*.[2] This determination is important because it directly relates to data quality. If the sampling performed is not representative of the pavement section under consideration, it could introduce bias in the test results and confound future analysis.

Level 1 and level 2 data analyses are interrelated. If a majority of the data is incomplete at level 1 for a given experiment, it can be expected that inadequate sampling would have been performed for many test sections in that experiment.

Table 104 and figure 111 present the level of data availability for all the test tables considered in this study. Based on the information presented, the test tables reviewed in this report can be classified into four categories, as shown in table 105. Also shown in the table are the criteria used to classify the tables in the various categories. Category I represents the tables with the most testing data, and category IV describes the tables with the least amount of testing data.

Table 104. Summary of data completeness analyses for all the data elements considered.

Test Table in LTPP Database	Level 1 Percent Records at Level E	Level 1 Number of Analysis Cells Represented	Level 2 Percent Cells with Minimum Tests Performed
TST_PC06	89.7	551	76.2
TST_PC09	91.5	90	59
TST_PC01	83.3	432	85.1
TST_PC03	100	173	--
TST_UG01_UG02_SS01	93	1557	87.3
TST_TB02	98.1	104	90.4
TST_AC01_LAYER	99.5	3663	48.7
TST_AC02	96.8	1083	82.7
TST_AC03	96.9	962	82.8
TST_AC04	99.3	968	83.7
TST_AG04	92.9	853	92.1
TST_SS03	97.4	1569	87.1
TST_AC05	55.7	23	26.1
TST_SS10	73.4	17	41.2

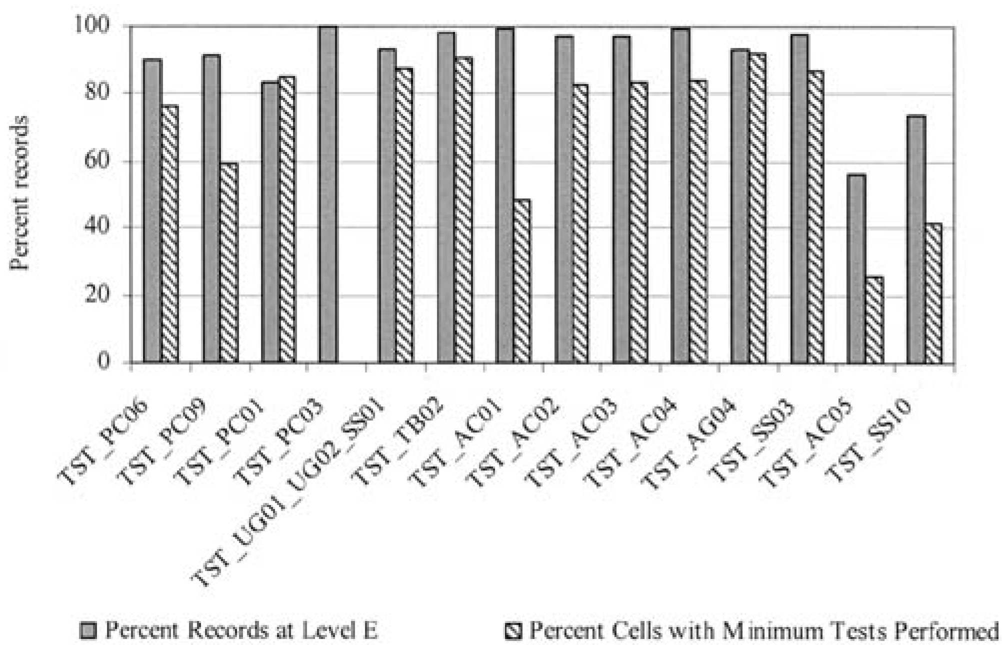

Figure 111. Summary of data completeness analysis.

Table 105. Test table categories based on data completeness analysis.

Category	Criteria	Test Tables
I	"Good" level 1 data completeness--80 to 100 percent of total test data (from all levels) is at level E.	TST_PC01, TST_UG01_UG02_SS01,TST_TB02, TST_AC02, TST_AC03, TST_AC04, TST_AG04, TST_SS03
I	"Good" level 2 data completeness--80 to 100 percent data has adequate sampling	TST_PC01, TST_UG01_UG02_SS01,TST_TB02, TST_AC02, TST_AC03, TST_AC04, TST_AG04, TST_SS03
II	"Poor" to "Fair" level 1 data completeness--0 to 80 percent of total test data (from all levels) is at level E.	--
II	"Good" level 2 data completeness--80 to 100 percent data has adequate sampling.	--
III	"Good" level 1 data completeness--80 to 100 percent of total test data (from all levels) is at level E.	TST_PC06, TST_PC09, TST_AC01
III	"Poor" to "Fair" level 2 data completeness--0 to 80 percent data has adequate sampling.	TST_PC06, TST_PC09, TST_AC01
IV	"Poor" to "Fair" level 1 data completeness--0 to 80 percent of total test data (from all levels) is at level E.	TST_AC05, TST_SS10
IV	"Poor" to "Fair" level 2 data completeness--0 to 80 percent data has adequate sampling.	TST_AC05, TST_SS10

It is important to emphasize that a lack of adequate testing data at level E may merely mean that a sizeable portion of the data is undergoing LTPP QA/QC checks. However, inadequate sampling introduces a potential for bias in the test data if the samples are not representative of the test sections being monitored. The quality of the data should be examined in light of this information.

Data Quality Assessment

The goal of the data quality assessment was to identify whether the existing data were reasonable. The research team assessed protocol compliance and determined the within-cell variability of test results.

The reasonableness of the data was determined by performing univariate analysis, plotting scattergrams, or bivariate analysis of the data and comparing the magnitudes and trends to typical values published in the literature. Subsequently, the data were checked for compliance with test protocols. Noncompliant data could potentially introduce bias in the test results and contribute to increased variability. Further, the within-cell variabilities (i.e., variability within multiple specimens of an analysis cell) of the data elements were computed and compared with typical variability measures from literature. Percent acceptable and percent questionable data were determined from this comparison. The typical variability values reflect sampling, testing, material, and construction process variabilities. Identification of data that are unreasonable or noncompliant with the sampling and testing program was necessary to identify anomalies and to investigate potential causes of excessive within-cell variability among results from multiple test specimens.

Some of the anomalies observed were:

- Erroneous material and layer type descriptions in the various data tables.
- Noncompliance with test protocols:
    - Tests performed on undersized samples.
    - Specimens with erroneous dimensions (L/D ratio < 1.0).
- Testing AC specimens with lengths less than 38 mm.
- Applying the wrong strain rate in unconfined compression testing of subgrades.

The following conclusions can be drawn:

- Most of the recommended sampling, testing, and QA/QC checks for test sections within the GPS sections have been done with data reported at level E in the existing data tables.
- Sampling, testing, and QA/QC for SPS experiments is not quite complete at this stage. This is understandable because some SPS construction is still ongoing.
- CTE of PCC had only single test data and has so far been performed for only selected GPS test sections.
- Atterberg limits testing for subgrade soils has been performed for only selected SPS projects, and the amount of data currently available is inadequate to complement the other data tables.
- AC moisture susceptibility testing has been performed for only selected SPS projects, and the amount of data currently available is inadequate to complement the other data tables.
- Overall, for the test tables evaluated, most of the data in the LTPP database were at level E.
- The level E data were generally of high quality with few anomalies.

Recommendations

Recommendations are provided for improving the current data collection procedure and for future data needs.

Improving Current Data Collection Procedures

- Only single CTE test values have been provided for the test sections with this important material parameter. Multiple tests should be performed, at least for selected test pavements or SPS projects, to provide other important statistics, such as the typical variability expected for such as test.
- For test sections or projects with missing data, it is recommended that forensic testing be performed. This will greatly improve upon the use of the current database.
- The research team recommends that specimen age be provided as a field in table TST_PC06 for compressive strength of PCC for SPS sections. This has been done for flexural strength data in table TST_PC09, and it reduces the occurrence of anomalies caused by computing test ages using construction data from different data tables.
- The suitability of the current moisture susceptibility test procedure--ASTM D4867--is being investigated through a research study sponsored by the National Cooperative Highway Research Program (NCHRP). Recommendations provided at the end of this study must be considered in future moisture susceptibility tests performed by LTPP.
- An additional field should be provided in table TST_SS10 (unconfined compressive test of subgrades) to inform users whether the tests were done using reconstituted or undisturbed test specimens.
- An additional field should be provided in table TST_PC03 (CTE for PCC cores) to inform users of the PCC coarse aggregate type (e.g., granite or limestone).

Future Data Collection Effort

The following additional data elements are recommended for future data collection because they are key inputs for mechanistic-empirical design:

- AC dynamic modulus.
- Resilient modulus of treated or untreated bases, subbase, and subgrade material.
- Indirect or direct tensile strength of concrete.
- PCC shrinkage.
- PCC dynamic modulus.
- Erosion of treated and untreated base and subbase

materials.

Summary

The material-related data tables developed in this study are generally considered to be of acceptable quality and, therefore, suitable for data users. The representative test values reduce the need for users to recompute such values. Descriptive statistics are provided to inform the user about data quality and reliability.

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