Development and Use of the LTPP Analysis-Ready Materials Dataset

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FOREWORD

Knowledge of the pavement layer structure and material properties are fundamental requirements for the development of meaningful pavement performance models and inputs for pavement design and performance modeling, among other uses. The Long-Term Pavement Performance (LTPP) program has a wealth of materials information and data from almost every program test section, as well as from a well-structured laboratory materials testing program to further classify and characterize pavement layers. However, understanding and using the database is not necessarily an easy undertaking. For starters, data are distributed among many tables, multiple values exist for a given layer, data are missing for some layers, and some data require further interpretation to provide meaningful results.

Therefore, the program developed a process to generate LTPP Analysis-Ready Materials Dataset (ARMAD). This dataset summarizes the material properties for every layer in the database, which has the benefit of substantially reducing researchers' time and making the data more accessible to all. The ARMAD dataset is now available on the LTPP InfoPave™ web portal (FHWA 2022a). This report provides the objectives, rationale, process, and results of the development of the ARMAD dataset and is useful to transportation agencies, consultants, and researchers who will use ARMAD to exploit LTPP data to gain knowledge into the how and why of pavement performance, which is the primary goal of the LTPP program.

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Director, Office of Infrastructure
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16. Abstract

The objective of the Federal Highway Administration Long-Term Pavement Performance (LTPP) program is to increase pavement life by the investigation of the long-term performance of various designs of pavement structures and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices. Information about pavement material properties is a key component of pavement performance and is of great interest to researchers. This report provides documentation regarding the objectives, scope, and approach of a study to develop an Analysis-Ready Materials Dataset (ARMAD), which integrates the material properties of several categories of pavement layers—asphalt concrete materials, portland cement concrete materials, unbound granular base/subbase, stabilized base/subbase, subgrade, and other layers such as surface treatments and engineering fabrics. The scope of this effort was to identify an essential set of material properties for each type of pavement layer, assemble and process the data of the selected material properties, assess the percentage of missing values in the selected material properties gathered from the LTPP database, impute or assume missing material properties, and populate the LTPP ARMAD. In addition, a data source and variability indicator was assigned to each material property so users can understand the method used to obtain the material property and hence the associated data derivation method and variability. This document provides details concerning how ARMAD's material properties were selected, how the ARMAD was populated, and what the resulting dataset contains. It could be used by researchers who will utilize the ARMAD dataset for their analyses. This document also provides references and resource documents to understand the overall LTPP materials sampling and testing program.

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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ARD	Analysis-Ready Dataset
ARMAD	Analysis-Ready Materials Dataset
ATB	asphalt-treated base
BSG	bulk specific gravity
CN	construction number
COV	coefficient of variation
CTB	cement-treated base
DAOFR	data analysis/operations feedback report
DSR	dynamic shear rheometer
EF	engineering fabrics
FHWA	Federal Highway Administration
GPS	General Pavement Studies
IDT	indirect tensile test
IMS	Information Management System
LTPP	Long-Term Pavement Performance
MEPDG	*Mechanistic-Empirical Pavement Design Guide*
PAV	pressure aging vessel
PCC	portland cement concrete
PMED	Pavement ME Design™
PPDB	Pavement Performance Database
RTFO	rolling thin-film oven test
SD	standard deviation
SDR	Standard Data Release
SHA	State highway agency
SHRP	Strategic Highway Research Program
SME	subject matter expert
SPS	Specific Pavement Studies
VFA	voids filled with asphalt
VMA	voids in the mineral aggregate

CHAPTER 1. INTRODUCTION

The objective of the Federal Highway Administration (FHWA) Long-Term Pavement Performance (LTPP) program is to increase pavement life by the investigation of long-term performance of various designs of pavement structures and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices. Specific goals for the LTPP program include the following:

- Evaluate existing design methods.
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements.
- Develop improved design equations for new and reconstructed pavements.
- Determine the effects of loading, environment, material properties and variability, construction quality, and maintenance levels on pavement distress and performance.
- Determine the effects of specific design features on pavement performance.
- Establish a national long-term pavement database to support future needs.

The LTPP program is a study of the behavior of pavement test sections located on in-service roadways. These in-service pavement test sections are classified in the LTPP program under General Pavement Studies (GPS) and Specific Pavement Studies (SPS). The GPS consists of a series of studies on 976 in-service pavement test sections to examine specific features of existing pavement. The SPS addresses specific variables involving new construction, maintenance treatments, and rehabilitation activities and presently comprises 1,605 pavement test sections. The sections are located throughout the United States and Canada (FHWA 2015).

Information about pavement material properties is a key component of all aspects of pavement engineering, such as design, construction, quality assurance, maintenance and rehabilitation, and management. The pavement layer structure and material properties are fundamental requirements for the development of meaningful pavement performance models and inputs for pavement design, among other uses. One of the uses of materials testing data is to provide the inputs needed for using the American Association of State Highway and Transportation Officials (AASHTO) AASHTOWare® Pavement ME Design™ (PMED) software for use in local calibration and other studies (AASHTO 2020).

The LTPP program has a wealth of materials information and data stored in the Pavement Performance Database (PPDB). Almost every test section in the program had materials sampling and testing conducted to ascertain the thickness and material types of the constituent layers. In addition, a well-structured laboratory materials testing program was undertaken to further classify and characterize the layers (Simpson, Schmalzer, and Rada 2007; Puccinelli et al. 2022).

However, the existing database of material properties had limitations, which include the following:

- Data are distributed across dozens of tables in the LTPP database, making some data elements hard to find, particularly for those not thoroughly familiar with the PPDB.
- There are multiple values for a given layer, making it difficult to discern which representative value(s) to use.
- Materials characterization data are missing for one or more pavement layers for a number of LTPP test sections.
- Some data have to be further interpreted to enable meaningful results usable as inputs to the PMED software and other pavement design/analysis applications.

The acquisition and interpretation of materials data required expert-level knowledge of the LTPP experiments' materials sampling and testing requirements, as well as their data classification and characterization. This high level of required knowledge created a barrier to implementation for practitioners and researchers. Consequently, an LTPP user would typically need to spend substantial effort finding, extracting, merging, and interpreting the available data to develop a suitable analysis dataset.

Therefore, the program developed a process to generate the LTPP Analysis-Ready Materials Dataset (ARMAD) for each test section and each layer in the LTPP database. ARMAD solves many of the challenges listed in the preceding paragraphs, including the following:

- Consolidating the number of tables from many to one main material properties table and one supporting data table for each material type.
- Creating one representative value for each material property and providing a relative variability scale for these values.
- Developing representative materials characterization data for every test section and every layer within LTPP.
- Interpreting the data to produce certain meaningful engineering properties for selected materials (such as subgrade resilient modulus).

The collective set of ARMAD tables contain more than 1 million records. ARMAD solves the stated challenges for the layer structure and material properties of all test sections in the LTPP database, except for the SPS-10 warm mix asphalt test sections. Testing for these SPS-10 test sections is presently ongoing, and the results will be incorporated into ARMAD upon completion.

This document provides the details concerning how ARMAD material properties were selected, how the database was populated, and what the resulting dataset contains. It should be used by researchers who will utilize the ARMAD dataset for their analysis. This document also provides references and resource documents to understand the overall LTPP materials sampling and testing program. Future planned Analysis-Ready Datasets (ARDs) for climatic conditions, traffic, and performance data will be incorporated into upcoming Standard Data Releases (SDRs) on the InfoPave™ website (FHWA 2022c).

ARMAD OBJECTIVE AND SCOPE

The objective of the ARMAD is to present a single representative value for the material properties of several categories of pavement layers—asphalt concrete (AC) materials, portland cement concrete (PCC) materials, unbound granular base/subbase, stabilized base/subbase, subgrade, and other layers, such as surface treatments and engineering fabrics (EF). The scope of this effort was to identify an essential set of material properties for each type of pavement layer, assemble and process the data of the selected material properties, assess the percentage of missing values in the selected material properties gathered from the LTPP database, impute or assume missing material properties, and populate the ARMAD. In addition, a variability and source indicator was assigned to each material property so users can understand the method used to obtain the material property, and hence the associated data variability.

A group of subject matter experts (SMEs) from academia and industry provided guidance for this effort. Their expert opinion was integral to key decisions made regarding mining data, developing an approach, populating ARMAD, and reviewing the materials dataset and documentations from both technical and practical standpoints.

LTPP MATERIALS TESTING PROGRAM SYNOPSIS

To better understand the foundation of the ARMAD data elements, it is important to review the history of LTPP's materials sampling and testing activities. LTPP materials data were needed to define the properties of structural pavement layers for every test section within the program. The field sampling efforts were performed in accordance with the *SHRP-LTPP Guide for Field Materials Sampling, Testing, and Handling,* Operational Guide No. SHRP-LTPP-OG-006 (Strategic Highway Research Program (SHRP) 1991). Each GPS experiment had a sampling plan specific to that experiment. The field guide provided each of these experiment sampling plans and covered the requirements associated with sample naming, labeling, identification, and shipping. The SPS projects differed from the GPS test sections in that each SPS project incorporated multiple colocated core test sections and, for selected projects, one or more some supplemental test sections at a location. Field sampling and laboratory testing plans were tailored for each specific SPS project based on the general set of sampling and testing plans for SPS experiments. Please see chapter 9 of this report, "Additional Reading," for a list of reference documents.

Testing for the LTPP program was typically carried out in accordance with the *SHRP-LTPP Interim Guide for Laboratory Materials Handling and Testing (PCC, Bituminous Materials, Aggregates, and Soils)*, Operational Guide No. SHRP-LTPP-OG-004 (SHRP 1992). The guide was first released in November 1989, and the latest version was released in 1992.

Beginning in 1992, under FHWA management, testing efforts were consolidated under two contracts. The objective of these contracts was to perform testing of the SPS projects and complete the resilient modulus testing for the GPS test sections. Additional testing to be performed under these contracts included testing of any overlays constructed on the GPS test sections as time progressed. SPS projects that received overlays and stayed in study were converted to GPS test sections. However, due to a lack of funding, the testing requirements were reduced to the resilient modulus and supporting tests for the SPS projects and GPS test sections. Because of these funding limitations, the remainder of the testing requirements were taken on by the State departments of transportation and Provincial agencies constructing the SPS projects and GPS overlays.

As part of a program assessment conducted in the mid-1990s, a review of the available materials data indicated that there were gaps—missing material test results— in the available data. An effort was undertaken to fill in these gaps and improve the overall quality of the available data, which was termed the Materials Action Plan.

Lastly, the SPS-10 experiment was implemented in 2014, and a laboratory contractor was engaged to conduct the materials sampling and testing for this experiment. At the time of writing of this report, the SPS-10 materials testing is ongoing, and the ARMAD dataset for SPS-10 is planned to be delivered for the SDR in 2023.

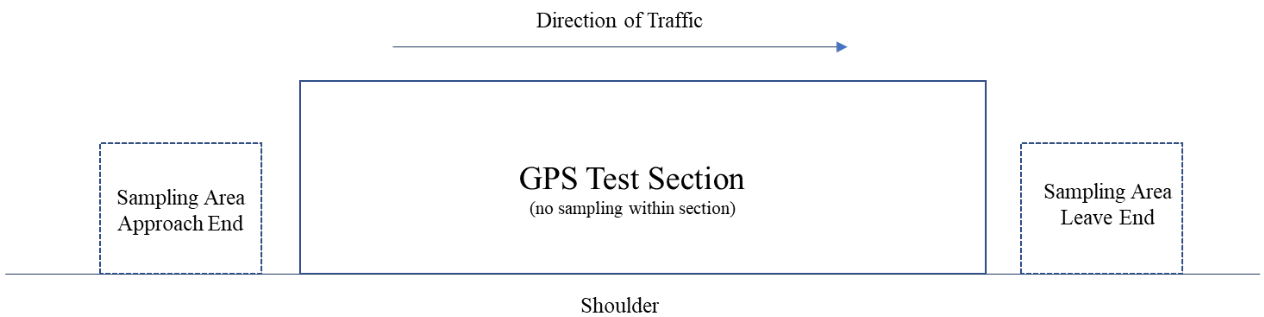
GPS AND SPS MATERIALS SAMPLING AND TESTING APPROACH

This section explains the general approach to materials sampling and testing for GPS and SPS sections. The details regarding the GPS and SPS materials sampling and testing programs can be reviewed through the documents in chapter 9 of this report, "Additional Reading." For a description of each experiment, please see the *Long-Term Pavement Performance Information Management System User Guide*, page 4 (GPS) and page 5 (SPS), available on the home page of the LTPP InfoPave website (Elkins and Ostrom 2021; FHWA 2022a).

GPS Test Sections

A typical materials sampling plan for a GPS section is shown in figure 1. In general, materials were sampled from the approach end and the leave end. Therefore, often for each layer, at least two samples or specimens were taken and tested: one from the approach end and one from the leave end. Typically, no destructive field sampling was conducted within the section, as this sampling could impact the performance (and hence performance measurements) of the test section.

The test results for the GPS sections represent different properties at the time of sampling and testing and not the time of construction, as these were already in-service test sections that were not constructed specifically for the LTPP program.



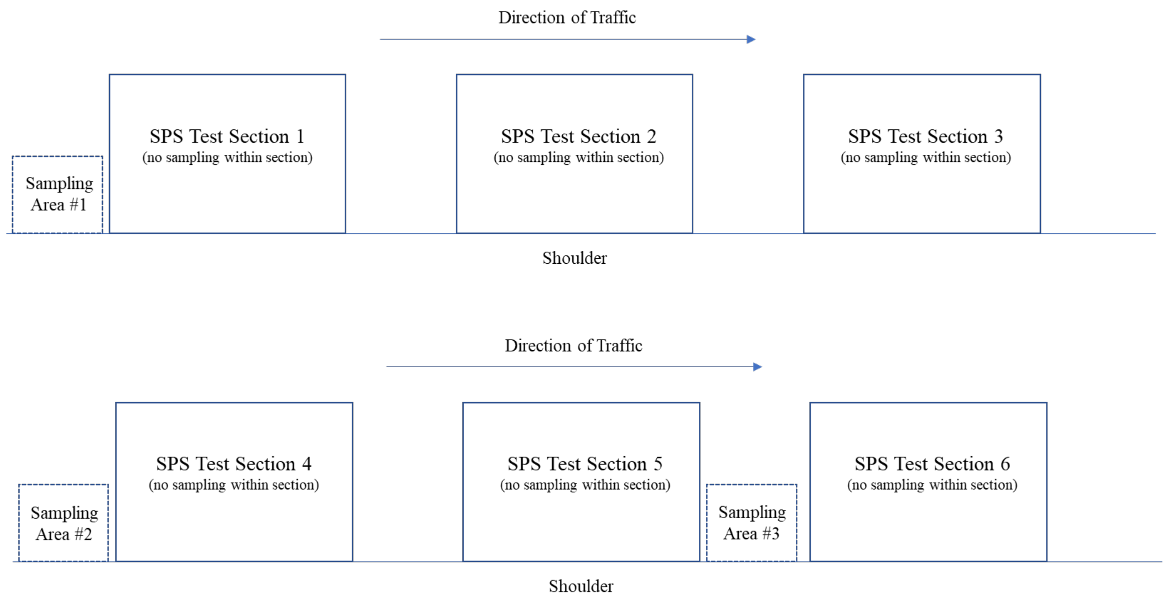
Source: FHWA.

Figure 1. Illustration. Typical sampling areas for an LTPP GPS test section.

SPS-1, SPS-2, SPS-5, SPS-6, SPS-7, SPS-8, SPS-9, and SPS-10 Test Sections

For the SPS studies, which consist of multiple test sections on a given section of roadway, a different approach was taken. In general, for all SPS projects other than SPS-3 and SPS-4, several samples of the different layers and materials were extracted and tested and then used to represent the entire project. For example, for unbound materials, three samples (sometimes more or less depending on the individual project and the variability of the layers) were taken to represent the entire project. These samples were tied to a particular test section, as illustrated in figure 2 for an example SPS project. In this example, three bulk samples of the subgrade and dense-graded aggregate base were taken within the project adjacent to sections 1, 3 and 4, and 5 and 6. Testing from these three locations was then tied to the other SPS test sections. For bound layers, a specimen was typically obtained and tested for each layer for each test section; the full suite of materials tests was conducted at each location. For the SPS-1, SPS-2, SPS-8, SPS-9, and SPS-10 projects, materials were sampled and tested during the construction process.

For each individual SPS project site, the LTPP program developed custom tailored materials sampling and testing plans, which can be downloaded from https://infopave.fhwa.dot.gov/Reports/Library (FHWA 2022e).

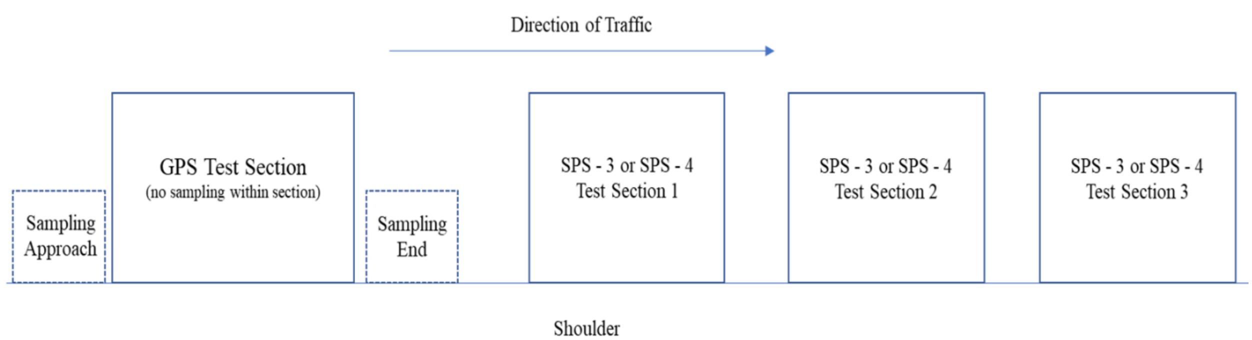


Source: FHWA.

Figure 2. Illustration. Example unbound materials sampling areas for an LTPP SPS project.

SPS-3 and SPS-4 Test Sections

For SPS-3 and SPS-4 projects, there was generally no sampling or testing of the layers, as this was a maintenance experiment and only the surface of the pavement was of concern. However, each SPS-3 and SPS-4 site often had a GPS test section (which was used as a control section) near it (figure 3). The material properties measured for the GPS section were used for the SPS-3 and SPS-4 test sections.



Source: FHWA.
Note: The distance between GPS and SPS test sections varied.

Figure 3. Illustration. Typical sampling areas for an LTPP SPS-3 or -4 project.

REPORT ORGANIZATION

The remainder of this report is divided into the following sections:

- Chapter 2. Example Use Cases of the LTPP Analysis-Ready Materials Dataset.
- Chapter 3. General Approach to Development of the Materials Analysis-Ready Dataset.
- Chapter 4. Generation of Unbound Materials Analysis-Ready Dataset.
- Chapter 5. Generation of PCC Materials Analysis-Ready Dataset.
- Chapter 6. Generation of Asphalt Concrete Materials Analysis-Ready Dataset.
- Chapter 7. Generation of Treated Materials Analysis-Ready Dataset.
- Chapter 8. Generation of Other Materials Analysis-Ready Dataset.
- Chapter 9. Additional Reading.
- References.

CHAPTER 2. EXAMPLE USE CASES OF LTPP ANALYSIS-READY MATERIALS DATASET

The ARMAD has many potential uses in the engineering profession. As mentioned in chapter 1, ARMAD is a summary of the vast amount of material property information contained in the LTPP database, along with inputted and calculated values. These material properties were selected based upon standard engineering properties needed to classify layers and properties needed to calibrate and run pavement performance and design software, with a focus specifically on the PMED software (AASHTO 2020).

Examples of the types of studies that can be performed with the ARMAD include the following:

- Developing a materials dataset for a selection of test sections as part of a broader pavement research study.
- Conducting materials data studies of in-service pavements.
- Developing correlations and prediction models (regression, machine learning, etc.) between material properties.
- Using the values contained in the ARMAD to perform pavement materials analysis, including laboratory to field comparisons and advanced materials testing analysis (resilient modulus, dynamic modulus).
- Using the material properties for local calibration of the PMED software (AASHTO 2020).
- Evaluating the impact of material properties on pavement preservation, maintenance, and rehabilitation.

USE CASES

The following two example use cases illustrate some of the potential uses of ARMAD.

Use Case 1: Materials Study

In this example, ARMAD is used in a simple materials study to evaluate air voids. Air voids have a significant effect on the performance of asphalt pavements. Air voids that are too low can cause bleeding, rutting, and shoving. High air voids, on the other hand, can lead to an increased potential for water infiltration, accelerated oxidation, raveling, cracking, and rutting in the wheelpath.

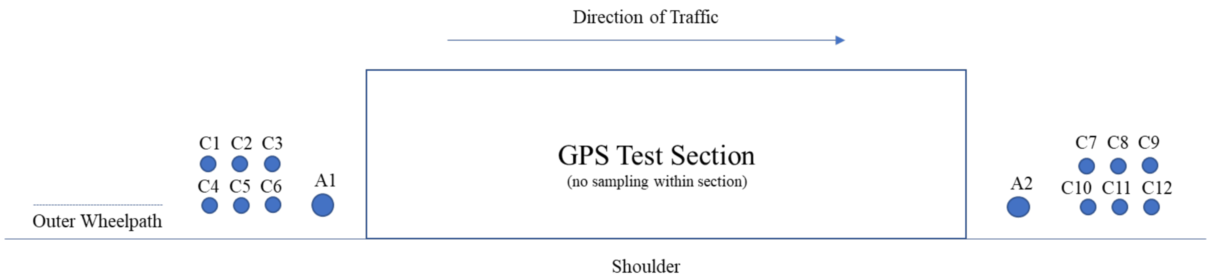
Percent air voids is calculated by comparing a test specimen's bulk specific gravity (BSG) with its theoretical maximum specific gravity and assuming the difference is due to air. To determine the air voids of a particular section, the equation given in figure 4 is used:

$$\%Air\ Voids\ =\ \left((G_{mm}-G_{mb})/G_{mm}\right)\times 100\%$$

Figure 4. Equation. Calculation of percent air voids.

Where:
- G_{mm} = maximum specific gravity.
- G_{mb} = BSG.

As discussed in chapter 1, GPS test section are sampled as illustrated in figure 5.



Source: FHWA.

Figure 5. Illustration. Partial depiction of sampling for asphalt layers for a GPS test section.

For this test section, 4-inch-diameter cores were drilled and obtained at the C-type locations (C1 to C12) in the outer wheelpath (C4–C6 and C10–C12) and in the midlane (C1–C3 and C7–C9). Six-inch-diameter cores were taken from the A1 and A2 locations. The C-type cores were used to measure BSG, and the A-type cores used to measure maximum specific gravity.

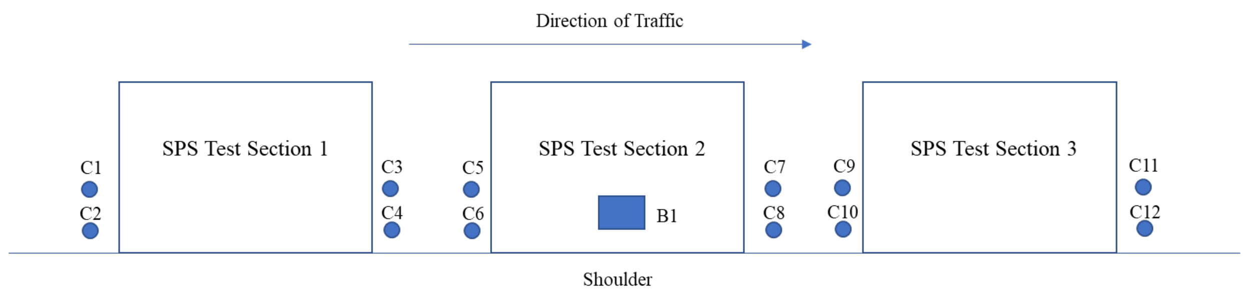
One approach to determining the air voids for the section is to combine the individual core results from C1 to C3 with the A1 result and the individual core results from C4 to C6 with the A1 result to obtain wheelpath and midlane air voids for one end of the section, which results in six air void values per asphalt layer tested. The results of the other end can be developed in a similar fashion, resulting in a total of 12 air void values per asphalt layer tested. The average of the ends of the section could be used to determine the wheelpath and midlane air voids for each asphalt layer tested in the section.

For those not intimately familiar with the LTPP database and the materials sampling and testing plans, this task could be daunting—to develop air void content values for thousands of test sections, many with multiple asphalt layers. Accordingly, ARMAD has been developed to perform this task for the user. In the AC dataset, wheelpath and midlane section-level air void content results are presented to the user as well as statistics, such as the minimum, maximum, and average values used in the calculation.

Use Case 2: Materials Engineering Research Project

In this use case, the first example is expanded to include other material properties. In this example, the user plans to perform a materials engineering study to determine the effects of gradation and air voids of the asphalt mix on dynamic modulus for an SPS-1 (Strategic Study of Structural Factors for Flexible Pavements) project (SHRP 1990a). To perform this study, the user must have air voids (as described in use case 1), the asphalt aggregate gradation, and a value for the dynamic moduli.

As noted in chapter 1, SPS projects did not have a full suite of sampling and testing performed on each test section. Figure 6, which shows a partial depiction of three sections from an SPS-1 site. In this figure, the C-type cores are 4-inch-diameter cores and the B1 is a bulk sample of asphalt taken from the paver. The C-type cores were used to measure BSG, and the bulk sample was used to measure gradation and maximum specific gravity. The dynamic modulus is calculated using the method from a previous study and is a project-level value (Kim et al. 2011). This method results in the matrix of test results presented in table 1 for this theoretical section.



Source: FHWA.

Figure 6. Illustration. Partial depiction of sampling for asphalt layers for an SPS-1 project.

Table 1. Matrix of test results for a theoretical partial SPS-1 project.

Section	Test Result
Project level	Dynamic modulus
Section 1	4 BSGs
Section 2	4 BSGs 1 Maximum specific gravity 1 Gradation
Section 3	4 BSGs

To arrive at the required dataset, it is necessary to calculate the air voids for each section, use the gradation from section 2, and use the project-level dynamic modulus. This process becomes significantly more complicated when the entire 12 sections of an SPS-1 project are used.

In summary, the ARMAD has been developed to provide these values in an easy-to-use format. For example, it provides one air void value for each wheelpath and midlane, contains a representative set of gradation values for each test section, and provides one dynamic modulus value per test section. Therefore, it has decreased the necessity to individually calculate these values for each test section, which would have required the following:

1. Studying the sampling and testing plan for each individual SPS-1 project.
2. Interpreting which test results belong with each test section.
3. Consolidating data from several tables in the LTPP database.
4. Deriving representative values (i.e., air voids, gradation, etc., for the use case no. 2).
5. Performing the analysis (i.e., performing the statistical analysis to evaluate the mixture properties correlation and their impact on the dynamic modulus).

The ARMAD eliminates the first four steps, which will lead to more efficient and effective research studies.

CONSIDERATIONS

Caution should be taken when using ARMAD, and the assumptions used to populate the dataset should be fully understood prior to using it. The ARMAD is a compilation of many data tables and values, including those directly measured, calculated, expanded, imputed, derived from inventory data, and assumed (as described in chapter 3, table 4). The purpose of developing this dataset was to make LTPP data extraction and use more accessible for LTPP users, using the best assumptions and algorithms known to LTPP at the time.

The following are several considerations to the use of the materials dataset that users should be aware of:

1. The material properties may not be measured values.
2. Material properties do not exist for some layer types.
3. Backcasted values contain many assumptions.
4. Other methods may exist to generate computed values.

Issues discovered with the data should be documented with a Data Analysis/Operations Feedback Report (DAOFR), as described at the end of this chapter.

Material Properties Values

The user should be aware that many of the values present in the dataset are not measured properties. The methods used to determine the material properties (as described in chapter 3, table 4) include the following:

- Measurements.
- Calculations.
- Expansion.
- Imputation.
- Use of inventory values.
- Assumed values.

As explained in chapter 3, the method used to generate each value is described in the dataset using the REP_CODE_SOURCE_VARIABILITY field. When using the ARMAD, it is important the user understand the method(s) used to populate the dataset with the layer properties that are to be used in any analysis.

Material Properties Do Not Exist for All Layers

Cases in which material properties do not exist for all the layers are the result of when there were no means to adequately use one of the methods listed previously to determine the value. Although every attempt was made at determining a complete set of material properties, in some cases this was not possible.

Assumptions for Backcasted Values

The PCC dataset contain values that are backcasted from the measured ones. For example, the PMED software requires PCC compressive or flexural strength values at 28 d as an input. The 28-d input value was not available for the LTPP experiments, with the exception of the SPS-2 experiment (Strategic Study of Structural Factors for Rigid Pavements) (SHRP 1990b). Therefore, the measured value at the time of testing was used to backcast the 28-d compressive strength using the algorithms selected by the project SMEs. These backcasted values contain many assumptions and were developed using methods the project SMEs approved.

Computed Values

Some of the ARMAD values were calculated. One prominent example is the calculation of the design resilient modulus of unbound materials. In the LTPP database, design resilient moduli for test sections were not calculated. Therefore, an adequate method was selected to calculate the design resilient modulus. The details of this calculation are presented in chapter 4. However, users may wish to use other models to derive calculated values. It is recommended that users should review and understand the methodology used to derive each ARMAD value before use.

Data Analysis Operations Feedback Reports

Users who discover potential problems with the ARMAD or the calculation of the material properties can file a DAOFR. The DAOFR form can be found on the LTPP InfoPave website at https://infopave.fhwa.dot.gov/Data/DAOFRForm (FHWA 2022b). Alternatively, users can report issues to the LTPP Customer Support Service Center via email at LTPPInfo@dot.gov.

CHAPTER 3. GENERAL APPROACH TO DEVELOPMENT OF THE MATERIALS ANALYSIS-READY DATASET

Chapter 3 describes the basic process used to develop the LTPP ARMAD. This process is then refined in chapters 4 through 8 for each type of material under investigation (PCC, AC, etc.). This process may be adjusted or repeated in future years with addition of more data. The refined process for each material group was developed to be as automated as possible (using an open-source programming language), with limited engineering judgment, imputation, or manual intervention. In addition, the process utilized four SMEs to guide the development efforts. Each step of the process was approved via consensus among FHWA, LTPP contractors, and SMEs before data release.

The ARMAD was developed using a phased approach by material type, in the following order:

1. Unbound materials (subgrade and unbound base/subbase).
2. PCC layers.
3. AC layers.
4. Treated material (asphalt-treated and cement-treated base (CTB)/subbase).
5. Fabrics and interlayers.

The development process for each type of material followed the five steps listed as follows and discussed further in this chapter:

1. Selecting material properties to be included in ARMAD.
2. Data mining to identify the source table(s) housing the data in the LTPP database and the extraction of data for each test section and layer.
3. Deriving representative values via a decision tree.
4. Populating the LTPP database with the material properties data.
5. Disseminating the final dataset via the LTPP InfoPave web portal.

SELECTION OF MATERIAL PROPERTIES

The starting point for developing ARMAD was identifying the key pavement layer material properties by layer type. ARMAD contains an essential set of material properties, as established by the SMEs, necessary to characterize each layer and effectively analyze pavement performance or calibrate pavement performance models and transfer functions, specifically (but not exclusively) for the PMED software. The criteria for selection of these properties are described in the following sections.

Fundamental Material Properties

Fundamental layer structure and material properties—such as layer thickness, material type, gradation, volumetric properties, strength properties, and so forth—were included in the dataset. These properties are essential to understanding the layered composition of test sections and their representative material characteristics.

Importance to Pavement Performance Analyses

To help focus the effort on the most important material characteristics, the material properties inputs for the AASHTO *Mechanistic-Empirical Pavement Design Guide* (MEPDG) local calibration, verification, and validation were used as a yardstick (AASHTO 2020). LTPP data are often used for calibrating MEPDG distress transfer functions or MEPDG performance analysis. These material properties are grouped based on the pavement layer material categories mentioned previously (PCC, AC, etc.).

Usefulness in Computing Other Data Elements

Some of the fundamental material properties, such as AC dynamic modulus and resilient modulus for unbound granular materials, were not measured on every pavement section or layer, due to the tests not being a routine production level at the time many of the LTPP test sections were sampled and tested or due to limited resources for performing laboratory tests. In the absence of the laboratory test results, correlation equations, prediction models, or both provided an alternative for estimating these properties based on other material properties. ARMAD also contains correlated material properties, which are useful in calculating missing properties and developing newer correlation equations.

Key Properties Availability

Table 2 presents the list of key material properties selected for representation in ARMAD. A review of the LTPP database was conducted to identify the availability of each selected material property. The results are shown in the third column of table 2, which indicates whether a given material property is collected by the LTPP program. Even if a material property is collected by the LTPP program, the indicated material property will still be missing from some layers for a given class of experiment (GPS or SPS), individual experiment, or test section.

Table 2. List of key material properties

Category	Material Element	Collected by the LTPP Program
Unbound base/subbase/subgrade materials	Layer thickness	Yes
	Material type	Yes
	Poisson's ratio	No
	Soil classification (gradation and Atterberg limits)	Yes
	Compaction characteristics (optimum moisture content and maximum dry density)	Yes
	Specific gravity	Yes
	Resilient modulus parameters	Yes
	Saturated hydraulic conductivity	Yes
PCC mixture	Layer thickness	Yes
	Material type	Yes
	Poisson's ratio	Yes
	Modulus of rupture	Yes
	Modulus of elasticity	Yes
	Compressive strength	Yes
	Tensile strength	Yes
	Coefficient of thermal expansion	Yes
	Mixture properties (unit weight, water-to-cement ratio)	Yes
	PCC shrinkage	No
	Thermal conductivity	No
	Heat capacity	No
	PCC zero-stress temperature	No
	Surface shortwave absorptivity	No
	Steel in concrete properties (diameter, depth, spacing, etc.)	Yes
AC mixture and asphalt-treated layers	Layer thickness	Yes
	Material type	Yes
	Poisson's ratio	Yes
	Asphalt binder complex shear modulus and phase angle—set of values at different frequencies and temperature to create master curve	Yes
	Binder type	Yes
	Viscosity	Yes
	Dynamic modulus—set of values at different temperatures and frequencies to build a master curve	Yes
	Tensile strength	Yes
	Creep compliance	Yes

Category	Material Element	Collected by the LTPP Program
	Volumetric properties (unit weight, BSG, maximum specific gravity, aggregates specific gravity, air voids, binder content, VMA, VFA)	Yes
	Aggregate gradation	Yes
	Thermal conductivity	No
	Heat capacity	No
	Aggregate coefficient of thermal contraction	No
	Surface shortwave absorptivity	No
Chemically stabilized materials	Layer thickness	Yes
	Material type	Yes
	Poisson's ratio	No
	Aggregate type	Yes
	Treatment type and details	Yes
	Heat capacity	No
	Thermal conductivity	No
	Resilient/elastic modulus	No
	Compressive strength	Yes
Surface treatments and EF	Layer thickness	Yes
	Material type	Yes

VFA = voids filled with asphalt; VMA = voids in the mineral aggregate.

DATA DISCOVERY

The next step in the process was to determine data availability in the LTPP database by GPS and SPS experiment. The basis for selection of the layers to be populated was the LTPP layering table, TST_L05B. The TST_L05B table was selected as the base table, given the previous completion of a rigorous section-by-section layering reconciliation process to identify the most representative source of information for layer thickness, material type, and material classification. Layer thicknesses for ARMAD were obtained directly from this table.

The LTPP key fields used to identify the section (STATE_CODE and SHRP_ID), associated construction events (CONSTRUCTION_NO), layer structure (LAYER_NO), layer material type (LAYER_TYPE, PROJECT_LAYER_CODE, and MATL_CODE), and layer thickness (REPR_THICKNESS) were retrieved from the TST_L05B table.

To extract data for an available material property from the LTPP database, the LTPP tables containing the indicated property were selected. The *Long-Term Pavement Performance Information Management System User Guide* was used extensively to confirm the relevant LTPP data tables (Elkins and Ostrom 2021).

For each material property indicated as available, a preliminary list of the appropriate LTPP tables was developed. Next, each property and each table were evaluated to identify the tables with the most representative value to include in the dataset. This selection varied based on the material property that was being evaluated. Finally, the table with the most representative values was selected along with secondary tables if they existed.

DERIVING REPRESENTATIVE VALUES

After the appropriate tables were selected, a decision tree was developed for each material type and data availability scenario to use as a basis to code the algorithms for developing the representative values. Statistical procedures were used to evaluate the data variability and select the most representative values or predict missing values. These decision trees are explained further in chapters 4 through 6 of this report.

For EF layers and other treated material layers (such as surface treatments), no laboratory testing was conducted, and only the representative thickness, material code, and layer description were populated directly from the TST_L05B table.

POPULATING ARMAD IN THE PPDB

The final data and metadata resulting from the ARMAD effort have been stored in the LTPP PPDB. For each material type, two new tables were created: the primary data table, ANALYSIS_TST_* (where * = the material type, such as AC, PCC, etc.) and the data support table, ANALYSIS_TST_*_SUPPORT. The metadata contains the data dictionary, table dictionary, and a description of field codes.

Primary Data Table: ANALYSIS_TST_*

Each ANALYSIS_TST_* table contains the representative layer properties for all relevant LTPP GPS and SPS layers. Practitioners and researchers can use this table as the LTPP representative value for each data element and pavement test section.

Data Support Table: ANALYSIS_TST_*_SUPPORT

The ANALYSIS_TST_* _SUPPORT table contains data statistics and the number of samples tested for each representative layer and layer property. The purpose of this table is to inform the user as to the variability and the method that was used to populate ARMAD. For each material property, the table contains the average, median, minimum, maximum, standard deviation (SD), coefficient of variation (COV), number of samples used in the calculation, and the source variability code of the value, as appropriate.

Data Tables

Table 3 contains a list of the actual tables created in the database. The collective set of tables contains more than a million records. The record count contained in ARMAD tables will increase with the incorporation of the SPS-10 laboratory testing data in future SDRs.

Table 3. List of tables created for ARMAD in the PPDB.

No.	Table Name	Description
1	ANALYSIS_TST_UNBOUND	Representative properties of unbound base, subbase, and subgrade materials.
2	ANALYSIS_TST_UNBOUND_SUPPORT	Support information for the unbound base, subbase, and subgrade material properties.
3	ANALYSIS_TST_PCC	Representative properties of PCC materials.
4	ANALYSIS_TST_PCC_SUPPORT	Support information for the PCC material properties.
5	ANALYSIS_TST_AC	Representative properties of AC materials.
6	ANALYSIS_TST_AC_SUPPORT	Support information for the AC material properties.
7	ANALYSIS_TST_AC_ESTAR	AC dynamic modulus data generated from an analysis study (Kim et al. 2011). No support table presently exists.
8	ANALYSIS_TST_AC_CREEP_COMP	AC creep compliance testing properties.
9	ANALYSIS_TST_AC_CRCOM_SUPPORT	Support information for the AC creep compliance values.
10	ANALYSIS_TST_ACT	Representative properties of ATB base and subbase testing materials.
11	ANALYSIS_TST_ACT_SUPPORT	Support information for the ATB base and subbase material properties.
12	ANALYSIS_TST_PCT	Representative properties of CTB base and subbase materials.
13	ANALYSIS_TST_PCT_SUPPORT	Support information for CTB base and subbase materials.
14	ANALYSIS_TST_TR	Representative properties of treatment layers.
15	ANALYSIS_TST_TR_SUPPORT	Support information for treatment layer types.
16	ANALYSIS_TST_EF	Representative properties of EF layers.
17	ANALYSIS_TST_EF_SUPPORT	Support table for EF layers.

ATB = asphalt-treated base.

Contents of Each ARMAD Material Property Table

In general, the contents of each material property table include a description of the section location, layer location in pavement structure, layer type, and construction/maintenance history (CONSTRUCTION_NO). These contents also include information on all material properties for a given layer. Therefore, the user can determine and use the materials information derived from ARMAD for each layer of the test section. These will likely be the tables of main interest to researchers, as they provide the most representative value for a given material property as vetted by the SMEs.

Contents of Each ARMAD Support Table

In general, the contents of each material support table include a set of key fields identifying the layer within the section and the State or Province, a description of the layer, and the basis for the material property value. The support table also includes the minimum, maximum, average, median, SD, COV, and sample count for each material property and each layer, as applicable. The user can merge the support table with the ARMAD material property table using the set of key fields to find statistics for each data field and further filter the data.

The data element termed REP_CODE_SOURCE_VARIABILITY in the ANALYSIS_TST_*_SUPPORT tables is an important element, as it informs the user of the variability and derivation method of the individual material property. Said element is a one- or two-character code. The first character specifies the data source code, as detailed in table 4, while the second character, when present, characterizes the representative source code variability. If the second character is not present, the variability is unknown or not applicable.

Table 4. Data source code descriptions.

Data Source Code	Description
A	Properties directly measured in the LTPP program by using field or laboratory materials sampling and testing.
B	Properties calculated by using measured parameters and assumed conditions.
C	Properties expanded to similar sections in an LTPP experiment by using the PROJECT_LAYER_CODE.
D	Properties estimated by using statistical methods and typical models.
E	Properties adopted from inventory or maintenance/rehabilitation data.
F	Properties assumed by basing them on the MEPDG or other reliable sources.

Table 5 provides a schematic of the classification system used for REP_CODE_SOURCE_VARIABILITY. In general, as the code goes from A to B to C and so on, the less confidence there is in the value; however, in all cases, the best value was selected for a particular layer and particular material property.

Table 5. Classification system used for REP_CODE_SOURCE_VARIABILITY field.

Data Source Group	Description	Data Source Code	Subgroups	REP_CODE_SOURCE_VARIABILITY
Measured	Properties directly measured by using standard testing in LTPP program.	A	Variability unknown or not applicable.	A
			More than one measured value with low COV.	AL
			More than one measured value with high COV.	AH
			Single value measured.	AS
Calculated	Properties calculated by using measured parameters and assumed conditions.	B	Variability unknown or not applicable.	B
			Calculated from more than one measured parameter with low COV.	BL
			Calculated from more than one measured parameter with high COV.	BH
			Calculated from one measured parameter.	BS
Expanded	Properties expanded to similar sections in an LTPP experiment using the PROJECT_LAYER_CODE.	C	Variability unknown or not applicable.	C
			More than one measured data from similar sections, low COV.	CL
			More than one measured data from similar sections, high COV.	CH
			One data point from similar sections.	CS
Imputed	Properties estimated by using statistical methods and typical engineering models.	D	Variability unknown or not applicable.	D
			Imputed from more than one measurement with low COV.	DL
			Imputed from more than one measurement with high COV.	DH
			Imputed from one measured value.	DS
Inventory	Properties adopted from inventory representing agency typical practices.	E	Variability unknown or not applicable.	E
			Inventory median for more than one value with low COV.	EL
			Inventory median for more than one value with high COV.	EH
			Inventory single value.	ES
Assumed	Properties estimated by basing them on the MEPDG or other reliable sources.	F	Assumed values.	F

The specific value for each data source code is described the following sections.

Measured Values—Code A

Material properties under this classification were directly measured using standard testing in the LTPP program. The following two primary scenarios were available:

- Layers with one specimen tested per layer: The table was populated with the single measured value.
- Layers with more than one specimen tested per layer: The layer was evaluated to determine if all tests were representative. If they were, an average or median (depending on data dispersion) was used. If not, then values were assessed to determine the most representative one(s) based on the project team's technical expertise and logic.

For layers with a single measurement, a second character of "S" (for single) was added to the data source code, resulting in "AS." Material properties with two or more measurements were divided into low COV and high COV based on thresholds identified from the data distributions and recommended by the SMEs, as appropriate for the property and material type. A second character of "L" (for low COV) or "H" (for high COV) was added to the data source, code resulting in "AL" or "AH." If the variability was unknown or not applicable, a second character was not added to the data source code. Please note that the threshold value varies based on the layer type. The approach described in this paragraph was also used for the remaining data source codes (i.e., B to F).

Calculated Values—Code B

Material properties within this classification were calculated using measured parameters and assumed conditions. In some cases, materials testing was conducted, but a final, representative value was not contained in the LTPP database. As an example, the unbound resilient modulus test has values for up to 15 stress sequences. The test was purposefully developed this way so users could derive their own resilient modulus values at a specified stress state. However, for the purposes of ARMAD, one value was desired, and thus it was calculated assuming typical stress states for different layers.

Expanded Values—Code C

Under this classification, the material properties for a given section were expanded from an adjacent LTPP section using the PROJECT_LAYER_CODE. Since SPS projects consist of multiple test sections, a project level layering structure was developed to keep track of pavement layering and test results from various test sections. The ultimate purpose of the project-level layering was to set up an accounting system to be used to link material tests for a given pavement layer in a particular section to other similar materials throughout the project (Simpson, Schmalzer, and Rada 2007). Therefore, the PROJECT_LAYER_CODE is an SPS project-level layer identifier and allows layers in different test sections on the same SPS project with the same material properties to be identified (Elkins and Ostrom 2021). In some cases, such as most SPS-3 and SPS-4 test sections, the materials on the test sections were not themselves sampled. The material properties may be derived from an adjacent GPS test section that was sampled and tested, as SPS-3 and SPS-4 test sections typically had GPS test sections nearby.

Imputed Values—Code D

Imputed values are properties that were estimated using engineering models or statistical methods. For example, the gradation of unbound materials not tested was imputed by deriving the mean percent passing of sieves based on layers with the same material type in the LTPP database. The appropriateness of the gradation was then checked by comparing the imputed soil classification against the classification for the same material type.

Inventory Values—Code E

When testing was not conducted, or a material test did not otherwise have a value for a given layer, in some cases inventory values were used. Inventory values are data gathered from agency records or agency specifications or from reported maintenance/rehabilitation data. These values were used on a case-by-case basis.

Assumed Values—Code F

The default input values from the PMED software (NCHRP 1-37A and AASHTO 2020 MEPDG Manual) were used for values for which there were no data in the LTPP database (AASHTO 2020; ARA, Inc., ERES Consultants Division 2004). This classification does not have a COV designation as these are assumed values, so it is a one-character value.

Tracking Changes in Pavement Structure Over Time

Each time an LTPP test section changes its characteristics due to rehabilitation treatments or the application of maintenance treatments, it is assigned a new construction number (CN) in the TST_L05B table. When a pavement section is first accepted into LTPP, it is assigned a CN of 1. CN is incremented by 1 for each successive maintenance or rehabilitation event. To perform the LTPP ARMAD process, it was necessary to assign material properties to all layers in the section for all CN events.

ARMAD QUALITY CONTROL

The data collected by the LTPP program are reviewed per the *LTPP Information Management System (IMS) Quality Control Checks,* available to download from the InfoPave website on the Library page (FHWA 2013, 2022e). In addition, the following lists of quality control checks were performed on the ARMAD dataset.

Data Structure Checks

1. Confirm that the properties approved by the ARMAD SMEs were included and loaded into the LTPP database (aka PPDB).

2. Ensure no reference tables contain measured values by the LTPP program for expanded, imputed, or missing data (i.e., fields that do not have REP_CODE_SOURCE_VARIABILITY = AS/AL/AH).

3. Cross-reference key fields in ARMAD with the TST_L05B table to ensure all layers are included (except for SPS-10 layers).

4. Confirm that there are no duplicates in key fields per layer per CN.

5. Verify that ANALYSIS_TST_AC, ANALYSIS_TST_AC_ESTAR, ANALYSIS_TST_AC_CREEP_COMP, and their SUPPORT tables are properly linked together.

IMS-Related Checks

1. Confirm that the existing fields in the LTPP database are named following the LTPP Data Dictionary (LTPPDD) nomenclature.

2. Verify that ARMAD's existing fields in the LTPP database have the same units as in the LTPPDD.

3. Ensure that ARMAD's newly created fields are added to the LTPPDD with the correct units, codes, and so forth.

4. Confirm that all code types and codes exist in the LTPP database. The one exception is REP_CODE_SOURCE_ VARIABILITY, which is a new code type.

Data Content Checks

1. Check the range of property values for reasonableness:

   a. Check the distribution of values for each property.

   b. Check the distribution of REP_SOURCE_CODE_ VARIABILITY for that property (measured versus nonmeasured category).

   c. Investigate and compare outliers and biases in data across experiments, studies, and States.

2. If the ANALYSIS_TST_PCC table, if the ELASTIC_MOD_AGE > 28, then confirm the ELASTIC_MOD_28_DAY < ELASTIC_MOD. Similar checks apply for other strength properties.

3. Verify that no property values for milled layers exist (REP_THICKNESS = 0).

4. Confirm that data expansions were performed correctly:

   a. That data and corresponding REP_CODE_SOURCE_ VARIABILITY are expanded correctly to higher CNs.

   b. In case of missing data, that data are expanded accordingly using PROJECT_LAYER_CODE if present.

Support Table Checks

1. Check that LAYER_COMMENT1, LAYER_COMMENT2, LAYER_COMMENT3, and COMMENT_NOTE fields in TST_L05B are translated properly into REP_CODE_SOURCE_ VARIABILITY for REP_THICKNESS field.

2. Confirm that PROPERTY_AVERAGE and PROPERTY_MEDIAN is equal or within PROPERTY_MINIMUM and PROPERTY_MAXIMUM in SUPPORT table.

3. Verify that when SAMPLE_COUNT = 1 then property's PROPERTY_AVERAGE = PROPERTY_MEDIAN = PROPERTY_MINIMUM = PROPERTY_MAXIMUM.

4. Confirm that representative values in ANALYSIS_TST tables are equal to or within PROPERTY_MINIMUM and PROPERTY_MAXIMUM values of their corresponding MATL_PROPERTY in SUPPORT table.

5. Verify that SUPPORT table COEFF_VARIATION = STANDARD_DEVIATION / PROPERTY_AVERAGE for all records.

6. Check REP_CODE_SOURCE_VARIABILITY and confirm that:

   a. Second character of REP_CODE_SOURCE_VARIABILITY is "S" in SUPPORT table when SAMPLE_COUNT = 1.

   b. Second character of REP_CODE_SOURCE_VARIABILITY is not "S" in the SUPPORT table when SAMPLE_COUNT > 1.

   c. Second character of REP_CODE_SOURCE_VARIABILITY is "H" in the SUPPORT table when COEFF_VARIATION > threshold%.

   d. Second character of REP_CODE_SOURCE_VARIABILITY is "L" in the SUPPORT table if COEFF_VARIATION =< threshold%.

   e. Stats in SUPPORT table are null when REP_CODE_SOURCE_VARIABILITY is "F" (Assumed).

DISSEMINATING DATA

The LTPP program uses InfoPave to disseminate data and information to users. This data portal can be accessed using the web address https://infopave.fhwa.dot.gov/ (FHWA 2022a). The LTPP database tables explained in table 2 can be found in the Data hub under Standard Data Release on the LTPP InfoPave website, https://infopave.fhwa.dot.gov/Data/StandardDataRelease/ (FHWA 2022c).

The data are also available in the LTPP InfoPave portal under the Data Selection and Download feature at https://infopave.fhwa.dot.gov/Data/DataSelection (FHWA 2022d). This method of download allows users to access an easy-to-use intuitive interface to select and download the data of their choosing.

Further information regarding dissemination of ARMAD, including coded database schema, database quality control, data dictionary, and codes, is included in the *Long-Term Pavement Performance Information Management System User Guide* (Elkins and Ostrom 2021).

CHAPTER 4. GENERATION OF UNBOUND MATERIALS ANALYSIS-READY DATASET

This chapter documents the development of the ARD for unbound granular base, subbase, and subgrade materials. Based on discussions within the LTPP program and input from the SMEs, the list of desired unbound granular material properties was presented in table 2 in this report.

DATA DISCOVERY

Table 6 presents the LTPP database tables and data sources used to extract the selected unbound material properties and layer characteristics. The experiment and section information were filtered to include unbound granular base, subbase, and subgrade material (LAYER_TYPE = GB, GS, and SS).

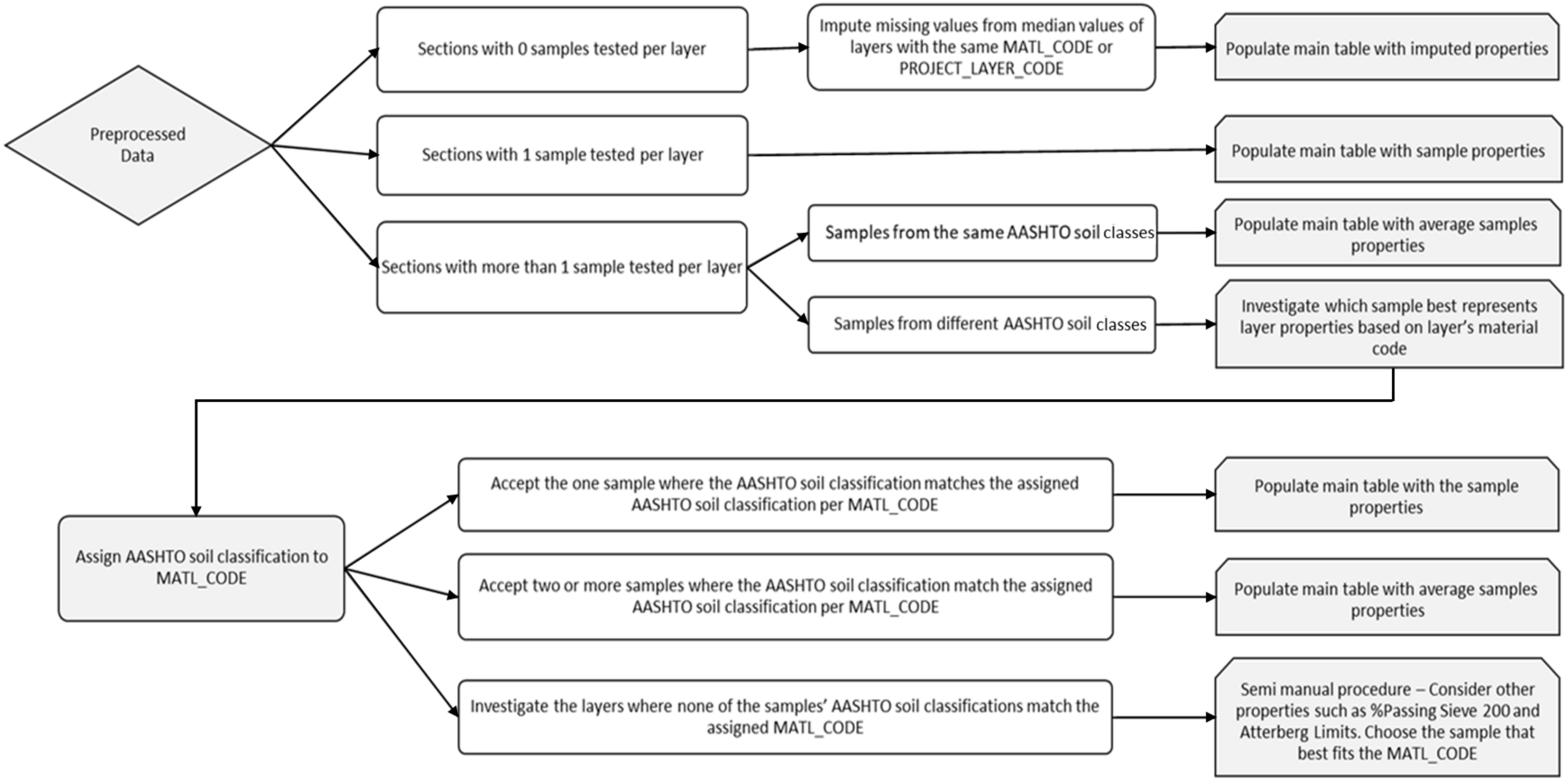
Table 6. The LTPP data table or source to extract each material property.

Properties	LTPP Data Table or Source
Experiment and section information	EXPERIMENT_SECTION
Layer thickness	TST_L05B
Resilient modulus	TST_UG07_SS07_WKSHT_SUM
Maximum dry density and optimum moisture content	TST_UG05_SS05
Gradation	TST_SS01_UG01_UG02
	TST_SS02_UG03
Soil classification	TST_SS04_UG08
Atterberg limits	TST_UG04_SS03
Specific gravity	TST_UNBOUND_SPEC_GRAV
Saturated hydraulic conductivity	TST_UG09, TST_SS11 MEPDG default value
Poisson's ratio	MEPDG default value

DERIVING REPRESENTATIVE VALUES

The decision tree shown in figure 7 summarizes the process to select the most representative material property for each LTPP layer. The complexities of establishing representative values can be observed in this decision tree. For example, the following three scenarios were available, depending on the data availability:

- Layers with zero specimens tested.
- Layers with one specimen tested.
- Layers with more than one specimen tested.



Source: FHWA.

Figure 7. Flowchart. Unbound materials decision tree.

The first scenario, layers with zero specimens tested, included cases for which an existing layer was not sampled and therefore not tested. For GPS test sections, this scenario generally occurred when the layer was too thin to obtain enough samples to test. For SPS sections, this scenario mostly occurred when a particular test section did not have the materials sampled. For unbound layers in GPS sections with missing gradation or Atterberg limits data, the following procedure was used to impute the missing values:

1. The MATL_CODE field was used to impute gradation and Atterberg limits. The median values of the properties from the same MATL_CODE for all LTPP data were assigned. The statistics of the properties used for imputation were included in the ANALYSIS_TST_UNBOUND_SUPPORT table.

2. The AASHTO classification was then generated from the imputed gradation and Atterberg limits; the resulting data were marked as "imputed" in the ANALYSIS_TST_UNBOUND_SUPPORT table.

3. The AASHTO classification was then used to impute other properties, such as optimum laboratory moisture content and maximum dry density. The median values for the LTPP materials (both SPS and GPS) with the same AASHTO classification were used. These fields were marked as "imputed" in the ANALYSIS_TST_UNBOUND_SUPPORT table.

For unbound layers in SPS sections, the following process was used:

1. If the SPS project had data for the same PROJECT_LAYER_CODE, the median value of the provided data for the SPS project was used to populate the ANALYSIS_TST_UNBOUND table for a missing layer property.

2. If the project had no data for the same PROJECT_LAYER_CODE, then:

    a. If the materials code of that layer was close to another PROJECT_LAYER_CODE's MATL_CODE in the same project, then the median of those properties was used for imputation.

    b. Otherwise, the median values for the properties with the same MATL_CODE were used for populating the ANALYSIS_TST_UNBOUND table.

The resulting data were marked as "imputed" in the ANALYSIS_TST_UNBOUND_SUPPORT table, and the statistics of the properties used for imputation were included in the table.

For the second scenario, layers with one specimen tested, the ANALYSIS_TST_UNBOUND table was populated with the single measured value, and the field was marked as "measured" in the ANALYSIS_TST_UNBOUND_SUPPORT table.

For the third case, layers with more than one specimen tested, the following process was used:

1. If two or more specimens tested were from the same AASHTO soil classification, then the average of the measured properties was provided in the ANALYSIS_TST_UNBOUND table and marked as "measured" in the ANALYSIS_TST_UNBOUND_SUPPORT table. If the specimens were not from the same AASHTO classification, then the sample(s) that best represented layer properties according to their LTPP material code were selected for the ANALYSIS_TST_UNBOUND table and marked as "measured" in the ANALYSIS_TST_UNBOUND_SUPPORT table.

2. In those rare cases in which none of the samples' AASHTO classification matched the material code, the data were reviewed manually to consider sample properties, such as the percentage passing sieve number 200 and Atterberg limits. These fields were marked as "measured" in the ANALYSIS_TST_UNBOUND_SUPPORT table.

The statistics (minimum, maximum, median, etc.) of the data used for populating the ANALYSIS_TST_UNBOUND table were included in the ANALYSIS_TST_UNBOUND_SUPPORT table.

CALCULATED VALUES

The only value calculated for ARMAD was the design resilient modulus of unbound granular materials. A substantial amount of resilient modulus testing was carried out by LTPP for unbound materials. In each test, 15 resilient modulus values were generated, which corresponded to the 15 stress states (different confining pressures and deviatoric stresses) specified in the procedure (Simpson, Schmalzer, and Rada 2007). The equation in figure 8 was used to calculate the design resilient modulus. The k_1, k_2, and k_3 parameters were calculated based on the test results, and the SD of residuals for k_1, k_2, and k_3 values was determined as a measure of goodness of fit. The confining pressures listed in table 7 and the bulk stresses provided in table 8 for subgrade materials and table 9 for unbound base and subbase materials were used in the design resilient modulus computations (Rao et al. 2012).

$$Mr = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\zeta_{oct}}{P_a} + 1\right)^{k_3}$$

Figure 8. Equation. Calculation of resilient modulus.

Where:

Mr = laboratory resilient modulus.
P_a = atmospheric pressure.
θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\sigma_c$.
σ_1 = major principal stress.
σ_2, σ_3 = minor principal stress.
σ_c = confining stress.
σ_d = deviatoric stress = $\sigma_1 - \sigma_3 = \theta - 3\sigma_c$.
ζ_{oct} = octahedral shear stress = $(\sqrt{2}/3)\ \sigma_d$.

Table 7. Confining pressures for unbound granular design resilient modulus computations.

Total Pavement Structural Thickness Above the Layer (inches)	Confining Pressure (psi)
<12	2.0
12–23.9	2.5
24–32	3.0
>32	3.5

Table 8. Unbound granular subgrade bulk stress (θ value in figure 8).

Pavement Type	Total Bulk Stress (psi)
PCC	9
AC < 9 inches	9
AC > 9 inches	11

Table 9. Unbound granular base/subbase bulk stress (θ value in figure 8).

Pavement Type	Total Bulk Stress (psi)
PCC	10
AC < 3 inches	60
AC 3–5 inches	30
AC 5–9 inches	15
AC > 9 inches	10

If a given unbound granular layer was sampled and tested in the laboratory, the design resilient modulus was computed as detailed in this section. However, when the layer was not sampled, the k_1, k_2, and k_3 regression parameters from layers with similar MATL_CODE or PROJECT_LAYER_CODE were used to calculate the design resilient modulus.

ASSUMED VALUES

The default values from the PMED software were used for the Poisson's ratio and hydraulic conductivity when missing from the LTPP database. Table 10 shows the values that were used for a variety of materials.

Table 10. Assumed Poisson's ratio and hydraulic conductivity values used in the dataset.

LTPP Material Class	Poisson's Ratio	Hydraulic Conductivity
River-run gravel	0.35	5.054e-02
Permeable aggregate	0.35	5.054e-02
Crushed stone	0.35	5.054e-02
Crushed gravel	0.35	5.054e-02
A-1-a	0.35	5.054e-02
A-1-b	0.35	2.303e-03
A-2-4	0.35	5.854e-04
A-2-5	0.35	4.64e-07
A-2-6	0.35	7.651e-06
A-2-7	0.35	6.832e-06
A-3	0.35	3.777e-03
A-4	0.35	8.325e-06
A-5	0.35	9.256e-07
A-6	0.35	1.95e-05
A-7-5	0.35	4.281e-06
A-7-6	0.35	8.946e-06

These values were input into ARMAD with the assumed label (code of "F") for the REP_CODE_SOURCE_VARIABILITY in the ANALYSIS_TST_UNBOUND_SUPPORT table.

DATA SOURCE AND VARIABILITY

The REP_CODE_SOURCE_VARIABILITY in the ANALYSIS_TST_UNOUND_SUPPORT table was assigned as follows:

- Measured—labeled as "A." For this classification, material properties having two or more measurements that were combined to generate a single value were divided into low-COV and high-COV thresholds based on a COV of 25 percent.[1] These properties were labeled as "AL" for low COV and "AH" for high COV. In cases in which only one measurement was available, an "S" was added to the variability code, resulting in "AS." Finally, for measurements with unknown COV, such as representative layer thickness (REPR_THICKNESS), a second character was not added to the variability code, leaving a single character "A."

- Calculated—labeled as "B." This classification was only used for resilient modulus data. The data were divided into low- and high-COV values depending on the COV of the k_1, k_2, and k_3 regression parameters used to calculate the resilient modulus. If two or more laboratory test results were combined to generate the resilient modulus, then a character of "L" for low (less than 25 percent) COVs was added to the variability code, resulting in

[1]The COV of 25 percent was determined as the threshold based on a review of the overall LTPP data statistics and the recommendations of the ARMAD SMEs.

"BL." If the COV was high (greater than 25 percent), then a character of "H" was added to the variability code, resulting in "BH." If the value was calculated from a single measurement, the character of "S" for single was added to the variability code, resulting in "BS."

- Expanded—labeled as "C." This classification was used for SPS sections' properties that were expanded to similar sections in an LTPP experiment using the PROJECT_LAYER_CODE. Material properties based on two or more measurements from similar sections were divided into low and high COV based on a COV threshold of 25 percent, which resulted in "CL" for low COV and "CH" for high COV. In cases in which the property was based on only one measurement, an "S" was added to the variability code, resulting in "CS." For cases in which the COV was unknown, such as representative layer thickness, a second character was not added to the variability code, resulting in the single character of "C" only.

- Imputed—labeled as "D." Generally, the data were averaged based on the material properties available for all test sections having the same layer and MATL_CODE. Like previous classifications, a threshold COV of 25 percent was used to divide the imputed values into "DL" for low COV and "DH" for high COV.

- Inventory—labeled as "E." This code only applied to the representative layer thickness of unbound materials, in which values were obtained from the respective agencies. For properties where the value was derived from data from multiple agencies, the classification was divided into low- ("EL") and high-COV ("EH") values based on a COV threshold of 25 percent. If the value was calculated from a single inventory value, it was labeled as "ES."

- Assumed—labeled as "F." This classification was used for Poisson's ratio and hydraulic conductivity data, as values for these two properties were not generally available in the LTPP database. This classification does not have a COV designation, as they are assumed values; i.e., only the single character of "F" is used.

CHAPTER 5. GENERATION OF PCC MATERIALS ANALYSIS-READY DATASET

This chapter documents the development of the ARD for PCC materials. The list of key PCC material properties selected for inclusion in ARMAD was presented earlier in the report in table 2.

DATA DISCOVERY

Table 11 presents the LTPP database tables and data sources used to extract the selected PCC material properties and layer characteristics. The following LTPP experiments have sections with PCC layer type that were included in ARMAD: GPS-3, GPS-4, GPS-5, GPS-7, GPS-9, SPS-1, SPS-2, SPS-4, SPS-6, SPS-7, SPS-8, and SPS-9. Please refer to the InfoPave website for more information regarding LTPP experiment types (FHWA 2022a). The referenced experiment and section information was filtered to include PCC layers (LAYER_TYPE = PC) and cementitious material types (MATL_CODE = 4, 5, 6, 90, and 334).

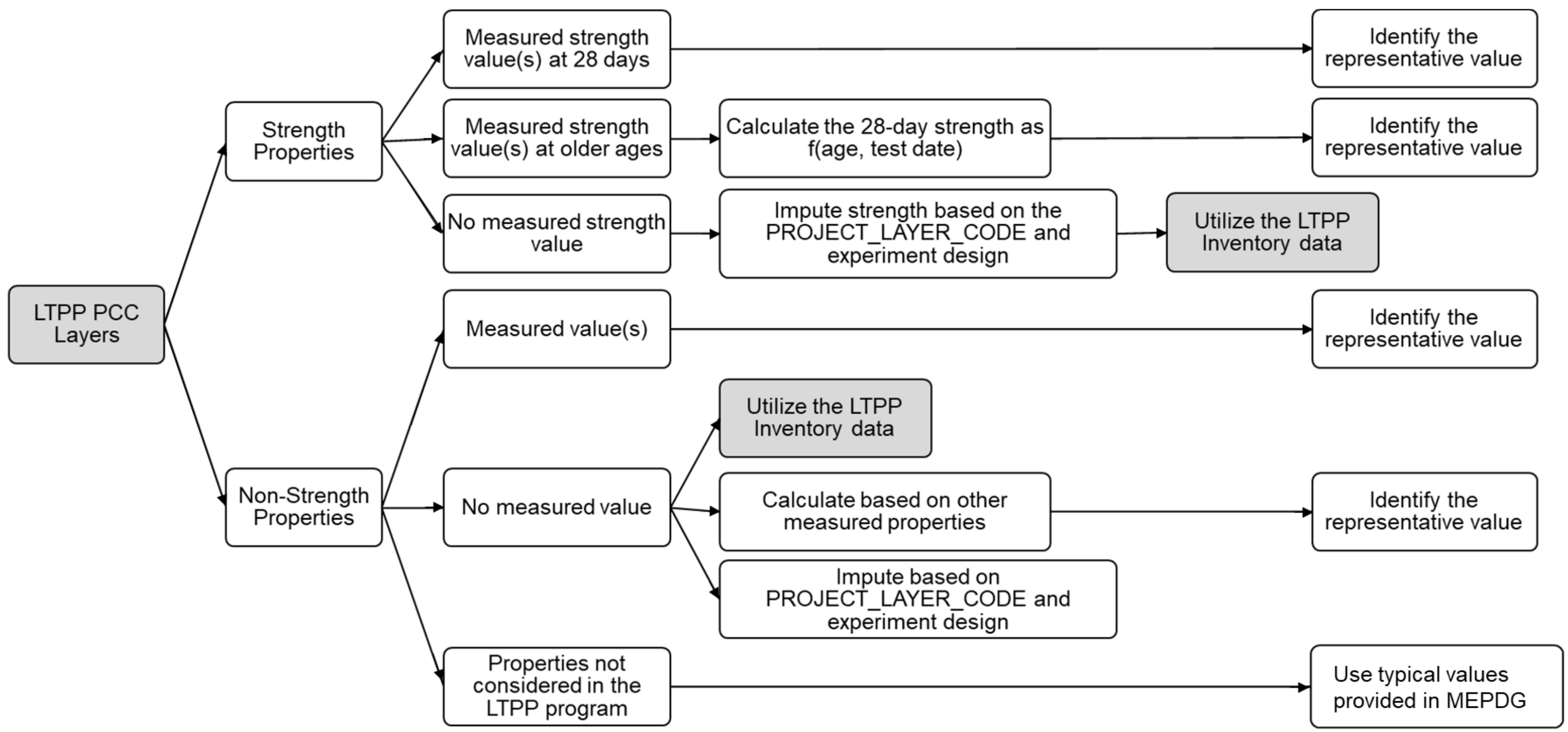
Table 11. The LTPP data table or source to extract each material property—PCC dataset.

Property Type	Properties	LTPP Tables
LTPP layer information	Layer information, thickness, and material type	EXPERIMENT_SECTION
		TST_L05B
	Construction date/placement date	INV_AGE
		PROJECT_HIST_AGE
		SPS2_PCC_PLACEMENT_DATA
		SPS6_OVERLAY
		SPS7_PCC_OVERLAY
		SPS8_PCC_PLACEMENT_DATA
		TST_FRESH_PCC
Strength properties	Modulus of elasticity	TST_PC04
		INV_PCC_STRENGTH
	Modulus of rupture (flexural strength)	TST_PC09 (for SPS sections only)
		INV_PCC_STRENGTH
	Tensile strength	TST_PC02
		INV_PCC_STRENGTH
	Compressive strength	TST_PC01
		INV_PCC_STRENGTH
		RHB_PCCO_STRENGTH
Mixture properties (nonstrength)	Unit weight	TST_PC05
	Air content	TST_PC05, TST_PC08
		INV_PCC_MIXTURE
		RHB_PCCO_MIXTURE
	Poisson’s ratio	TST_PC04
	Water-to-cement ratio	INV_PCC_MIXTURE
		SPS2_PCC_MIXTURE_DATA
		SPS8_PCC_MIXTURE_DATA
		SPS7_PCC_OVERLAY

Property Type	Properties	LTPP Tables
Thermal properties (nonstrength)	Coefficient of thermal expansion	TST_PC03
	Surface shortwave absorptivity	MEPDG default value
	Thermal conductivity	MEPDG default value
	Heat capacity	MEPDG default value
	PCC zero-stress temperature	MEPDG prediction equation
Construction properties (nonstrength)	Curing method	INV_PCC_MIXTURE
		SPS2_PCC_PLACEMENT_DATA
		SPS8_PCC_PLACEMENT_DATA
		SPS7_PCC_OVERLAY
		RHB_PCCO_CONSTRUCTION
	Ultimate shrinkage	MEPDG prediction equation
	Reversible shrinkage	MEPDG default value
	Time to develop 50 percent of ultimate shrinkage	MEPDG default value
	Reinforcement steel in concrete (diameter, depth, spacing, etc.)	INV_PCC_STEEL
		SPS2_PCC_STEEL
		RHB_PCCO_STEEL

DERIVING REPRESENTATIVE VALUES

The properties that table 11 lists are categorized into two main types: strength/response properties (modulus of elasticity, modulus of rupture, tensile strength, and compressive strength) and nonstrength properties (PCC mixture properties, PCC construction properties, and thermal characteristics). Figure 9 illustrates the decision tree used to derive the PCC layer-level representative properties. Challenges with populating these data in the ARMAD are discussed in this section.



Source: FHWA.

Figure 9. Flowchart. Decision tree for deriving PCC layers' representative properties.

PCC Strength/Response Properties

PCC strength/response properties include compressive strength, tensile strength, modulus of rupture (flexural strength), and modulus of elasticity. The 28-d PCC strength properties are typically required as inputs for the PMED software. However, LTPP PCC layers, particularly for GPS experiments, were tested at a later time than 28 d after the construction, in many cases years after placement of the PCC layer.

Consequently, 28-d strength properties were estimated based on the growth models used in the MEPDG (AASHTO 2020; ARA, Inc., ERES Consultants Division 2004), as detailed in this section. The distributions of the resulting backcasted strength values were compared with the distribution of LTPP sections with actual measured 28-d strength properties to check the validity of each estimation. Since the distributions characteristics were similar, these estimations were included in the ARMAD, and are identified by a "* _28_DAY" extension in their field name—for example, "ELASTIC_MOD_28_DAY," "COMP_STRENGTH_28_DAY," "MODULUS_OF_RUPTURE_28_DAY," and "TENSILE_STRENGTH_28_DAY."

28-d Compressive Strength Calculation

The 28-d compressive strength was estimated using the *F_STRRATIO* ratio of modulus of rupture and its relationship with the compressive strength using the MEPDG growth function model (AASHTO 2020). Figure 10 provides the specific equations used to estimate the 28-d compressive strength.

$$MR(t) = 9.5 \times \sqrt{f_c'(t)}$$

Considering:

$$MR(28) = \frac{MR(t)}{F\_STRRATIO}$$

And,

$$F\_STRRATIO = 1.0 + 0.12log_{10}\left(\frac{t}{0.0767}\right) - 0.01566\left[log_{10}\left(\frac{t}{0.0767}\right)\right]^2$$

Then,

$$f_c'(28) = \left(\frac{MR(28)}{9.5}\right)^2 = \left(\frac{9.5 \times \sqrt{f_c'(t)}}{9.5 \times F\_STRRATIO}\right)^2 = \frac{f_c'(t)}{F\_STRRATIO^2}$$

Figure 10. Equation. Calculation of 28-d compressive strength of PCC.

Where:

f_c' = compressive strength.

$MR(t)$ = modulus of rupture at time t.

$MR(28)$ = 28-d modulus of rupture.

F_STRRATIO = modulus of rupture at a given age to modulus of rupture at 28 d (single-point estimate).

f_c' (28) = 28-d compressive strength.

28-d Elastic Modulus Calculation

The 28-d elastic modulus, $E_c(28)$, was calculated using the *F_STRRATIO* ratio using the MEPDG growth model (AASHTO 2020). The specific equation used is provided in figure 11.

$$E_c(28) = \frac{E_C(t)}{F\_STRRATIO}$$

Figure 11. Equation. Calculation of 28-d elastic modulus of PCC.

Where:

$E_c(28)$ = 28-d elastic modulus.

$E_c(t)$ = elastic modulus at time t.

28-d Modulus of Rupture Calculation

Similarly, the 28-d modulus of rupture, $MR(28)$, was estimated using the equation provided in figure 12, which is based on the MEPDG growth model (AASHTO 2020).

$$MR(t) = 9.5 \times \sqrt{f_c'}$$

And,

$$MR(t) = F\_STRRATIO \times MR(28)$$

Therefore,

$$MR(28) = \frac{MR(t)}{F\_STRRATIO}$$

Figure 12. Equation. Calculation of the 28-d PCC modulus of rupture.

28-d Tensile Strength Calculation

The 28-d tensile strength, $f_t(28)$, was estimated using the *T_STRRATIO_3* ratio using the equation provided in figure 13, which is based on the MEPDG growth function model (AASHTO 2020).

$$T\_STRRATIO\_3 = 0.67 \times F\_STRRATIO$$

And,

$$T\_STRRATIO\_3 = \frac{f_t(t)}{f_t(28)}$$

Then,

$$f_t(28) = 1.49 \times \frac{f_t(t)}{F\_STRRATIO}$$

Figure 13. Equation. Calculation of the 28-d tensile strength of PCC.

Where:

T_STRRATIO_3 = level 3 ratio of tensile strength at a given age to tensile strength at 28 d.
$f_t(t)$ = tensile strength at time *t*.
$f_t(28)$ = 28-d tensile strength.

PCC Nonstrength/Response Properties

PCC Mixture Properties

The AASHTO MEPDG requires multiple volumetric and mixture property inputs to characterize PCC layers (AASHTO 2020). Following is the list of PCC mixture properties that are included in ARMAD:

- Water-to-cement ratio (WATER_CEMENT_RATIO).
- Unit weight (UNIT_WT).
- Poisson's ratio (POISSON_RATIO).

The LTPP program acquired part of these data from State highway agency (SHA) construction documentation and stored them in the LTPP database's inventory module (INV). PCC unit weight and Poisson's ratio were measured on some sections as a part of the testing program.

The general approach for identifying the representative layer properties discussed in chapter 3 was used to obtain mixture properties depending on the data availability in the LTPP database.

PCC Construction Properties

The LTPP database stores information on PCC curing method and reinforcement steel properties (DEPTH_TO_REINFORCEMENT, LONG_BAR_DIAMETER, LONG_BAR_SPACING, TRANSVERSE_BAR_DIAMETER, and TRANSVERSE_BAR_SPACING), which was obtained from SHA construction documentation and is stored in the LTPP database inventory module. The following properties are considered in the PMED software and have been included in the ARMAD:

- Ultimate shrinkage (ULT_SHRINKAGE): The equation provided in figure 14, obtained from the PMED software source code (Bazant and Murphy 1995), was used to estimate the ultimate shrinkage in ARMAD:

$$\varepsilon_{ult-shrinkage} = C_1 \times C_2 \times [26 \times w^{2.1} \times (f_c')^{-0.28} + 270]$$

Figure 14. Equation. Estimation of the PCC ultimate shrinkage.

Where:

$\varepsilon_{ult–shrinkage}$ = ultimate shrinkage microstrain.

C_1 = cement type factor for:

- cement Type I = 1.0.
- cement Type II = 0.85.
- cement Type III = 1.1.

C_2 = curing method for:

- wet curing = 1.0.
- curing compound = 1.2.

w = water content calculated using cement content and water/cement ratio (lb/ft^3).

- Reversible shrinkage (REVERS_SHRINKAGE): The MEDPG default value of 50 percent was used (AASHTO 2020).
- Time to develop 50 percent of ultimate shrinkage (T_HALF_ULT_SHRINKAGE): The MEPDG default value of 35 d was used (AASHTO 2020).

Thermal Characteristics

The following PCC thermal characteristics were included in ARMAD:

- Coefficient of thermal expansion (COEF_THERMAL_EXPANSION), which was obtained from one of the following two methods:
  - Representative LTPP measurements.
  - The MEPDG default value of 4.9 × 10^{-6}/°F based on the NCHRP 20-07 report (AASHTO 2020).
- Surface shortwave absorptivity (SUR_SHORTWAVE_ABSORP): The MEPDG default value of 0.85 was used as the recommended input in the PMED software.
- Thermal conductivity (THERMAL_CONDUCTIVITY): Typical values for PCC range from 0.2 to 2.0 BTU/ft/hr/°F. The MEPDG default value of 1.25 BTU/ft/hr/°F was used to populate ARMAD (AASHTO 2020).
- Heat capacity (HEAT_CAPACITY): Typical values for PCC heat capacity range from 0.1 to 0.50 BTU/lb/°F. The MEPDG default value of 0.28 BTU/lb/°F was used for ARMAD (AASHTO 2020).
- PCC zero-stress temperature (ZERO_STRESS_TEMP): The PCC zero-stress temperature or set temperature, T_z, was calculated for ARMAD using the MEPDG equation contained in figure 15 (AASHTO 2020).

Considering:

$$H = -0.0787 + 0.007 \times MMT - 0.00003 \times MMT^2$$

Then,

$$T_z = \left(\frac{C_C \times 0.59328 \times H \times 0.5 \times 1000 \times 1.8}{1.1 \times 2400}\right) + MMT$$

Figure 15. Equation. Prediction of PCC zero-stress temperature.

Where:

H = computed parameter as a function of mean monthly temperature construction month.

MMT = mean monthly temperature for month of construction, °F.

T_z = PCC zero-stress temperature (allowable range is 70–212 °F).

C_C = cementitious content (lb/yd^3).

DATA SOURCE AND VARIABILITY

The REP_CODE_SOURCE_VARIABILITY in the ANALYSIS_TST_PCC_SUPPORT table was assigned as follows:

- Measured—labeled as "A." Under this classification, mixture and as-measured strength properties with two or more measurements that were combined to generate a single value were divided into low or high COV based on a threshold of 10 percent.[1] These properties were labeled as "AL" for low COV and "AH" for high COV. Properties with a single measurement were included in this classification and labeled as "AS." For properties with unknown COV, such as representative layer thickness (REPR_THICKNESS), the values are labeled as a single character "A."

- Calculated—labeled as "B." This classification was used for calculated 28-d strength properties. For properties where the value was derived from multiple measurements, the classification was divided into low- ("BL") and high-COV ("BH") values based on a COV threshold of 10 percent. If the value was calculated from a single measurement, it was labeled as "BS."

- Expanded—labeled as "C." This classification was used for the strength and nonstrength properties of SPS test sections that were expanded to other similar SPS test sections using the PROJECT_LAYER_CODE. Properties that were determined based on two or more measurements from similar sections were labeled as "CL" for low COV and "CH" for high COV, based on a COV threshold of 10 percent. If the COV was unknown, such as representative layer thickness, values were labeled by the single character "C."

[1]The COV of 10 percent was determined as the threshold based on a review of the overall LTPP PCC data statistics and the recommendations of the ARMAD SMEs.

- Imputed—labeled as “D.” Modulus of rupture values of PCC materials were imputed based on the measured or expanded compressive strength. The properties were labeled as “DL” for low COV or “DH” for high COV based on a COV threshold of 10 percent.

- Inventory—labeled as “E.” This classification was applied to the PCC construction and mixture properties, where values were obtained from the respective agencies. For properties where the value was derived from multiple agency data, the classification was divided into low- (“EL”) and high-COV (“EH”) values based on a COV threshold of 10 percent. If the value was calculated from a single inventory value, it was labeled as “ES.”

- Assumed—labeled as “F.” This classification was used for representative values adopted from the MEPDG or default PMED software inputs, such as thermal characteristics and PCC shrinkage properties. This classification does not have a COV designation as these are assumed values.

CHAPTER 6. GENERATION OF ASPHALT CONCRETE MATERIALS ANALYSIS-READY DATASET

This chapter documents the development of the ARD for AC materials. The key AC material properties selected for inclusion in ARMAD were presented earlier in table 2.

DATA DISCOVERY

Table 12 presents the LTPP database tables and data sources used to extract the selected AC material properties and layer characteristics. The following LTPP experiments have sections with an AC layer type that were included in ARMAD: GPS-1, GPS-2, GPS-3, GPS-5, GPS-6, GPS-7, GPS-9, SPS-1, SPS-2, SPS-3, SPS-5, SPS-6, SPS-7, SPS-8, and SPS-9 (refer to FHWA 2022a for more information regarding LTPP experiments). Materials testing of the AC layers of the SPS-10 experiment is ongoing; therefore, it is not included in ARMAD in SDR 36. The referenced experiment and section information was filtered to include AC layer and asphalt treated base/subbase/subgrade for the following layer types and material codes:

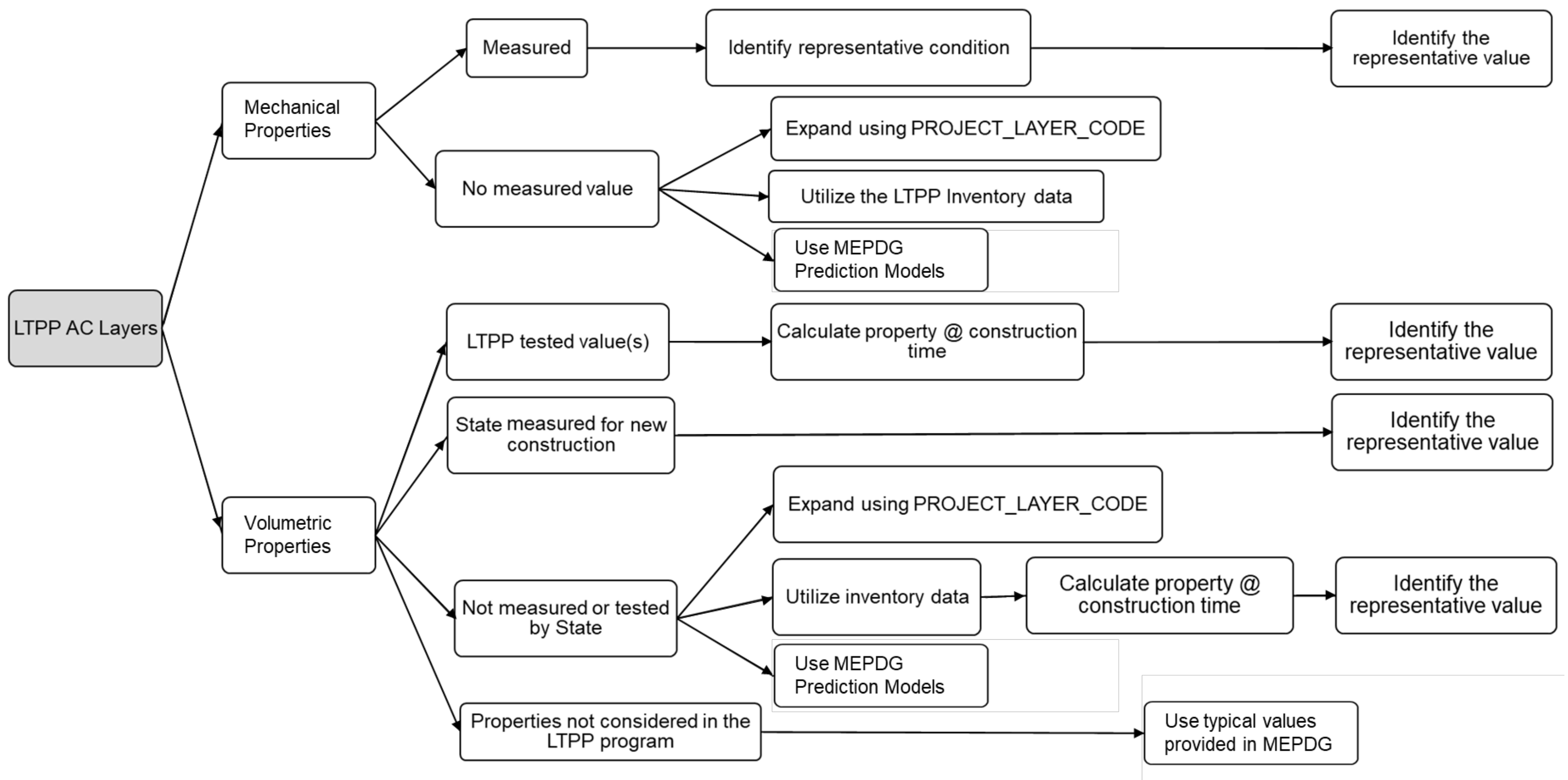
- LAYER_TYPE = "AC" and MATL_CODE = 1, 2, 9, 13, 14, 15, 16, and 319.
- LAYER_TYPE = "TS" and MATL_CODE = 319, 320, 321, and 325.
- LAYER_TYPE = "TB" and MATL_CODE = 322, 323, 324, 326, 327, and 328.

Table 12. The LTPP data table or source to extract each material property—AC dataset.

Property Type	Properties	LTPP Table
LTPP layer information	Layer thickness and material type	TST_L05B
	Section information	EXPERIMENT_SECTION
	Construction date	INV_AGE
Mechanical properties	AC Poisson's ratio	TST_AC07_V2_IDT_SUM
	Asphalt binder complex shear modulus and phase angle	AC_DSR_EXP
	Binder type	AC_BINDER_EXP
	Binder viscosity	TST_AE05
	Dynamic modulus	TST_ESTAR_MASTER
		TST_ESTAR_MODULUS
	Tensile strength	TST_AC07_V2_IDT_SUM
	Creep compliance	TST_AC07_V2_CREEP_COMP_SUM
	Aggregate coefficient of thermal contraction	MEPDG default value
Volumetric properties	Maximum specific gravity	TST_AC03
	Binder content percent total by weight	TST_AC04
	Air voids	TST_AIR_VOIDS_SECT
	Aggregate gradation	TST_AG04
	BSG	TST_AC02
Thermal properties	Heat capacity	MEPDG default value
	Thermal conductivity	MEPDG default value
	Surface shortwave absorptivity	MEPDG default value

DETERMINING REPRESENTATIVE VALUES

The properties listed in table 12 were classified into the following three types: mechanical properties, volumetric properties, and thermal properties. Figure 16 exhibits the decision tree used to derive the AC layer-level representative mechanical and volumetric properties. The recommended default values provided in the MEPDG (AASHTO 2020) were used to establish the ARMAD AC thermal properties.



Source: FHWA.

Figure 16. Flowchart. Decision tree for deriving AC layers' representative properties.

Mechanical Properties

AC Poisson's Ratio

In the PMED software, there are two methods for entering Poisson's ratio to predict distresses: using a single value entered by the designer that is assigned to that layer for all temperatures calculated by the software and having the software's internal regression equation calculate Poisson's ratio as a function of layer temperature. The designer is unable to change the coefficients of the regression equation in the software, so a single value for Poisson's ratio was included in ARMAD. The AC Poisson's ratio (IDT_POISSON_USED) is measured in the LTPP Program during the indirect tensile test (IDT) at 25 °C. For those AC layers where Poisson's ratio is unavailable (i.e., missing values), the recommended MEPDG default value of 0.35 at 25 °C was used to populate ARMAD (AASHTO 2020).

Asphalt Binder Complex Shear Modulus and Phase Angle

In the LTPP program, the binder complex shear modulus and phase angle were measured using the dynamic shear rheometer (DSR) test for original binder from the tank, aged binder using rolling thin-film oven (RTFO), and pressure aging vessel (PAV) per *Long-Term Pavement Performance Project Laboratory Materials Testing and Handling Guide* (Simpson, Schmalzer, and Rada 2007).

The DSR_COMPLEX_MODULUS_TANK, DSR_COMPLEX_PHASE_ANGLE_TANK, DSR_COMPLEX_MODULUS_RTFO, DSR_COMPLEX_PHASE_ANGLE_RTFO, DSR_COMPLEX_MODULUS_PAV, and DSR_COMPLEX_PHASE_ANGLE_PAV fields were determined following the general approach detailed in chapter 3, which depended on data availability.

Binder Viscosity

Representative values of binder absolute viscosity at 140 °F (ABSOLUTE_VISC_140_F) and binder kinematic viscosity at 275 °F (KINEMATIC_VISC_275_F) were measured via laboratory testing on bulk samples or binder extracted from cores, depending on the projects. Representative values were established following the general approach detailed in chapter 3, which depended on data availability. The viscosity and other rheology properties measured on extracted binder from field cores represent the time of sampling. The input properties required by the PMED software need to represent the short-term aged binder at construction. These rheology properties on the extracted binder were not backcast to the time of construction.

Dynamic Modulus

FHWA performed a study titled *LTPP Computed Parameter: Dynamic Modulus*, which made use of available AC material properties in the LTPP database to predict dynamic modulus when these values were not directly measured (Kim et al. 2011). In this study, several artificial neural network models were developed and compared, and the data were incorporated in the LTPP database. These data in ANALYSIS_TST_AC_ESTAR can be merged with the ANALYSIS_TST_AC table using the ESTAR_LINK_GROUP field for each layer.

Tensile Strength

Two IDT strengths were measured and reported within the LTPP program. The first IDT strength was measured at 25 °C at a loading rate of 25 mm/min in accordance with AASHTO TP 09 (AASHTO 1996). In contrast, the second IDT strength was measured at much lower temperatures and much slower loading rates in accordance with AASHTO T 322 (AASHTO 2007). Please note that the PMED software's input is IDT at −10 °C per AASHTO T 322 specification and with a different loading rate. The IDT_AVERAGE, IDT_TEST_TEMPERATURE, and IDT_LOADING_RATE fields were populated following the general approach detailed in chapter 3, which depended on data availability.

Creep Compliance

LTPP AC creep compliance testing was performed at temperatures of 14, 41, and 77 °F and 1-, 2-, 5-, 10-, 20-, 50-, 100-s frequencies. Again, the testing temperatures and loading rates used in the LTPP testing were different than those used as inputs to the PMED software. The PMED software requires inputs for creep compliance in accordance with AASHTO T 322 (AASHTO 2007). These data are provided in a separate table (ANALYSIS_TST_AC_CREEP_COMP) and linked to the main AC table (ANALYSIS_TST_AC) via the CREEP_COMP_LINK field for each layer.

Aggregate Coefficient of Thermal Contraction

The coefficient of thermal contraction (COEF_THERMAL_CONTRACTION) for the aggregate in AC mixtures was estimated using the MEPDG equation provided in figure 17 (AASHTO 2020).

$$L_{MIX} = \frac{VMA \times B_{ac} + V_{agg} \times B_{agg}}{3 \times V_{TOTAL}}$$

Figure 17. Equation. Estimation of the aggregate coefficient of thermal contraction in AC.

Where:

VMA = volume of voids in the mineral aggregate (VMA) (percentage).
V_{agg} = volume of aggregate in the mixture (percentage).
V_{TOTAL} = 100 percent.
L_{MIX} = 2.2 to 3.4×10^{-5}/°C (linear).
B_{ac} = 3.5 to 4.3×10^{-4}/°C (cubic).
B_{agg} = 21 to 37×10^{-6}/°C (cubic).

Volumetric Properties

The AC mixture volumetric properties included in ARMAD were derived as follows:

1. The following properties were determined from LTPP laboratory testing carried out in accordance with the *Long-Term Pavement Performance Project Laboratory Materials Testing and Handling Guide* (Simpson, Schmalzer, and Rada 2007):

    - Maximum specific gravity (MAX_SPEC_GRAVITY).
    - Binder content (ASPHALT_CONTENT_MEAN).
    - Air voids (AIR_VOIDS_AVG_WP and AIR_VOIDS_AVG_NWP); WP represent wheelpath and NWP non-wheelpath.
    - Aggregate gradation (ONE_AND_HALF_PASSING, ONE_PASSING, THREE_FOURTHS_PASSING, ONE_HALF_PASSING, THREE_EIGHTHS_PASSING, NO_4_PASSING, NO_10_PASSING, NO_40_PASSING, NO_80_PASSING, and NO_200_PASSING).
    - Bulk specific gravity (BSG).

2. To calculate VMA and VFA, binder and aggregate specific gravities were assumed to be typical values. The equations presented in figure 18 and figure 19 were used to calculate the VMA and VFA, respectively:

    - Binder specific gravity (BINDER_SPEC_GRAVITY).
    - Aggregate specific gravity (AGGR_SPEC_GRAVITY).
    - VMA (VOIDS_MINERAL_AGGR).
    - VFA (VOIDS_FILLED_ASPHALT).

$$VMA = \left[1 - BSG \times \left(1 - \frac{\%\ binder\ content}{\text{aggregate specific gravity}}\right)\right] \times 100$$

Figure 18. Equation. Calculation of AC VMA.

$$VFA = \left(\frac{VMA - \%\ average\ air\ voids}{VMA}\right) \times 100$$

Figure 19. Equation. Calculation of AC VFA.

The general approach described in chapter 3 was used to obtain representative AC volumetric properties, which depended on the layer-level data availability.

Thermal Properties

The following AC thermal properties were included in ARMAD:

- Heat capacity (HEAT_CAPACITY): The MEPDG recommended default value of 0.28 BTU/lb/°F was used (AASHTO 2020).
- Thermal conductivity (THERMAL_CONDUCTIVITY): The MEPDG default value of 1.25 BTU/ft/hr/°F was used (AASHTO 2020).
- Surface shortwave absorptivity (SUR_SHORTWAVE_ABSORP): The MEPDG default value of 0.85 was used (AASHTO 2020).

DATA SOURCE AND VARIABILITY

The REP_CODE_SOURCE_VARIABILITY in the ANALYSIS_TST_AC_SUPPORT table was assigned as follows:

- Measured—labeled as "A." For this classification, material properties with two or more measurements that were combined to generate a single representative value and were divided into low-COV ("AL") and high-COV ("AH") thresholds based on a threshold COV of 10 percent.[1] Material properties with only a single ("S") measurement were included in this classification under the label of "AS." For measurements with unknown COV, such as measured representative layer thickness (REPR_THICKNESS), only the classification code was used; i.e., "A."
- Calculated—labeled as "B." This classification was used for calculated VMA, VFA, and air voids. The classification was divided into material properties with low ("BL") and high ("BH") COV based on a threshold COV of 10 percent. If the value was calculated from a single ("S") measurement, it was labeled as "BS."
- Expanded—labeled as "C." This classification was applied to the material properties of SPS sections that were expanded to similar sections using the PROJECT_LAYER_CODE. Material properties established based on two or more measurements from similar sections were labeled as "CL" for low COV or "CH" for high COV based on a threshold COV of 10 percent. Material properties established based on one measurement from a similar section were labeled as "CS." For expanded values with an unknown COV, such as representative layer thickness, the classification was labeled as the single character "C."

[1]The COV of 10 percent was determined as the threshold based on a review of the overall LTPP AC data statistics and the recommendations from the ARMAD SMEs.

- Inventory—labeled as “E.” This classification was applied to the AC viscosity and DSR values, which were obtained from SHA-provided information. For properties where the value was derived from data from multiple agencies, the classification was divided into low- (“EL”) and high-COV (“EH”) values based on a COV threshold of 10 percent. If the value was calculated from a single inventory value, it was labeled as “ES.”
- Assumed—labeled as “F.” This classification was used for representative values adopted from the MEPDG or default PMED software inputs, such as the AC thermal characteristics (AASHTO 2020). This classification does not have a COV designation as the values were assumed.

CHAPTER 7. GENERATION OF TREATED MATERIALS ANALYSIS-READY DATASET

This chapter documents the development of the ARD for treated or stabilized materials. The list of key material properties selected for inclusion in ARMAD was provided in table 1 earlier in the report.

DATA DISCOVERY

Table 13 presents the LTPP database tables and data sources used to extract the selected material properties and layer characteristics. The experiment and section information was filtered to include treated subgrade and base layers for the following layer types and material codes:

- LAYER_TYPE = "TS" and MATL_CODE = 309, 331, 333, 338, 339, 340, and 360.
- LAYER_TYPE = "TB" and MATL_CODE = 332, 334, and 350.

Table 13. The LTPP data table or source to extract each material property—treated materials dataset.

Material Properties	LTPP Tables/Source
Layer thickness and material type	TST_L05B
Section information	EXPERIMENT_SECTION
Soil and aggregate type	TST_TB01
Treatment type	TST_TB01
Compressive strength	TST_TB02
	TST_SS10
Resilient modulus	MEPDG estimation equation/default value
Elastic modulus	MEPDG estimation equation/default value
Poisson's ratio	MEPDG default value
Unit weight	MEPDG default value
Thermal conductivity	MEPDG default value
Heat capacity	MEPDG default value

DETERMINING REPRESENTATIVE VALUES

The procedure used to determine layer-level representative values for ARMAD's ANALYSIS_TST_TR and ANALYSIS_TST_TR_SUPPORT tables is described in this section.

Material and Treatment Type

Representative properties for soil geological classification (GEOL_CLASS), treatment type (TREAT_TYPE), and aggregate type (AGGR_TYPE) were identified for each treated layer in the LTPP database. For treated layers with two or more measurements available, the dominant material and treatment type were identified as the representative values. Table 14 to table 16 summarize these cases; the "combined code" column presents the representative value selected.

Table 14. Soil classification for combined geological class cases.

GEOL_CLASS_1	GEOL_CLASS_1_DETAIL	GEOL_CLASS_2	GEOL_CLASS_2_DETAIL	Combined Code
32	Boulder clay	43	Alluvial clays and/or peat	43
32	Boulder clay	36	Ground moraine	36
30	Other rock type (specify if possible or state unknown)	47	Wind-blown sand	47
1	Granite	10	Dolomite	10
41	River gravels	60	Other limerock materials	41
9	Limestone	60	Other limerock materials	9
41	River gravels	47	Windblown sand	41
9	Limestone	41	River gravels	41
30	Other rock type (specify if possible or state unknown)	52	Residual soils derived from granites, gneisses, and schists	52
9	Limestone	33	Glacial sands and gravels	9
9	Limestone	41/60	River gravels/other limerock materials	9

Table 15. Treatment types for combined treatment cases.

TREAT_TYPE_1	TREAT_TYPE_1_DETAIL	TREAT_TYPE_2	TREAT_TYPE_2_DETAIL	Combined Code
334	Lean concrete	354	Treatment: cement—portland cement	334
182	Cement-treated subgrade soil	338	Lime-treated soil	182
338	Lime-treated soil	354	Treatment: cement—portland cement	354
334	Lean concrete	354	Treatment: cement—portland cement	354
331	Cement aggregate mixture	354	Treatment: cement—portland cement	354
351	Treatment: lime, all classes of quick lime and hydrated lime	354	Treatment: cement—portland cement	354

Table 16. Aggregate types for combined aggregate type cases.

AGGR_TYPE_1	AGGR_TYPE_1_DETAIL	AGGR_TYPE_2	AGGR_TYPE_2_DETAIL	Combined Code
402	Crushed stone	403	Crushed gravel	402
401	Gravel	402	Crushed stone	402
403	Crushed gravel	411	Blend (different sized fine aggregates)	411
409	Natural sand	412	Other (specify)	409
401	Gravel	411	Blend (different sized fine aggregates)	411
402	Crushed stone	408	Other (specify)	402
402	Crushed stone	405	Blend (several sizes of coarse aggregates)	405
405	Blend (several sizes of coarse aggregates)	408	Other (specify)	405
401	Gravel	402/409	Crushed stone/natural sand	402

Strength Properties

The compressive strength test was performed on samples taken from LTPP treated base and subgrade layers. The process detailed in chapter 3 was used for determining the representative compressive strength value based on the available data.

The MEPDG recommended input parameters (levels 2 and 3) for chemically stabilized material properties were used to establish the ARMAD elastic and resilient modulus (ELASTIC_MOD and RES_MOD) values (AASHTO 2020). The MEPDG recommends estimating elastic or resilient modulus as a function of the measured unconfined compressive strength from laboratory samples or extracted cores. In the absence of compressive strength data, the MEPDG recommends default values. The relationships presented in table 17 provide the basis used for estimating the ARMAD moduli as a function of LTPP material type. Similarly, the MEPDG-recommended Poisson's ratio (POISSON_RATIO) values are presented in table 18 as a function of LTPP material type.

Table 17. MEPDG-recommended elastic/resilient modulus for LTPP chemically treated material types.

MATL_ CODE	Detail	LAYER_ TYPE	ELASTIC_MOD (psi)	RES_MOD (psi)
309	Fine-grained soils	TS	N/A	45,000
331	Cement aggregate mixture	TS	$57{,}000(f_c')^{0.5}$ or 1,000,000	N/A
332	Econocrete	TB	$57{,}000(f_c')^{0.5}$ or 1,000,000	N/A
333	Cement-treated soil	TS	$1{,}200(f_c')$ or 500,000	N/A
334	Lean concrete	TB	$57{,}000(f_c')^{0.5}$ or 2,000,000	N/A
338	Lime-treated soil	TS	N/A	$124(f_c') + 9.98$ or 45,000
339	Soil cement	TS	$1{,}200(f_c')$ or 500,000	N/A
340	Pozzolanic aggregate mixture	TS	$500 + f_c'$ or 1,500,000	N/A
350	Other	TB	N/A	45,000
360	Treatment: other (specify, if possible)	TS	N/A	45,000

N/A = No data.

Table 18. MEPDG-recommended Poisson's ratio values for each LTPP treated material type

MATL_CODE	Detail	POISSON_RATIO
309	Fine-grained soils	0.15
331	Cement aggregate mixture	0.15
332	Econocrete	0.15
333	Cement-treated soil	0.25
334	Lean concrete	0.15
338	Lime-treated soil	0.175
339	Soil cement	0.25
340	Pozzolanic-aggregate mixture	0.125
350	Other	0.2
360	Treatment: other (specify, if possible)	0.2

The MEPDG-recommended default unit weight (UNIT_WEIGHT), thermal conductivity (THERMAL_CONDUCTIVITY), and heat capacity (HEAT_CAPACITY) values for treated materials are 150 pcf, 1.25 BTU/ft/hr/°F, and 0.28 BTU/lb/°F, respectively.

DATA SOURCE AND VARIABILITY

- Measured—labeled as "A." For this classification, material properties (material type, treatment type, and compressive strength) with two or more measurements that were combined into a single representative value were divided into low ("AL") and high ("AH") COV based on a threshold COV of 10 percent.[1] For measurements with unknown COV, the values were labeled as a single character "A."

- Calculated—labeled as "B." This classification was used for calculated elastic modulus based on the measured compressive strength. The classification was divided into low ("BL") and high ("BH") COV based on a threshold COV of 10 percent. If the representative value was calculated from a single ("S") measurement, the value was labeled as "BS."

- Expanded—labeled as "C." This classification was applied to the material properties of SPS sections that were expanded to similar sections using the PROJECT_LAYER_CODE. Properties that were established based on two or more measurements from similar sections were labeled as "CL" for low COV and "CH" for high COV based on a threshold COV of 10 percent. For expanded values with unknown COV, such as representative layer thickness, the values were labeled as a single character "C."

- Inventory—labeled as "E." Applied to representative thickness that was adopted from SHA-provided information. For properties where the value was derived from multiple agency data, the classification was divided into low- ("EL") and high-COV ("EH") values based on a COV threshold of 10 percent. If the value was calculated from a single inventory value, it was labeled as "ES."

- Assumed—labeled as "F." This classification was used for representative values adopted from the MEPDG or default PMED software's inputs, including resilient modulus, elastic modulus, unit weight, thermal conductivity, heat capacity, and Poisson's ratio. This classification does not have a COV designation as the values have been assumed.

[1]The COV of 10 percent was determined as the threshold based on a review of the overall LTPP AC data statistics and the recommendations from the ARMAD SMEs.

CHAPTER 8. GENERATION OF OTHER MATERIALS ANALYSIS-READY DATASET

This chapter documents the development of the ARD for other materials such as surface treatments, EF, and interlayers. Although their presence is noted in the LTPP database, these types of layers were generally not tested by the LTPP program; that is, no physical measurements were conducted.

DATA DISCOVERY AND DETERMINING REPRESENTATIVE VALUES

The only designated property for these material types was layer thickness, which was extracted directly from the TST_L05B table for the test section. The experiment and section information were filtered to include EF, interlayers, and surface treatment material types for the following layer types and material codes:

- ANALYSIS_TST_EF and SUPPORT tables were populated for LAYER_TYPE = EF.
- ANALYSIS_TST_TR and SUPPORT tables were populated for:
    - LAYER_TYPE = AC and surface treatment material types including chip seal, slurry seal, sand seal, seal coat (MATL_CODE = 11, 12, 71, 72, 73, 81, 82, and 83).
    - LAYER_TYPE = AC and material types including stress-absorbing membrane, dense-graded AC, and open-graded AC interlayers (MATL_CODE = 77, 78, 80).

DATA SOURCE AND VARIABILITY

The REP_CODE_SOURCE_VARIABILITY in the ANALYSIS_TST_TR_SUPPORT and ANALYSIS_TST_EF_SUPPORT table was assigned for the layer thickness only (REPR_THICKNESS) as follows:

- Measured—labeled as “A.” For this classification, layer thickness was measured in the field. The layer thickness variability is unknown or not applicable; therefore, only the character code of “A” was used for this classification.
- Expanded—labeled as “C.” These layer thickness values were obtained from a nearby section because a thickness was not obtained for the subject test section. The variability was unknown or not applicable; therefore, only the character code of “C” was used for this classification.
- Inventory—labeled as “E.” In this classification, layer thickness values were not available, so they were obtained from inventory data. The variability was unknown or not applicable; therefore, only the character code “E” was used for this classification.
- Assumed—labeled as “F.” This classification was used when layer thickness values were not available in the LTPP database, so the thickness values were assumed. Because assumed values were used, this classification only uses the single character code of “F.”

CHAPTER 9. ADDITIONAL READING

The following resource documents can be useful in understanding the LTPP material characterization program. These documents can be downloaded from https://infopave.fhwa.dot.gov/Reports/Library.

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