SHRP-A-407

The Superpave Mix Design Manual for New Construction and Overlays

Ronald J. Cominsky
University of Texas at Austin

With contributions by:

Gerald A. Huber
Heritage Research Group

Thomas W. Kennedy
University of Texas at Austin

Michael Anderson
The Asphalt Institute

Strategic Highway Research Program
National Research Council
Washington, DC 1994

SHRP-A-407
Contract A-001
ISBN 0-309-05804-X
Product No.: 1012

Program Manager: *Edward T. Harrigan*
Program Area Secretary: *Juliet Narsiah*
Production Editor: *Michael Jahr*

May 1994

key words:
aggregate
asphalt binder
asphalt cement
asphalt modifier
bending beam rheometer
direct tension
dynamic shear rheometer
environmental conditioning system
gyratory compaction
hot mix asphalt
indirect tensile test device
net adsorption
performance grade
pressurized aging vessel
rolling wheel compaction
shear test device
SUPERPAVE®

Strategic Highway Research Program
National Research Council
2101 Constitution Avenue N.W.
Washington, DC 20418

(202) 334-3774

1.5M/NAP/594

Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

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1 Introduction

1.1 The Purpose of This Manual

This laboratory manual presents the Superpave mix design system in a complete, step-by-step format. It is intended for engineers and technicians in public and private organizations to use when designing paving mixes for all classes of highways, from farm-to-market roads to urban freeways.

An essential companion to this manual is *The Superpave Mix Design System Manual of Specifications, Test Methods and Practices*.

The Superpave software program (*The Superpave Specification, Mix Design and Support Program*) and its users manual are also necessary to take full advantage of the mix design system. This software is designed to run on an 80386-based or, preferably, an 80486-based personal computer.

1.2 The Superpave Mix Design System

The Superpave mix design system is a comprehensive method of designing paving mixes tailored to the unique performance requirements dictated by the traffic, environment (climate), and structural section at a particular pavement site. It facilitates selecting and combining asphalt binder, aggregate, and any necessary modifier to achieve the required level of pavement performance.

The Superpave system is applicable to virgin and recycled, dense-graded, hot mix asphalt (HMA), with or without modification. In addition, the Superpave performance tests are applicable to the characterization of a variety of specialized paving mixes such as stone matrix asphalt (SMA). It can be used when constructing new surface, binder, and base layers, as well as overlays on existing pavements. Through materials selection and mix design, it directly addresses the reduction and control of permanent deformation, fatigue cracking, and low-temperature cracking. It also explicitly considers the effects of aging and moisture sensitivity in promoting or arresting the development of these three distresses.

The objective of the Superpave mix design system is to define an economical blend of asphalt binder and aggregate that yields a paving mix having

- sufficient asphalt binder,
- sufficient voids in the mineral aggregate (VMA) and air voids,
- sufficient workability, and
- satisfactory performance characteristics over the service life of the pavement.

The Superpave mix design system has several distinctive features. First, only performance-based and performance-related properties are used as the criteria for selection of a mix design. *Performance-based properties* directly govern the response of the pavement to load; performance can be predicted from this response. *Performance-related* properties are those which are indirectly related to performance. They affect performance, but do not, in themselves, control it.

As the traffic and environmental demands on the pavement increase, the Superpave mix design system relies more on performance-based properties to select the optimum mix design. The maximum possible contribution of the materials in the paving mix to pavement performance can be achieved regardless of its structure.

Second, the Superpave performance-based specification for asphalt-aggregate mixtures is based on the predicted performance of the pavement built with the paving mix under design. The Superpave system provides a uniquely tailored specification, expressed in terms of the rut depth, area of fatigue cracking, and spacing of low-temperature cracking expected over a selected service life, for any paving project with significant traffic and environmental demands. These specifications may be compared to criteria presented in this manual or to criteria established by agency policy for discrete classes of traffic.

Third, in determining pavement performance, Superpave explicitly considers the interaction of pavement structure, traffic, and environment with the paving mix. Thus, the mix design and structural design can be integrated into an single system.

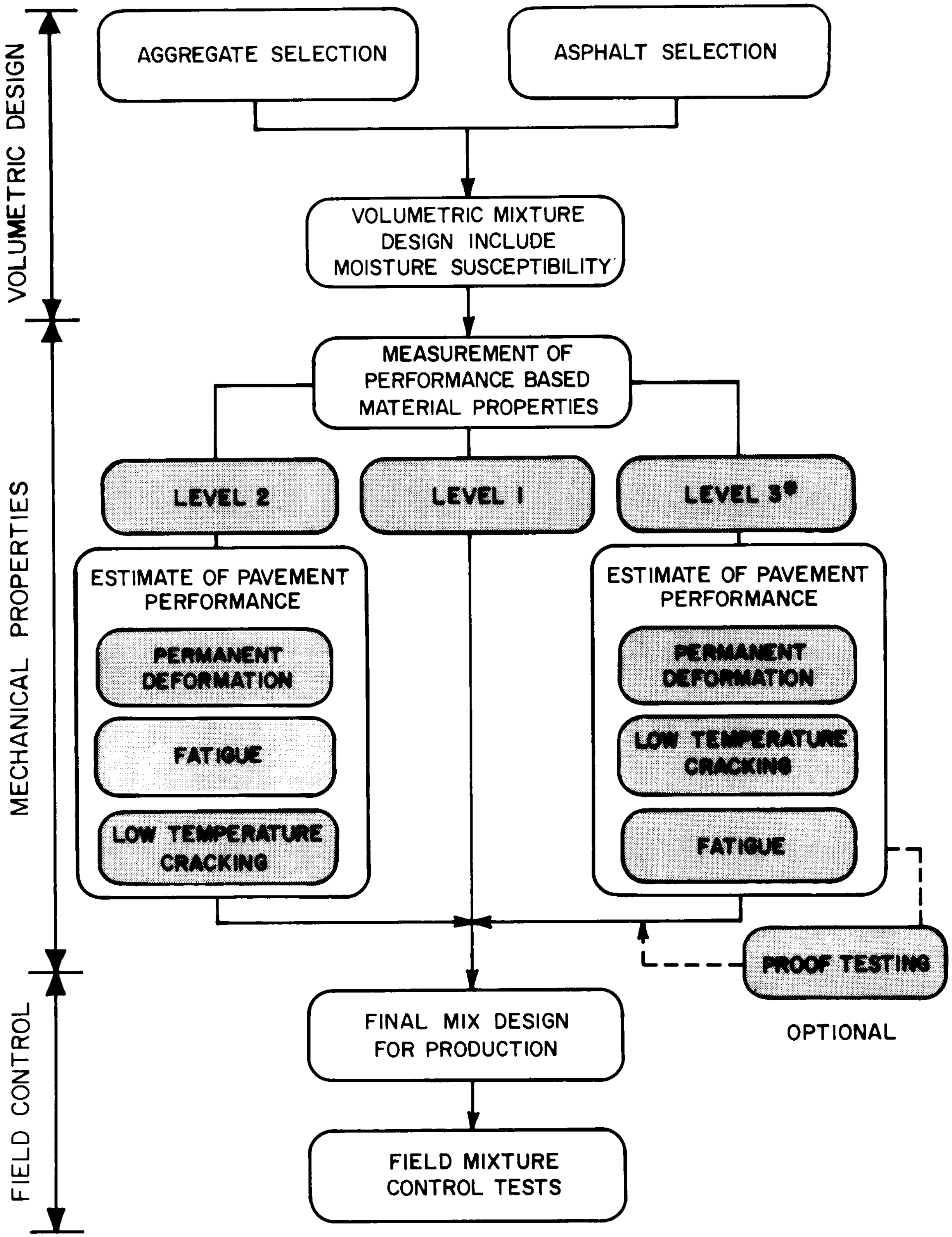
Finally, the design method provides a truly objective measure of the benefits or penalties associated with the use of materials of varying levels of quality.

1.2.1 Concept of the Superpave Mix Design

The concept behind the Superpave mix design system is straightforward: use available materials to prepare a mix design that achieves a level of performance commensurate with the demands of traffic, environment, structure, and reliability (or, conversely, risk) on the pavement.

This concept is illustrated by the general flow of a Superpave mix design (figure 1.1). At each step in the design, from materials selection through volumetric design and

Figure 1.1. Structure of the Superpave Mix Design System



* LEVEL 3 PROVIDES THE HIGHEST RELIABLE ESTIMATE OF PAVEMENT PERFORMANCE

engineering evaluation of trial mix designs to field control, decisions must be made on the basis of satisfying the specific pavement performance requirements to the extent possible.[1]

1.2.2 Low-, Intermediate-, and High-Traffic Level Designs

The Superpave mix design system contains three distinct levels of design, termed *level 1*, *level 2*, and *level 3*. This feature permits the agency to select a design process that is appropriate for the traffic loads and volume (expressed as total 80 kN equivalent single axle loads (ESALs) over the service life of the pavement) expected for the paving project. General recommendations for applying the three design levels are presented in table 1.1.

Table 1.1. Recommended Design Traffic For Level 1, 2, and 3 Mix Designs

Design Level	Design Traffic (80 kN ESALs)
1 (low)	$\leq 10^6$
2 (intermediate)	$\leq 10^7$
3 (high)	$> 10^7$

These traffic levels are presented as suggested guidelines only. Higher or lower transition points may be set on the basis of individual agency policy.

In addition, all three design levels explicitly consider the effects of the climate (environment) on pavement performance. Selection of the performance grade of asphalt binder is guided by the high and low pavement design temperatures at the paving project, the traffic speeds, and the design traffic levels. Candidate paving mixes are evaluated for unacceptable moisture sensitivity. Both asphalt binders and candidate paving mixes are aged in the laboratory to simulate the effects of both short- and long-term aging in pavement service.

The complexity of the design process increases significantly from level 1 to level 3. Level 3 requires a greater number of tests, more test specimens, and more time to complete a design. In return, the reliability of the design — that is, the probability that the paving

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[1] By contrast, the widely used Marshall and Hveem methods of mix design are neither performance-based nor performance-related. They are concerned primarily with achieving a mix design with a stable, economical balance of aggregate and asphalt binder that features sufficient workability to permit efficient placement of the mix. Both methods attempt to gauge anticipated performance with empirical properties, such as Marshall stability and flow, but neither method can ensure that a trial mix design will meet specific pavement performance criteria.

mix will provide satisfactory pavement service under the anticipated conditions of traffic and climate-increases proportionally.

The Superpave mix design system provides flexibility to deal with one, two, or all three of the major distress types which it addresses. As examples, at the discretion of the agency, designs for warm weather climates can concentrate on permanent deformation only or on permanent deformation and fatigue cracking. In extreme cold weather climates, designs can be aimed exclusively toward preventing low-temperature cracking without regard for the development of other distresses. In a climate that experiences extremes of both heat and cold, the agency can choose to use a level 3 design for permanent deformation, while addressing fatigue and low-temperature cracking with the level 2 design process.

1.2.2.1. Level 1 (Low Traffic) Mix Design

The Superpave level 1 mix design is presented as a flow chart in figure 1.2 and is described in detail in chapters 2 and 3 of this manual.

Level 1 mix design employs a performance-based asphalt binder specification with empirical, performance-related aggregate specifications, and principles of volumetric mix design to obtain a paving mix with satisfactory performance for low-traffic paving projects without the need for performance-based testing. Final selection of the design asphalt content is based upon attaining specified levels of air voids, voids in mineral aggregate, and voids filled with asphalt at initial, design, and maximum levels of compaction.

It is not possible to estimate the pavement performance of level 1 mix designs with regard to permanent deformation, fatigue cracking, or low-temperature cracking without the level 2 or 3 performance-based tests. However, the level 1 mix design provides a reasonable guarantee of adequate performance if all of the specified criteria are met.

Gyratory compaction is the key to successful level 1 mix designs. In addition, this design level explicitly considers the effects of moisture sensitivity and aging in selecting the final mix design.

1.2.2.2 Level 2 (Intermediate Traffic) Mix Design

The Superpave level 2 mix design is presented as a flow chart in figure 1.3 and is described in detail in chapter 4 of this manual.

The level 2 mix design incorporates the selection of a design asphalt content with the volumetric (level 1) design procedure. Candidate mixes prepared at the design asphalt content and at a high and a low asphalt content bracketing the design value are subjected to a series of performance-based tests selected for use in routine mix designs.

Figure 1.2. Level 1 Superpave Mix Design (Note: All specimens are compacted from paving mix that has been short-term aged (SHRP M-007)).

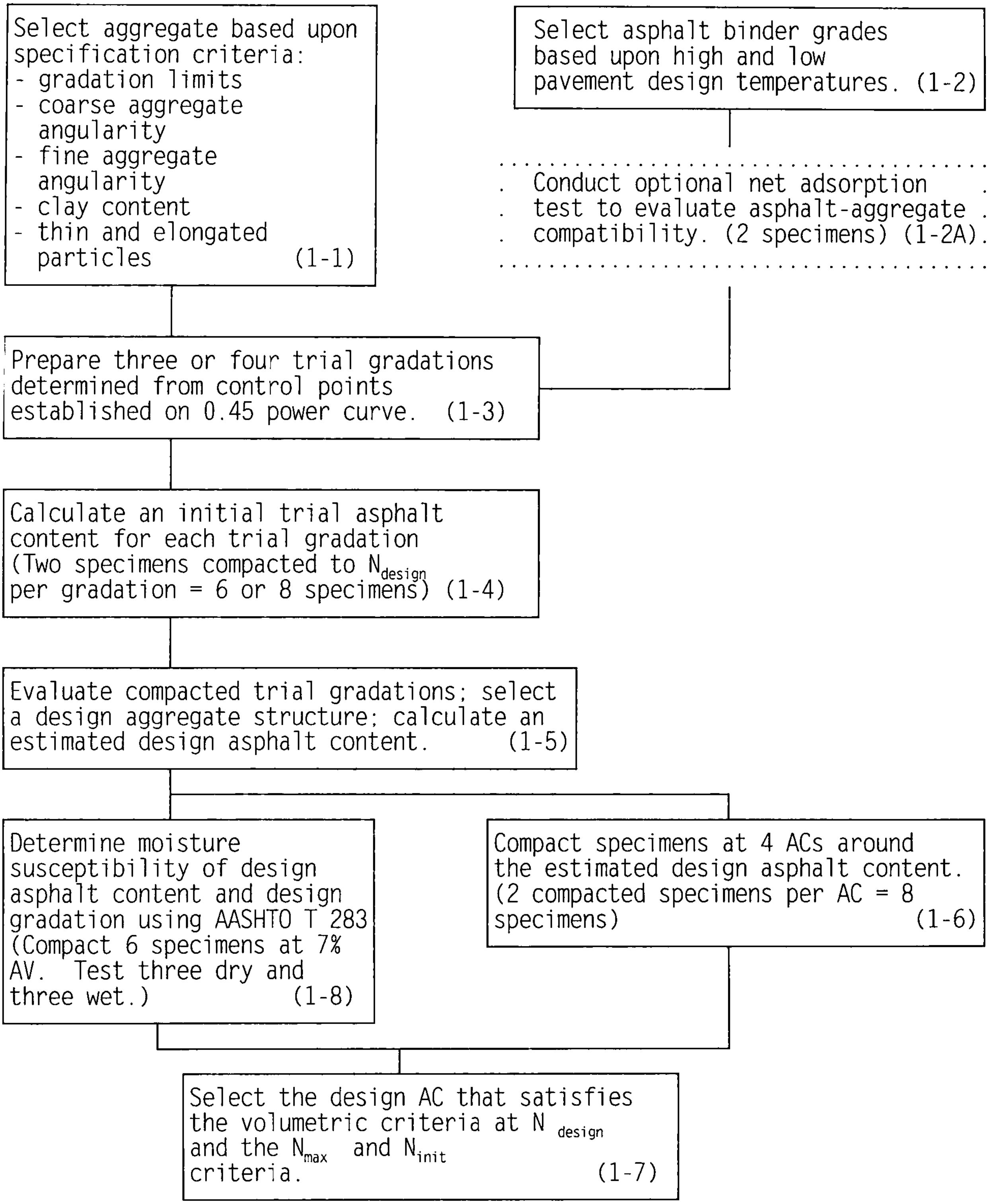
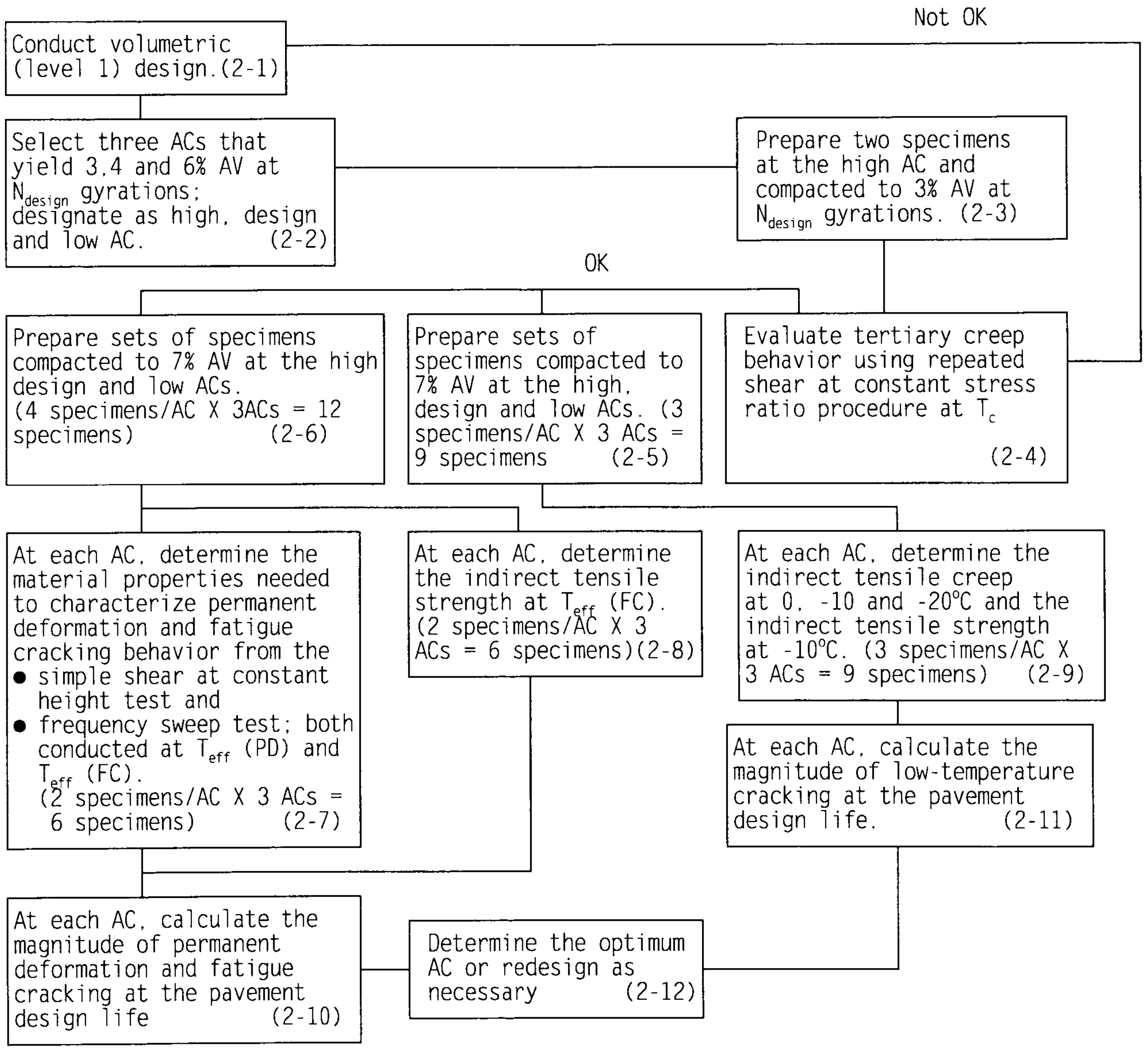


Figure 1.3. Superpave Level 2
(Note: All specimens are compacted from paving mix that has been short-term aged (SHRP M-007))



The Superpave software uses these test results to estimate pavement performance predictions for permanent deformation, fatigue cracking, and low-temperature cracking. The reliability of these predictions is consistent with the designation of level 2 as the method of choice for routine mix designs. The optimum asphalt content is determined from these performance predictions.

The use of gyratory compaction and the Strategic Highway Research Program (SHRP) shear test device is essential to successful level 2 mix designs. This design level also introduces a test for tertiary creep to screen out early in the design process trial mixes that may be susceptible to catastrophic rutting failures or unacceptable long-term permanent deformation[2]. In addition, this design level explicitly considers the effects of moisture sensitivity and aging in selecting the final mix design.

Together, level 2 and level 1 mix designs should be suitable for 95 percent or more of the mix design work conducted by a state agency in a typical year; in many states, these design levels will be satisfactory for all mix designs.

1.2.2.3 Level 3 (High Traffic) Mix Design

The Superpave level 3 mix design is presented as a flow chart in figure 1.4 and is described in detail in chapter 5 of this manual.

The level 3 mix design incorporates the selection of a design asphalt content with the volumetric (level 1) design procedure. Candidate mixes prepared at the design asphalt content and at a high and a low asphalt content bracketing the design value are subjected to a series of performance-based tests selected to develop mix designs suitable for very heavy traffic, severe climates, or any situation where only a minimal design risk is tolerable. Level 3 mix designs require considerably more time and a greater number of specimens than level 2 designs.

The Superpave software uses these test results to estimate pavement performance for permanent deformation, fatigue cracking, and low-temperature cracking. The degree of reliability of these estimates is consistent with the designation of level 3 as the method of choice for mix designs where high performance is mandatory. The optimum asphalt content is determined from these performance estimates.

The use of gyratory compaction and the SHRP shear test device is essential to successful level 3 mix designs. This design level also uses a test for tertiary creep to screen out early in the design process those trial mixes that may be susceptible to catastrophic

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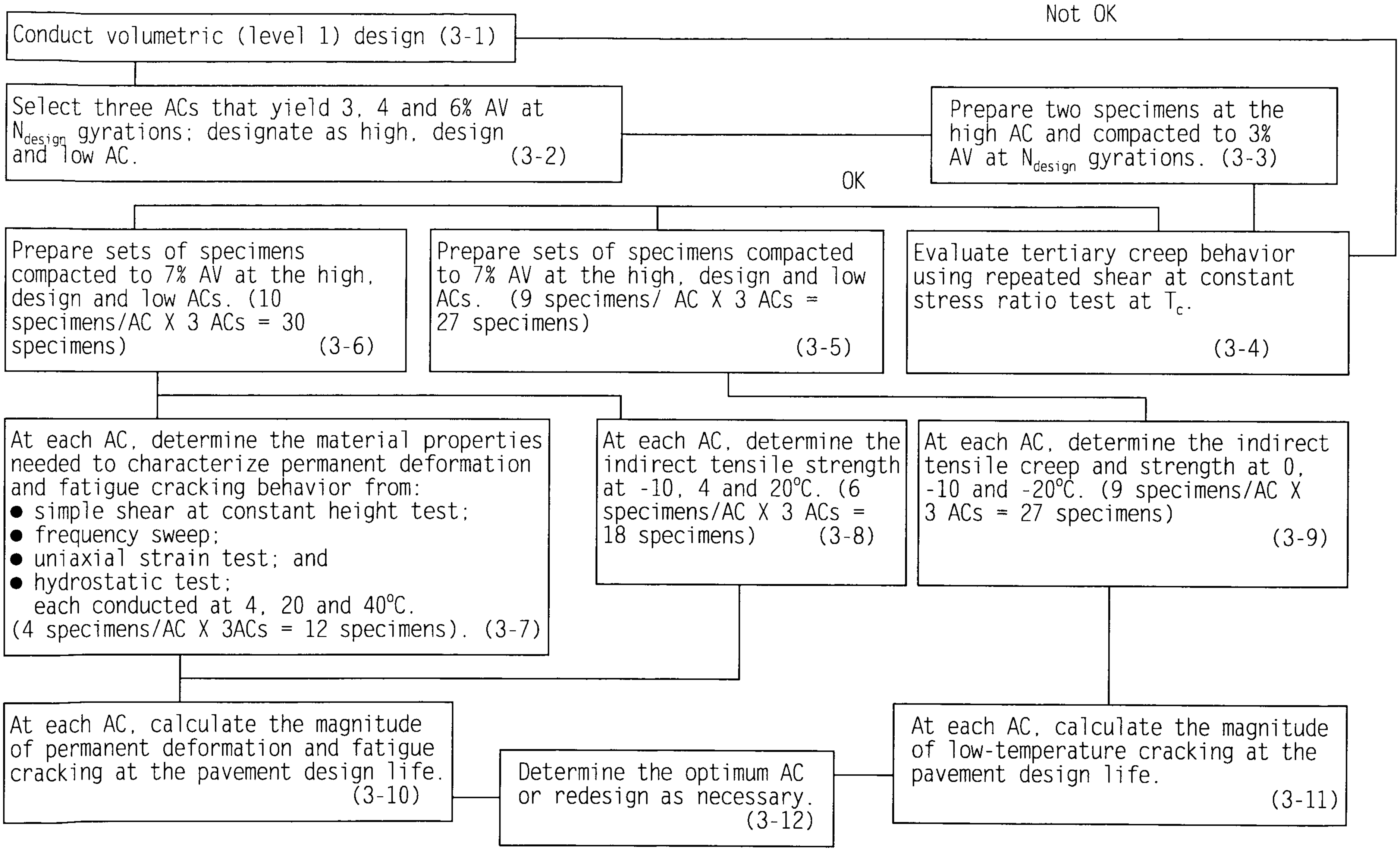
[2] It is anticipated that the test for tertiary creep will not be needed if the compactibility of the mix conforms to the Superpave guidelines.

Figure 1.4. Superpave Level 3
(Note: All specimens are compacted from paving mix that has been short-term aged (SHRP M-007))



rutting failures or unacceptable long-term permanent deformation. In addition, this design level explicitly considers the effects of moisture sensitivity and aging in selecting the final mix design.

The level 3 mix design also provides a battery of optional proof tests recommended to confirm the results of the performance-based tests for paving projects where the reliability of the mix design must be unquestioned.

1.3 The Superpave Performance-Based Test Methods for Paving Mixes

The Superpave mix design system uses a compaction method that simulates field compaction, field-validated conditioning procedures, and, in levels 2 and 3, a set of performance-based test methods for paving mixes. These allow the development of trial mix designs and the characterization of their engineering capabilities through the measurement of fundamental material properties. These methods and procedures, and the equipment required for each, are presented in table 1.2.

Table 1.2. Superpave Mix Design Tests and Equipment

Method or Procedure	Test Equipment	Relevant SHRP or Other Test Designation
Gyratory compaction	SHRP gyratory compactor	M-002
Moisture sensitivity	Testing machine per AASHTO T 167 *or* environmental conditioning system	AASHTO T 283 *or* M-006
Short and long-term aging	Forced draft oven	M-007
Frequency sweep at constant height	Shear test device	M-003, P-005
Simple shear at constant height	Shear test device	M-003, P-005
Uniaxial strain	Shear test device	M-003, P-005
Volumetric (hydrostatic)	Shear test device	M-003, P-005
Repeated shear at constant stress ratio	Shear test device	M-003, P-005
Repeated shear at constant height (optional)	Shear test device	M-003, P-005
Indirect tensile creep	Indirect tensile test device	M-005
Indirect tensile strength	Indirect tensile test device	M-005

1.3.1 Laboratory Compaction

The SHRP gyratory compactor is an effective tool to simulate the field compaction process and to ensure that engineering properties of laboratory compacted specimens are equivalent to those of the in-place paving mix. This unit is capable of central laboratory and field control operations. It permits real-time determination of specific gravity and air voids content during compaction; this capability is required for the volumetric (level 1) mix design discussed in chapter 3. The gyratory compactor produces a cylindrical, 150 mm diameter test specimen of paving mix through a combination of vertical consolidation pressure and gyratory kneading effort. It is capable of producing specimens up to 150 mm in height. The paving mix is prepared in the laboratory or at a plant site and brought to the proper compaction temperature. The loose mix is placed into a heated mold, and a vertical pressure of 0.6 MPa is applied by means of a vertical ram. The mold is set for a 1.25°+ 0.02 angle of rotation, and the specimen is compacted at 30 revolutions per minute to a predetermined number of gyrations based on anticipated traffic or other factors. At completion, the mold is removed and the test specimen is extruded immediately.

NOTE: Agencies already owning another gyratory compactor such as a gyratory testing machine (GTM) meeting the requirements of ASTM D 3387 may use it to produce compacted specimens in lieu of the SHRP gyratory compactor. **The GTM model (or any other gyratory compactor) must be capable of: 1) maintaining a fixed angle of gyration equal to 1.25°± 0.02; 2) operating at a speed of gyration of 30.0 rpm; 3) applying a constant ram pressure of 0.60 MPa; and 4) producing 150 mm-diameter specimens.**

1.3.2 Test Procedures for Moisture Sensitivity

Either AASHTO T 283, *Resistance of Compacted Bituminous Mixture to Moisture Induced Damage,* or SHRP Method of Test M-006, *Determining the Moisture Susceptibility of Modified and Unmodified Hot Mix Asphalt with the Environmental Conditioning System,* is used in the Superpave mix design system to evaluate the moisture sensitivity of trial mix designs.

Use of SHRP method M-006 requires an environmental conditioning system[3]. This is a modified triaxial test unit in which the dynamic resilient modulus of a cylindrical or prismatic mixture specimen can be continually measured as moisture is forced through it. Moisture susceptibility is characterized by the resilient modulus ratio of conditioned to unconditioned specimens.

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[3] Developed under SHRP contract A-003A.

1.3.3 Conditioning Procedure for Aging

Principal control on aging in the Superpave mix design system is through the combined use of the rolling thin film oven test and the pressure aging vessel to measure the long-term propensity of the asphalt binder to aging. Since laboratory mixtures are made with unaged asphalt binders, the conditioning procedure for paving mixes must mimic both plant and pavement aging in these laboratory mixtures.

In the short-term aging procedure for paving mixes, loose mix is placed in a tray (immediately after mixing) to a uniform depth. The mix is held in a forced draft oven for 4 hours at 135°C, after which the mix is brought to the appropriate compaction temperature and the specimen compacted. This procedure simulates the aging that takes place during HMA production and the pavement construction process.

In the optional long-term aging procedure for paving mixes, compacted specimens are placed (prepared from loose mix which has undergone short-term aging) in a forced draft oven at 85°C. The time of exposure in the oven varies depending on the length of pavement service that is simulated. The recommended exposure time is 2 days which is equivalent to about 10 years of pavement service. Longer periods can be utilized at the designer's discretion.

1.3.4 Performance Testing with the Shear Test Device

The ability of a paving mix to resist permanent deformation and fatigue cracking is estimated through the use of the shear test device. The series of tests listed in table 1.2 provides the material properties that are used in the Superpave pavement performance prediction models. The development over time of permanent deformation and fatigue cracking is predicted for the trial mix design in a particular pavement under specific traffic and environmental conditions.

The shear test device simulates the comparatively high shear stresses that exist near the pavement surface at the edges of vehicle tires; these stresses lead to lateral and vertical deformation. The shear test device has the ability to apply vertical and horizontal loads simultaneously to the specimen in order to simulate both the compression and shear forces applied to the pavement by loaded tires.

The primary components of the test device are a load frame, vertical and horizontal actuators, environmental and confining pressure control systems, and a computer-controlled test operation and data acquisition system.

The nonlinear viscous and elastic material behavior of the paving mix are measured through a series of distinct tests conducted with the shear test device. These tests capture critical aspects of this material behavior: dilatancy in shear; stiffening with increased confining stress; and temperature and rate dependence. In addition, the accumulation of permanent strain in the specimen under repetitive shear stress is determined. A brief description of each shear test follows. The actual material properties determined from these test results are discussed in chapter 6.

1.3.4.1 Nonlinear Elastic Behavior

Three tests are required to describe the nonlinear elastic response of the paving mix.

- Simple Shear at Constant Height Test: A specimen (typically 150 mm in diameter and 65 mm in height) is maintained at constant height while a shear load is applied at 70 kPa/s. The load is applied very rapidly to ensure that only the elastic response is measured (i.e., virtually no creep occurs in the specimen) and yet slowly enough to avoid inertial effects. The shear stress causes a horizontal displacement, and the axial load is varied to maintain the specimen at constant height.

- Uniaxial Strain Test: A specimen encased in a rubber membrane is subjected to an axial load applied at a rate of 70 kPa/s. Confining pressure is controlled simultaneously by closed-loop feedback to maintain the specimen at constant circumference.

- Volumetric (or hydrostatic state of stress) Test: A specimen is completely surrounded by a rubber membrane. A radial LVDT is placed around the circumference of the specimen to monitor lateral deformation. A confining pressure is applied to all specimen surfaces at a rate of 70 kPas, and the change in its perimeter is recorded.

1.3.4.2 Viscoelastic Behavior

A single test determines the viscoelastic response of the paving mix.

- Frequency Sweep at Constant Height: This test employs a specimen and loading configuration identical to that of the Simple Shear at Constant Height test. A sinusoidal shear strain of 1×10^{-4} is applied at frequencies of 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, and 0.02 Hz. The vertical load on the specimen is continually varied to maintain the specimen at constant height. Analysis of the test data provides the phase angle (ϕ) and complex shear modulus (G^*) of the paving mix.

1.3.4.3 Tertiary Creep

A single test determines the accumulation of tertiary creep damage in shear at a state of stress similar to that induced in a pavement by application of a loaded tire.

- Repeated Shear at Constant Stress Ratio: The specimen is subjected to the application of a haversine shear pulse while the vertical load is continually adjusted to maintain it in constant proportion to the shear (horizontal) load. Typically, 20,000 load applications are applied. The linearity of the log-log relationship between the accumulated permanent strain and the number of load cycles is evaluated.

1.3.4.4 Rutting Potential (Optional)

A single test rapidly estimates the potential for rutting induced in a paving mix by the shearing action of loaded tires over the anticipated service life of the pavement. This optional test is described in Appendix A of SHRP Standard Practice P-005.

- Repeated Shear at Constant Height: The specimen is subjected to the application of a haversine shear pulse. The specimen height is kept constant through the action of a vertical (axial) load actuator, using as feedback the output of an LVDT that measures the relative displacement between end caps mounted on the specimen. Typically, the test is run for 5,000 load applications or until a shear strain of 5 percent is obtained. The number of ESALs necessary to induce a given rut depth is empirically estimated from the relationship between the log of the permanent shear strain and the log of the number of repetitive shear cycles.

1.3.4.5 Performance Testing with the Indirect Tensile Test Device

The ability of a paving mix to resist the development of fatigue cracking and low-temperature cracking is estimated through the use of the indirect tensile test device. The series of tests listed in table 1.2 provides the material properties that are used in the Superpave pavement performance prediction models. The development over time of fatigue cracking and low-temperature cracking is predicted for the trial mix design in a particular pavement under specific traffic and environmental conditions.

The indirect tensile test device consists of a testing machine, environmental chamber, and a control and data collection computer. (The capabilities of the testing machine are same as those presented in section 5.1 and Note 2 of ASTM Standard Test Method D 4123, *Indirect Tension Test for Resilient Modulus of Bituminous Mixtures*; this method and equipment is required for the Long-Term Pavement Performance program.)

Two test methods, described in the following sections, are conducted at low and intermediate temperatures with the indirect tensile test device in the Superpave mix design system. Analysis of the test results yields the stiffness master curve; the slope of the stiffness versus loading time relationship; and the tensile strength. The capability of the paving mix to resist the development over time of cracking through the application of load or temperature-induced stresses is estimated from these material properties.

- Indirect Tensile Creep Test: A 150 mm diameter specimen is subjected to a diametral preconditioning load to obtain uniform deformation. A fixed static load is then applied for 1000 s, while maintaining constant temperature. The horizontal and vertical deformations are monitored during the entire loading period across a gage length of one-quarter of the specimen diameter.

- Indirect Tensile Strength Test: A compressive load is applied along the diametral axis of 150 mm diameter specimen at a controlled vertical deformation rate until failure occurs.

1.4 Interaction with the Superpave Software

The Superpave specification, mix design, and support software are integrated in the Superpave program. When used in conjunction with this manual, the Superpave software guides the mix design process from beginning to end. It provides an orderly, self-contained means for recording all test data and analysis results, performance prediction, and other record keeping required for a complete mix design at levels 1, 2, or 3. The need for manual computations is eliminated at every stage of the laboratory mix design and during field control operations. The flow of the Superpave software mirrors that of the mix design system shown in figure 1.1.

At the conclusion of the design, an individual computer file is produced for the archives containing all essential information about the project design, from the initial selection of materials to field control during HMA production and pavement construction.

Figure 1.5 shows the general structure of the Superpave software in schematic form. The program core[4] contains

- the SHRP performance-based asphalt binder specification and the algorithms and weather databases required to choose an appropriate binder performance grade for the project;

- material databases of pertinent test results on asphalt binders and aggregates;

- the algorithms required to conduct the volumetric (level 1) mix design; and

- direction and control routines necessary for the orderly transfer of data from computer files generated by test equipment, through algorithms for the analysis of materials properties, to the performance prediction models.

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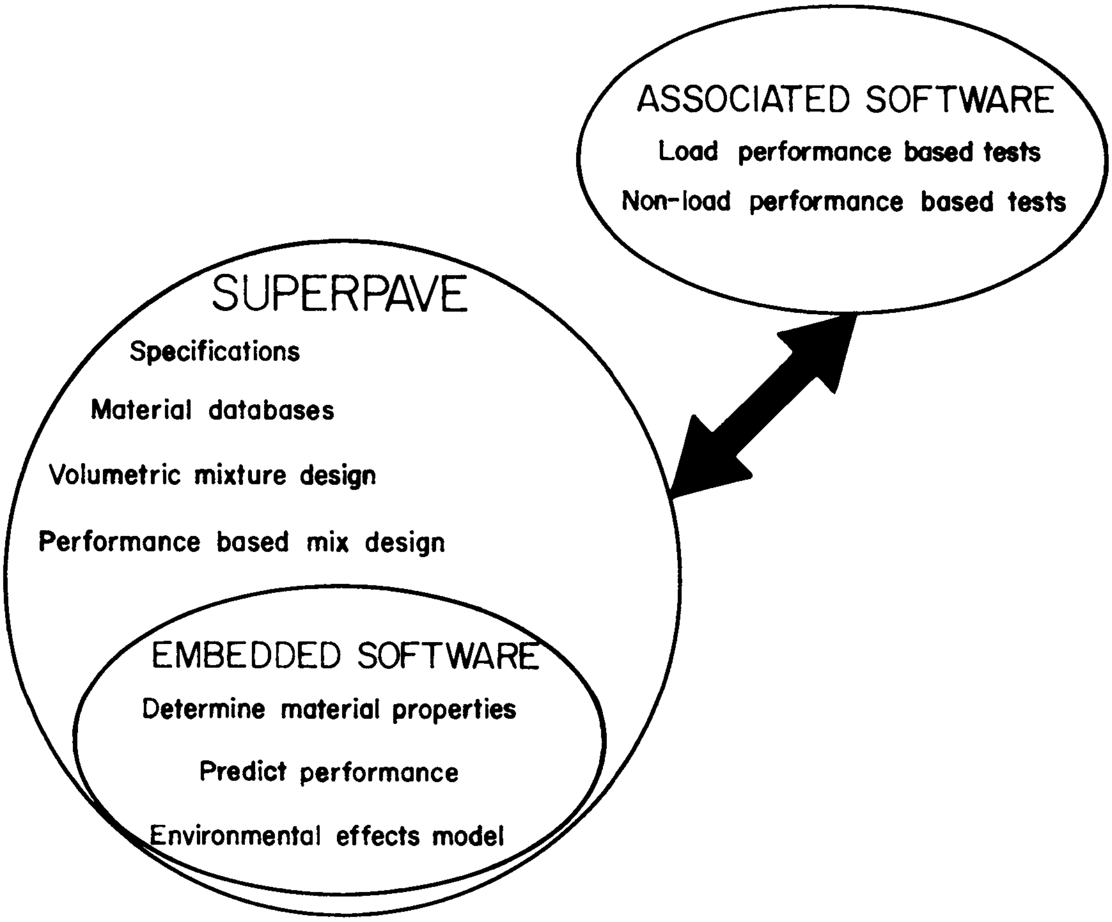
[4] Developed under SHRP contract A-001.

Figure 1.5. Structure of the Superpave Specification, Mix Design and Support Program



Several complete, self-contained programs are embedded in the Superpave software and accessed automatically by its direction and control routines:

- algorithms[5] that calculate fundamental material properties, used in performance prediction models, from the results of the load-related and nonload-related performance tests described in section 1.3;
- performance prediction models[6] that estimate the development of permanent deformation, fatigue cracking, and low-temperature cracking over the life of the pavement from the material properties of the paving mix and environmental, structural, and traffic loading factors; and
- a version of the Federal Highway Administration's Environmental Effects Model, tailored for use with the Superpave software, that generates pavement temperature files used by the performance prediction models.

Finally, there are several programs that are associated with the Superpave software but are not part of it. These programs control the operation of the load-related and nonload-related performance tests, conduct preliminary analyses of the test data, and store the data in computer files directly readable by the Superpave software.

A significant part of the Superpave software is devoted to user-defined databases of information on asphalt binders, aggregates, mix designs, construction history (field control), and environment (weather). Another portion deals with specifications for asphalt binders and aggregates. A typical user has read-only access to the specifications and environmental databases; however, these files may be changed at the agency or consensus level.

A complete description of the Superpave software and instructions for its use are contained in *The User's Manual for Superpave System Software.*

1.5 Use of Modified Materials

Modified asphalt binders will be needed to supply the required levels of binder performance at extreme temperature or traffic conditions. The use of modified paving mixes, containing fibers or hydrated lime for example, may be warranted for certain stringent conditions of pavement service.

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[5] Developed under SHRP contract A-005.

[6] Developed under SHRP contract A-005.

In general, the Superpave mix design system does not require special tests to judge the effect of modified materials. Specifications and test methods, because they are performance-based, are identical for unmodified and modified materials and paving mixes. The only exception is in evaluating the fatigue-cracking behavior of paving mixes (see chapters 4 and 5 of this manual). At present, the test method used to characterize fatigue-cracking behavior, a frequency sweep with the SHRP shear test device, is directly applicable only to unmodified HMA.

When preventing or reducing fatigue cracking is the principal goal of the use of a modified paving mix, flexural beam fatigue tests (chapter 5) must be directly employed to estimate the change in fatigue behavior compared to an unmodified paving mix.

SHRP Standard Practice P-001 (AASHTO Standard Practice PP5), *Laboratory Evaluation of Modified Systems*, provides a means to quantify the increased performance capabilities of modified binders and mixes or to guide the selection of appropriate modifiers to achieve specific performance levels.

1.6 Multilayer Designs in the Superpave System

The Superpave system and software provides a complete design and analysis system for projects with multiple new layers, such as constructing a base, binder, and surface course on a project. The Superpave material specifications account directly for differences arising from the position of the layer in the pavement structure. For example, the Superpave system will consider the variation in temperature at different depths of pavement, which may allow selection of a different binder grade in the base course than in the surface course.

The Superpave software is capable of sequentially accessing and carrying out analyses with external performance test data from as many as two distinct mix designs, each with as many as three trial asphalt contents. As discussed in section 1.7, the material properties from each layer can be combined to obtain an estimate over time of the pavement performance for the multilayer design.

In addition, the Superpave software provides the capability to use default design values for the moduli of existing, underlying layers (including asphalt concrete and portland cement concrete, granular bases, and subgrade) when calculating pavement performance estimates for a new mix design. The input data include the type, classification and thickness of up to eight layers, in addition to the new asphalt layer for which the Superpave mix design is carried out.

1.7 Ground Rules for Use of the Superpave Mix Design System

The Superpave mix design system has certain ground rules which the user must know in advance and keep in mind while producing designs.

1.7.1 Accounting for the Effects of Moisture Sensitivity

In itself, moisture sensitivity (or damage) is not a pavement distress mechanism, but it does lead to or accelerate the occurrence of distress mechanisms such as raveling, cracking, or rutting. Moisture sensitivity may be considered in a performance-based mix design system in two ways.

In one approach, the moisture sensitivity of a trial mix design is tested directly, and the test result is compared to a pass/fail criterion. If the trial mix design fails, remedial action, such as introducing an antistrip agent or completely redesigning the mix, is necessary.

In the second approach, the effect of moisture conditioning on the estimated pavement performance of the trial mix design is determined. Testing and analysis of both dry and conditioned specimens will provide an appraisal of the performance penalty expected from accelerated distress development due to pavement moisture.

The Superpave mix design system employs the first approach. The moisture sensitivity of a trial mix design is assessed by use of AASHTO Standard Method of Test T 283, *Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*, or SHRP Standard Method of Test M-006, *Determining the Moisture Susceptibility of Modified and Unmodified Hot Mix Asphalt with the Environmental Conditioning System*, and compared to a pass/fail criterion.

If the trial mix design fails the moisture sensitivity test, remedial action is required before proceeding with the remainder of the mix design process. The performance characteristics of a trial mix design that passes the moisture sensitivity test are evaluated without further moisture conditioning.

Superpave Ground Rule for Moisture Sensitivity Moisture-sensitive mix designs are screened out or remedied. The performance characteristics of the mix design are then evaluated on the premise that moisture damage will not contribute to the long-term development of pavement distress.

1.7.2 Accounting for the Effects of Aging

Like moisture sensitivity, aging of the asphalt binder is not a pavement distress mechanism, but it does affect the rate of those mechanisms, particularly of low- temperature cracking, fatigue cracking, and permanent deformation. Aging is accounted for in the Superpave system through both pass/fail tests and conditioning procedures.

The asphalt binder must satisfy a pass/fail mass loss requirement in the rolling thin film oven test (AASHTO Standard Method of Test T 240, *Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin Film Oven Test)*). This test is intended to simulate the effect of hot mix production on the asphalt binder. The asphalt binder residue conditioned in the rolling thin film oven test and in the pressure aging vessel must satisfy specific rheological requirements related to pavement performance. These requirements assess the behavior of the asphalt binder at the time of pavement construction and after long-term (5 years or more) exposure in the pavement.

Compacted specimens used in a Superpave mix design are prepared from loose mix that has been conditioned in a forced draft oven to simulate the HMA production process and several years of pavement service. Therefore, all estimates of pavement performance obtained in a level 2 or level 3 Superpave mix design are calculated from material properties similar to those found in an in-service pavement.

The Superpave system also provides an optional conditioning procedure that simulates about 10 years of pavement service through the long-term oven aging of compacted specimens. Use of this procedure permits an estimate of the effects of long-term pavement service on predicted pavement performance, particularly the development of fatigue cracking and low-temperature cracking.

Superpave Ground Rule for Aging The aging of pavements in service is simulated for both the asphalt binder and the paving mix and is directly accounted for when the performance characteristics of the mix design are estimated.

1.7.3 Superpave Mix Designs for New Construction

In order to facilitate the interaction between the Superpave mix design system and the Superpave software, specific ground rules govern the treatment of the three pavement distresses, permanent deformation, fatigue cracking, and low-temperature cracking, in level 2 or level 3 mix designs for new construction.

For permanent deformation, a distinct mix design can be performed for each HMA layer, and the Superpave software can use the computed performance characteristics of up to two new layers to estimate the expected pavement performance over time. For projects with three or more new HMA layers, selected layers must be combined in order for the software to estimate pavement performance.

For fatigue cracking, the mixture characterization is performed for the lowest layer only. For projects where several new HMA layers, each with a distinct mix design, are being placed, the material properties of the mix design used in the layer that is placed within the bottom one-quarter of the overall HMA thickness are used in calculating the predicted fatigue cracking over time. However, the layer thickness is assumed to be the combined thickness of all the new HMA layers, and the material properties are those associated with the material in the bottom one-quarter of the total layer thickness.

For low-temperature cracking, only the uppermost layer is evaluated. For projects where several new HMA layers, each with a distinct mix design, are being placed, the material properties of the structural layer that is closest to the pavement surface are used in calculating predicted low-temperature cracking over time. As with fatigue cracking, the layer thickness is the combined thickness of all new HMA layers.

Superpave Ground Rule for New Construction: In predicting pavement performance for multilayer, new construction projects, the Superpave system can accommodate the measured material properties of mix designs for the following number of layers:

- Permanent deformation-up to two layers.
- Fatigue cracking-one layer within the bottom one-quarter of the new construction.
- Low-temperature cracking-one structural layer nearest the pavement surface.

1.7.4 Superpave Mix Designs for HMA Overlays

In order to facilitate the interaction between the Superpave mix design system and the Superpave software, specific ground rules govern the treatment of the three pavement distresses, permanent deformation, fatigue cracking, and low-temperature cracking, in level 2 or level 3 mix designs for HMA overlays over existing HMA or portland cement concrete pavements.

For permanent deformation, a distinct mix design can be performed for each HMA layer, and the Superpave software can use the computed performance characteristics of up to two new layers can to estimate the expected pavement performance over time. For projects with three or more new HMA layers, selected layers must be combined in order for the software to estimate pavement performance. Thus, the treatment of HMA mix designs for permanent deformation is the same, regardless of whether the mix is intended for new construction or for an overlay over an existing flexible or rigid pavement.

For fatigue cracking, no testing or pavement performance prediction is performed, since mixture fatigue properties of the existing HMA or PCC are not known. Generally, fatigue cracking is not a predominant form of distress in HMA overlays.

For low-temperature cracking, no predictions are made due to the prevalence of reflection cracking.

Superpave Ground Rule for HMA Overlays on Existing HMA: The Superpave system level 2 and level 3 mix design methods are not recommended for the mix design of any HMA layer less than 50 mm in thickness.

In predicting pavement performance for multi-layer overlays on existing flexible or rigid pavements, the Superpave system can accommodate the measured material properties of mix designs for the following number of layers:
- Permanent deformation-up to two layers.
- Fatigue cracking-not evaluated.
- Low-temperature cracking-not evaluated.

1.7.5 Accounting for Reflection Cracking

By design, the Superpave system does not provide the capability to directly predict or control the occurrence of reflection cracking in HMA overlays on existing flexible or rigid pavements. This research area was specifically excluded from the scope of the SHRP asphalt research program during its planning stages[7].

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[7] See Strategic Highway Research Program Research Plans, Transportation Research Board, Washington DC, 1986, page A-13.

Superpave Ground Rule for Reflection Cracking: The Superpave mix design system is not directly applicable to the prediction or control of reflection cracking in HMA overlays over existing flexible or rigid pavements.

1.7.6 Units of Measurement in the Superpave System

The current trend in the United States is toward adopting the metric system of units in the fields of manufacturing, engineering, and science. Accordingly, the Superpave system uses units presented in the International or SI System of Units (see ASTM Standard for Metric Practice E 380) wherever possible.

Superpave Ground Rule for Units of Measurement: The Superpave mix design system uses the SI system of units wherever possible.

1.7.7 Pavement Structural Factors in Superpave

Both level 2 and level 3 Superpave mix designs employ pavement structural factors, specifically layer thicknesses and moduli, in the computation of predicted distresses. Consequently, the better the quality of the structural data, the more reliable the final decision on the optimum mix design. If little or no information is available on the underlying pavement structure, the benefit of using Superpave techniques may be diminished.

Superpave Ground Rule for Pavement Structural Factors: The better the structural information, the more benefit is derived from the use of the Superpave mix design method.

2

Selecting Mixture Materials

The first, critical step in the Superpave mix design process is selecting materials suited to the demands of traffic and environment expected over time at the paving project.

This chapter presents guidelines and requirements for selecting aggregate, asphalt binder, and modifier on the basis of specific pavement performance criteria related to

- the environment (climate);
- the anticipated traffic volume over the service life of the pavement; and
- the pavement structure.

It also presents a method for determining the chemical compatibility of the asphalt binder and aggregate in the presence of moisture.

A mix design must balance the fulfillment of performance requirements against the cost and availability of materials. The Superpave system simplifies this balancing process by providing objective performance criteria that are used to directly assess the potential benefits or penalties of the use of one material compared to another and decide on the most cost-effective combination of materials that satisfies the project specifications.

2.1 Aggregate

The procedures in this section correspond with blocks (1-1) and (1-3) in figure 1-2, the flow chart for level 1 mix designs.

The Superpave mix design system contains specific performance-related characteristics (sections 2.1.1 through 2.1.9) to assist in selecting acceptable aggregate materials and developing a satisfactory aggregate blend for a given situation. Aggregate characteristics are specified as either agency standards or consensus standards. Except as noted in section 2.1.1, the aggregate criteria in this section apply to materials intended for dense graded paving mixes as well as special purpose paving mixes such as stone matrix asphalt (SMA).

The Superpave mix design system accommodates coarse aggregate up to a maximum size (see definition in section 2.1.1) of 50.0 mm. Table 2.1 presents recommended maximum aggregate sizes for the design of paving mixes for base, binder, and surface courses. This table provides guidelines for situations where the maximum size is not already dictated by existing agency policy.

The SUPERPAVE™ system provides three levels of mix design. This permits the development of designs that will meet the demands of progressively higher levels of traffic, environmental severity and reliability. Materials selection criteria are recommended as either guidelines or requirements, depending upon the level of mix design being employed. A *guideline* is defined as a specified value which is provided as design guidance, but to which conformance is not mandatory. A *requirement* is a specified value which the material must meet.

Table 2.1. Suggested Maximum Aggregate Sizes

Pavement Layer	Nominal Maximum Aggregate Size
Surface	9.5 - 12.5mm
Binder	25.0 - 37.5mm
Base	25 - 37.5 mm

Any sound, clean aggregate of local origin that meets these criteria may be chosen as a candidate material in the Superpave mix design system. There are no requirements for geologic type or composition other than the need to meet the optional asphalt binder compatibility guideline in section 2.2.3 and the moisture sensitivity requirements for mixtures presented in chapters 3, 4, and 5. If aggregates that meet the project requirements are unavailable locally, the cost of importing suitable materials must be carefully weighed against the penalties in long-term performance that will arise from the use of substandard materials.

Techniques for gradation analysis and for the proportioning of two or more aggregates to meet specific blended gradation requirements are beyond the scope of this manual. Appendix A, "Gradation Analysis of Aggregates", of Asphalt Institute Manual MS-2, *Mix Design Methods for Asphalt Concrete*, 1994 edition, gives complete, detailed instructions on these topics.

The following rules apply generally to aggregate gradation analysis and the development of aggregate blends in the Superpave mix design system:

- Washed sieve analysis of all fractions, including filler, must be conducted in order to ensure maximum accuracy in proportioning.
- The gradation of an aggregate or aggregate blend is specified on the basis of the total aggregate gradation, that is, on the total percent by weight passing the designated sieve sizes.
- Following the conventions stated in Asphalt Institute Manual MS-2, the individual fractions of the total aggregate gradation are designated as shown in table 2.2.

Table 2.2. Definition of Aggregate Fractions

Coarse aggregate	Retained on the 2.36 mm sieve
Fine aggregate	Passing the 2.36 mm sieve
Mineral filler	Passing the 75 µm sieve

When aggregate materials are designated by the terms *rock*, *sand*, and *filler*, these terms are generally defined as shown in table 2.3:

Table 2.3. Definition of Aggregate Types

Rock	Predominately coarse aggregate (retained on the 2.36 mm sieve)
Sand	Predominately fine aggregate (passing the 2.36 mm sieve)
Filler	Predominately mineral dust (passing the 75 µm sieve)

2.1.1 Gradation Control

The Superpave mix design system guides selection of an acceptable aggregate gradation for a dense graded paving mix by means of control points and a restricted zone. The control points and restricted zone are graphed on the Federal Highway Administration grading chart on which the percentage of aggregate passing a sieve size is plotted against the sieve opening size raised to the 0.45 power (figure 2.1). The ASTM sieves specified for the SUPERPAVE system are presented in table 2.4.

Figure 2.1. Federal Highway Administration 0.45 Aggregate Grading Chart

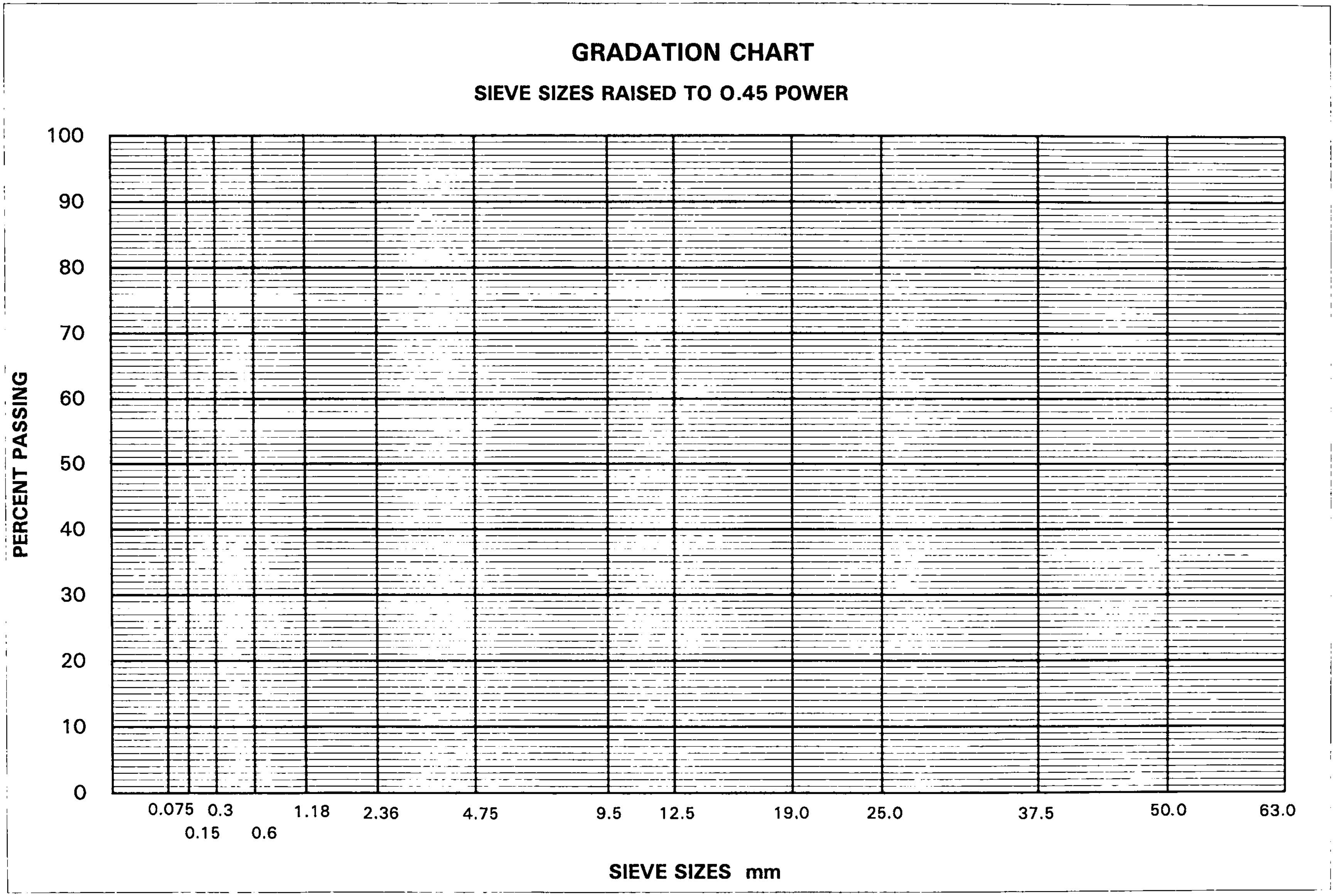
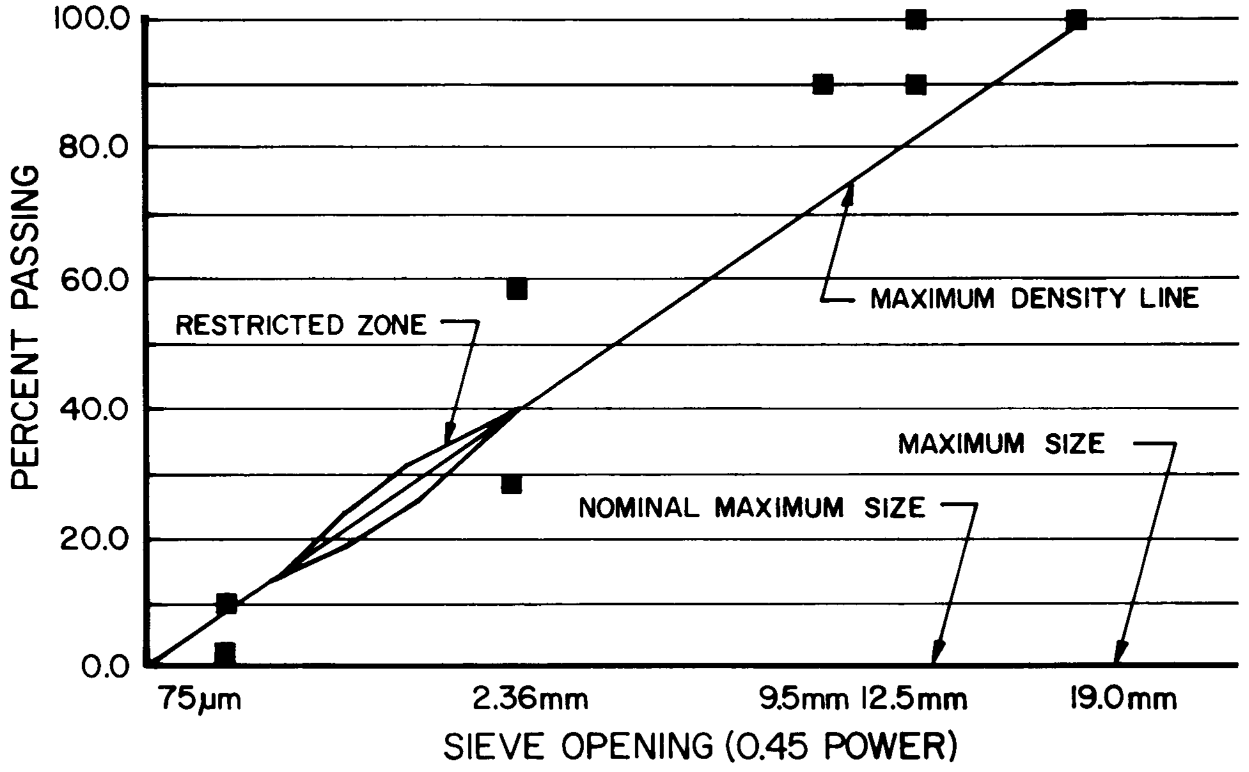


Figure 2.2. Superpave Gradation Control Points and Restricted Zone for a 12.5 mm Nominal Maximum Size Aggregate Gradation



A typical example of gradation control is shown in figure 2.2 for a 12.5 mm nominal maximum aggregate size. This figure illustrates the following definitions:

- Nominal maximum size: one sieve size larger than the first sieve to retain more than 10 percent of the aggregate.
- Maximum size: one sieve size larger than the nominal maximum size.
- Maximum density line: a line drawn from the origin of the 0.45 power chart to the point at which the maximum sieve size intersects the 100 percent passing line.
- Restricted zone: a zone lying on the maximum density line and extending from the 300 µm sieve to the 2.36 mm sieve through which it is usually undesirable for the gradation to pass. For 25 mm and 37.5 mm nominal maximum size gradations, the restricted zone extends to the 4.75 mm sieve.
- Control points: maximum and minimum limits established for each set of gradation controls.

Table 2.4 illustrates the limits to which the blended aggregate gradation must conform for a 12.5 mm nominal maximum size mixture.

Table 2.4. Aggregate Gradation Control Points

	Control Point (Percent Passing)	
Sieve Size	Minimum	Maximum
75 µm	2	10
2.36 mm	28	58
9.5mm	—	90
Nominal maximum (12.5 mm)	90	100
Maximum (19.0 mm)	100	—

Tables A.1 through A.6 in appendix A present the control points and restricted zones for gradations with nominal maximum sizes of 37.5 mm, 25.4 mm, 19.0 mm, 12.5 mm, and 9.5 mm.

Table 2.5 Common Sieves Sizes Used by State Highway Agencies

AASHTO Sieve Size and Designation	Approximate English Equivalent
63.0 mm	2½ in.
50.0 mm	2 in.
37.5 mm	1½ in.
25.0 mm	1 in.
19.0 mm	¾ in.
12.5 mm	½ in.
9.5 mm	⅜ in.
4.75 mm	#4
2.36 mm	#8
1.18 mm	#16
600 μm	#30
300 μm	#50
150 μm	#100
75 μm	#200

In general, it is recommended (but not required) that as the traffic level increases, the aggregate gradation move toward the minimum control points, below the restricted zone. Gradations that pass above or below the restricted zone, but within the relevant control points, should produce acceptable mixtures in the Superpave mix design system. No guideline or requirement is given for selecting the appropriate nominal maximum size. Specifying agencies may select or specify a nominal maximum size for surface, binder, and base course mixtures according to established policy, their past experience, or by reference to the suggested nominal maximum sizes in Table 2.1.

Gradation control requirements in this section do not apply to special-purpose paving mixes such as SMA or porous asphalt. Past experience and engineering judgment should be used to develop specific gradation controls for the design and field control of special-purpose paving mixes.

2.1.2 Coarse Aggregate Angularity

Coarse aggregate angularity is defined as the percent by weight of the aggregate particles larger than 4.75 mm with one or more fractured faces. *A fractured face* is defined as an angular, rough, or broken surface of an aggregate particle created by crushing, by other artificial means, or by nature. A face is considered fractured only if it has a projected area at least as large as one quarter of the maximum projected area (maximum cross-sectional area) of the particle and also has sharp and well-defined edges[1].

Coarse aggregate angularity is measured on the coarse particles of the blended aggregate (specifically those retained on the 4.75 mm sieve) by Pennsylvania [Department of Transportation] Test Method No. 621, *Determining the Percentage of Crushed Fragments in Gravel*[2]. The results of this test are used in the laboratory during the Superpave mix design process, as well as in field control to monitor aggregate production.

Coarse aggregate angularity criteria for increasing levels of total traffic in equivalent single axle loads (ESALs) over the planned or estimated service life of the pavement are presented in table 2.6. These are the requirements for level 1, 2, and 3 mix designs.

Table 2.6. Coarse Aggregate Angularity Criteria

	Depth From Surface	
Traffic (ESALs)	< 100 mm	> 100 mm
$<3x10^5$	55/-	-/-
$<1x10^6$	65/-	-/-
$<3x10^6$	75/-	50/-
$<1x10^7$	85/80	60/-
$<3x10^7$	95/90	80/75
$<1\times10^8$	100/100	95/90
$>1x10^8$	100/100	100/100

Note: "85/80" denotes that 85 percent of the coarse aggregate has one fractured face and 80 percent has two fractured faces.

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[1] To check this criterion, hold the aggregate particle so that the face is viewed directly. If the face constitutes at least 25 percent of the area of the outline of the aggregate particle visible at that orientation, it is considered a *fractured face*.

[2] See appendix C of this report. ASTM is currently developing a standard test method for coarse aggregate angularity. Pennsylvania DOT Method No. 621 is recommended for use until the ASTM method is adopted.

2.1.3 Fine Aggregate Angularity

Fine aggregate angularity is defined as the percent of air voids present in loosely compacted aggregate that passes the 2.36 mm sieve. Fine aggregate angularity is measured on the fine aggregate portion of the blended aggregate by AASHTO Standard Method of Test TP 33 (ASTM Standard Method of Test C1252), *Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)*. The results of this test are used in the laboratory during the Superpave mix design process, but not as a field control tool to monitor aggregate production.

Fine aggregate angularity criteria for increasing levels of total traffic in ESALs over the planned or estimated service life of the pavement are presented in the table 2.7. These are the requirements for level 1, 2, and 3 mix designs.

Table 2.7. Fine Aggregate Angularity Criteria

	Depth From Surface	
Traffic (ESALs)	< 100 mm	> 100 mm
$<3\times10^5$	—	—
$<1\times10^6$	40	—
$<3\times10^6$	40	40
$<3\times10^7$	45	40
$<1\times10^8$	45	45
$>1\times10^8$	45	45
Note: Criteria are presented as minimum percent air voids in loosely compacted fine aggregate.		

2.1.4 Toughness

Aggregate toughness is defined as the percent loss of materials from the blended aggregate during the Los Angeles Abrasion Test (AASHTO Standard Method of Test T 96, *Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine*). The results of this test are used in the laboratory during the Superpave mix design process and may be used as a source acceptance control for aggregate suppliers. No specific levels of aggregate toughness are required in the Superpave mix design method. Agencies should specify relevant guidelines or requirements in standards for their local situation.

2.1.5 Soundness

Aggregate soundness is defined as the percent degradation of the blended aggregate during the sodium or magnesium soundness test (AASHTO Standard Method of Test T 104, *Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate*). The results of this test are used in the laboratory during the Superpave mix design process and may be used as a source acceptance control for aggregate suppliers.

No specific levels of aggregate soundness are required in the Superpave mix design method. Agencies should specify relevant guidelines or requirements in agency standards for their local situation.

2.1.6. Deleterious Materials

Deleterious materials are defined as the percent by weight of undesirable contaminants, such as soft shale, coal, wood, or mica—in the blended aggregate. This is measured with AASHTO Standard Method of Test T 112, *Clay Lumps and Friable Particles in Aggregate*. The results of this test are used in the laboratory during the Superpave mix design process and may be used as a source acceptance control for aggregate suppliers. No specific levels for deleterious materials are required in the Superpave mix design method. Agencies should specify relevant guidelines or requirements in standards for their local situation.

2.1.7. Clay Content

Clay content is a measure of the amount of clay material present in the portion of aggregate that passes the 4.75 mm sieve. Clay content is measured on the portion of the blended aggregate passing the 4.75 mm sieve by means of the sand equivalent test (AASHTO Standard Method of Test T 176, *Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test*). The results of this test are used in the laboratory during the Superpave mix design process, as well as in field control to monitor aggregate production.

The sand equivalent (SE) of the aggregate fraction is defined in AASHTO T 176 by the equation

$$SE = \frac{SR}{CR} \times 100$$

where SR = the sand reading from AASHTO T 176; and
CR = the clay reading from AASHTO T 176.

Therefore, larger values of SE are indicative of lower clay contents in the aggregate.

Clay content criteria for increasing levels of total traffic in ESALs over the planned or estimated service life of the pavement are presented in table 2.8. These are requirements for level 1, 2, and 3 mix designs.

Table 2.8. Clay Content Criteria

Traffic (ESALs)	Sand Equivalent
$<3\times10^6$	40
$<3\times10^7$	45
$\geq3\times10^7$	50

2.1.8 Thin, Elongated Particles

The term *thin, elongated particle*s denotes the coarse aggregate particles which have a ratio of maximum to minimum dimensions greater than five (5).

The percentage of thin, elongated particles is measured on the portion of the blended aggregate retained on the 4.75 mm sieve by ASTM Standard Method of Test D 4791, *Flat or Elongated Particles in Coarse Aggregate*. The results of this test are used in the laboratory during the Superpave mix design process and may be used as a source acceptance control for aggregate suppliers.

Maximum criteria for thin, elongated particles for increasing levels of total traffic in ESALs over the planned or estimated service life of the pavement are presented in table 2.9. These are requirements for level 1, 2, and 3 mix designs.

Table 2.9. Criteria For Thin, Elongated Particles

Traffic (ESALs)	Maximum Weight Percent of Thin, Elongated Particles
$\geq1\times10^6$	10

2.1.9. Dust Proportion

Dust proportion is defined as the ratio of the percent by weight of aggregate passing the 75 µm sieve to the effective asphalt binder content expressed as percent by weight of the total mix. Thus, the asphalt binder content does not include the asphalt binder absorbed by the aggregate. Dust proportion is calculated and checked during the volumetric (level 1) mix design as a measure of mix acceptability. Criteria for dust proportion for all traffic levels over the planned or estimated service life of the pavement are presented in table 2.10. These are suggested for level 1, 2 and 3 designs for dense graded paving mixes. It should be noted, however, that these suggested limits are very dependent on the size and specific gravity of the dust. Dust smaller than 20 to 30 μm may act as an extender of the binder rather than a filler. Fillers with low specific gravities will represent a greater volume of dust.

Table 2.10. Criteria For Dust Proportion

Traffic (ESALs)	Dust Proportion
All levels	0.6 - 1.2

2.2 Asphalt Binders

The performance-based specification for asphalt binders within the Superpave system is designed to quantify and maximize the performance of the binder in reducing the occurrence of permanent deformation, fatigue cracking, and low-temperature cracking.

2.2.1 General Treatment of the Asphalt Binder in the Superpave System

The choice of asphalt binder grade alone will not eliminate permanent deformation which is strongly dependent upon the aggregate properties and the volumetric properties of the as-constructed paving mix, or fatigue cracking which is also highly dependent upon pavement structure. However, selecting the proper grade asphalt binder essentially eliminate low-temperature cracking. The Superpave mix design system facilitates selecting asphalt binders that provide different levels of protection or reliability.

The performance grade of an asphalt binder (PG x-y) is verified in accordance with AASHTO Standard Practice PP6, *Practice for Grading or Verifying the Performance Grade of an Asphalt Binder*. The following is a summary of the verification procedure:

(1) Determine the flash point of the asphalt binder in accordance with AASHTO T 48. Report the flash point temperature (C°).

(2) Test the binder with a rotational viscometer in accordance with ASTM D 4402 at 135°C. Report the viscosity.

(3) Test the asphalt binder in accordance with AASHTO TP5 at T_{max} (generally 45°C to 75°C). Determine $G^*/\sin\delta$. (T_{max} is determined from the average 7-day maximum pavement design temperature; see AASHTO specification MP1. G^* is the complex shear modulus; δ is the phase angle).

(4) Test the asphalt binder in accordance with AASHTO TP1. At 1 and 24 hours, determine the creep stiffness and the slope of creep stiffness versus time relationship at T_{min} + 10°C

(generally -36°C to 0°C). Calculate and report the physical hardening index, h. (T_{min} is determined from the minimum pavement design temperature; see AASHTO specification MP1).

(5) Age the asphalt binder in the rolling thin film oven test (RTFOT) (AASHTO T 240). Report the percent mass loss.

(6) Test the RTFOT residue of the asphalt binder in accordance with AASHTO TP5 at T_{max} (generally 45°C to 75°C). Determine $G^*/\sin \delta$.

(7) Age the RTFOT residue in the pressure aging vessel (PAV) (AASHTO PP1).

(8) Test the RTFOT-PAV residue of the asphalt binder in accordance with AASHTO TP1. Determine the creep stiffness and the slope of creep stiffness versus time relationship at T_{min} + 10°C (generally -36°C to 0°C).

(9) Test the RTFOT-PAV residue of the asphalt binder in accordance with AASHTO TP5 at T_{avg} (generally 7°C to 34°C). Determine $G^* \sin \delta$. (T_{avg} is a function of T_{max} and T_{min}; see AASHTO specification MP1.)

(10) If necessary, test the RTFOT-PAV residue in accordance with AASHTO TP3 at T_{min} + 10°C (-36°C to 0°C). Determine the failure strain.

(11) Compare all test results with the specification requirements for the performance grade, PG T_{max} - T_{min}.

The Superpave asphalt binder specification (figure 2.3a and b) is stored in the Superpave software for use as a look-up table to categorize asphalt binders according to test results in SHRP Practice P-002. Additional grades can be added as needed. Test results are entered into the software, and can be checked for conformance with the required specification limits. During the mix design, the specification is used as a look-up table to determine the grade of asphalt binder required for a specific project. This is based upon the selection of high and low design pavement temperatures for the project (section 2.2.2), and consideration of traffic.

2.2.2 Selecting an Asphalt Binder Performance Grade Based Upon High and Low Pavement Design Temperatures and Traffic Level

The procedures in this section correspond with block (1-2) in figure 1.2, the flow chart for a level 1 mix design.

Figure 2.3a Performance Graded Asphalt Binder Specification (AASHTO MPI)

PERFORMANCE GRADE	PG 46-			PG 52-							PG 58-					PG 64-					
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Average 7-day Maximum Pavement Design Temperature, °C[a]	<46			<52							<58					<64					
Minimum Pavement Design Temperature, °C[a]	>-34	>-40	>-46	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
ORIGINAL BINDER																					
Flash Point Temp, T48: Minimum °C	230																				
Viscosity, ASTM D4402:[b] Maximum, 3 Pa•s, Test Temp, °C	135																				
Dynamic Shear, TP5:[c] $G^*/\sin\delta$, Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
ROLLING THIN FILM OVEN																					
Mass Loss, Maximum, percent	1.00																				
Dynamic Shear, TP5: $G^*/\sin\delta$, Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
PRESSURE AGING VESSEL RESIDUE (PP1)																					
PAV Aging Temperature, °C[d]	90			90							100					100					
Dynamic Shear, TP5: $G^*\sin\delta$, Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Physical Hardening[e]	Report																				
Creep Stiffness, TP1:[f] S, Maximum, 300 MPa, *m* - value, Minimum, 0.300 Test Temp @ 60s, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
Direct Tension, TP3:[f] Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

[a] Pavement temperatures are estimated from air temperatures using an algorithm contained in the Superpave software program, may be provided by the specifying agency, or by following the procedures as outlined in PPX.

[b] This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.

[c] For quality control of unmodified asphalt cement production, measurement of the viscosity of the original asphalt cement may be substituted for dynamic shear measurements of $G^*/\sin\delta$ at test temperatures where the asphalt is a Newtonian fluid. Any suitable standard means of viscosity measurement may be used, including capillary or rotational viscometry (AASHTO T201 or T202).

[d] The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures 90°C, 100°C or 110°C. The PAV aging temperature is 100°C for PG 58- and above, except in desert climates, where it is 110°C.

[e] Physical Hardening — TP1 is performed on a set of asphalt beams according to Section 13.1, except the conditioning time is extended to 24 hrs ± 10 minutes at 10°C above the minimum performance temperature. The 24-hour stiffness and *m*-value are reported for information purposes only.

[f] If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness is between 300 and 600 MPa the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement. The *m*-value requirement must be satisfied in both cases.

Figure 2.3b Performance Graded Asphalt Binder Specification (AASHTO MP1) (Continued)

PERFORMANCE GRADE	PG 70-						PG 76-					PG 82-				
	10	16	22	28	34	40	10	16	22	28	34	10	16	22	28	34
Average 7-day Maximum Pavement Design Temp, °C[b]	<70						<76					<82				
Minimum Pavement Design Temperature, °C[b]	>-10	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-10	>-16	>-22	>-28	>-34
ORIGINAL BINDER																
Flash Point Temp, T48: Minimum °C	230															
Viscosity, ASTM D4402:[b] Maximum, 3 Pa•s, Test Temp, °C	135															
Dynamic Shear, TP5:[c] $G^*/\sin\delta$, Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	70						76					82				
ROLLING THIN FILM OVEN (T240)																
Mass Loss, Maximum, percent	1.00															
Dynamic Shear, TP5: $G^*/\sin\delta$, Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	70						76					82				
PRESSURE AGING VESSEL RESIDUE (PP1)																
PAV Aging Temperature, °C[d]	100(110)						100(110)					100(110)				
Dynamic Shear, TP5: $G^*\sin\delta$, Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	34	31	28	25	22	19	37	34	31	28	25	40	37	34	31	28
Physical Hardening[e]	Report															
Creep Stiffness, TP1:[f] S, Maximum, 300.0 MPa, *m* - value, Minimum, 0.300 Test Temp @ 60s, °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24
Direct Tension, TP3:[f] Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24

The correct performance grade of asphalt binder is determined in the Superpave paving mix design process through consideration of the climate and the type of traffic loading at the site of the paving project. The use of this performance grade is a suggested requirement for level 1, 2, and 3 mix designs. The Superpave software guides the mix designer through this process. The statistical distributions, expressed as the means and standard deviations, of the yearly 7-day average maximum air temperature and the yearly 1-day minimum air temperature are available in the Superpave software for 5313 weather stations in the United States and 1515 weather stations in Canada.

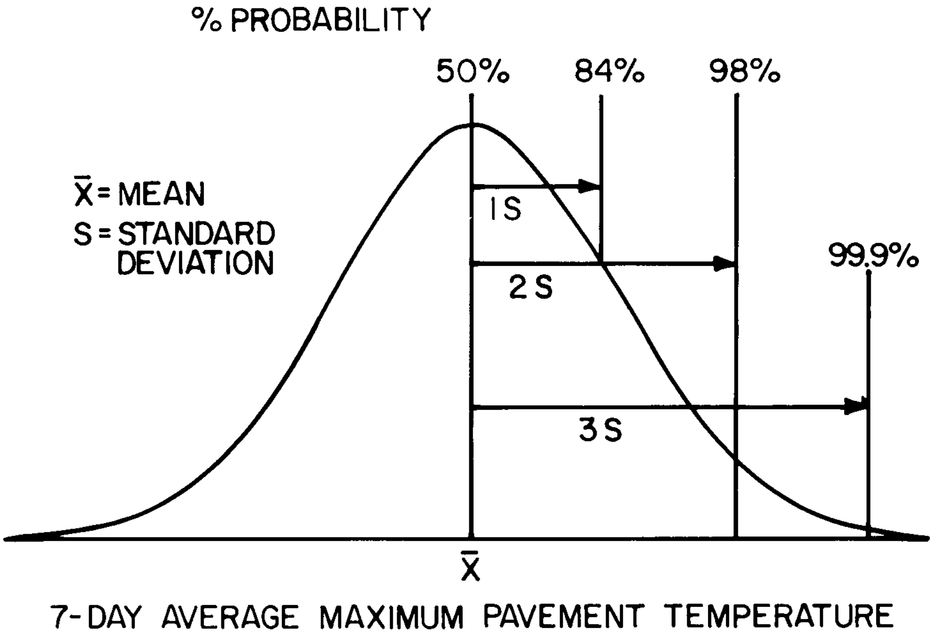
The Superpave software calculates the distribution of design pavement temperatures from the air temperature data, and guides selection of the minimum required performance grade of asphalt binder that will satisfy the conditions. These distributions may be viewed along with the degrees of probable risk associated with the selection of any particular design temperature. Thus, a binder performance grade may be selected for the project that either minimizes the probable design risk for high or low temperature pavement performance, or accepts some higher degree of probable risk when required by agency policy for the class of highway, the cost, and other relevant factors.

Figure 2.4 illustrates the relationship between the mean and the standard deviation of the pavement temperature distributions, and *the probability that in a given year the actual temperature will **not** deviate beyond a certain value*. Specifically, there is an 50 percent probability in any given year that the actual temperature will not deviate beyond the mean, an 84 percent probability that it will not deviate beyond the mean plus one standard deviation (*1S*), a 98 percent probability that it will not deviate beyond the mean plus two standard deviations (*2S*), and a 99.9 percent probability that it will not deviate beyond the mean plus three standard deviations (*3S*).

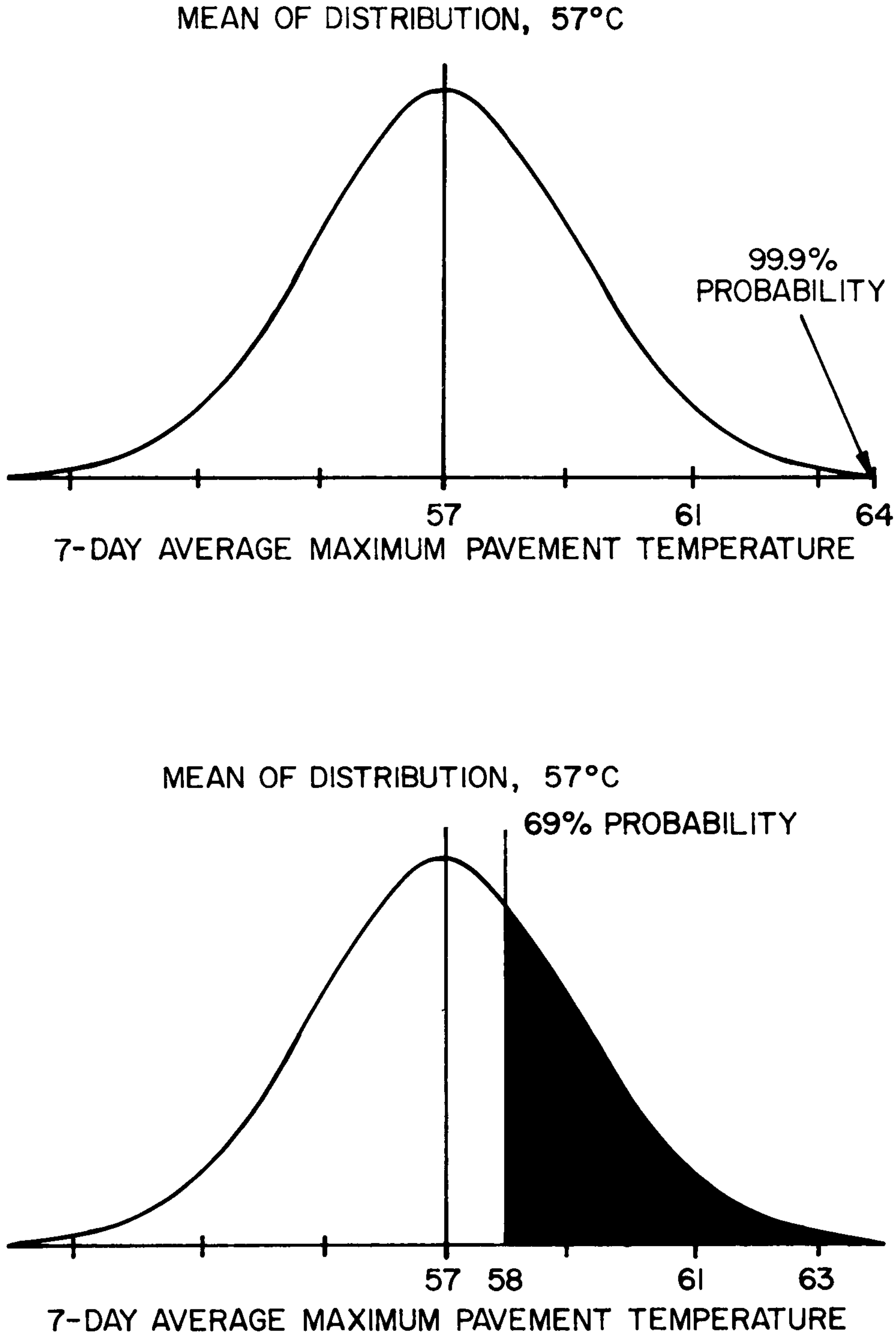
In practice, the mix designer will be concerned with the probabilities in a given year that the actual 7-day average maximum pavement temperature will **exceed** the historical mean of the 7-day average maximum pavement temperatures and (or) that the actual 1-day minimum air temperature will **fall below** the historical mean of the 1-day minimum pavement temperatures. Since the temperature distributions represented by figure 2.4 are approximately symmetrical around the mean values, there are corresponding probabilities (less than 50 percent) that the actual temperature will fall below the historical mean of the 7-day average maximum air temperatures or exceed the historical mean of the 1-day minimum pavement temperatures. Generally, these situations will not be of practical importance since binder grade selection is aimed at the prevention of distress development in normal weather years or years in which the weather is more severe than normal.

Several examples may be presented to illustrate the use of these temperature distributions in binder grade selection, and the interaction of the fixed 6°C steps between (high and low temperature) performance grades with the probabilities developed from the means and standard deviations. In example 1 (figures 2.5a and 2.5b), the distribution of 7-day average maximum pavement temperatures at a hypothetical weather station has a

Figure 2.4. Typical Probability Distribution of the 7-Day Average Maximum Pavement Temperature



Figures 2.5a and 2.5b. Example 1: Probabilities for a Mean of 57°C and a Standard Deviation of 2°C



mean of 57°C and a standard deviation of 2°C. The mean is one degree below the nearest performance grade step. There is a 69 percent probability in a given year that the actual temperature will not exceed 58°C and a 99.9 percent probability that it will not exceed 64°C. Selection of a PG 52 grade for this location would not provide an adequate level of high temperature protection since the risk (defined here as *100 - Probability*) in a given year that the actual temperature would exceed 52°C is considerably greater than 50 percent. Selection of a PG 58 grade (the next step up from a PG 52) would reduce the risk to 31 percent (*100-69*) while going up one more step (to PG 64) would reduce the risk to virtually zero.

Example 2 (figures 2.6a and 2.6b) illustrates the situation where the mean 7-day average maximum pavement temperature is 59°C and the standard deviation is 2°C. The mean is one degree above the nearest performance grade step. In this case, selection of a PG 58 grade, although only one degree below the mean temperature, would entail a 69 percent risk (*100-31*) that the high temperature performance of the binder would be inadequate in any given year. Selection of the next higher grade, a PG 64, would reduce the risk to less than one percent (*100-99.4*)

Finally, example 3 (figure 2.7) illustrates the situation where the mean 7-day average maximum pavement temperature of 61°C and the standard deviation is 2°C. The mean is midway between two performance grade steps (PG 58 and PG 64). In this case, selection of a PG 58 would entail a very high risk (greater than 93 percent) of inadequate high temperature performance in any given year. Selection of a PG 64 grade would be almost mandatory, and would reduce the risk to less than seven percent. The same type of analysis would apply to the selection of the low-temperature performance grade on the basis of the mean and standard deviation of the historical distribution of 1-day minimum pavement temperatures.

Alternatively, the Superpave software will accept a performance grade of asphalt binder and estimate the degree of risk engendered by its use at a particular project site. This capability in the software provides a rapid means of evaluating the suitability of locally available or low cost materials.

This procedure for performance grade selection assumes that the pavement will experience an average mix of car and truck traffic moving at moderate to high speeds (the fast transient condition). Figure 2.8 permits an upward adjustment of the maximum design temperature-based performance grade to compensate for: 1) a larger than average proportion of slow-moving, heavy trucks or a frequent incidence of heavy standing loads; and 2) expected traffic volumes in excess of 10^7 ESALs.

Figures 2.6a and 2.6b. **Example 2: Probabilities for a Mean of 59°C and a Standard Deviation of 2°C**

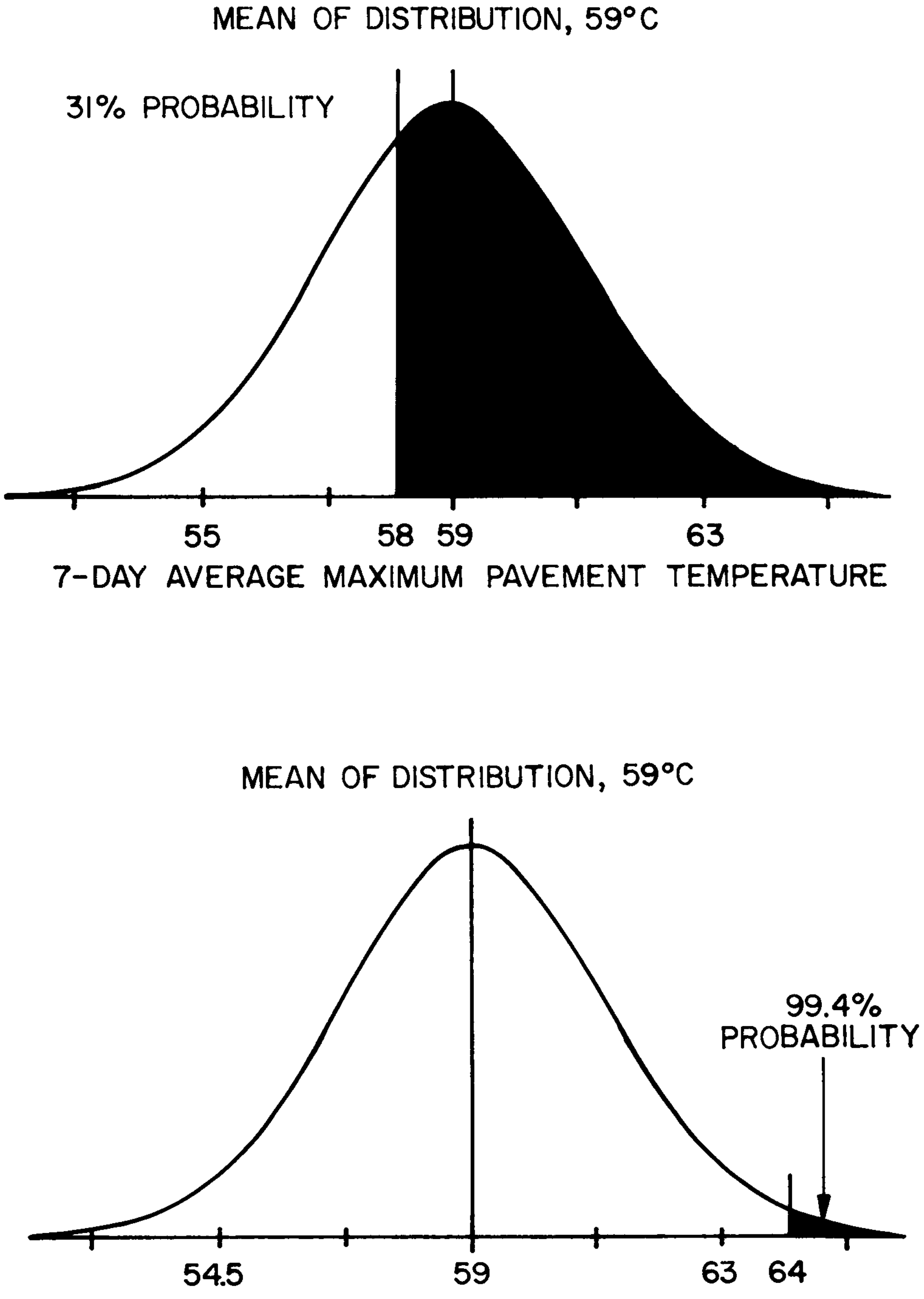
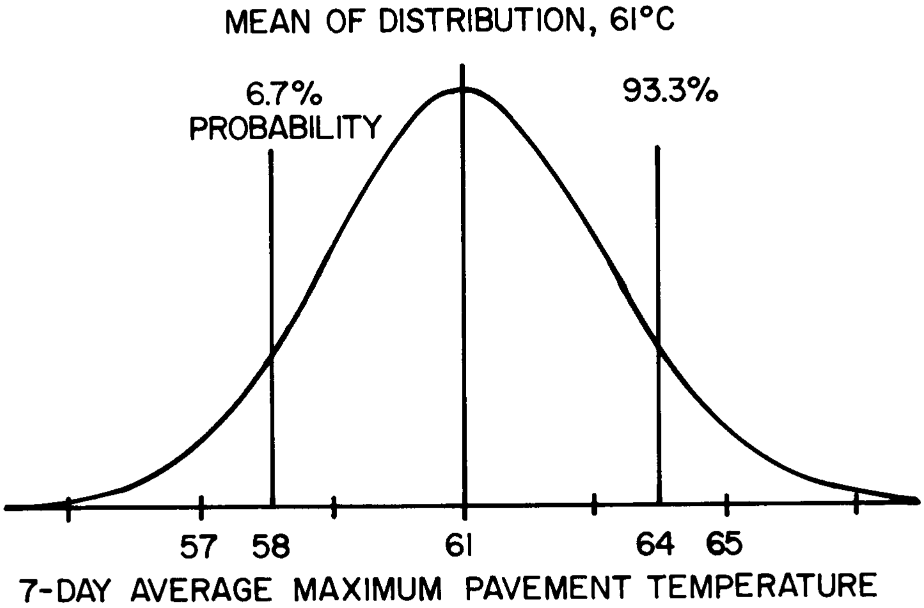


Figure 2.7. Example 3: Probabilities for a Mean of 61°C and a Standard Deviation of 2°C



For example, suppose that a PG 58-28 grade of asphalt binder is selected on the basis of maximum and minimum design pavement temperatures for a pavement project adjoining a ready-mix concrete plant. The pavement experiences a much higher than normal volume of slow-moving, heavily loaded concrete trucks. Using figure 2.8, the binder grade is moved up to PG 64-28 to enhance the ability of the binder to resist pavement rutting at high temperatures. Thus, the effect of slow-moving, heavy traffic is compensated by a 6°C increase in the design high pavement temperature, equivalent to raising the high temperature performance range of the binder by one grade.

Similarly, suppose that the asphalt binder will be used on a pavement experiencing fast transient traffic with an expected volume of 3×10^7 ESALs. Using figure 2.8, the binder grade is moved up to PG 64-28 to enhance the binder's ability to resist rutting at high temperatures.

In summary, selecting a design asphalt binder grade requires the following steps carried out with the aid of the Superpave software:

(1) Select weather stations in the vicinity of the paving project. Weather data from as many as three stations may be evaluated to estimate the climate at a paving site remote from established stations. (Note: At its discretion, the agency may input specific weather data for the site.)

(2) Select a degree of design reliability for high and low temperature performance. The reliability for a particular project is established by agency policy or assigned on the basis of the engineer's judgment of direct and indirect costs for maintenance and rehabilitation.

(3) Estimate the design pavement temperatures corresponding to the assigned reliability at the location of the paving project.

(4) Determine the minimum required performance grade of asphalt binder that will satisfy the selected maximum and minimum design pavement temperatures (and the associated risks).

(5) For paving projects in locations that experience, slow or heavy truck traffic, frequent braking or acceleration of heavy vehicles, frequent, heavy standing loads, and (or) traffic volumes above 10^7 ESALs, adjust the performance grade determined in step 4 using figure 2.8.

At the discretion of the agency, asphalt binder performance grades may also be determined from maps assigning specific grades to selected areas and classes of highway within districts, counties, etc.

Figure 2.8. Selection of Asphalt Binder Performance Grades on the Basis of Climate, Traffic Speed, and Traffic Volume

RECOMMENDATION FOR SELECTING BINDER PERFORMANCE GRADES

LOADS	HIGH PAVEMENT DESIGN TEMPERATURE °C						
STANDING	28 TO 34	34 TO 40	40 TO 46	46 TO 52	52 TO 58	58 TO 64	64 TO 70
(50 K/H) SLOW TRANSIENT	34 TO 40	40 TO 46	46 TO 52	52 TO 58	58 TO 64	64 TO 70	70 TO 76
(100 K/H) FAST TRANSIENT	34 TO 46	46 TO 52	52 TO 58	58 TO 64	64 TO 70	70 TO 76	76 TO 82
LOW PAVEMENT DESIGN TEMPERATURE °C							
> -10	PG46-10	PG52-10	PG58-10	PG64-10	PG70-10	PG76-10	PG82-10
-10 TO -16	PG46-16	PG52-16	PG58-16	PG64-16	PG70-16	PG76-16	PG82-16
-16 TO -22	PG46-22	PG52-22	PG58-22	PG64-22	PG70-22	PG76-22	PG82-22
-22 TO -28	PG46-28	PG52-28	PG58-28	PG64-28	PG70-28	PG76-28	PG82-28
-28 TO -34	PG46-34	PG52-34	PG58-34	PG64-34	PG70-34	PG76-34	PG82-34
-34 TO -40	PG46-40	PG52-40	PG58-40	PG64-40	PG70-40		
-40 TO -46	PG46-46	PG52-46	PG58-46	PG64-46			
	ALASKA-CANADA NORTHERN U.S.		CANADA NORTH U.S.	SOUTHERN U.S.	SOUTHWEST U.S.-DESERT CONTINENTAL U.S.-SLOW/HEAVY TRAFFIC		

1. SELECT THE TYPE OF LOADING
2. MOVE HORIZONTALLY TO THE HIGH PAVEMENT DESIGN TEMPERATURE.
3. MOVE DOWN THE LOW PAVEMENT DESIGN TEMPERATURE.
4. IDENTIFY THE BINDER GRADE.
5. ESALS $> 10^7$ CONSIDER INCREASE OF ONE HIGH TEMPERATURE GRADE.
   ESALS $> 3 \times 10^7$ INCREASE ONE HIGH TEMPERATURE GRADE.

EXAMPLE
STANDING LOAD, HIGH DESIGN TEMPERATURE = 57°C
LOW DESIGN TEMPERATURE = -25°C
GRADE = PG70-28

2.2.3. Asphalt-Aggregate Compatibility with the Net Adsorption Test (Optional)

The procedures in this section correspond with block (1-2A) in figure 1.2, the flow chart for a level 1 mix design.

The net adsorption test (SHRP Test M-001, *Measurement of Initial Asphalt Adsorption and Desorption in the Presence of Moisture*) gauges the ability of an asphalt binder to adhere to the surface of the fine aggregate portion of the total aggregate. It also assesses the strength of the initial adhesion of the asphalt binder to the aggregate in the presence of moisture. This optional screening procedure evaluates the chemical compatibility of an asphalt binder and fine aggregate fraction, as well as the effect of moisture on this compatibility. It provides guidance on the stripping potential of an asphalt binder-aggregate pair, but it should not be used as the sole determinant of the pair's satisfactory resistance to moisture damage in a paving mix.

Measuring the net adsorption behavior of an asphalt binder-aggregate pair requires the following steps (consult SHRP Method of Test M-001 for the full procedure):

(1) Prepare a solution of the asphalt binder in toluene (approx 1 g of asphalt binder per liter of toluene).

(2) Remove 4 ml of the solution, dilute to a total volume of 25 ml in a volumetric flask, and determine the light absorbance at 410 nm with a spectrophotometer that has been zeroed with pure toluene.

(3) Place 50 g of the portion of the total aggregate passing the 4.75 mm sieve size and 140 ml of the asphalt binder solution in a 500 ml Erlenmeyer flask.

(4) Agitate the solution and aggregate on a shaker table for 6 hours.

(5) Remove a 4 ml sample of the solution from the flask, dilute to 25 ml with toluene, and determine the light absorbance.

(6) Determine (from the difference in absorbance readings) the amount of asphalt that has been adsorbed from the solution due to the chemical attraction of the molecular components of the asphalt cement with the aggregate surface.

(7) Immediately after the second solution sample is taken, add 2 ml of water to the flask.

(8) Shake the solution for another 8 hours.

(9) Take a final 4 ml of solution from the flask at the end of 8 hours, dilute to 25 ml with toluene, and determine the absorbance at 410 nm.

(10) Determine (from the increase in absorbance) the amount of asphalt binder that has been displaced from the aggregate surface by water molecules.

(11) Report the net adsorption of the asphalt binder on the aggregate as the percent of initially adsorbed asphalt binder remaining on the aggregate after the introduction of moisture.

Criteria for net adsorption are presented in table 2.11. These criteria are suggested guidelines for level 1, 2, and 3 designs for dense graded paving mixes.

Table 2.11. Suggested Net Adsorption Criteria

Net Adsorption (%)	Moisture Sensitivity of Asphalt Binder-Aggregate Pair
>70	Acceptable
>55	Marginal
<55	Poor

Asphalt binder-aggregate pairs that exhibit acceptable behavior in this test must always be tested for moisture sensitivity of compacted paving mixes in the level 1 design method (block 1-8 of figure 1.2).

If an asphalt binder-aggregate pair exhibits marginal or poor behavior in the net adsorption test, selection of asphalt binder or aggregate from different sources that meet the criteria in sections 2.1 and 2.2.1 should be considered[3]. If no other sources of acceptable materials are available, the original pair should be used only if the results of the moisture sensitivity test (block 1-8 of figure 1.2) on the compacted paving mix are satisfactory.

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[3] The results of research conducted in SHRP contract A-003B and other SHRP studies strongly suggest that the aggregate is the principal determinant of the moisture sensitivity of paving mixes.

2.3 Modifiers

This section applies to modifiers intended either for direct addition to the asphalt binder or for incorporation in the hot mix asphalt during production. The SUPERPAVE™ mix design system does not deal with modified aggregates.

Modifiers can enhance the ability of paving mixes to resist the development of pavement distress. There are no strict guidelines to determine beforehand when modifiers may be required in a mix design or to select among the many modifiers intended to control one distress or another. Nonetheless, it should be noted that when a binder grade is selected that binder may have to be modified to satisfy the performance properties. The modification technique is the responsibility of the supplier. In a sense, the need for modification is determined by the initial binder grade selection. The need for a modifier may also become evident at any one of several stages in the Superpave mix design process:

- Past agency experience with similar materials or project requirements may demonstrate the effectiveness of modifier use.
- The Superpave system may indicate the need for a performance grade of asphalt binder that can meet a very high or very low pavement design temperature with a high degree of reliability (section 2.2.1). Generally, modified asphalt binders are needed to meet such requirements.
- In level 2 and 3 mix designs (chapters 4 and 5 of this manual), the estimated pavement performance of the trial design may be unsatisfactory, requiring a change in the trial design. Depending on the performance area of interest, modification strategies such as use of a modified asphalt binder, addition of liquid antistrip agent, treatment of the aggregate with hydrated lime, or even addition of fibers or fillers to the mixture may be required to bring the estimated performance up to satisfactory levels.

Once the need for modification is established, several factors complicate the selection of a modifier to remedy a specific performance defect:

- A wide array of materials is marketed commercially as modifiers for asphalt binders and paving mixes.
- The effectiveness of any modifier usually depends on the chemical and physical properties of the asphalt cement and aggregate with which it is combined, as well as on the modifier's concentration in the asphalt cement.

- Introducing a modifier into a paving mix may significantly affect performance characteristics other than the one targeted for enhancement.

Therefore, it is not possible to provide a straightforward list of modifiers that will remedy specific pavement distress problems in all situations.

In the Superpave mix design system, AASHTO Practice PP5, *The Laboratory Evaluation of Modified Asphalt Systems*, guides the selection of appropriate modifiers to enhance the pavement performance of new mix designs. The practice employs the same test methods to evaluate the performance characteristics of modified binders and mixes as those used for unmodified materials. In addition, the practice contains several special methods and procedures, such as a test for storage stability of modified asphalt binders, that may facilitate the routine use of modifiers in mix design.

A general procedure for design and evaluation of a modified paving mix includes the following steps (for details, refer to AASHTO Practice PP5).

(1) Identify the need to use a modifier on the basis of
- a design grade of asphalt binder that exceeds the capabilities of available unmodified asphalt cements;
- a mix design that has unsatisfactory estimated performance;
- agency policy; or
- past experience with available materials or project requirements.

(2) Determine whether changes in the original materials—for example, using a different trial gradation or increasing the level of angular coarse aggregate particles—will adequately improve the estimated performance characteristics of the mix design.

(3) If changes in the initial materials or mix design are not sufficient, select a class of modifier to address the specific performance characteristic, and consult with modifier vendors or an agency database to choose representative materials for laboratory evaluation.

(4) Using the methods and procedures in chapters 3 through 5, evaluate the effect of candidate modifiers on the performance-based properties of the asphalt binder and the paving mix. Evaluate modifiers at concentrations recommended by vendors or as suggested by past experience, with the goal of optimizing performance at an acceptable cost. Consider the need to vary the performance grade of the base asphalt binder to obtain maximum benefit from the modifier.

(5) Determine the safety, chemical compatibility, homogeneity (storage stability), and workability of the successful candidate modified binders from step 4 using the methods and procedures in AASHTO Practice PP5.

(6) Select the combination of modifier, base asphalt binder, and aggregate that best fulfills the requirements of steps 4 and 5.

(7) Consult with the modifier vendor to determine any special safety, workability, or field control requirements that must be observed during hot mix asphalt (HMA) production and pavement construction.

2.4 Next Steps in the Design Process

At this point in the Superpave mix design procedure, the following steps are complete:

- identification of the required performance grade of asphalt binder;
- selection of aggregate stockpiles suitable for use in the volumetric (level 1) design;
- an optional evaluation of the chemical compatibility of the asphalt binder-aggregate pair in the presence of moisture; and
- selection of a modifier as required by agency policy, past experience, or the results of either a previous asphalt binder evaluation or a full level 2 or level 3 mix design.

In the next chapter, the design aggregate structure and design asphalt binder content are determined through a volumetric (level 1) mix design process with gyratory-compacted specimens.

3

Level 1 Mix Design (Low Traffic Levels—Volumetric Design)

3.1 Introduction

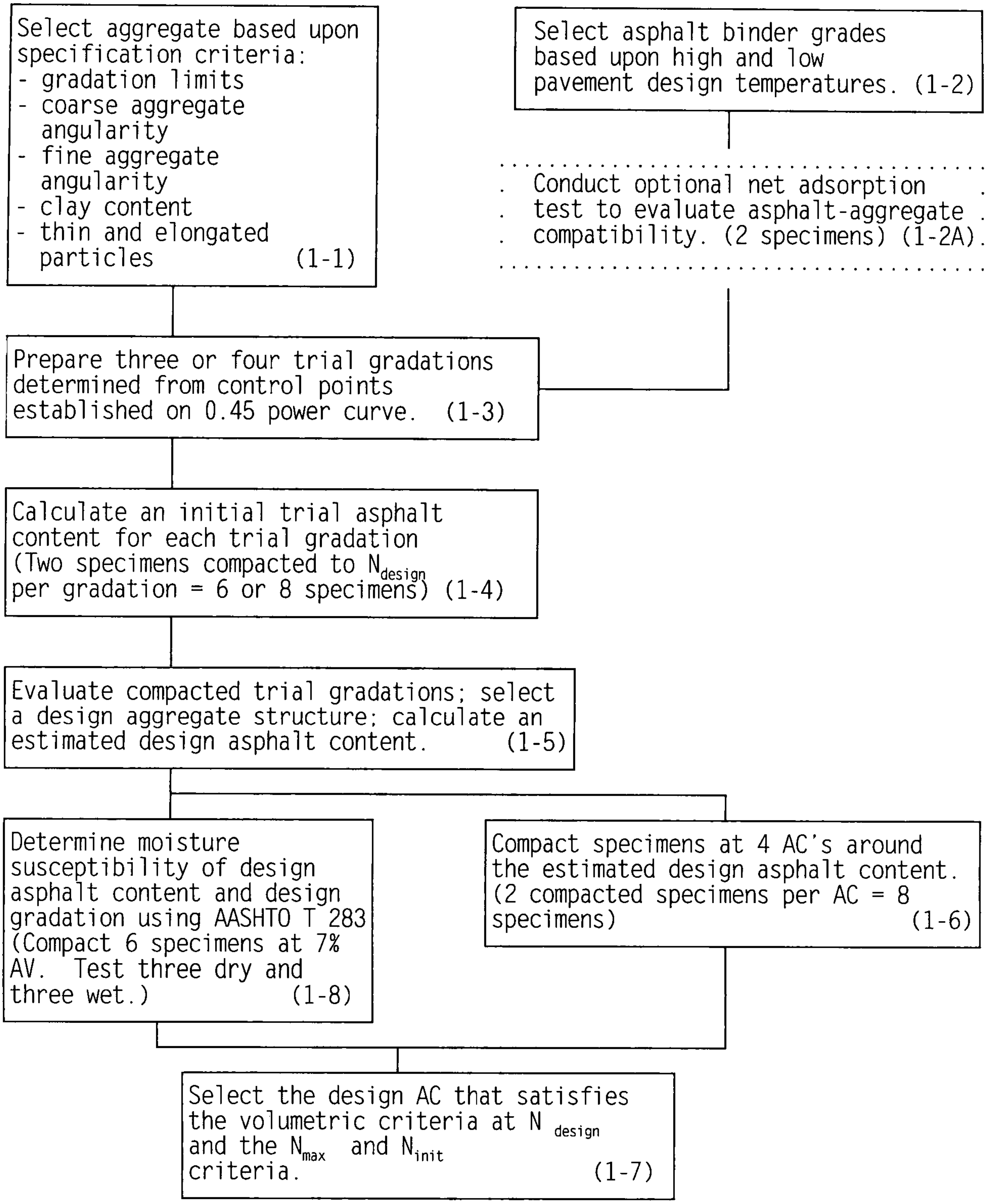
The Superpave level 1 mix design is based on empirical performance-related aggregate and mixture properties. Empirical properties are used to ensure adequate performance for lower volume pavements and to provide initial selection of a robust mix design as a platform for level 2 and 3 mix design procedures (chapters 4 and 5, respectively). Level 1 mix design is based on the proposition that performance properties of the asphalt binder and aggregate characteristics such as crushed aggregate faces and gradation, combined with volumetric properties such as air voids and voids in mineral aggregate, can be used as surrogate mixture properties to ensure adequate performance. Figure 3.1 shows the level 1 mix design flow chart.

Pavements with low traffic may not warrant the time and expense of testing for performance-based properties associated with level 2 and 3 mix design procedures. Therefore, volumetric design is recommended for low traffic projects having less than or equal to 10^6 design equivalent single axle loads (ESALs). The value of 10^6 ESALs can be changed at the discretion of the agency since it is purely a policy decision. Project traffic is defined as the expected ESALs on the design lane during the design life of the pavement structure. Design ESALs may be estimated using traffic information from any source or may be calculated using average annual daily traffic (AADT), and Federal Highway Administration vehicle-type and lane distribution factors.

3.2 Volumetric Properties

This section describes the volumetric properties of the paving mix that are used in the level 1 design method as surrogate properties to ensure adequate performance. Selection of an asphalt binder grade and aggregate with satisfactory characteristics is described in chapter 2.

Figure 3.1. **Level 1 Superpave Mix Design (Note: All specimens are compacted from paving mix that has been short-term aged (SHRP M-007)).**



3.2.1 Definitions

Volumetric properties are defined in accordance with the representation of the volume of an asphalt paving mix shown in figure 3.2.

- Air voids (V_a) are the percent by volume of air between coated aggregate particles in the compacted asphalt mixture.
- Voids in mineral aggregate (VMA) are the volume of compacted paving mix not occupied by the aggregate when the volume of the aggregate is calculated from its bulk specific gravity (not the effective or apparent specific gravities).
- Absorbed asphalt volume (V_{ba}) is the volume of asphalt binder absorbed into the aggregate. It is equal to the difference between the aggregate volume when calculated with bulk specific gravity and with effective specific gravity. Absorbed asphalt volume is represented by the overlap of asphalt volume and bulk aggregate volume shown in figure 3.2.
- Asphalt content (P_b) is the percent by weight of asphalt binder in the total mixture, including asphalt binder and aggregate.
- Effective asphalt volume (V_{be}) is the volume of asphalt binder which is not absorbed into the aggregate. It is represented by the portion of the asphalt binder volume shown above the bulk aggregate volume in figure 3.2.
- Voids filled with asphalt (VFA) is the percentage of VMA filled with asphalt binder. It is the effective asphalt volume divided by the voids in the mineral aggregate.

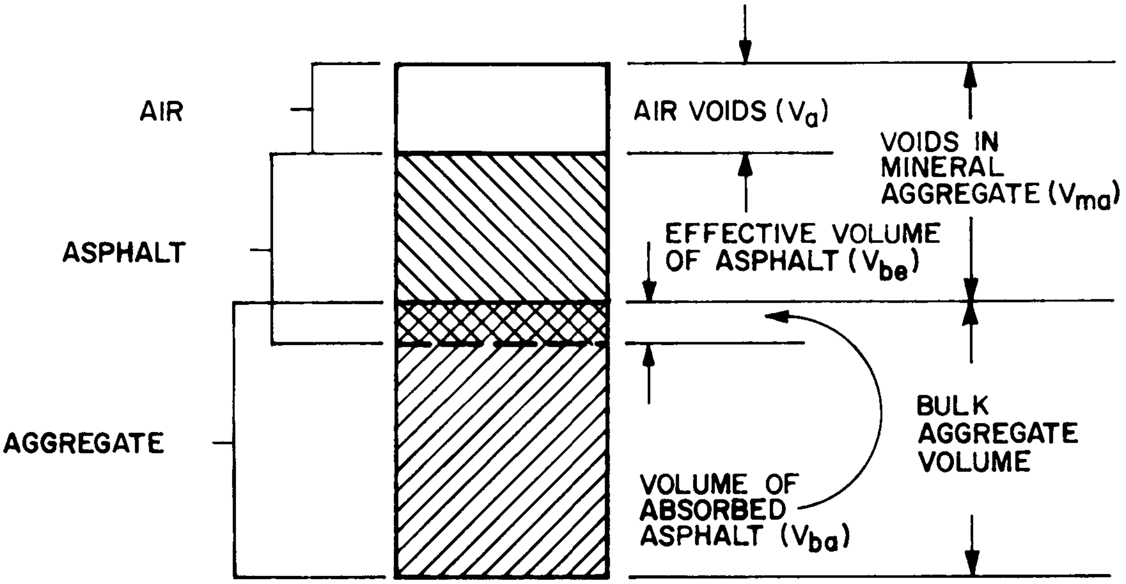
A method for volumetric analysis of compacted paving mixes is presented in SHRP Standard Practice P-004, *Volumetric Analysis of Compacted Hot Mix Asphalt.*

3.2.2 Air Voids

Air voids in compacted mixtures are defined as those air spaces contained between the asphalt binder-coated aggregate particles. The percent of air voids in a compacted paving mix is calculated from the bulk specific gravity of the compacted specimen (AASHTO T 166) and the theoretical maximum specific gravity (AASHTO T 209) of the paving mix by the equation

$$V_a = 100\,\frac{G_{mm} - G_{mb}}{G_{mm}} \qquad \textbf{(3-1)}$$

Figure 3.2. Definitions of the Volumetric Properties of Compacted Asphalt Paving Mix



where

V_a = air voids in the compacted specimen as a percent of total volume;

G_{mm} = maximum specific gravity of paving mixture; and

G_{mb} = bulk specific gravity of compacted mixture.

The recommended design air voids for all levels of traffic is four percent (Table 3.1).

Table 3.1. Air Voids Criteria[1]

Traffic (ESALs)	Design air voids (%)
All Levels	4

3.2.3 *Voids in the Mineral Aggregate*

The volume contained between aggregate particles in a compacted paving mix is termed the voids in the mineral aggregate (VMA). It is composed of the air voids and the effective asphalt volume. An adequate level of VMA ensures that sufficient asphalt binder is provided for satisfactory durability. In a paving mix with inadequate asphalt content, accelerated hardening of the asphalt binder occurs. This leads to raveling of the exposed surface aggregate particles by abrasive traffic forces and to fatigue cracking because of an inability of the pavement to flex under traffic. It may also contribute to moisture damage.

VMA may be determined by subtracting the volume of aggregate particles from the volume of the compacted mixture. The volume of the aggregate particles is calculated using the <u>bulk specific gravity of the aggregate</u> as determined by AASHTO T 84, T 85, and T 100. The following equation is used to calculate VMA:

$$VMA = 100 - \frac{G_{mb}P_s}{G_{sb}} \qquad \textbf{(3-2)}$$

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[1] Specified values for Superpave specimens may not be directly comparable to existing mix designs because oven curing at or near compaction temperature is required to allow absorption and aging to occur. Therefore, the same aggregate gradation and asphalt binder content may produce Superpave specimens with air voids different from Marshall or Hveem specimens.

where

VMA = voids in mineral aggregate (percent of bulk volume);

G_{sb} = bulk specific gravity of aggregate;

G_{mb} = bulk specific gravity of compacted paving mix (AASHTO T 166); and

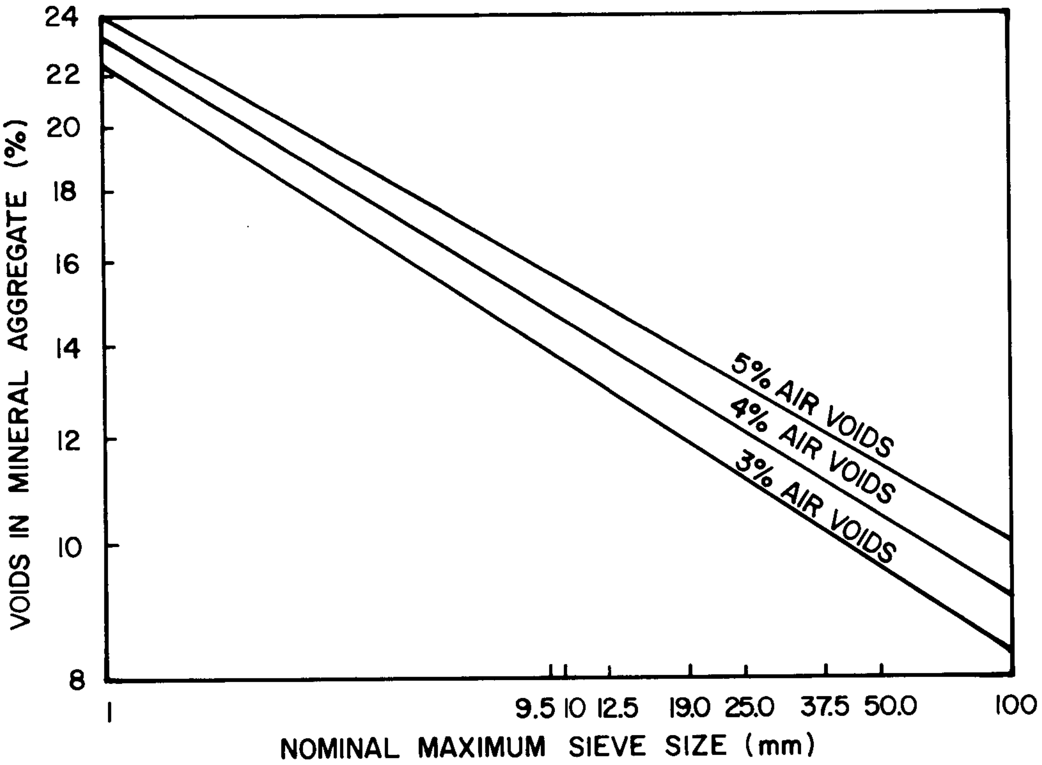
P_s = aggregate, percent of total weight of mixture.

VMA is used to control the durability of paving mixes at low traffic volumes. VMA criteria vary with the nominal maximum size of the aggregate gradation. Acceptable values are shown in table 3.2 for mixes with four percent air voids. Recommended minimum values for three and five percent air voids are shown in figure 3.3.

Table 3.2. Voids in Mineral Aggregate Criteria

Nominal Maximum Size	Minimum Voids in Mineral Aggregate (%)
9.5 mm	15.0
12.5 mm	14.0
19.0 mm	13.0
25.0 mm	12.0
37.5 mm	11.0
50.0 mm	10.5

Figure 3.3. Minimum Percent Voids in Mineral Aggregate (VMA) for 3, 4 and 5 Percent Air Voids



3.2.4 *Voids Filled with Asphalt*

The percentage of voids in the mineral aggregate filled with asphalt is termed the voids filled with asphalt (VFA). VFA is the volume of effective asphalt binder expressed as a percentage of the VMA. The following equation is used to calculate the VFA:

$$VFA=\frac{VMA-V_a}{VMA}\times 100 \qquad \mathbf{(3\text{-}3)}$$

Experience has shown that VFA should lie within limits which prevent both mix instability under high shear stress and accelerated aging. For low traffic volumes, the shear resistance and aging properties are not measured directly; therefore, VFA is a criterion which must be met in the volumetric design. Acceptable values of VFA for increasing traffic are shown in table 3.3. Specification of VFA in addition to air voids and VMA effectively places a maximum value on VMA and allows for greater asphalt binder contents for low traffic volume conditions.

Table 3.3. Voids Filled With Asphalt Criteria

Traffic Level (ESALs)	Design Voids Filled With Asphalt (%)
$<3 \times 10^5$	70 - 80
$<3 \times 10^6$	65 - 78
$<1 \times 10^8$	65 - 75
$> 1 \times 10^8$	65 - 75

3.3 Outline of the Level 1 (Volumetric) Design Method

The Superpave level 1 (volumetric) design method includes three principal parts: (1) selection of materials; (2) selection of a design aggregate structure (expressed as an aggregate gradation); and (3) selection of a design asphalt (binder) content.

In practice, paving mixes containing differing aggregate structures and asphalt binder contents are compacted with the gyratory compactor. The volumetric properties of the paving mixes are evaluated at several points along the compaction-density curve in order to select a satisfactory design aggregate structure and design asphalt content. The compaction levels at which the evaluation takes place are determined by the traffic projected for the pavement over its service life. Therefore, asphalt binder properties, aggregate characteristics, and volumetric properties are used as surrogate values to ensure adequate pavement performance.

Within each principal part of the level 1 design method, several specific steps are required.

(1) Select materials.

- Select the asphalt binder and aggregate stockpiles that meet the environmental and traffic requirements of the paving project (chapter 2 of this manual).
- Determine the bulk specific gravity of all aggregates proposed for blending and the specific gravity of the asphalt binder.

(2) Select the design aggregate structure.

- Blend trial aggregate gradations (preferably three or more) from selected aggregate stockpiles.
- Calculate an initial trial asphalt content and compact two specimens for each trial gradation.
- Select a design aggregate structure and a corresponding estimated design asphalt content on the basis of satisfactory conformance of a trial gradation with requirements for V_a, VMA, and VFA at the initial (N_{init}), design (N_{design}), and maximum (N_{max}) compaction levels (measured in terms of gyrations applied with the SHRP gyratory compactor).

(3) Select the design asphalt (binder) content.

- Compact two specimens at the estimated design asphalt content and at the estimated design asphalt content ± 0.5 percent and + 1.0 percent.
- Select the design asphalt content on the basis of satisfactory conformance with requirements for V_a, VMA, and VFA at the initial (N_{init}), design (N_{design}) and maximum (N_{max}) compaction levels.
- Evaluate the moisture sensitivity of the design aggregate structure at the design asphalt content and an air voids content (V_a) of 7 percent.

3.4 Equipment

The equipment required for the preparation of compacted specimens is as follows:

- *Pan*: metal, flat bottom, for heating aggregates.
- *Pans:* metal, round, approximately 4-liter capacity, for mixing asphalt and

aggregates.

- *Oven and hot plate:* electric, for heating aggregates, asphalt, and equipment as required. Oven must also be capable of maintaining temperature for short-term aging.

- *Scoop:* for batching aggregates.

- *Containers:* gill-type tins, beakers, pouring pots, or sauce pans, for heating asphalt.

- *Thermometers:* armored, glass, or dial-type with metal stem, 10°C to 230°C, for determining temperature of aggregates, asphalt, and asphalt mixtures, preferably ASTM certified.

- *Balance:* 5-kg capacity, sensitive to 1 g for weighing aggregates and asphalt. *Balance*, 2-kg capacity, sensitive to 0.1 g for weighing compacted specimens.

- *Mixing spoon:* large, or *trowel:* small.

- *Spatula:* large.

- *Mechanical mixer*: (optional) commercial bread dough mixer 4 l capacity or larger, equipped with two metal mixing bowls and two wire stirrers, or suitable equivalent.

- *Gyratory compactor*: capable of providing a consolidation pressure of 0.6 MPa, an angle of gyration of 1.25 degrees and speed of gyration of 30 rpm; SHRP model or equivalent.

- *Cylindrical molds*: large enough to accommodate the following specimen size requirements: 150 mm diameter, 150 mm maximum height, and 90 mm minimum height.

- *Extrusion jack* or *arbor press*: for extruding compacted specimens from mold.

- *Gloves, welders*: for handling hot equipment. *Gloves,* rubber: for removing specimens from water bath.

- *Marking crayons*: for identifying test specimens.

3.5 Gyratory Compaction

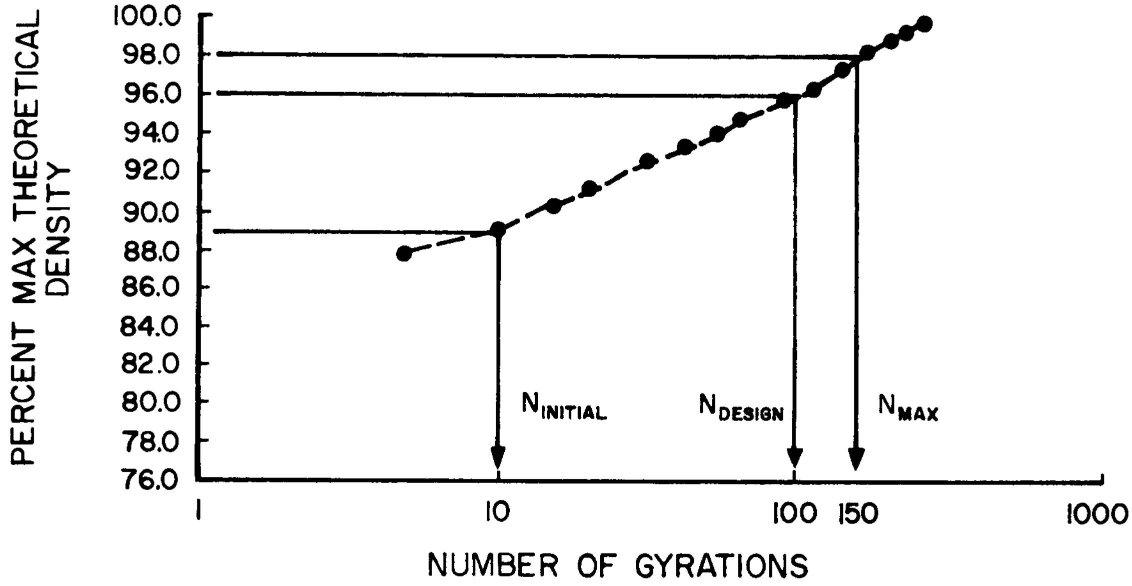
The Superpave level 1 (volumetric) mix design method requires specimen compaction with a gyratory compactor in accordance with SHRP Standard Method of Test M-002. This compactor can monitor the increase in specimen density (expressed as a percent of its theoretical maximum specific gravity) with increasing compactive effort. Superpave software analyzes the densification data directly from the SHRP gyratory compactor; data can also be collected manually or with a dedicated computer connected to the compactor. Compaction is carried out at an equiviscous temperature determined in SHRP Method of Test M-002 or at an appropriate temperature selected by the mix designer.

Density is evaluated at three points along the densification curve as shown in figure 3.4. The design aggregate structure and design asphalt binder content are selected in the level 1 (volumetric) mix design to produce a densification curve which passes through 96% of theoretical maximum specific gravity at the design number of gyrations (N_{design}); thus, the design asphalt content is selected at 4% air voids at N_{design}. The value of N_{design} used in a mix design is selected from table 3.4; it is determined from the traffic level expected on the pavement and the design 7-day maximum air temperature for the pavement site.

Table 3.4. Number of Initial (N_i), Design (N_d) and Maximum (N_m) Gyrations Required For Various Traffic Levels and Maximum Temperature Environments

Traffic (ESALs)	Design 7-day Maximum Air Temperature (°C)											
	< 39			39 - 41			41 - 43			43 - 45		
	N_i	N_d	N_m	N_i	N_d	N_m	N_i	N_d	N_m	N_i	N_d	N_m
<3 × 10^5	7	68	104	7	74	114	7	78	121	7	82	127
<1 × 10^6	7	76	117	7	83	129	7	88	138	8	93	146
<3 × 10^6	7	86	134	8	95	150	8	100	158	8	105	167
<1 × 10^7	8	96	152	8	106	169	8	113	181	9	119	192
<3 × 10^7	8	109	174	9	121	195	9	128	208	9	135	220
<1 × 10^8	9	126	204	9	139	228	9	146	240	10	153	253
≥1 × 10^8	9	143	235	10	158	262	10	165	275	10	172	288

Figure 3.4. Typical Densification Curve Obtained With SHRP Gyratory Compactor



At the maximum number of gyrations (N_{max}), the paving mix must attain less than 98% of theoretical maximum specific gravity or an air voids content of more than two percent. The value of N_{max} used in a mix design is presented in table 3.4 and determined from N_{design} by the equation

$$\log N_{max} = 1.10 \log N_{design} \tag{3-4}$$

At the initial number of gyrations (N_{init}), the paving mix must attain 89% of theoretical maximum specific gravity or less. The value of N_{init} used in a mix design is presented in table 3.4 and determined from N_{design} by the equation

$$\log N_{init} = 0.45 \log N_{design} \tag{3-5}$$

These compaction level-density requirements are summarized in table 3.5.

Table 3.5. General Superpave Compaction Requirements

Compaction Level	Required Density (% of Theoretical Maximum Specific Gravity)
N_{init}	$C_{init} < 89$
N_{design}	$C_{design} = 96$
N_{max}	$C_{max} < 98$

EXAMPLE: What are the values of N_{init}, N_{design}, and N_{max} required for a Superpave level 1 mix design conducted for a paving project with an anticipated traffic level of 8×10^5 ESALs and an average design air temperature of 39°C?

Referring to table 3.4, the value of N_{design} is found at the intersection of the row labelled $<1 \times 10^6$ and the column headed 39 - 41. Therefore, $N_{design} = 83$.

Then,

$$\log N_{init} = 0.45\log(83) = 0.86$$
$$N_{init} = 7$$

and

$$\log N_{max} = 1.10\log(83) = 2.11$$
$$N_{max} = 129$$

The density calculated at any point in the compaction process from the weight of the specimen and its height is termed the *uncorrected* density (C_{ux}). The uncorrected density at x gyrations is calculated as a percentage of the theoretical maximum specific gravity of the paving mix by the equation:

$$C_{ux} = 100\left[\frac{W_{mx}}{d_w V_{mx}}\right] / G_{mm} \qquad (3\text{-}6)$$

where V_{mx}, the volume of the paving mix at x gyrations in mm^3, is given by the equation

$$V_{mx} = \frac{\pi d^2 h_x}{4} \qquad (3\text{-}7)$$

and W_{mx} = the weight of the paving mix at x gyrations in g;

G_{mm} = the theoretical maximum specific gravity of the paving mix;

d = the inside diameter of the specimen mold in mm;

h_x = the height of the specimen in mm; and

d_w = density of water at the temperature at which G_{mm} is measured, in g/mm.

At the completion of the compaction process, the bulk specific gravity of the compacted specimen is measured using AASHTO T 166. The bulk specific gravity is used to correct the uncorrected density C_{ux} by the equation

$$C_x = \frac{C_{ux} G_{mb} V_{mm}}{W_{mx} d_w} \tag{3-8}$$

where C_x = corrected density expressed as a percentage of the theoretical maximum specific gravity;

V_{mm} = the volume of the mixture calculated at the maximum number of gyrations;

W_{mx} = the weight of the paving mix at x gyrations in g;

G_{mb} = the measured bulk specific gravity of the compacted paving mix at $N_{max;}$ and

d_w = density of water at the temperature at which G_{mm} is measured, in g/mm.

The corrected density is plotted against the logarithm of the number of gyrations to produce densification curves. Figure 3.5 illustrates typical densification curves, showing the change in corrected density (C_x) as the compaction progresses from five to a maximum of 230 gyrations. Four densification curves are presented, one for each of four asphalt contents with the same aggregate structure. Note that as the asphalt content increases, the densification curves shift to the left but remain roughly parallel.

3.6 Short-Term Aging of Selected Target Asphalt-Aggregate Blend

All specimens of paving mix compacted in the level 1 mix design are conditioned as loose mix according to the short-term aging procedure in SHRP Standard Method of Test M-007. This conditioning simulates the aging of hot mix asphalt (HMA) paving mixes during field plant mixing operations. It also permits asphalt absorption to proceed to completion.

3.7 Selecting the Design Aggregate Structure (Skeleton)

The purpose of this part of the level 1 mix design is to evaluate the effect of aggregate structure on mixture volumetric properties, predominately VMA. The objective is to select a design aggregate structure (skeleton) that meets the Superpave requirements. Specifically, the design aggregate structure must:

- provide adequate VMA at the design number of gyrations and 4% air voids;
- meet density requirements at N_{init} gyrations; and
- meet density requirements N_{max} gyrations.

In this section, the design aggregate structure is selected.

At this point in the level 1 design process, both asphalt binder and aggregate fractions that meet the requirements for the paving mix as specified in chapter 2 have been identified.

Several trial aggregate gradations will be developed and evaluated. An initial trial asphalt content is calculated for each. Compacted specimens are prepared for each trial gradation-trial asphalt content combination; their densification curves and volumetric properties are evaluated; and a design aggregate structure is selected.

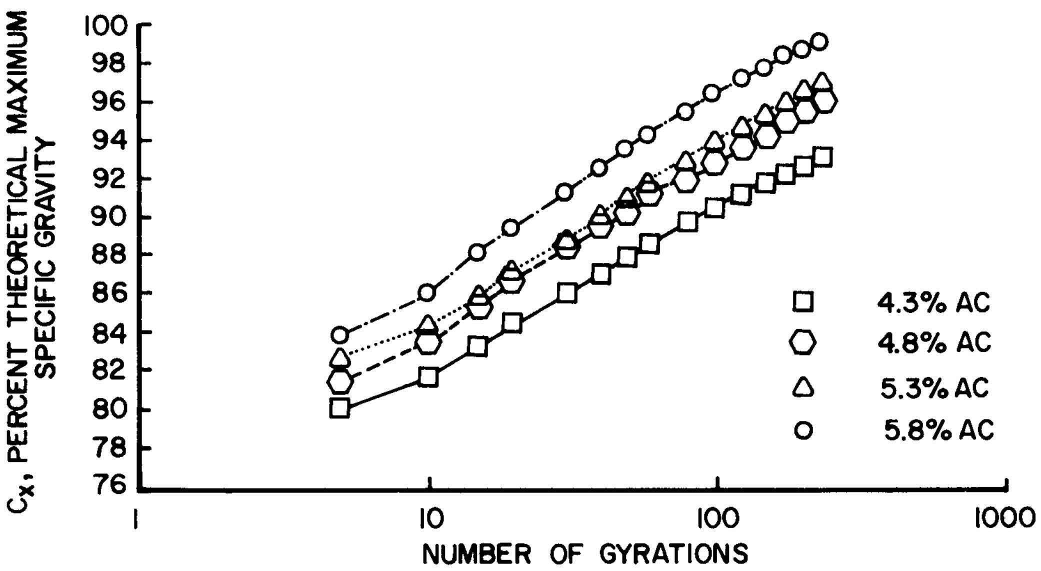
Selecting a design aggregate skeleton requires the following steps:

(1) Select aggregates meeting Superpave criteria for acceptable aggregate characteristics (chapter 2 of this manual).
(2) Blend aggregate stockpiles to meet specified gradation controls. Typically, three trial gradations or more covering the range of allowable gradations should be evaluated (section 3.7.1).
(3) Calculate an initial trial asphalt content for each trial gradation (section 3.7.2).
(4) Compact specimens at the initial trial asphalt content (section 3.7.3).
(5) Evaluate paving mix densification curves for each trial gradation (section 3.7.4).
(6) Select a design aggregate structure which best meets the volumetric and densification requirements (section 3.7.5).

3.7.1 Aggregate Trial Blend Gradations

The procedures in this section correspond with block (1-3) in figure 3.1, the flow chart for a level 1 mix design.

Figure 3.5. Gyratory Compaction Densification Curves for Four Asphalt Binder Contents



(1) Refer to section 2.1.1 for gradation control requirements. The main purpose of the gradation evaluation is to determine whether a selected gradation which meets the gradation controls is likely to meet the VMA requirements. VMA is influenced predominantly by aggregate characteristics such as gradation, angularity, and surface texture.

(2) Using stockpiles selected in chapter 2, perform a blending analysis to determine which gradation(s) will be used in the volumetric proportioning phase. The goal is to evaluate how various volumetric proportions of the available stockpiles fit the gradation controls. See chapter 3, Evaluation of Aggregate Gradation, Asphalt Institute Manual MS-2, *Mix Design Methods for Asphalt Concrete and other Hot Mix Types*, 6th Edition, 1994, for a detailed exposition of this procedure.

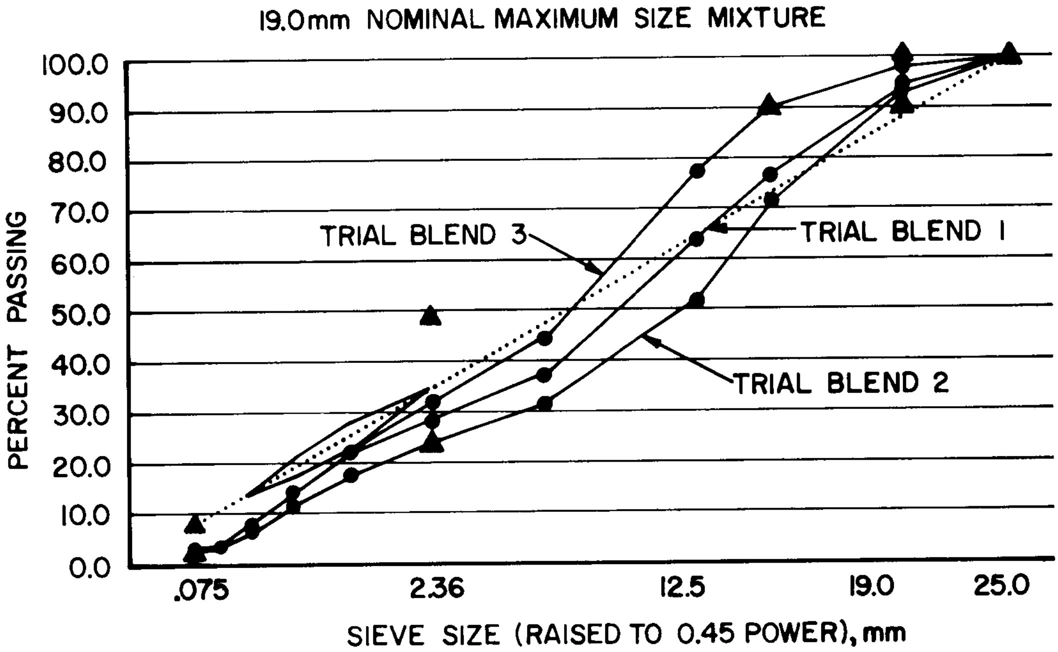
(3) Develop three or four trial aggregate gradations, and plot the results of the blending analysis on a 0.45 power gradation analysis chart as shown in figure 3.6 confirming that each meets the Superpave gradation controls (Appendix A).

Blends 1, 2, and 3 in figure 3.6 are three examples of trial aggregate gradations.

3.7.2 Calculate an Initial Trial Asphalt Content for each Trial Aggregate Gradation.

The procedure in this section and section 3.7.3 corresponds with block (1-4) in figure 3.1, the flow chart for a level 1 mix design.

Figure 3.6. Evaluation of the Aggregate Gradations of Three Trial Blends



The next step in the level 1 (volumetric) mix design is to estimate an initial trial asphalt content P_{bi} for each trial gradation. This is the starting point for the subsequent laboratory determination of the level 1 design aggregate structure and design asphalt content. The procedure in this section permits the calculation of an initial trial asphalt content for any trial aggregate gradation. The actual calculations are performed by the Superpave software. It provides a reasonably precise estimate of the asphalt content required by the trial gradation to meet minimum VMA requirements (Table 3.2) on the basis of aggregate characteristics, including specific gravity and nominal maximum size.

The procedure calculates an initial trial asphalt content that satisfies a minimum criterion for allowable effective asphalt content while compensating for asphalt absorption by the aggregate. It is recommended that bag house fines be added to simulate field conditions if a bag house is to be used. The amount can be based on experience or a value of two percent by weight of the aggregate can be used. The minimum effective asphalt content is determined from a regression equation which relates it to the nominal maximum sieve size of the trial aggregate gradation. Asphalt absorption is approximated from the bulk and apparent specific gravities of the aggregate fractions used in the trial aggregate gradation.

Calculating an initial trial asphalt content requires the following steps:

(1) Determine the bulk and apparent specific gravity of each aggregate fraction in the trial gradation using AASHTO Standard Methods of Test T 84, *Specific Gravity and Absorption of Fine Aggregate,* T 85, *Specific Gravity and Absorption of Coarse Aggregate,* and T 100, *Specific Gravity of Soils.*

(2) Calculate the bulk and apparent specific gravities G of the total aggregate in the trial gradation as follows:

$$G=\frac{(P_1+P_2+\ldots+P_n)}{\frac{P_1}{G_1}+\frac{P_2}{G_2}+\ldots+\frac{P_n}{G_n}} \qquad (3-9)$$

where P_1, P_2,....P_n = the weight percent of aggregate fraction 1, 2, ..., n in the total aggregate, and

G_1, G_2,....G_n = the bulk or apparent specific gravities of aggregate fractions 1, 2, ..., n.

(3) Estimate the effective specific gravity[2] of the total aggregate in the trial aggregate gradation by the equation

$$G_{se}=G_{sb}+0.8\,(G_{sa}-G_{sb}) \tag{3-10}$$

where G_{se} = the effective specific gravity of the total aggregate,
G_{sb} = the bulk specific gravity of the total aggregate, and
G_{sa} = the apparent specific gravity of the total aggregate.

(4) Estimate the percent volume of asphalt absorbed into the aggregate (V_{ba}) as follows:

$$V_{ba}=W_s\left(\frac{1}{G_{sb}}-\frac{1}{G_{se}}\right) \tag{3-11}$$

where W_s, the weight percent of the aggregate, is calculated as

$$W_s=\frac{P_s\times(1-V_a)}{\dfrac{P_b}{G_b}+\dfrac{P_s}{G_{se}}} \tag{3-12}$$

where P_b = weight percent of asphalt binder, in decimal equivalent, assumed to be 0.05;
P_s = weight percent of aggregate, in decimal equivalent, assumed to be 0.95;
G_b = the specific gravity of the asphalt binder, measured or assumed to be 1.02; and
V_a = the volume of air voids, fixed at 4 percent.

Note that this procedure calculates the volume of asphalt absorbed into the aggregate and, subsequently, the initial trial asphalt content at an air voids content of four percent, the design criterion presented in table 3.1.

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[2] The Superpave mix design system includes a short-term aging step before the compaction of all specimen; this generally permits asphalt absorption to proceed to completion. Therefore, the effective specific gravity of Superpave - designed paving mixes will tend to be close to the apparent specific gravity, in contract to other design methods where the effective specific gravity generally will lie near the midpoint between the bulk and apparent specific gravities.

(5) Estimate the volume percent of effective asphalt binder, V_{be}, from the following empirical regression equation:[3]

$$V_{be}=0.176-(0.0675)\log(S_n) \tag{3-13}$$

where V_{be} = the volume of effective asphalt binder content; and
S_n = the nominal maximum sieve size of the total aggregate in the trial aggregate gradation, mm.

(6) Using the volume of absorbed asphalt binder (V_{ba}) and the volume of effective asphalt binder (V_{be}), calculate the initial trial asphalt content (P_{bi}), expressed as percent of asphalt binder by weight of the total paving mix, by the equation

$$P_{bi}=\frac{G_b(V_{be}+V_{ba})}{(G_b(V_{be}+V_{ba}))+W_s} \tag{3-14}$$

where G_b = the specific gravity of the asphalt binder, measured or assumed to be 1.02; and
W_s = the weight of the aggregate.

The estimation of the initial trial asphalt content carried out above is based on

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[3] This regression equation is derived from an empirical relationship between VMA and V_{be} when the air voids content V_a is equal to 4 percent:

$$V_{be}=VMA-V_a=VMA-4$$

and the relationship between VMA and nominal maximum sieve size of the aggregate in table 3.2.

- an assumed asphalt content in step 4;
- an assumed specific gravity of the asphalt binder in steps 5 and 6; and
- an estimated effective specific gravity for the total aggregate in step 3.

At this point in the selection of the design aggregate structure, several trial aggregate gradations have been developed and an initial trial asphalt content has been calculated for each. In the following steps, actual specimens will be compacted for each trial gradation at its initial trial asphalt content, and their volumetric properties will be evaluated in order to select a satisfactory design aggregate structure.

The procedure in this section corresponds to block (1-5) in Figure 3.1, the flow chart for Level 1 mix design.

3.7.3 Compact Specimens of Each Trial Gradation

Duplicate specimens are mixed and compacted at the initial trial asphalt content for each of the chosen trial aggregate gradations. The compaction effort, the number of design gyrations (N_{design}), is selected based on traffic level. Determine N_{init}, N_{design}, and N_{max} for the paving project from table 3.4.

For each initial trial asphalt content-trial aggregate gradation combination:

(1) Compact two specimens to N_{max} gyrations in accordance with SHRP Method of Test M-002 from loose paving mix aged in the short-term aging procedure (SHRP Method of Test M-007).

(2) Determine the theoretical maximum specific gravity (G_{mm}) of the paving mix.

3.7.4 Evaluate Compacted Trial Aggregate Gradations

In this step, the compaction characteristics of each trial aggregate gradation are evaluated. Specifically, the volumetric properties of the paving mix are determined at N_{design} gyrations and the VMA is estimated at the four percent air voids level by shifting the measured densification curve. Then, the density at N_{init} and N_{max} gyrations are evaluated to determine the acceptability of the trial aggregate gradation as defined by the Superpave criteria.

Although the initial trial asphalt content was estimated for an air voids content of four percent, at N_{design} the actual air voids content is unlikely to be exactly four percent.

Therefore, the change in asphalt content needed to obtain a four percent air voids content is estimated from shifted densification curves, and the change in VMA caused by this change in asphalt content is calculated. These calculations permit the evaluation of the VMA and VFA of each trial aggregate gradation at the *same design air voids content*, four percent.

3.7.4.1 Shifting Trial Aggregate Gradation Densification Curves

Trial aggregate gradations were compacted at a trial asphalt content. Evaluation of a specific gradation requires the densification curve to be shifted as follows:

(1) Calculate the difference between air voids at N_{design} for the trial gradation and 4% air voids.

$$\Delta V_a = 4 - V_a \tag{3-15}$$

(2) Calculate the slope of trial gradation densification curve (see figure 3.7):

$$Slope = \frac{\log 30 - \log 10}{C_{30} - C_{10}} \tag{3-16}$$

(3) Calculate the horizontal shift factor:

$$Shift = \Delta V_a \left(\frac{\log 30 - \log 10}{C_{30} - C_{10}}\right) \tag{3-17}$$

(4) Horizontally shift the trial gradation densification curve. Shift each data point, C_x, with the equation

$$\log x' = \log x + Shift \tag{3-18}$$

where

C_x = measured density at x gyrations for trial gradation,

x = measured number of gyrations corresponding to density Cx, and

x′ = estimated number of gyrations for the shifted densification curve.

Some extrapolation and truncation will be required depending upon the direction of the shift. For the example shown in figure 3.8 the densification curve must be extrapolated to N_{max}. The extrapolated portion is a straight line projected using the slope of the last segment of the measured curve. At the other end of the shifted curve several data points are truncated such that the shifted curve begins at the same number of gyrations as the original curve.

3.7.4.2 Determination of Estimated Design Parameters

Once the densification curve has been shifted, specific level 1 mix criteria can be compared to properties estimated from the shifted curve. Specifically the mix is evaluated based on density at N_{init}, density at N_{max} and VMA at N_{design}.

(1) Evaluate the densification curve and determine the estimated specimen densities, C_{init}, and C_{max}, at the key compaction points, N_{init}, and N_{max}.

(2) Compare C_{init} and C_{max} to specification requirements. C_{init} must be less than 89% and C_{max} must be less than 98%.

(3) Determine estimated VMA when C_{design} equals 96%. At N_{design} gyrations determine the bulk specific gravity of specimen using C_{design} and the theoretical maximum specific gravity.

$$G_{mb}=C_{design}\times G_{mm} \tag{3-19}$$

where G_{mb} = bulk specific gravity of the compacted mixture;
C_{design} = corrected density of the compacted specimen at N_{design}, and
G_{mm} = maximum theoretical specific gravity.

Figure 3.7. Calculating the Slope of a Densification Curve

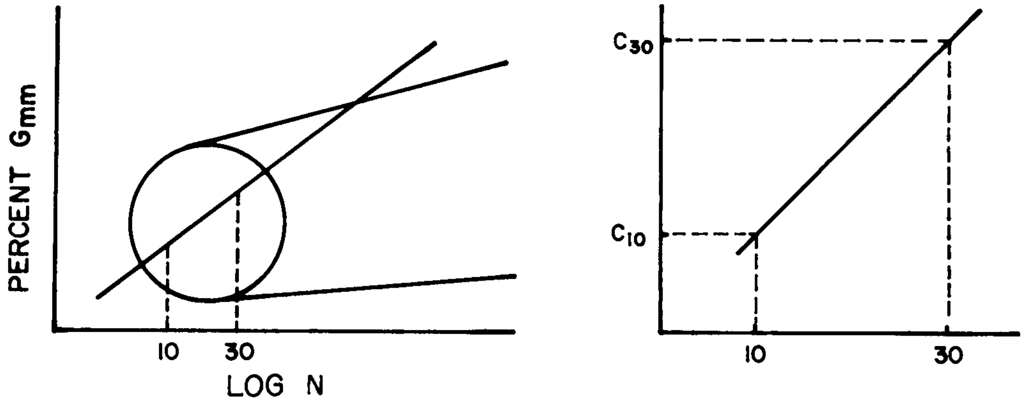
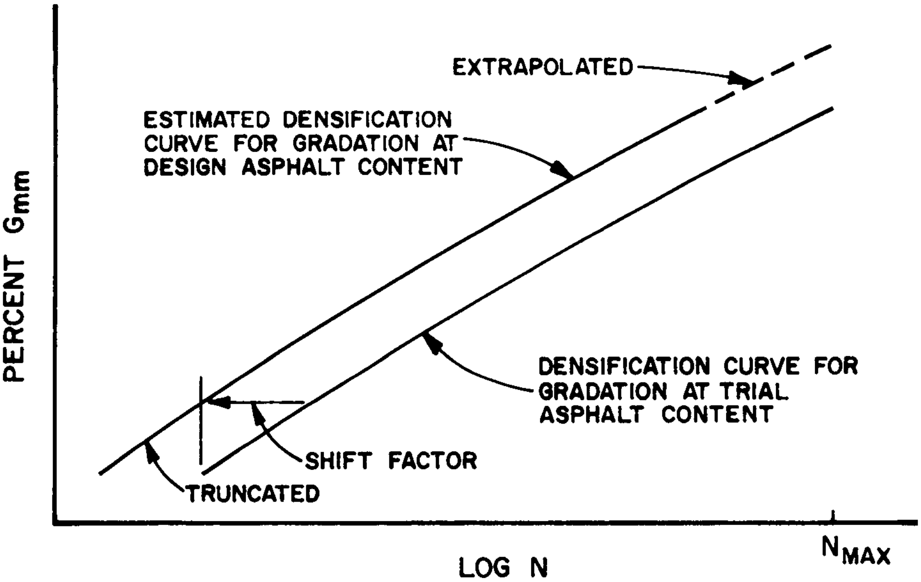


Figure 3.8. Shifting the Densification Curve of a Trial Asphalt Content



(4) Calculate V_a and VMA at N_{design} with the following equations:

$$V_a = 100 \frac{G_{mm} - G_{mb}}{G_{mm}} \tag{3-20}$$

and

$$VMA = 100 - \frac{G_{mb} P_s}{G_{sb}} \tag{3-21}$$

(5) Estimate VMA at four percent air voids and compare to the VMA requirements (Table 3.2).

(6) Determine the difference in air voids content (ΔV_a) of the compacted specimen from the design level of 4 percent:

$$\Delta V_a = 4 - V_a \tag{3-22}$$

where V_a = air voids content of the trial blend at N_{design} gyrations.

(7) Estimate the change in asphalt content (ΔP_b) needed to change the air voids content to 4 percent:

$$\Delta P_b = -\Delta V_a \times 0.4 = -0.4 (\Delta V_a) \tag{3-23}$$

where ΔP_b = change in asphalt content; and
ΔV_a = required change in air voids content from step (6) above.

(8) Estimate the change in VMA (ΔVMA) caused by the change in the asphalt content (ΔP_b) determined in step (7) with the appropriate equation in table 3.6.

A change in asphalt content affects the VMA through a change in the mixture compactibility.

(9) Calculate the VMA at the design level of 4 percent air voids by the equation

$$VMA_{design} = VMA_{trial} + \Delta VMA \tag{3-24}$$

where VMA_{design} = the VMA estimated at a design air voids content of four percent; and

VMA_{trial} = the VMA determined at the initial trial asphalt content.

Table 3.6. Calculation of ΔVMA

V_a For Initial Trial Asphalt Content	ΔVMA
> 4.0%	$0.2x\Delta V_a$
< 4.0%	$-0.1x\Delta V_a$

In the last step the design aggregate structure or gradation is selected from among the several trial aggregate gradations by comparing the estimated volumetric properties of the adjusted (to four percent air voids) paving mixes to the Superpave criteria for VMA and density.

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(10) Compare estimated volumetric properties at the adjusted design asphalt content to the Superpave criteria summarized in table 3.7 and select as the design aggregate structure the trial aggregate gradation that best satisfies the criteria.

Table 3.7. Summary of Volumetric Design Criteria

Volumetric Property	Superpave Limit
V_a at N_{design}	4%
VMA at N_{design}	Set by nominal maximum size of aggregate (Table 3.2)
C_{init}	< 89.0% of G_{mm}
C_{max}	< 98.0% of G_{mm}

Table 3.8 presents an example of the selection of a design aggregate structure from among three trial aggregate gradations.

The top portion of table 3.8 presents measured compaction densities and volumetric properties for specimens prepared for each trial aggregate gradation at the initial trial asphalt content. Note that none of the specimens had an air voids content of exactly 4 percent. Therefore, the procedures described above must be applied to (1) estimate the design asphalt content at 4 percent air voids, and (2) obtain adjusted VMA and compaction density values at this estimated asphalt content.

The middle portion of table 3.8 presents the change in asphalt content (P_b) and VMA that occurs when V_a is adjusted to 4 percent for each trial aggregate gradation.

As an example, consider trial aggregate gradation #2 in table 3.8. Calculation of ΔV_a, ΔP_b and ΔVMA yields :

$$\Delta V_a = 4 - (V_a @ N_{design}) = 4 - (4.7) = -0.7 \tag{3-25}$$

$$\Delta P_b = -0.4 \times \Delta V_a = (0.7) \times (0.4) = 0.3 \tag{3-26}$$

$$\Delta VMA = 0.2 \times \Delta V_a = (0.2 \times (-0.7)) = -0.1 \tag{3-27}$$

which are summarized in table 3.8.

Table 3.8. Selection Of a Design Aggregate Structure

Volumetric Property	Trial Aggregate Gradation			Criteria
	1	2	3	
At the initial trial asphalt content				
P_b(trial)	4.4	4.4	4.4	—
C_{init}(trial)	88.1	86.5	87.1	—
C_{design}	95.9	95.3	94.7	—
C_{max}(trial)	97.6	97.3	96.4	—
V_a at N_{design}	4.1	4.7	5.3	4.0
VMA_{trial}	12.9	13.4	13.9	—
Adjustments to reach design asphalt content (V_a = 4% at N_{design})				
ΔV_a	-0.1	-0.7	-1.3	—
ΔP_b	0.0	0.3	0.5	—
ΔVMA	0.0	-0.1	-0.3	—
At the estimated design asphalt content (V_a = 4% at N_{design})				
Estimated P_b(design)	4.4	4.7	4.9	—
VMA_{design}	12.9	13.3	13.6	>13.0
C_{init}(design)	88.2	87.2	88.4	<89.0
C_{max}(design)	97.7	98.0	97.7	<98.0

The bottom portion of table 3.8 carries the analysis to the last stage, estimating the compaction densities and volumetric properties at the design asphalt content and comparing these estimates to the Superpave criteria. Again using trial aggregate gradation # 2 as an example, the VMA and the densities at N_{init} and N_{max} are calculated as:

$$VMA_{design}=VMA_{trial}+\Delta VMA=13.4+(-0.1)=13.3 \qquad (3\text{-}28)$$

$$C_{init}(design)=C_{init}(trial)-\Delta V_a=86.5-(-0.7)=87.2 \qquad (3\text{-}29)$$

$$C_{max}(design)=C_{max}(trial)-\Delta V_a=97.3-(-0.7)=98.0 \qquad (3\text{-}30)$$

as shown in table 3.8.

Comparing the VMA and densities at the estimated design asphalt content with the criteria in the last column of table 3.8 shows that trial gradation # 1 does not have sufficient VMA (12.9 % versus a requirement of >13.0%). Trial gradation has sufficient VMA, but #2 exceeds the criterion for density at maximum gyrations (98.0 versus a requirement of <98.0). Trial gradation #3 meets the requirements for density and VMA and in this example is selected as the design aggregate structure.

Finally, the dust proportion, the ratio of the percent by weight of aggregate in the design aggregate structure passing the 75µm sieve to the effective asphalt binder content, V_{be}, is calculated and checked against the requirement in table 2.9.

3.7.4.3 Possible Remedies When Trial Aggregate Gradations Do Not Meet Superpave Criteria

Many trial aggregate gradations will fail the VMA criterion. Generally, the C_{init} and C_{max} criteria will be met if the VMA criterion is satisfied. Two options exist to increase the VMA of the trial aggregate gradation. First, the total gradation may be changed within the control points to boost VMA by changing the proportion of the aggregate fractions. Generally the VMA will increase as the gradation moves away from the 0.45 power maximum density line. Second, the aggregate shape or texture characteristics can be adjusted to boost the VMA.

If the trial aggregate gradations have been chosen to cover the entire range of the gradation controls, then the only remaining solution is to find a new source of aggregate.

The aggregates that fail to meet the required criteria will not produce an adequately strong aggregate structure and hence should not be used. One or more of the aggregate stockpiles should be replaced with another material that produces a stronger structure. For example, a quarry stone can replace a crushed gravel, or crushed fines can replace natural fines.

With a design aggregate structure selected, the level 1 design procedure proceeds to the next step, selecting the design asphalt content.

3.8 Selecting the Design Asphalt Content

This procedure described in this section corresponds with blocks (1-7) and (1-8) of figure 3.1, the flow chart of level 1 mix design.

Once the design aggregate structure is selected, the design asphalt content is determined for that structure. The design asphalt content is defined as the asphalt content that provides 4 percent air voids at the N_{design} gyrations.

Paving mix specimens, all containing the selected design aggregate structure, are prepared at several asphalt contents and compacted to N_{max} gyrations. The asphalt content that produces an air voids content (V_a) equal to 4 percent at N_{design} gyrations is selected as the design asphalt content.

Specifically, selecting of the design asphalt content includes the following steps:

- Select four asphalt binder contents (section 3.8.1).
- Mix the binder and aggregate, and short-term age the loose mix.
- Compact specimens for evaluation at each asphalt content (section 3.8.2).
- Determine the asphalt content that produces an air voids content equal to four percent (section 3.8.3).
- Compare the volumetric properties at the design asphalt content to the Superpave criteria and confirm their satisfactory compliance (section 3.8.4).

3.8.1 Selecting of Asphalt Contents for Evaluation

Determine the four asphalt contents at which to compact specimens with the design aggregate gradation:

- the estimated design asphalt content, P_b(design), from section 3.7.
- asphalt content 0.5 percent below P_b (design);
- asphalt content 0.5 percent above P_b (design); and
- asphalt content 1.0 percent above P_b (design).

3.8.2 Compact Specimens at Four Asphalt Contents

This section corresponds with block (1-7) in figure 3.1, the flow chart for level 1 mix design.

Duplicate specimens are mixed, aged and compacted at each asphalt content determined in section 3.8.1. The compaction effort, the number of design gyrations (N_{design}), is selected on the basis of the anticipated traffic level.

(1) Determine N_{init}, N_{design}, and N_{max} for the paving project from table 3.4.

(2) Compact two specimens to N_{max} gyrations in accordance with SHRP Method of Test M-002 from loose paving mix aged in the short-term aging procedure (SHRP Method of Test M-007).

(3) Determine the theoretical maximum specific gravity (G_{mm}) of the paving mix.

3.8.3 Select the Design Asphalt Content Corresponding to an Air Voids Content of Four Percent at N_{design}

This section corresponds with block (1-8) in figure 3.1, the flow chart for level 1 mix design.

For each asphalt content, evaluate the densification curve and measure the corrected specimen densities, C_{init}, C_{design} and C_{max}, at the three key compaction points, N_{init}, N_{design}, and N_{max}.

Determine V_a, VMA, and VFA at N_{design}. This requires calculating of the bulk specific gravity of the compacted paving mix at N_{design} from the density and the theoretical maximum specific gravity according to equation 3-15:

$$G_{mb} = (C_{design})\,(G_{mm}) \tag{3-31}$$

where G_{mb} = bulk specific gravity of the compacted mixture;
C_{design} = density of the compacted specimen at N_{design}; and
G_{mm} = maximum theoretical specific gravity.

Calculate V_a, VMA, and VFA at N_{design} from equations 3.1, 3.2, and 3.3:

$$V_a = 100 \frac{G_{mm} - G_{mb}}{G_{mm}} \tag{3-32}$$

$$VMA = 100 - \frac{G_{mb} P_s}{G_{sb}} \tag{3-33}$$

$$VFA = \frac{VMA - V_a}{VMA} \times 100 \tag{3-34}$$

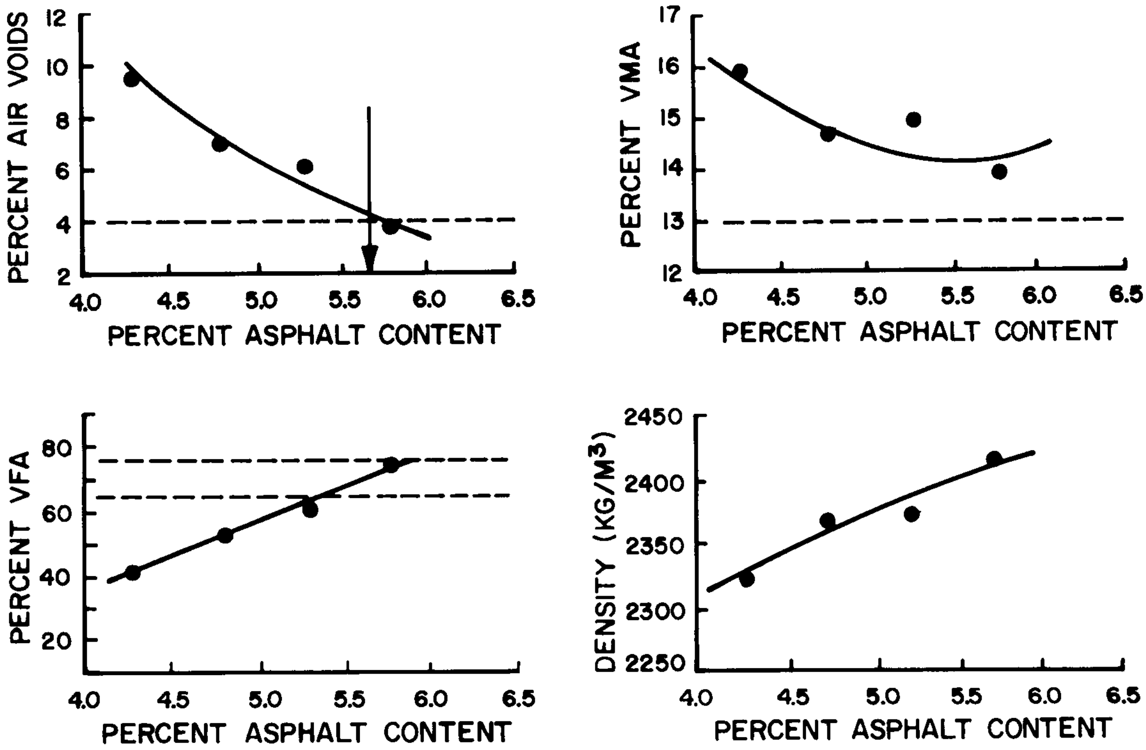
Plot V_a, VMA, VFA, and C_{design} versus asphalt content as shown in figure 3.9.

The Superpave software automatically generates all the graphs shown in figure 3.9.

By graphic interpolation, determine the design asphalt content (P_b) (to the nearest tenth of a percent) at which V_a is equal to four percent.

By graphic interpolation, verify that the paving mix meets the Superpave requirements for VMA and VFA (tables 3.2 and 3.3) at the design asphalt content.

Figure 3.9. Plots of Percent Air Voids, Percent VMA, Percent VFA and Density versus Percent Asphalt Content



As an example of selecting the design asphalt content, consider the sample data presented in table 3.9 and graphed in figure 3.9.

In this example, the estimated design asphalt content is 4.8 percent, the minimum VMA requirement for the design aggregate structure (19.0 mm nominal maximum size) is 13 percent, and the VFA requirement is 65 to 78 percent.

Entering the plot of percent air voids versus percent asphalt content in the upper left quadrant of figure 3.9 at 4 percent air voids, the design asphalt content is determined as 5.7 percent.

Entering the plots of percent VMA versus percent asphalt content (figure 3.9, upper right quadrant) and percent VFA versus percent asphalt content (figure 3.9, lower left quadrant) at 5.7 percent asphalt content, the paving mix is seen to meet the Superpave VMA and VFA requirements at the design asphalt content.

Table 3.9. Sample Volumetric Design Data at N_{design}

P_b (%)	V_a (%)	VMA (%)	VFA (%)	Density (kg/m^3)
4.3	9.5	15.9	40.3	2320
4.8	7.0	14.7	52.4	2366
5.3	6.0	14.9	59.5	2372
5.8	3.7	13.9	73.5	2412

3.8.4 Compare Volumetric Properties To Design Criteria at N_{init} and N_{max}

This section corresponds with block (1-7) in figure 3.1, the flow chart for level 1 mix design.

In this section, the density requirements, C_{init} and C_{max}, at the design asphalt content are checked against the requirements in table 3.5.

It is unlikely that an actual densification curve will be available at the design asphalt content. Therefore, it is necessary to estimate it by shifting a measured densification curve by an amount equal to the difference in the air voids contents (V_a) at the design asphalt content (4 percent by specification) and at the asphalt content corresponding to the measured densification curve.

The same shifting procedures used in 3.7.4 are used to determine C_{init} and C_{max}. From the shifted densification curve prepared at 4% air voids in section 3.7, determine C_{init} and C_{max}. Confirm that C_{init} and C_{max} satisfy the Superpave design requirements in table 3.5 at the design asphalt content.

This completes the selection of the design asphalt content, P_b.

3.9 Evaluate Moisture Susceptibility of the Design Aggregate Structure at the Design Asphalt Content

The procedure in this section corresponds with block (1-8) of figure 3.1, the flow chart for level 1 mix design.

3.9.1 Evaluation of Moisture Susceptibility with AASHTO Method of Test T 283 (Superpave Alternative I)

(1) Compact six[1] specimens composed of the design aggregate structure at the design asphalt content with the gyratory compactor in accordance with SHRP Method of Test M-002. Referring to the shifted densification curve from section 3.7, apply sufficient gyrations to produce an air voids content of 7 percent.

(2) Condition three specimens in accordance with AASHTO T 283. The remaining three specimens are tested dry (i.e., without conditioning).

(3) Test the six specimens in accordance with AASHTO T 283.

(4) Calculate the tensile strength ratio (TSR) as follows:

$$TSR=\frac{S_2}{S_1}\times 100 \qquad \textbf{(3-35)}$$

where S_1 = average tensile strength of dry subset, and
S_2 = average tensile strength of conditioned subset.

---

[1] Currently AASHTO T 283 recommends 100 mm diameter specimens, but permits 150 mm diameter specimens.

(5) If the TSR is less than 80 percent, remedial action such as the use of antistrip agents is required to improve the moisture susceptibility of the paving mix. The paving mix must be then be retested to ensure compliance with the minimum 80 percent requirement.

3.9.2 Evaluation of Moisture Susceptibility with SHRP Method of Test M-006 (Superpave Alternative II)

(1) Compact six[2] specimens composed of the design aggregate structure at the design asphalt content with the gyratory compactor in accordance with SHRP Method of Test M-002. Referring to the shifted densification curve from section 3.8.4, apply sufficient gyrations to produce an air voids content of 7 percent.

(2) Condition three specimens in accordance with SHRP Method of Test M-006. The remaining three specimens are tested dry (i.e., without conditioning).

(3) Test the six specimens in accordance with Method of Test M-006.

(4) Calculate the resilient modulus ratio ($M_R R$) as follows:

$$M_R R = \frac{M_{R2}}{M_{R1}} \times 100 \qquad (3\text{-}35)$$

where M_{R1} = average resilient modulus of dry subset, and
M_{R2} = average resilient modulus of conditioned subset.

(5) If the $M_R R$ is less than 70 percent, remedial action such as the use of antistrip agents is required to improve the moisture susceptibility of the paving mix. The paving mix must be then be retested to ensure compliance with the minimum 70 percent requirement.

3.10 Adjusting Mixture To Meet Properties

If the criteria in sections 3.8 or 3.9 cannot be met, adjustments must be made to the paving mix. Possible areas of noncompliance with criteria include VMA, VFA, and moisture susceptibility.

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[2] The environmental conditioning system requires 100 mm diameter, 100 mm high specimens.

3.10.1 Voids in Mineral Aggregate (VMA)

VMA failures will be rare since the selection of design aggregate structure is based on meeting the VMA criterion. However, if a change in the design aggregate skeleton is required, there are three likely options:

- Change the gradation. The gradation should be moved further from the maximum density line. Changing gradation may not be an option if the trial aggregate gradation analysis spans the full gradation control area.

- Reduce the minus 75µm fraction. Reducing the dust content of the paving mix will typically increase the VMA. If the dust content is already low, this is not a viable option.

- Change the surface texture, or shape of one or more of the aggregate fractions. This option will require further processing of existing materials or a change in aggregate sources.

3.10.2 Voids Filled With Asphalt (VFA)

The lower limit of the VFA range should always be met at 4 percent air voids if the VMA meets requirements. If the VFA upper limit is exceeded, then the VMA is substantially above the minimum required. If so, the mixture should be redesigned to reduce the VMA. There are three likely options:

- Change the gradation. The gradation should be moved closer to maximum density line.

- Increase the minus 75µm fraction. The dust content should be increased if room is available within the specification control points.

- Change surface texture and shape of aggregates. The aggregate should be changed to incorporate material with better packing characteristics (e.g., fewer thin, elongated aggregate particles).

3.10.3 Retained Tensile Strength or Resilient Modulus

Retained tensile strength or resilient modulus can be increased as follows:

- by addition of chemical antistrip agents to the asphalt binder to promote adhesion in presence of water; or

- by addition of hydrated lime to the paving mix.

3.11 Final Result of a Superpave Level 1 Mix Design

To promote uniformity and ease of comparison among different agencies and laboratories, paving mixes prepared by the Superpave mix design method are classified according to the designators described in Appendix D.

The final products of a level 1 mix design are:

- a design aggregate structure; and
- a design asphalt content.

The level 1 mix design procedure can be used as a stand alone design for low-volume roadways or as the starting point for either a level 2 or level 3 mix design as required by anticipated traffic requirements. The level 2 mix design procedure is described in chapter 4 of this manual, the level 3 procedure in chapter 5. A worked example of a level 3 mix design, including a complete treatment of level 1 design is presented in chapter 6.

4

Level 2 Mix Design (Intermediate Traffic Levels)

4.1 Introduction

The Superpave level 2 mix design builds upon the historical mix design practices found in the level 1 mix design, and involves performance tests which measure fundamental properties and predict pavement performance. These tests are described in chapter 1. The tests required are the repeated shear at constant stress ratio, simple shear at constant height, frequency sweep at constant height, and indirect tensile strength to predict permanent deformation and fatigue cracking; and the indirect tensile creep and indirect tensile strength to predict low-temperature cracking. These predictions are based on validated material properties which have been linked to pavement performance.

For permanent deformation, the simple shear at constant height, repeated shear at constant stress ratio, and frequency sweep at constant height are conducted at the effective temperature for permanent deformation. This effective temperature is calculated from the pavement temperatures for the project site. For fatigue cracking, the frequency sweep at constant height, the simple shear at constant height, and the indirect tensile strength tests are conducted at the effective temperature for fatigue cracking. This effective temperature is also calculated from the pavement temperatures for the project site.

Predictions for low-temperature cracking are based on indirect tensile creep tests performed at 0°C, -10°C, and -20°C and on indirect tensile strength tests performed at -10°C. Bending beam test data from the asphalt binder test are used in conjunction with the creep data to predict low-temperature response. A time series of historical pavement temperatures is used to predict tensile stress and fracture.

Since the analyses are independent of each other, the test sequence for any of the three distress types can be eliminated. Thus the design can be focussed on distress types of primary concern. Additionally, the three shear tests can be conducted using the SHRP shear test device, or in an intermediate shear test device designed to operate at elevated temperatures without confining pressure.

Level 2 mixture design has been kept uncomplicated enough for routine use. Figure 4.1 illustrates the flow chart for the level 2 mix design process. In situations where level 1 mixture design with no mechanical property measurement is not considered to be sufficiently reliable, level 2 mixture design should be used. Level 2 mixture design is expected to be the most common design type used in typical highway applications. The level 2 mix design should be used for project traffic having greater than 10^6 but less than 10^7 design equivalent single axle loads (ESALs). Level 2 mixture design will provide a mix design that will perform as required without excessive design effort and expense.

4.2 Outline of Level 2 Mix Design Method

The procedure for the Superpave level 2 (intermediate traffic) mix design method starts with the sample preparation and volumetric design method (level 1 design) described in Chapter 3. The level 2 design method is applied when the design ESALs over the anticipated service life of the pavement are projected to fall between 10^6 and 10^7.

In the Superpave mix design method, the steps needed to perform the level 2 (intermediate traffic) mix design include:

- Conduct volumetric (level 1) mix design.
- Select three asphalt contents bracketing the level 1 design asphalt content.
- Specify distress types for evaluation.
- Obtain pavement temperature history.
- Calculate effective temperatures.
- Run performance-based tests.
- Evaluate test data to calculate material properties.
- Obtain predicted traffic levels.
- Obtain structural layer information.
- Predict pavement performance.

Table 4.1 shows the tests required for the various distress factors. Table 4.2 illustrates the number of compacted specimens by distress factor and test. Appendix B provides for reference the system of specimen coding used by the Superpave software.

Figure 4.1. Superpave Level 2 Mix Design
(Note: All specimens are compacted from paving mix that has been short-term aged (SHRP M-007)

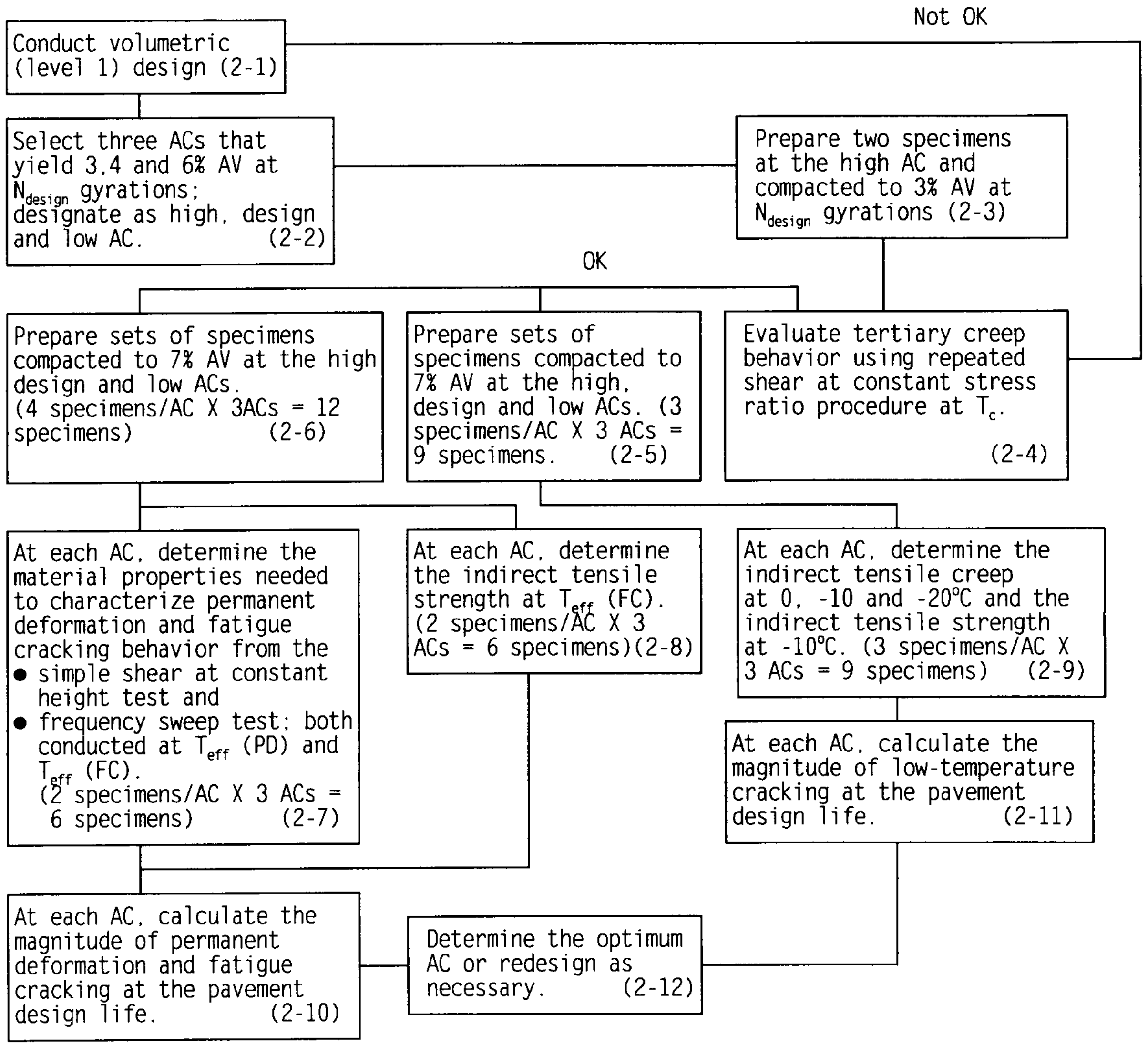


Table 4.1. Performance Tests For Level 2 Mix Design

Permanent Deformation Tests	Fatigue Cracking Tests	Low-Temperature Cracking Tests
Repeated shear at constant stress ratio (tertiary creep)*	Simple shear at constant height at T_{eff}	Indirect tensile creep at 0°C, -10°C and -20°C.
Simple shear at constant height at T_{eff}	Frequency sweep at T_{eff}	Indirect tensile strength at -10°C.
Frequency sweep at T_{eff}	Indirect tensile strength at T_{eff}	Creep stiffness (S) and slope (m) of binder from bending beam test

*Conducted to insure that excessive permanent deformation will not occur early in the pavement service life.

Table 4.2. Compacted Specimen Requirement for Level 2 Mix Design (Per Asphalt Content)

Method of Test	Testing Temperature (°C)				
	-20	-10	0	T_{eff}(PD)	T_{eff}(FC)
Repeated shear at constant stress ratio (tertiary creep)				2 (at T_c)	
Simple shear at constant height				2*	2*
Frequency sweep at constant height				2*	2*
Indirect tensile strength (50 mm/min loading rate)					2
Indirect tensile creep	3*	3*	3*		
Indirect tensile strength (12.5 mm/min loading rate)		3*			

*Tests performed on same specimens.

4.2.1 Historical Air Temperature

Superpave uses a 10-year block of historical temperatures in performance prediction. Unlike the statistical air temperature information used for asphalt binder grade selection in level 1 design, a database containing 10 years of historical daily minimum and maximum temperatures for all of the United Stated is impractical. A library of historical air temperature for each state is available with the Superpave software. Mix designers can install temperature files for areas of interest, thus reducing the volume of unneeded information.

4.2.2 Historical Pavement Temperature

Historical air temperatures are converted into historical pavement temperatures using the Federal Highway Administration Environmental Effects Model which is embedded in the Superpave software. The output of the Environmental Effects Model used by the Superpave software is limited to pavement temperatures. Temperatures of other layers and other model outputs are not used.

4.2.3 Pavement Temperature Converted Into Effective Temperature

The level 2 mix design predicts performance for permanent deformation and fatigue cracking by collapsing the entire pavement temperature history into a single effective temperature at which the material properties are measured and for which pavement performance is predicted. The effective temperature differs for permanent deformation and fatigue cracking. The Superpave software calculates both effective temperatures which are used as test temperatures for the performance-based tests.

4.2.4 Calculate Material Properties

The Superpave software accesses data files created by the data collection software which is associated with the Superpave performance test equipment. Testing machines have stand-alone software to control execution of the performance-based test protocols. The Superpave software processes the data files using embedded software to obtain material properties.

4.2.5 Predict Pavement Performance

The Superpave software predicts pavement performance using material properties, traffic, pavement temperature, and pavement structure, and displays results in terms of distress versus time.

4.3 Equipment

The equipment required to prepare and test compacted specimens is as follows:

- *Pan:* metal, flat bottom, for heating aggregates.
- *Pans*: metal, round, approximately 4-l capacity, for mixing asphalt and aggregates.
- *Oven and hot plate*: electric, for heating aggregates, asphalt, and equipment as required. Oven must also be capable of maintaining the temperature for short-term aging (SHRP Method M-007).
- *Scoop*: for batching aggregates.
- *Containers:*, gill-type tins, beakers, pouring pots, or sauce pans, for heating asphalt.
- *Thermometers:* armored, glass, or dial-type with metal stem, 10°C to 230°C, for determining temperature of aggregates, asphalt, and asphalt mixtures.
- *Balance*: 5-kg capacity, sensitive to 1 g for weighing aggregates and asphalt. *Balance* 2-kg capacity, sensitive to 0.1 g for weighing compacted specimens.
- *Mixing spoons:* large, or *trowel*: small.
- *Spatula*: large.
- *Mechanical mixer:* (optional), commercial bread dough mixer 4-l capacity or larger, equipped with two metal mixing bowls and two wire stirrers.
- *Gloves*: welders, for handling hot equipment. *Gloves:* rubber, for removing specimens from water bath.
- *Marking crayons*: for identifying test specimens.
- *SHRP gyratory compactor*: capable of providing a consolidation pressure of 0.60 MPa, an angle of gyration of 1.25 degrees, and speed of gyration of 30.0 rpm, as described in SHRP Method of Test M-002.
- *Cylindrical molds*: large enough to accommodate the following specimen size requirements: 150 mm diameter, 150 mm maximum height and 90 mm minimum height.
- *Extrusion jack* or *arbor press*: for extruding compacted specimens from mold.

- *Superpave shear test device*: meeting the requirements in SHRP Method of Test M-003, or capable of conducting the shear tests required.
- *Indirect tensile test device*: meeting the requirements in SHRP Method of Test M-005, or capable of conducting the indirect tensile tests required.

4.4 Selecting of Mixture Materials for Volumetric Design

The procedures in this section correspond with block (2-1) in figure 4.1, the flow chart for level 2 (intermediate) mix design.

The first important step in the level 2 mix design procedure is selecting materials suited to the demands of traffic and environment expected over time for the paving project.

(1) Select the fine and coarse aggregate for trial blends, in accordance with the details provided in chapter 2 of this manual.

(2) Select the performance grade of the asphalt binder in accordance with the details provided in chapter 2.

(3) Conduct the (optional) net adsorption test to evaluate asphalt-aggregate compatibility, in accordance with the details provided in section 2.2.3.

(4) Conduct the trial asphalt content and trial gradation evaluations and determine the design aggregate structure and the design asphalt content based on volumetric properties requirements, in accordance with the procedures provided in chapter 3 of this manual.

Note: The design traffic level (N_{design}) for the level 2 mix design is between 10^6 and 10^7 ESALs as discussed in chapter 3. N_{init} and N_{max} are presented in table 3.4.

4.5 Selecting of Asphalt Contents to Yield 3, 4, and 6 percent Air Voids

This procedure presented in this section corresponds with block (2-2) of figure 4.1, the flow chart of level 2 mix design.

(1) Refer to section 3.8.3 for the level 1 volumetric mix design. At the design number of gyrations (N_{design}) volumetric properties are calculated for each asphalt content as shown in table 3.9. Air voids, VMA, and VFA are plotted for each asphalt content as shown in figure 3.9.

(2) From the plot of percent air voids versus percent asphalt content (figure 3.9), determine the asphalt contents at three, four, and six percent air voids.

(3) Designate the asphalt contents at three, four, and six percent air voids as high, design, and low, respectively.

4.6 Determining the Effective Temperature for Fatigue Testing

Several approaches were investigated to establish an effective temperature for fatigue cracking ($T_{eff}(FC)$) analogous to that illustrated in section 4.7 for permanent deformation. In the level 2 mix design procedure $T_{eff}(FC)$ is defined as a single test temperature at which an amount of fatigue damage would occur equivalent to that measured by considering each season separately throughout the year.

Because the fatigue cracking mechanism consists of two separate phases, crack initiation and crack propagation, procedures for selecting an equivalent temperature were complex and inappropriate for use in routine mix design applications. A simplified approach was used in which the total fatigue damage was computed with the Superpave fatigue cracking model on a month-by-month basis for 12 Long-Term Pavement Performance GPS pavement sections with varying levels of fatigue cracking. The average monthly total fatigue damage was then calculated and used to determine a single test temperature for each pavement that would result in an equivalent amount of fatigue cracking.

For simplicity, the fatigue damage equivalent temperatures were compared to the mean annual pavement temperatures for each pavement. This analysis showed that a good value for the equivalent fatigue damage temperature, $T_{eff}(FC)$, can be estimated from the mean annual pavement temperature with the following equation:

$$T_{eff}(FC) = 0.8(MAPT) - 2.7 \tag{4-1}$$

where $T_{eff}(FC)$ = the effective test temperature in °C for fatigue cracking; and

MAPT = the mean annual pavement temperature in °C calculated at one-third of the depth of the pavement layer from climatic data for its geographic location.

For example, the MAPT for an asphalt surface course that is 30 mm thick would be calculated at one-third the depth of the pavement layer or at a position 10 mm below the top of the layer.

$T_{eff}(FC)$ is automatically calculated for level 2 mix designs through menu-driven routines contained in the Superpave software.

4.7 Determining the Effective Temperature for Permanent Deformation Testing Including Tertiary Creep

The effective temperature for permanent deformation, T_{eff}(PD), is defined as a single test temperature at which an amount of permanent deformation would occur equivalent to that measured by considering each season separately throughout the year. T_{eff}(PD) is the temperature at which the tests to evaluate permanent deformation are conducted. This approach simplifies testing, but is less accurate than the environmental effects model used with the level 3 mix design approach.

T_{eff}(PD) is automatically calculated for level 2 mix designs through menu-driven routines contained in the Superpave software. The following sections illustrate the methodology of the calculation of T_{eff}(PD) used in the software.

For the desired critical depth, Z_{cr}, the T_{eff}(PD) for the level 2 mix design is calculated from the following equations:

$$T_{eff}(PD) = 30.8 - 0.12 Z_{cr} + 0.92 MAAT_{design} \qquad \textbf{(4-2)}$$

where

T_{eff}(PD) = effective temperature (°C);

Z_{cr} = critical depth within the mix layer in question (mm); and

and

$$MAAT_{design} = MAAT_{average} + K_{\alpha} \sigma_{MAAT} \qquad \textbf{(4-3)}$$

where

$MAAT_{(average)}$ = average mean annual air temperature computed from historical data;

σ_{MAAT} = standard deviation of the distribution of mean annual air temperature for the geographic location; and

K_{α} = value computed from normal probability tables and related to the designer's selection of an appropriate reliability level (R) desired for the project.

Appropriate values of K_{α} for given reliability levels (R) are given in table 4.3:

Table 4.3. Values of K_α

R (Reliability)	K_α
50 %	0.000
75 %	0.674
85 %	1.037
90 %	1.282
95 %	1.645
99 %	2.327

As an example, consider a surface course mix to be placed on a major interstate highway near Richmond, Virginia. For these conditions, the following values have been selected:

Z_{cr} = 25 mm (surface course analysis),

MAAT = 14.4°C,

R = 95% (high reliability desired for interstate-type pavement), and

σ_{MAAT} = 3.0°C (computed from historic temperature data).

Therefore,

$$MAAT_{design}=MAAT_{average}+K_\alpha \sigma_{MAAT} \tag{4-4}$$

$$MAAT_{design}=14.4+(1.645)(3.0) \tag{4-5}$$

$$MAAT_{design}=19.3°C \tag{4-6}$$

The design T_{eff}(PD) value is therefore

$$T_{eff}(PD)=30.8-(0.12)(25)+(0.92)(19.3) \tag{4-7}$$

$$T_{eff}(PD)=45.6°C \tag{4-8}$$

4.8 Tertiary Creep Evaluation

The tertiary creep evaluation is a screening process to identify a mix that exhibits tertiary plastic flow leading to gross mix instability. If the mix fails the screening test, it will be necessary to either make adjustments to the mix proportioning or to redesign the mix completely. If the mix passes the screening test requirements, the mix may be subjected to the battery of tests for the characterization of permanent deformation, fatigue cracking, and low-temperature cracking.

Figure 4.2 illustrates conceptually the relationship between tertiary plastic flow and the performance prediction model established in the Superpave software. For a particular test temperature, the laboratory relationship between the log of the permanent strain, ε_p, and the log of the number of load repetitions, N, for a specific mix may actually result in the relationship shown in figure 4.2. For this case, it is obvious that tertiary plastic flow leading to gross mix instability is present. However, the Superpave performance model analysis uses a linear model, or steady-state secondary creep, (i.e. the slope S) shown in figure 4.2. Therefore, analysis of permanent deformation using the test methods in table 4.2 and the Superpave performance model are not sufficient to identify a mix design that will exhibit tertiary creep under certain circumstances.

The procedure outlined in this section corresponds with blocks (2-3) and (2-4) in figure 4.1, the flow chart for the Superpave level 2 mix design. Steps (2) through (10) are guided by the Superpave software.

Primary Procedure

(1) Prepare two specimens at the high asphalt content as determined in section 4.5 and compact to 3 percent air voids at N_{design} gyrations, using SHRP Method of Test M-002.

(2) For the mix type and layer thickness in question, select an appropriate value of Z_{cr}. (This can be simplified by selecting Z_{cr}= 25 mm for a surface course layers; Z_{cr}= 62.5 mm for a binder course; Z_{cr}= 100 mm for a base course; etc.).

(3) Determine the mean annual air temperature (MAAT) and the corresponding standard deviation (σ_{MAAT}) for the design site location.

(4) Determine the design traffic repetition value *N(des)*, and select appropriate values for the design reliability (R) and the K_α.

(5) Compute the T_{eff} value for the pavement location.

(6) Plot the point (*N(des)*-T_{eff}) on Figure 4.3 and determine the appropriate Curve ID letter. If this point plots "beyond Curve M", go to the alternative procedure, steps (8) through (10).

(7) Determine the recommended control temperature, T_c, at which to conduct the repeated shear test at constant stress ratio (SHRP Standard Practice P-005) from the following table:

Curve ID	T_c(°C)	Curve ID	T_c(°C)
A	29	H	49
B	32	I	52
C	35	J	54
D	38	K	57
E	41	L	60
F	43	M	63
G	46		

Figure 4.2. Typical Relationship of Plastic (Permanent) Strain, ε_p, and Load Repetitions, N, For Mixes with Tertiary Creep (Plastic Flow)

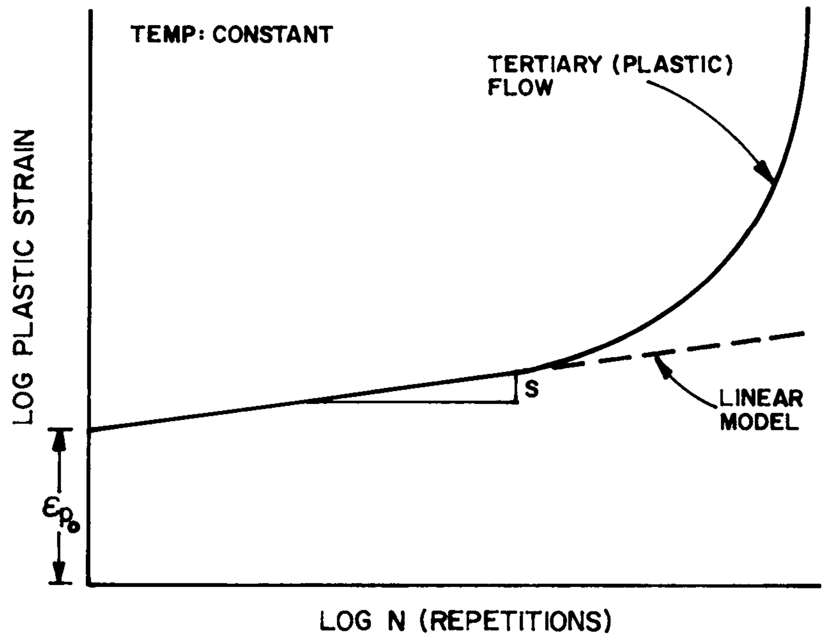
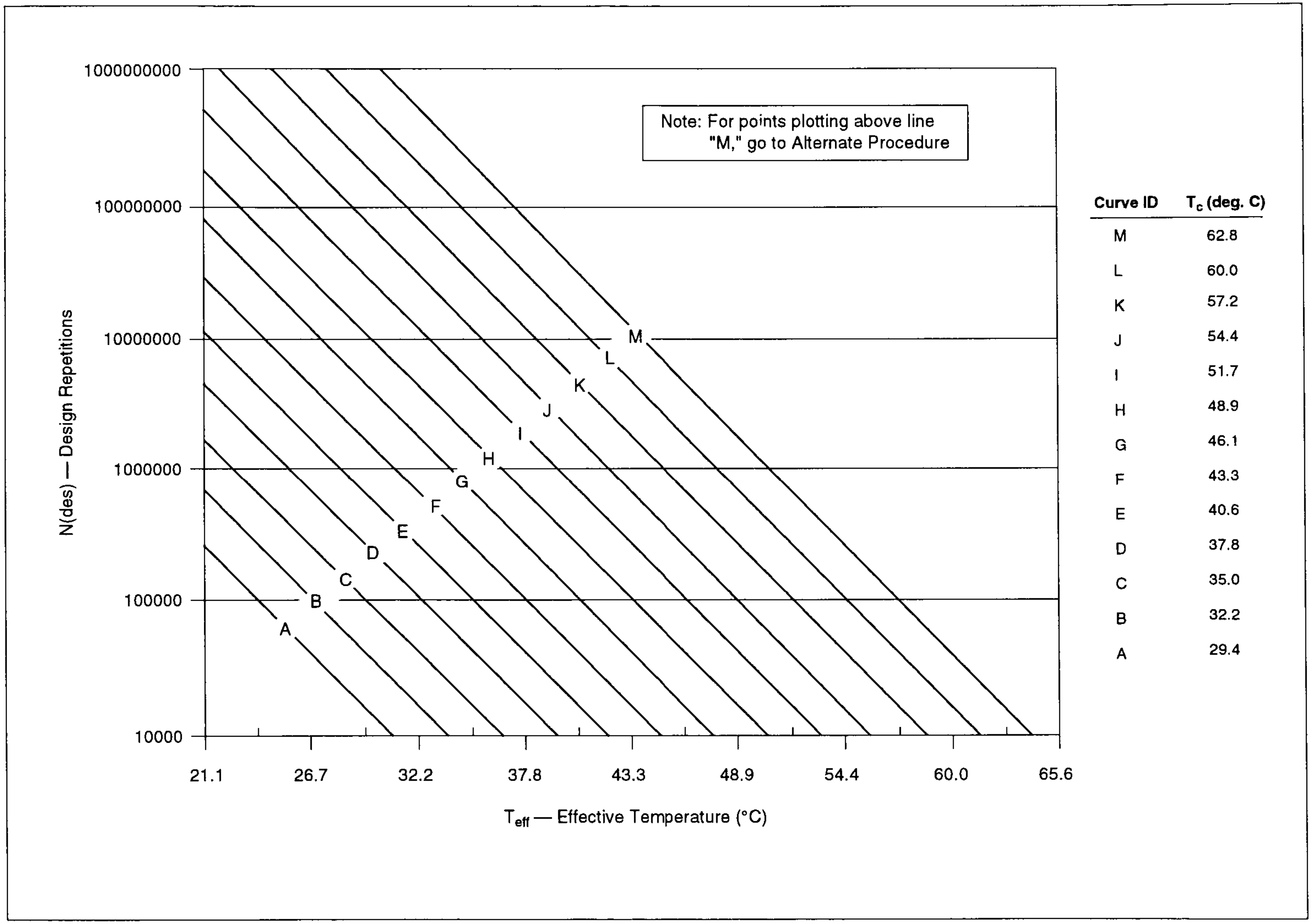


Figure 4.3. Selection of Approximate Control Temperature (T_c) Curve



At this T_c, the repeated shear test is conducted for 20,000 repetitions, at the shear and compressive stresses selected from table 4.4; this requires 4 hours of testing.

Table 4.4. Maximum Shear and Compressive Stress Levels

Base Condition	Maximum Shear (τ) And Compressive (σ_v) Stress Levels (kPa) at Asphalt Binder Content		
	Above Design	Design	Below Design
	τ σ_v	τ σ_v	τ σ_v
Weak	84 119	63 98	49 56
Strong	98 175	84 105	56 91

Note: A weak base is defined as an unbound granular or crushed stone material (i.e; new construction); a strong base is defined as an existing asphalt concrete or portland cement concrete pavement, a cement-stabilized or asphalt-stabilized base, or a strong crushed stone base material (i.e., a resilient modulus of 560,000 kPa or greater).

Alternative Procedure

This procedure is employed when a value of T_c greater than 63°C would be required for the primary procedure.

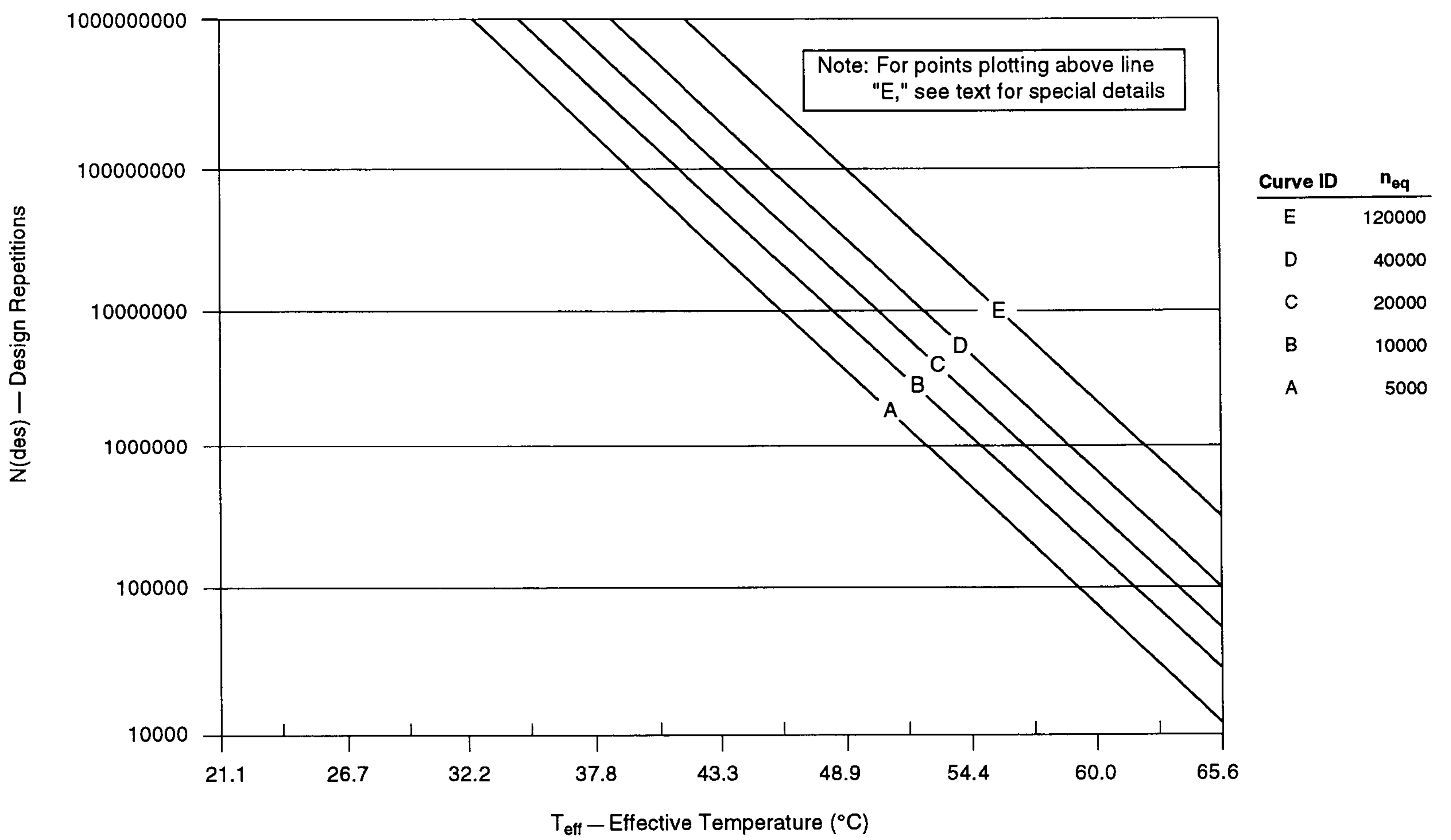
(8) Plot the point (N(*des*)-T_{eff}) on figure 4.4 and determine the appropriate Curve ID letter. If this point plots "beyond Curve E," see the instructions following step 10.

(9) Determine the required number of repeated shear test repetitions, N_{eq}, and the expected test period from the following table:

Curve ID	N_{eq}	Time (hr)
A	5,000	1
B	10,000	2
C	20,000	4
D	40,000	8
E	120,000	24

(10) Conduct the repeated shear test at constant stress ratio at a test temperature of T_c = 63°C and the stress and compressive stresses determined from table 4.4 for the number of test repetitions determined in step (9).

Figure 4.4. Selection of the Approximate Equivalent Laboratory Repetition Curve


Note: For points plotting above line "E," see text for special details

Points plotting beyond Curve ID "E" on figure 4.4 will generally be very difficult to test due to the combinations of high temperature, stress state, and the required repetition level (i.e., time of test). For these rare cases, it is suggested that a reduced design period be selected and the process repeated until a solution is feasible (step (7) or step (9)). When this case occurs, the mix design engineer should realize that full assurance of the mix quality cannot be made for the original design period desired.

Data from the repeated shear at constant stress ratio test is plotted as shown in Figure 4.2. Suitability of the mixture is determined qualitatively; if the mixture exceeds the linear phase and enters the tertiary flow region the mixture is judged unsuitable for the intended purpose.

Note that tertiary creep evaluation is performed only on the uppermost pavement layer at the highest asphalt content to be evaluated.

4.9 Permanent Deformation and Load-Associated Fatigue Property Characterization

The procedures described in this section correspond with blocks (2-6), (2-7), and (2-8) in figure 4.1, the flow chart for level 2 mix design.

The procedures presented in this section determine by appropriate test methods the material properties needed to predict the mix's potential for permanent deformation and load-associated fatigue over its service life.

(1) Compact (by SHRP Method of Test M-002) three sets of four specimens each to 7 percent air voids at the high, design, and low asphalt contents determined in section 4.5. Twelve specimens are prepared (4 specimens per asphalt content times 3 asphalt contents = 12).

(2) Six specimens (2 specimens per asphalt content times 3 asphalt contents = 6) are selected for testing for permanent deformation and load-associated fatigue properties. The other six specimens will be used for determining the indirect tensile strength in step 6.

(3) For each asphalt content, test one pair of specimens by performing the frequency sweep at constant height, in accordance with section 7.5 of SHRP Practice P-005. Nine frequency sweeps are conducted at 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, and 0.02 Hz. Each series of sweeps is conducted at the T_{eff}(FC) determined for fatigue cracking in section 4.6. Record the axial deformation, shear deformation, axial load, and shear load during the load cycles at the rate specified in SHRP P-005 and in a format suitable for analysis by the Superpave software.

(4) Using the same pair of specimens tested in step 3 conduct the frequency sweep at constant height with section 7.5 of SHRP Practice P-005. Conduct the same nine frequency sweeps as specified in step 3. Each series of sweeps is conducted at the T_{eff}(PD) determined for permanent deformation in section 4.7. Record the same measurements specified in step 3.

(5) Using the same pair of specimens tested in steps 3 and 4, conduct the simple shear at constant height test in accordance with section 7.4 of SHRP Practice P-005 at T_{eff}(PD) and T_{eff}(FC), respectively. At both test temperatures, record the axial deformation, the shear deformation, the axial load, and the shear load at a rate of about 10 data points per second. The data recorded must be in a format suitable for analysis by Superpave software.

(6) For each asphalt content, test the remaining pair of specimens prepared in step 1 by performing the indirect tensile strength test in accordance with SHRP Method of Test M-005 at T_{eff}(FC). Record the maximum peak load at a ram load rate of 50mm per minute in a format suitable for analysis by the Superpave software.

4.10 Predicting Permanent Deformation and Load-Associated Fatigue Cracking at the Pavement Design Life

The procedure outlined in this section corresponds with block (2-10) in figure 4.1, the flow chart for level 2 mix design.

(1) The data recorded in section 4.9, steps 3 through 6, are transferred to the Superpave software in a format suitable for analysis.

(2) The Superpave software predicts permanent deformation for a standard load applied to a pavement structure at the effective temperature. Stresses are calculated within each pavement layer using pavement temperature and mixture stiffness obtained from the frequency sweep test data. Permanent deformation of the pavement layer is calculated using simple shear test results, and total permanent deformation (rut depth) at the pavement surface is calculated versus time.

(3) Fatigue cracking is estimated using an effective temperature for a single season, as calculated for fatigue cracking in section 4.6. Stresses within each pavement layer are calculated for the layer stiffness representative of the temperature under a standard load. Dissipated energy is calculated for each single season, and the cumulative dissipated energy is used to estimate the percent of fatigue cracking over the anticipated or designated service life of the pavement is predicted.

4.11 Low-Temperature Cracking (Non-Load Associated) Property Characterization

The procedures in this section correspond with blocks (2-5 and 2-9) in figure 4.1, the flow chart for level 2 mix design.

The procedures outlined in this section determine the material properties by appropriate test methods in order to predict the mix design's potential to experience low-temperature cracking over its service life.

(1) Compact (by SHRP Method of test M-002) three sets of three specimens each to seven percent air voids at the high, design, and low asphalt contents as determined in section 4.5. Nine specimens are prepared (3 specimens per asphalt content times 3 asphalt contents = 9).

(2) For each asphalt content, test three specimens by performing the indirect tensile creep test at -20°C, - 10°C and 0°C and the indirect tensile strength test at -10°C in accordance with section 9.7 of SHRP Method of Test M-005. For each specimen, continuously record the load and the vertical and horizontal deformation measurements in a format suitable for analysis by the Superpave software.

4.12 Predicting Low-Temperature Cracking at the Pavement Design Life

The procedure outlined in this section corresponds with block (2-11) in figure 4.1, the flow chart for Level 2 mix design.

(1) The data recorded in section 4.11 are entered into the Superpave software in a format suitable for analysis.

(2) Low-temperature cracking is predicted using low-temperature creep behavior and low temperature fracture strengths. Predictive models are used with statistical weather data to predict stresses caused by overnight temperature cycles. Fracture mechanics is used in conjunction with tensile strength and predicted tensile stress to determine the advancement of cracking. Estimates are obtained of crack spacing with time.

4.13 Selecting the Optimum Asphalt Content

The procedure outlined in this section corresponds with block (2-12) in figure 4.1, the flow chart for level 2 mix design.

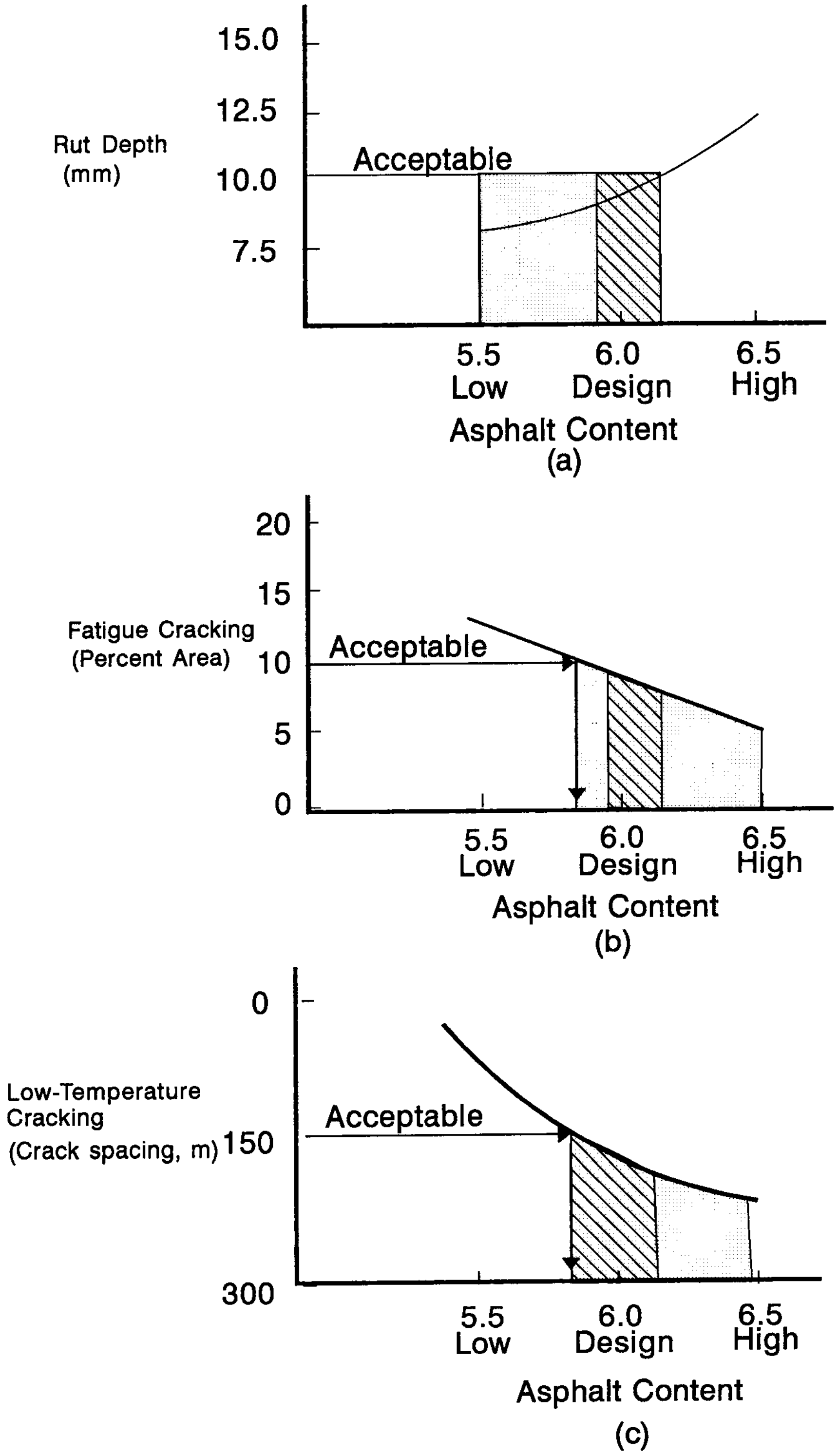
The predicted values of permanent deformation (rut depth), fatigue cracking (percentage of pavement area) and low-temperature cracking (crack spacing) are used to select the optimum asphalt content.

The magnitudes of the predicted values for the distress factors determined in sections 4.10 and 4.12 are plotted against the asphalt contents tested in sections 4.9 and 4.11. Figure 4.5, illustrates the plots. Table 4.5 presents suggested acceptable levels of performance for each distress. These may be adjusted as the design agency acquires more data or totally replaced by the design agency's specific levels. The design agency's acceptable levels for permanent deformation, fatigue cracking, and low-temperature cracking are identified on the vertical axis of the graphs and projected to the right to intersect with the plot. A vertical line is projected at this point of intersection perpendicular to the horizontal axis as shown in figure 4.5.

Table 4.5. Suggested Acceptable Levels of Performance
Level 2 Mix Design

Distress Factor	Acceptable Level
Permanent Deformation Reliability (%) Average rut depth (in)	 95 10
Fatigue Cracking Reliability (%) % of Area	 90 10
Low-Temperature Cracking Reliability (%) Crack Spacing, m	 80 >150

Figure 4.5. Selection of Optimum Asphalt Content Range Satisfying Three Distress Factor Conditions



Asphalt contents to the left of the vertical line (figure 4.5, top) as shown by the shaded area satisfy the permanent deformation requirement. Asphalt contents to the right of the vertical line (figure 4.5, middle and bottom) as shown by the shaded area satisfy the fatigue and low temperature requirements.

The dashed area indicates the range of asphalt contents that will satisfy all three distress factor requirements related to the design agency's acceptable levels. Select an asphalt content within this band and designate as the optimum asphalt content to be used for mix production.

If only two distress factors are of prime importance to the designer, a similar procedure is used (figure 4.6). For this example, permanent deformation and fatigue cracking are being considered. The dashed area indicates the range of asphalt contents that will satisfy the design agency's acceptable levels for these two distress types. The optimum asphalt content is selected within this range.

If one distress factor is of primary concern the following approach is used. Refer to figure 4.5 or 4.6. Using permanent deformation as an example, the asphalt contents to the left of the vertical line (as shown by the shaded area) satisfy the permanent deformation requirement. The same approach is used for fatigue or low temperature cracking, except the shaded area to the right of the vertical line in figure 4.6 satisfies the requirement. The optimum asphalt content may be selected within this range identified by the shaded area.

If a range of acceptable asphalts cannot be established to select an optimum asphalt content that satisfies all the distress factors evaluated, the mix proportioning can be adjusted or a modifier or modified binder should be considered in the mix design.

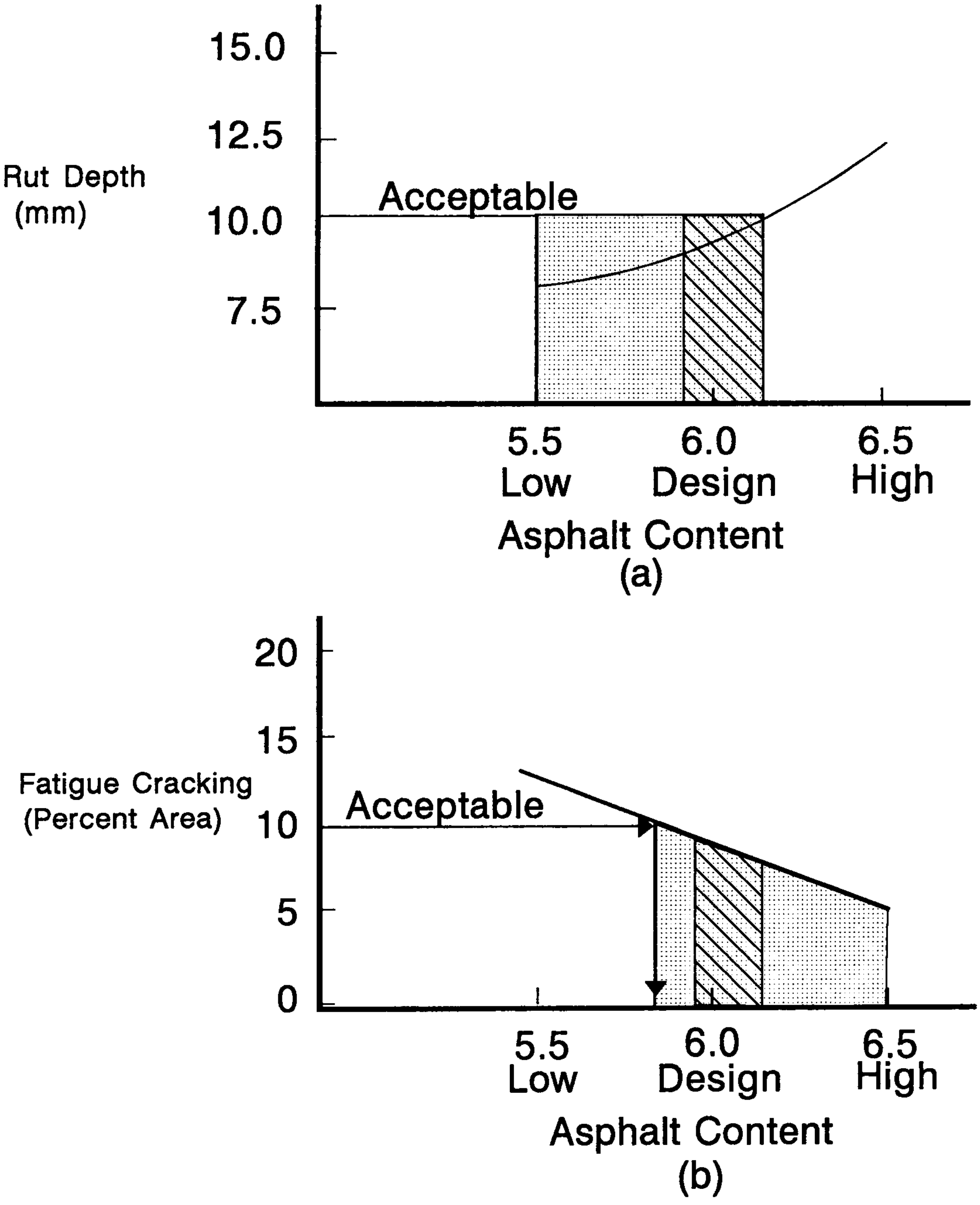
The Superpave software provides the comparative plots discussed in this section. They are generated from the test input data and the design agency's acceptable level of performance.

4.14 Treatment of Modified Materials and Mixtures

If a modifier is used to enhance the mix performance capability, the procedures outline previously for permanent deformation and low-temperature cracking apply also to modified mixtures. The prediction models used in Superpave will apply to both conventional and modified asphalts and mixtures for evaluating pavement performance in terms of permanent deformation and low-temperature cracking.

However, if fatigue is the principal distress type addressed by a modifier, flexural beam testing is recommended in place of the frequency sweep, simple shear at constant height, and indirect tensile strength test procedures. No prediction capability is available for this situation with the Superpave models. A comparison of the cycles to failure can be made between the conventional and modified mixture.

Figure 4.6. Selection of Optimum Asphalt Content Range Satisfying Two Distress Factor Conditions



5

Level 3 Mix Design (High Traffic Levels)

5.1 Introduction

The Superpave level 3 mix design is similar to the level 2 mix design procedure, except that a more complete set of performance-based mixture properties are obtained, and the performance models used to predict fatigue and permanent deformation are more comprehensive in level 3 than in level 2.

To complete the characterization of material properties, two tests are used in addition to the performance-based tests from level 2. Figure 5.1 shows the level 3 mix design flow chart. The following tests are performed:

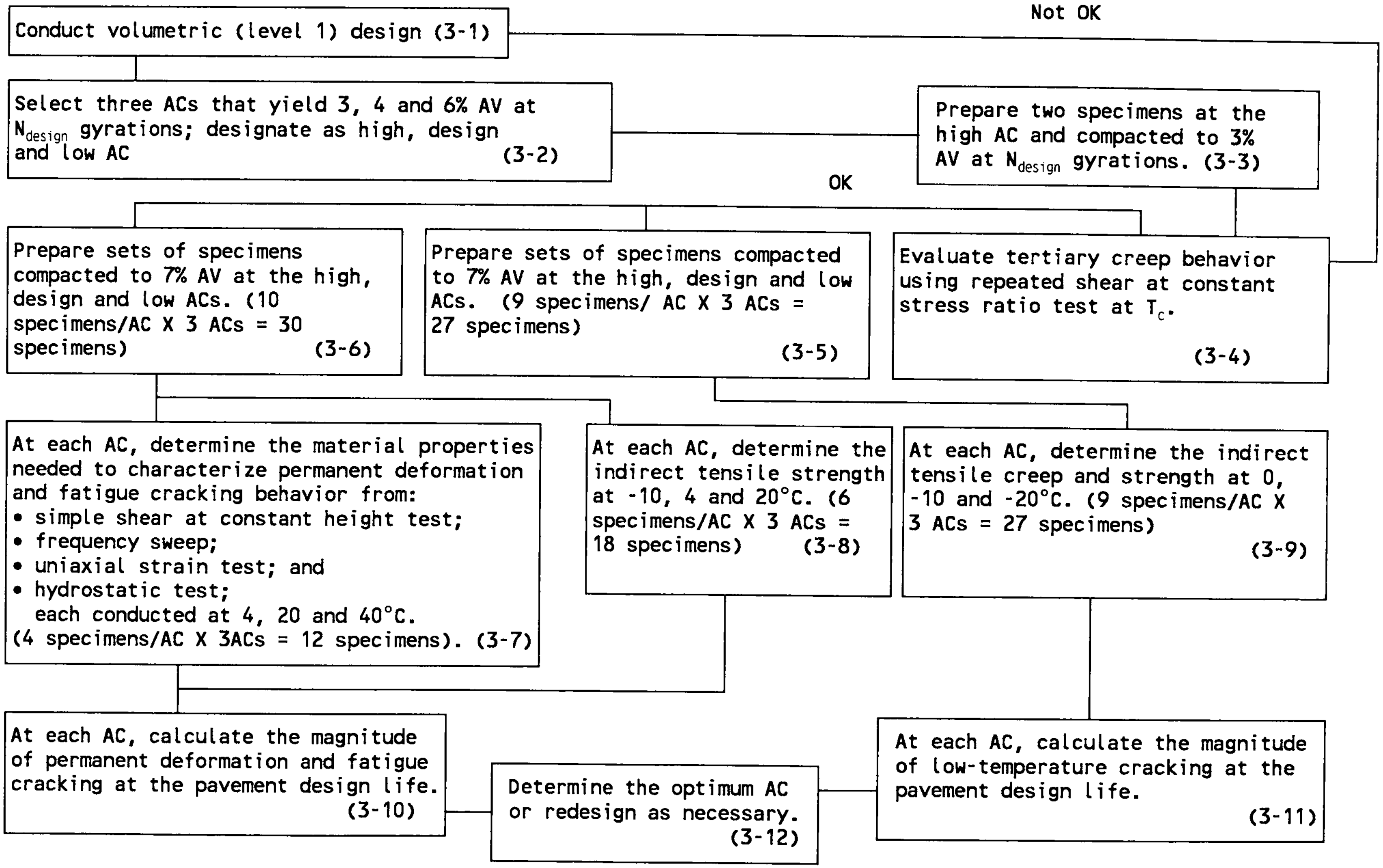
- repeated shear test at constant stress ratio (tertiary creep);
- frequency sweep at constant height;
- simple shear at constant height;
- uniaxial strain;
- hydrostatic state of stress (volumetric);
- indirect tensile creep; and
- indirect tensile strength.

The simple shear at constant height, repeated shear at constant stress ratio, frequency sweep at constant height, indirect tensile creep, and indirect tensile strength tests are performed in the same manner as in level 2 mixture design except they are conducted over a range of temperatures and must utilize the SHRP shear test device or its equivalent.

In the level 3 design, the hydrostatic state of stress (volumetric) test and the uniaxial strain test are used to measure the nonlinear elastic behavior of the aggregate skeleton. Nonlinear elastic behavior comes from aggregate particles. As the particles move in contact with each other, the stiffness of the aggregate skeleton increases. Mixture performance predictions for the level 3 mix design are performed in a similar manner as in level 2. The main differences from level 2 are the following:

- Material property characterization is more complete including nonlinear elastic behavior for level 3 mix design.

Figure 5.1. Superpave Level 3 Mix Design



- Weather data and lower layer moduli are evaluated in a more rigorous manner for level 3 mix design. The year is divided into seasons, each with specific pavement temperatures and lower layer moduli.

In terms of other input data, predicting pavement performance is done in the same manner as in the level 2 mix design discussed in chapter 4.

5.2 Outline of Level 3 Mix Design Method

The procedure for the SHRP level 3 mix design method starts with the sample preparation and volumetric design method (level 1 design) described in Chapter 3. However, the design equivalent single axle loads (ESALs) related to the gyratory compactor described in chapter 3 are usually greater than 10^7, although this value can be increased or decreased at the discretion of the agency.

With the Superpave mix design system, the steps to performing the level 3 mix design include the following:

- Conduct volumetric mix design;
- Select three asphalt contents bracketing the level 1 design content;
- Obtain historical pavement temperatures;
- Run performance-based tests;
- Evaluate test data to obtain material properties;
- Obtain predicted traffic volume;
- Obtain structural layer information; and
- Predict pavement performance.

Tables 5.1 and 5.2 identify the tests and the number of compacted specimens necessary to perform a level 3 mix design. Appendix B provides for reference the system of specimen coding used by the Superpave software.

5.2.1 Historical Air Temperature

The Superpave software uses a 10-year block of historical temperatures in performance prediction. Unlike the statistical air temperature information used for asphalt binder grade selection in level 1 design, a database containing 10 years of historical daily minimum and maximum temperatures for all of the United States is impractical. A library of historical air temperatures for each state is provided with the Superpave software. Mix designers can install temperature files only for areas of interest, thus reducing the volume of unneeded information.

5.2.2 Historical Pavement Temperature

Historical air temperatures are converted into historical pavement temperatures using the Federal Highway Administration Environmental Effects Model which is embedded in the Superpave software. Model output used by Superpave is limited to pavement temperatures. Temperatures of other layers and other model outputs are not used.

5.2.3 Calculate Material Properties

The Superpave software accesses data files created by the data collection software which is associated with the performance tests. Testing machines have stand-alone software to control execution of the performance-based test protocols. The Superpave software processes the data files using embedded software to obtain material properties.

5.2.4 Predict Pavement Performance

The Superpave software predicts pavement performance using material properties, traffic, pavement temperature, and pavement structure, and displays results in terms of distress versus time.

5.3 Equipment

The equipment required for preparing and testing compacted specimens is as follows:

- *Pan:* metal, flat bottom, for heating aggregates.

- *Pans:* metal, round, approximately 4-l capacity, for mixing asphalt and aggregates.

- *Oven and hot plate:* electric, for heating aggregates, asphalt, and equipment as required. Oven must also be capable of maintaining the temperature for short-term aging.

- *Scoop*: for batching aggregates.

- *Containers:* gill-type tins, beakers, pouring pots, or sauce pans, for heating asphalt.

- *Thermometers:* armored, glass, or dial-type with metal stem, 10°C to 230°C, for determining temperature of aggregates, asphalt, and asphalt mixtures.

Table 5.1. Performance Tests for Level 3 Mix Design

Permanent Deformation	Fatigue Cracking	Low-Temperature Cracking
Repeated shear at constant stress ratio (T_{eff} (PD)) Volumetric (4, 20, 40°C) Uniaxial strain (4, 20, 40°C) Frequency sweep at constant height (4, 20, 40°C) Simple shear at constant height (4, 20, 40°C)	Frequency sweep at constant height (4, 20, 40°C) Indirect tensile strength (50 mm/min) (-10, 4, 20°C)	Indirect tensile creep (-20, -10, 0°C) Indirect tensile strength (12.5 mm/min) (-20, -10, 0°C)

Table 5.2. Numbers of Compacted Specimen Required for Level 3 Mix Design (Per Asphalt Content)

Method of Test	Test Temperature (°C)						
	-20°C	-10°C	0°C	4°C	20°C	40°C	T_{eff}(PD)
Repeated shear at constant stress ratio (Tertiary Creep)	-	-	-	-	-	-	2
Volumetric	-	-	-	2^a	2^a	2^a	
Uniaxial strain	-	-	-	2^a	2^a	2^a	
Simple shear at constant height	-	-	-	2^b	2^b	2^b	
Frequency sweep at constant height	-	-	-	2^b	2^b	2^b	
Indirect tensile strength (50 mm/min loading rate)	-	2	-	2	2	-	
Indirect tensile creep	3^c	3^d	3^e	-	-	-	
Indirect tensile strength (12.5 mm/min loading rate)	3^c	3^d	3^e	-	-	-	

[a] Tests performed on same specimens.
[b] Tests performed on same specimens.
[c] Tests performed on same specimens.
[d] Tests performed on same specimens.
[e] Tests performed on same specimens.

- *Balance*: 5-kg capacity, sensitive to 1 g for weighing aggregates and asphalt. *Balance*, 2-kg capacity, sensitive to 0.1 g for weighing compacted specimens.

- *Mixing spoon:* large, or *trowel,* small.

- *Spatula*: large.

- *Mechanical mixer:* (optional) commercial bread dough mixer, 4-l capacity or larger, equipped with two metal mixing bowls and two wire stirrers.

- *Gloves:* welders, for handling hot equipment, and *Gloves:* rubber, for removing specimens from water bath.

- *Marking crayons*: for identifying test specimens.

- *SHRP gyratory compactor*: capable of providing a consolidation pressure of 0.60 MPa, an angle of gyration of 1.25 degrees, and speed of gyration of 30.0 rpm, as described in SHRP Method of Test M-002.

- *Cylindrical molds*: large enough to accommodate the following specimen size requirements: 150 mm diameter, 150 mm maximum height, 90 mm minimum height.

- *Extrusion jack* or *arbor press*: for extruding compacted specimens from mold.

- *Superpave shear test device*: meeting the requirements presented in SHRP Method of Test M-003.

- *Indirect tensile test device*: meeting the requirements of SHRP Method of Test M-005.

5.4 Selecting Mixture Materials for Volumetric Design

The procedures in this section correspond with block (3-1) in figure 5.1, the flow chart for the level 3 mix design.

The first important step in the level 3 mix design procedure is selecting materials suited to the demands of traffic and environment expected over time for the paving project.

(1) Select the fine and coarse aggregate and trial blends in accordance with the details provided in chapter 2 of this manual.

(2) Select the performance grade of the asphalt binder in accordance with the details provided in chapter 2.

(3) Conduct the net adsorption test to evaluate asphalt-aggregate compatibility in accordance with the details provided in chapter 2.

(4) Conduct initial trial asphalt content and trial aggregate gradation evaluations and determine the design aggregate gradation and design asphalt content, based on volumetric property requirements in accordance with the procedures provided in chapter 3 of this manual. The design traffic level (N_{design}) discussed in chapter 3 is greater than 10^7 ESALs for the level 3 mix design. N_{init} and N_{max} are presented in table 3.4.

5.5 Selecting Asphalt Contents to Yield 3, 4 and 6 percent Air Voids

The procedure presented in this section corresponds with block 3-2 of figure 5-1, the flow chart for the level 3 mix design.

(1) Refer to section 3.8.3, for the level 1 volumetric mix design. At the design number of gyrations (N_{design}) volumetric properties are calculated for each asphalt content as shown in table 3.9. Air voids, VMA, and VFA are plotted for each asphalt content as shown in figure 3.9.

(2) From the plot of percent air voids versus percent asphalt content shown in figure 3.9, determine the asphalt contents at three, four and six percent air voids.

(3) Designate the asphalt contents at three, four and six percent air voids as high, design, and low, respectively.

5.6 Determining Effective Temperature for the Screening Test for Tertiary Creep

Determine the effective temperature (T_{eff}) at which to conduct the tertiary creep screening test. Refer to section 4.7.

5.7 Tertiary Creep Mix Evaluation

The procedure outlined in this section corresponds with blocks (3-3 and 3-4) in figure 5.1, the flow chart for level 3 mix design.

The tertiary creep evaluation is a screening process to identify a mix that exhibits tertiary creep (plastic flow) leading to gross mix instability. If the mix fails the screening test it will be necessary either to make minor adjustments to the mix proportioning or to redesign the mix completely. If the mixture passes the test requirements, it is then subjected to the battery of tests for permanent deformation, fatigue, and low-temperature cracking characterization.

Evaluate the mix's potential for tertiary creep by performing the steps outlined in section 4.8 of this manual.

5.8 Permanent Deformation and Load-Associated Fatigue Property Characterization

The procedures outlined in this section correspond with blocks (3-6, 3-7, and 3-8) in figure 5.1, the flow chart for level 3 mix design.

This section presents appropriate test methods to determine material properties for use in predicting the mixture's potential for permanent deformation and load-associated fatigue over its service life.

(1) Prepare duplicate sets of specimens (150 mm diameter by 50 mm high) compacted at N_{design} by SHRP Method of Test M-002 to seven percent air voids at the high, design, and low asphalt contents as determined in section 5.5. The total number of specimens prepared is 30 (10 specimens per asphalt content times 3 asphalt contents = 30).

(2) Select twelve of these specimens (4 specimens per asphalt content times 3 asphalt contents = 12) to test permanent deformation and load-associated fatigue properties. The remaining eighteen specimens will be used to determine the indirect tensile strength in step (7) below.

(3) Frequency sweep at constant height test: Test six of the 12 specimens (2 specimens at three asphalt contents = 6) prepared above by performing the constant height frequency sweep in accordance with SHRP Standard Practice P-005. Conduct nine frequency sweeps at 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, and 0.02 Hz. Each series of sweeps, at each asphalt content, is conducted at 4, 20, and 40°C, for a total of 27 sweeps. Record axial deformation, shear deformation, axial load, and shear load at a rate of about 50 data points per load cycle in a format suitable for analysis by the Superpave software.

(4) Simple shear at constant height: Using the same six specimens tested in step 3, conduct the constant height simple shear test, in accordance with SHRP Standard

Practice P-005. Conduct the test at each asphalt content at 4, 20 and 40°C. Record the axial deformation, the shear deformation, the axial load and the shear load at a rate of about 10 data points per second in a format suitable for analysis by the Superpave software.

(5) Volumetric test: Using the remaining six specimens (2 specimens at three asphalt contents = 6) conduct the volumetric test in accordance with SHRP Standard Practice P-005. Perform the test for each asphalt content at 4, 20, and 40°C. Record the axial deformation on both sides of the specimens, radial deformation, and hydrostatic pressure in a format suitable for analysis by the Superpave software.

(6) Uniaxial strain test: Using the same six specimens tested in step 5 conduct the uniaxial strain test in accordance with the SHRP Standard Practice P-005. Conduct the test for each asphalt content at 4, 20, and 40°C. Record the axial deformation on both sides of the specimens, radial deformation, axial load, and confining pressure during the cycles specified in SHRP P-005 and in a format suitable for analysis by the Superpave software.

(7) Indirect tensile strength test: Using the remaining eighteen specimens (6 specimens per asphalt content times three asphalt contents = 18) prepared in step (1) conduct the indirect tensile strength test in accordance with SHRP Method of Test M-005 at -10, 4, and 20°C. Record the maximum peak load at a ram load rate of 50 mm per minute. The data must be recorded in a format suitable for analysis by the Superpave software.

5.9 Predicting Permanent Deformation and Load-Associated Fatigue Cracking at the Pavement Design Life

The procedure outlined in this section corresponds with block (3-10) in figure 5.1, the flow chart for level 3 mix design.

(1) The data recorded in section 5.8, steps (3) through (7) are entered into the Superpave software in a format suitable for analysis.

(2) Permanent deformation is predicted by the Superpave software system for a standard load applied to a pavement structure at the design pavement temperature. Stresses are calculated within each pavement layer using pavement temperature and mixture stiffness obtained from the frequency sweep test data. Total permanent deformation (rut depth) at the pavement surface is calculated versus time.

(3) Fatigue cracking is estimated using a single season analysis to calculate fatigue. Stresses within each pavement layer are calculated for the layer stiffness

representative of the temperature under a standard load. Dissipated energy is calculated for each season, and the cumulative dissipated energy is used to estimate percent fatigue cracking. Total area of fatigue cracking as a percentage of total pavement area is predicted versus time.

5.10 Low-Temperature Cracking (Nonload Associated) Property Characterization

The procedures in this section correspond with blocks (3-5 and 3-9) in figure 5.1, the flow chart for level 3 mix design.

This section outlines appropriate test methods to determine the material properties needed to predict the mixture's potential to experience low-temperature cracking.

(1) Prepare nine triplicate sets of specimens compacted by SHRP Method of Test M-002 to 7 percent air voids at the high, design and low asphalt contents as determined in sections 5.5. Twenty seven specimens are prepared (9 specimens per asphalt content times 3 asphalt contents = 27).

(2) For each asphalt content, test 3 specimens each at -20°C, 3 specimens at -10°C, and 3 specimens at 0°C by performing the indirect tensile creep and strength tests in accordance with SHRP Method of Test M-005. For each specimen calculate and record the creep compliance at 100 seconds in a format suitable for analysis by Superpave. Increase the load at a rate of 12.5 mm of ram movement per minute until failure occurs. Record the peak load in a format suitable for analysis by the Superpave software.

5.11 Predicting Low-Temperature Cracking at the Pavement Design Life

The procedure outlined in this section corresponds with block (3-11) in figure 5.1, the flow chart for level 3 mix design.

(1) The data recorded in section 5.10 are entered into the Superpave software in a format suitable for analysis.

(2) Low-temperature cracking is predicted using low-temperature creep behavior and low-temperature fracture strengths. Predictive models are used with statistical weather data to predict stresses caused by overnight temperature cycles. Fracture mechanics is used in conjunction with tensile strength and predicted tensile stress to

determine the advancement of cracking. The test estimates the development of crack spacing with time.

5.12 Selecting the Optimum Asphalt Content

The procedure outlined in this section corresponds with block (3-12) in figure 5.1, the flow chart of level 3 mix design.

The predicted values of permanent deformation (rut depth), fatigue cracking (percent of area), and low-temperature cracking (crack spacing) are used to select the optimum asphalt content.

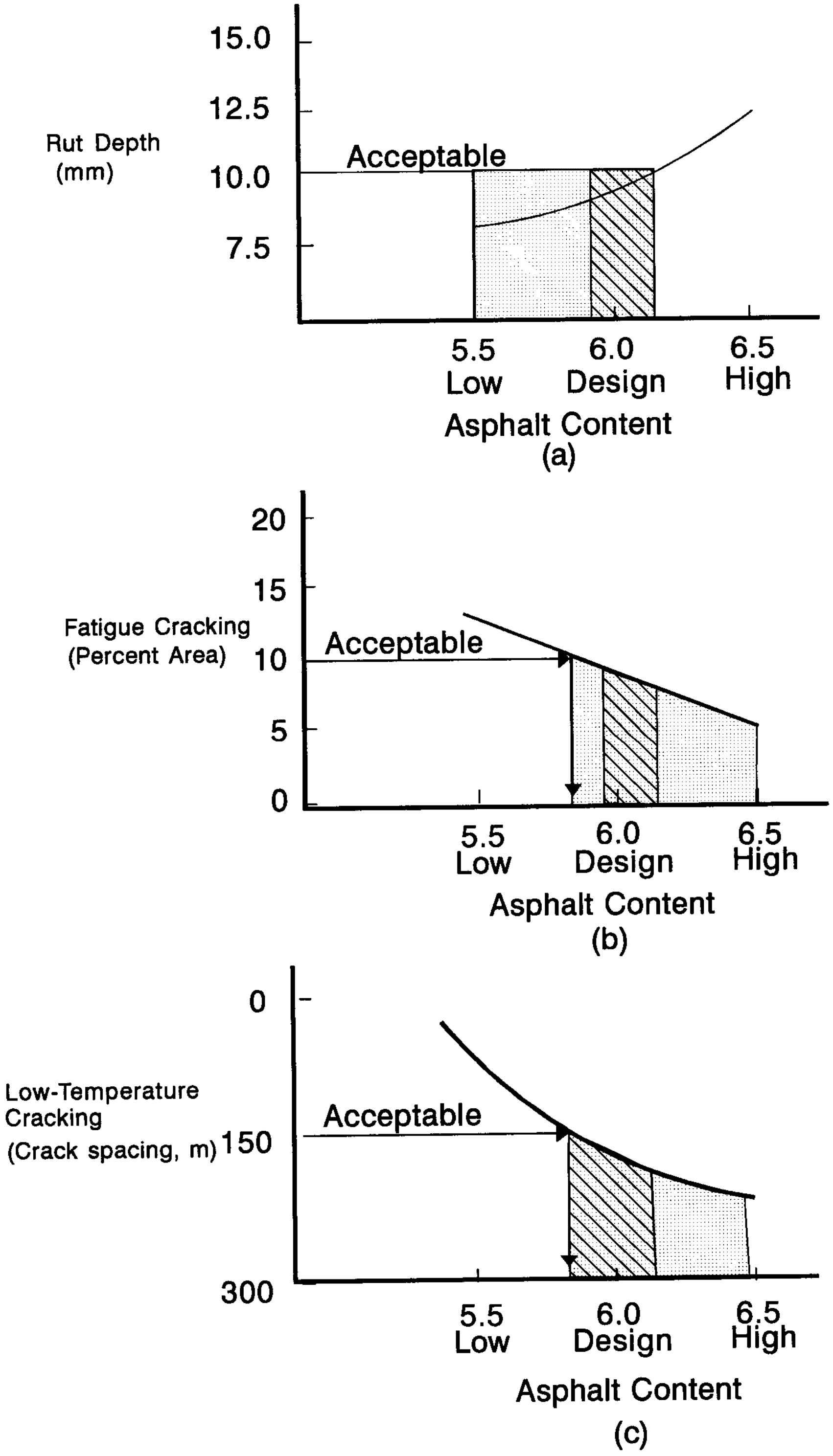
(1) The magnitudes of the predicted values for the distress factors determined in sections 5.9 and 5.11 are plotted against the asphalt contents tested in sections 5.8 and 5.10 (figure 5.2). Table 5.3 presents suggested acceptable levels of performance for each distress. These may be adjusted as the design agency acquires more data or totally replaced by the design agency's specific levels.

Table 5.3. Suggested Acceptable Levels Of Performance Requirements (Level 3 Mix Design)

Distress Factor	Acceptable level
Permanent Deformation	
Reliability (%)	95
Average rut depth (mm)	10
Fatigue Cracking	
Reliability (%)	95
Percent of area	10
Low-Temperature Cracking	
Reliability (%)	80
Crack spacing, m	> 150

(2) The design agency's acceptable levels for permanent deformation, fatigue cracking, and low-temperature cracking are identified on the vertical axis of the graphs and projected to the right to intersect with the plot. At this point of intersection, a vertical line is projected perpendicular to the horizontal axis as shown in figures 5.2.

Figure 5.2. Selection of an Optimum Asphalt Content Range Satisfying Three Distress Factor Conditions



Asphalt contents to the left of the vertical line in the top third of figure 5.2 (as shown by the shaded area) satisfy the permanent deformation requirement. Asphalt contents to the right of the dotted of the vertical line in the middle and bottom thirds of figure 5.2 (as shown by the shaded area) satisfy the fatigue and low-temperature requirements.

(3) The dashed area indicates the range of asphalt contents that will satisfy all three distress factor requirements related to the design agency's acceptable levels. Select an asphalt content within this band and designate it as the optimum asphalt content to be used for mix production.

(4) If only two distress factors are of prime importance to the designer, a similar procedure is used as in step 3 (figure 5.3). For this example, permanent deformation and fatigue cracking are being considered. The dashed area indicates the range of asphalt contents that will satisfy the design agency's acceptable levels for these distress types. The optimum asphalt content is selected within this range.

(5) If one distress factor is of primary concern, the following approach is used. Refer to figure 5.2 or 5.3. Using permanent deformation as an example, the asphalt contents to the left of the vertical line (as shown by the shaded area) satisfy the permanent deformation requirement. The same approach is used for fatigue or low-temperature cracking, except the shaded area to the right of the vertical line as shown in figure 5.3 satisfies the requirement. The optimum asphalt content may be selected within this range identified by the shaded area.

(6) If a range of acceptable asphalts cannot be established to select an optimum asphalt content that satisfies the distress factors evaluated, the mix proportioning must be adjusted or a modifier or modified binder should be considered in the mix design.

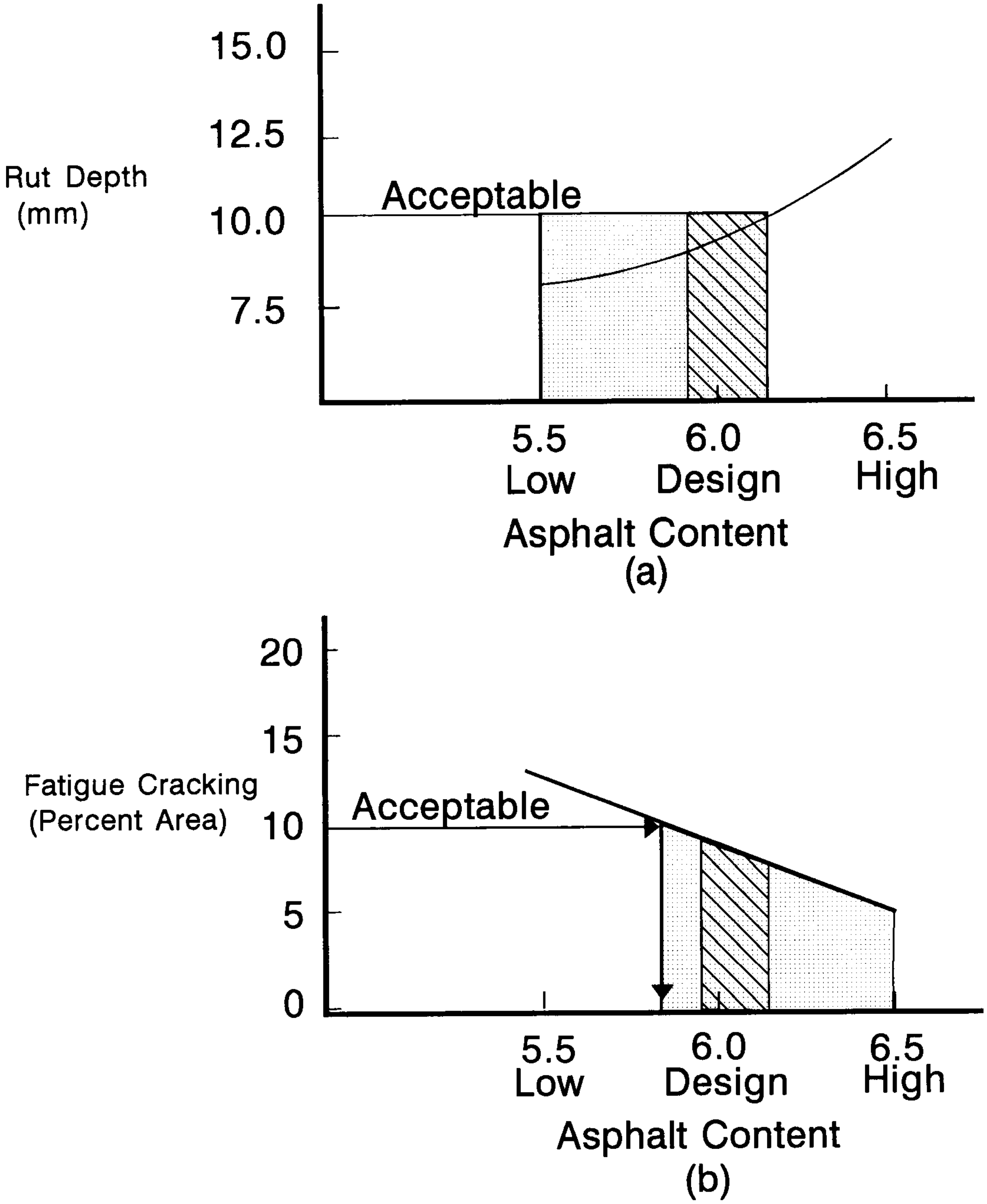
(7) The Superpave software provides the comparative plots discussed in steps 2 through 5. The plots are generated from the test as input data and the design agency's acceptable level of performance requirements.

5.13 Treating Modified Materials and Mixtures

If a modifier is used to enhance the mix performance capability, the procedures outlined previously for permanent deformation and low-temperature cracking apply also to modified mixtures. The prediction models used in the Superpave software will evaluate pavement performance of both conventional and modified asphalt binders and paving mixes in terms of permanent deformation and low-temperature cracking.

However, if fatigue cracking is the principal distress type addressed by a modifier, flexural beam testing is recommended in place of the simple shear at constant height, indirect tensile strength, frequency sweep, and related procedures. No prediction capability

Figure 5.3. Selection of an Optimum Asphalt Content Range Satisfying Two Distress Factor Conditions



is available for this situation with the Superpave models. A comparison of the cycles to failure can be made between the conventional and modified mixtures.

5.14 Proof Testing

Proof testing provides an independent confirmation of routine Superpave test results and laboratory performance estimates for situations with severe service requirements; when an exceptional degree of design reliability is required; when unusual or new materials are used; or when paving mixes have a top-size aggregate greater than two inches.

5.14.1 Rolling Wheel Compaction

This compaction procedure produces a slab from which beams may be sawn or large cylindrical specimens cored. It produces test specimens with a known air void content at a specified asphalt content. The procedure recommended is SHRP Method of Test M-008, *Preparation of Asphalt Concrete Mixture Test Specimens by Means of Rolling Wheel Compaction.*

5.14.2 Wheel-Tracking Device

Wheel-tracking test devices of various sizes and degrees of complexity are available to evaluate a mixture's resistance to permanent deformation. These devices employ pneumatic rubber-tired, steel wheels or hard-rubber-tired wheels. The equipment measures the rut depth created by a repeated passage of a wheel over a slab prepared in the laboratory or cut from a field pavement.

The dependence of the rut depth in the specimen on material types, number of loading cycles, tire pressure, wheel load, temperatures, and moisture conditioning can be determined. The test is a laboratory simulation of the rutting phenomenon with actual pavement stress conditions. One device that has been used successfully for extensive mix design evaluation is the rolling wheel rut tester developed at the Laboratoire Central des Ponts et Chausees (LCPC) in Nantes, France.

5.14.3 Flexural Beam Fatigue Test

The design agency can employ this test in level 3 mix design to evaluate modified mixtures discussed in section 5.12. The test is conducted in accordance with SHRP Method of Test M-009, *Determining the Fatigue Life of Modified and Unmodified Hot Mix Asphalt Subjected to Repeated Flexural Bending.* The beams are sawn from a rolling wheel compacted slab. The failure point is defined as the load cycle at which the specimen exhibits a 50 percent reduction in stiffness relative to the initial stiffness. No prediction based on the Superpave prediction models can be made. Instead a comparison of the cycles to failure is made among different mix designs or materials.

5.14.4 Thermal Stress Restrained Specimen Test

The design agency may opt to verify that the fracture temperature established in the low-temperature cracking analysis is realistic or reasonable. The measured fracture temperature may be compared to historical low pavement temperatures related to low-temperature cracking. The test to determine the fracture strength and fracture temperature for verification purposes is SHRP Method of Test M-010, *Determining the Fracture Strength and Temperature of Modified and Unmodified Hot Mix Asphalt Subjected to Cold Temperatures.* The test system is capable of cooling the mixture specimen at a constant rate while restraining the specimen from contraction; it periodically measures the tensile load and the specimen temperature from the beginning of the test to specimen failure. No prediction based on the Superpave prediction models can be made. The fracture strength and temperature are evaluated only by comparative analysis.

6

Superpave Mix Design: An Example

This chapter provides a worked example of a Superpave level 1/level 3 mix design for a simulated paving project located on I-43 near Milwaukee, Wisconsin.

6.1 Select Materials

The first step in a Superpave mix design is selection of the asphalt binder and aggregate stockpiles that meet the environment and traffic requirements present at the paving project.

The design equivalent single axle loads (ESALs) for the project are determined to be 18 million. This puts the design in the category of 10 million to 30 million ESALs, or Traffic level 5. Traffic levels are used to determine design requirements such as number of design gyrations for compaction, aggregate physical property requirements, and mixture volumetric requirements. The traffic level also determines the level of mixture design required. For traffic levels of 10^7 ESALs and higher, a level 3 design is recommended. This is a full level 1 design to determine mixture volumetric properties, followed by performance prediction tests.

The mixture in this example is an intermediate course mixture. It will have a nominal maximum particle size of 19.0 mm. It will be placed at a depth less than 100 mm from the surface of the pavement.

Environmental conditions are determined from weather station data stored in the Superpave software database. The project is near Milwaukee, which has two weather stations; the relevant data are presented in table 6.1.

Table 6.1. Project Weather Data

Weather Station	Min. Pvmt. Temp. (°C)	Max. Pvmt. Temp. (°C)	Binder Grade	Design Air Temp. (°C)
Low Reliability (50%)				
Milwaukee Mt. Mary Milwaukee WSO AP	-26 -25	52 51	PG 52-28 PG 52-28	32 31
Paving location	-26	52	PG 52-28	32
High Reliability (98%)				
Milwaukee Mt. Mary Milwaukee WSO AP	-32 -33	55 54	PG 58-34 PG 58-34	36 34
Paving location	-32	55	PG 58-34	35

The low and high reliabilities are in parentheses. These are the probabilities that in a given year the actual pavement temperature will not exceed or fall below the minimum and maximum pavement temperatures, respectively, listed in table 6.1. It is possible to select high reliability for one condition, such as minimum pavement temperature, while selecting low reliability for another condition, such as maximum pavement temperature. In this example, the designer chooses high reliability for all conditions. This requires a PG 58-34 binder.[1] The average design high air temperature is 35°C.

An appropriate asphalt binder is selected and tested for specification compliance. Test results are presented in table 6.2.

Comparing the test results to the specification criteria, the mix designer verifies that the asphalt binder meets the required PG 58-34 grade. Specification testing requires only that rotational viscosity be performed at 135°C. Additional testing is performed at 175°C to establish mixing and compaction temperatures. Based on the test results, 165 to 173°C is determined as the mixing range, and 150 to 157°C as the compaction range.

Next, the designer selects the aggregates to use in the paving mix. For this example, there are five stockpiles of materials consisting of three coarse materials and two fine materials. The materials are split into representative samples, and washed sieve analysis is performed for each aggregate. Test results are presented in section 6.2.

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[1] In practice, additional grading requirements based upon traffic speed and volume should be considered; see chapter 2.

Table 6.2. Binder Specification Test Results

Test	Property	Test Result	Criteria
Original Binder			
Flash point	n/a	304°C	230°C minimum
Rotational viscosity	135°C	0.575 Pa-s	3 Pa-s maximum
Rotational viscosity	175°C	0.142 Pa-s	n/a
Dynamic shear rheometer	$G^*/\sin\delta$ @ 58°C	1.42 kPa	1.0 kPa minimum
RTFO-aged Binder			
Mass loss	n/a	-0.14%	± 1.0% maximum
Dynamic shear rheometer	$G^*/\sin\delta$ @ 58°C	2.41 kPa	2.2 kPa minium
PAV-aged Binder			
Dynamic shear rheometer	$G^*\sin\delta$ @ 16°C	1543 kPa	5000 kPa max.
Bending beam rheometer	Stiffness @ -24°C	172,000 kPa	300,000 kPa max.
Bending beam rheometer	Slope m @ -24°C	0.321	0.300 min.

The specific gravity (bulk and apparent) of each aggregate is determined. These specific gravities are used in trial binder content calculations and the percent VMA calculations. Test results are presented in table 6.3:

Table 6.3. Aggregate Specific Gravities

Aggregate	Bulk Specific Gravity	Apparent Specific Gravity
#1 stone	2.703	2.785
1/2" chip	2.689	2.776
3/8" chip	2.723	2.797
Manufactured sand	2.694	2.744
Screen sand	2.679	2.731

In addition to sieve analysis and specific gravity determination, the Superpave design method requires the performance of certain consensus aggregate tests to ensure that the aggregate blend selected for the mix design is acceptable. Four tests are required: coarse aggregate angularity; fine aggregate angularity; thin and elongated particle determination; and clay content. In addition, the specifying agency can select any other aggregate tests deemed important. These tests may include sulfate soundness, Los Angeles abrasion, and friable particle content among others.

At this point the designer has the option of performing the four consensus aggregate tests on each stockpile or performing the test on each trial aggregate blend. The former choice allows the designer an opportunity to use the test results in narrowing the blend percentages of the aggregates for mix design. It also allows for greater flexibility if multiple trial blends are attempted. Performing the tests on each trial blend is technically correct, but requires that aggregate blending be performed ahead of the determination of the aggregate physical characteristics. Either method is appropriate. For this example, the test results are shown for each stockpile as well as for the aggregate trial blends.

6.1.1 Coarse Aggregate Angularity

This test is performed on the coarse aggregate particles of the aggregate stockpiles. The coarse aggregate particles are defined in the test as particles larger than 4.75 mm. Test results are presented in table 6.4.

Table 6.4. Coarse Aggregate Angularity

Aggregate	1+Fractured Faces, %	Criterion	2+Fractured Faces, %	Criterion
#1 stone	92	95% min	88	90% min
1/2" chip	97		94	
3/8" chip	99		95	

6.1.2 Fine Aggregate Angularity

This test is performed on the fine aggregate particles of the aggregate stockpiles. Particles smaller than 2.36 mm are defined as fine aggregate particles. Test results are shown in table 6.5.

Table 6.5. Fine Aggregate Angularity

Aggregate	% Air Voids (Loose)	Criterion (%)
Manufactured Sand	62	45 min
Screen Sand	35	

Note that this test is not performed on the three coarse aggregates, even though they have some small percentage of particles passing the 2.36 mm sieve. The #1 stone has 1.9 percent passing, the 1/2" chip has 2.6 percent passing, and the 3/8" chip has 3.0 percent passing the 2.36 mm sieve.

Table 6.5 gives the criterion for fine aggregate angularity based on the traffic (level 5) and the depth from the surface (<100 mm). The criteria change as the traffic level and layer depth change. The criteria are also based on the test results from the aggregate *blend* rather than individual materials. The screen sand appears to be below the minimum criterion, but it can be used as long as the selected *blend* of aggregates meets the criterion in table 6.5.

6.1.3 Thin and Elongated Particles

This test is performed on the coarse aggregate particles of the aggregate stockpiles. For this test the coarse aggregate particles are defined as particles larger than 4.75 mm. Test results are presented in table 6.6.

Table 6.6. Thin and Elongated Particles

Aggregate	% Thin and Elongated	Criterion (%)
#1 stone	0	10 max.
1/2" chip	0	
3/8" chip	0	

Note that this test is not performed on the two fine aggregates, even though they have some small percentage retained on the 4.75 mm sieve. The manufactured sand has 4.5 percent retained and the screen sand has 10.5 percent retained on the 4.75 mm sieve.

Table 6.6 also indicates the criterion for the percentage of thin and elongated particles based on traffic (level 5) only. The criterion changes as the traffic level changes. The criteria are also based on the test results from the aggregate blend rather than individual materials. In this case, the aggregates are cubical and not in danger of failing the criteria.

6.1.4 Clay Content (Sand Equivalent)

This test is performed on the fine aggregate particles of the aggregate stockpiles. The fine aggregate particles are defined as particles smaller than 2.36 mm. Test results are shown in table 6.7.

Table 6.7. Clay Content (Sand Equivalent)

Aggregate	Air Voids (Loose) (%)	Criteria (%)
Manufactured Sand	47	45 min.
Screen Sand	70	

Note that this test is not performed on the three coarse aggregates, even though they have some small percentage passing the 2.36 mm sieve. The #1 stone has 1.9 percent passing, the 1/2" chip has 2.6 percent passing, and the 3/8" chip has 3.0 percent passing the 2.36 mm sieve.

Table 6.7 gives the criterion for clay content (sand equivalent) based on traffic (level 5) only. The criterion changes as the traffic level changes. The criteria are also intended for application to the test results from the aggregate blend rather than individual materials. Both fine aggregates are above the minimum requirements, so there the blend should not present problems.

The material selection process is complete with the completion of the aggregate testing and selection. The next step in the design is to determine a design aggregate structure.

6.2 Select Design Aggregate Structure

To select the design aggregate structure, the designer establishes trial blends by mathematically combining the gradations of the individual materials into a single gradation. The blend gradation is then compared to the specification requirements for the appropriate sieves. Gradation control is based on four control sieves: the maximum sieve size (defined in chapter 2), the nominal maximum sieve (defined in chapter 2), the 12.5 mm sieve, the 2.36 mm sieve, and the 0.075 mm sieve. There is also a restricted zone that is an area on either side of the maximum density line generally starting at the 2.36 mm sieve and extending to the 0.3 mm sieve. The minimum and maximum values required for the control sieves change (as does the restricted zone) as the nominal maximum size of the mixture changes. Table 6.8 indicates the gradation requirements for this example.

Table 6.8. Gradation Criteria for 19.0 mm Nominal Maximum Size Aggregate

Sieve	Minimum (% pass)	Maximum (% pass)
25.4 mm	100.0	100.0
19.0 mm	90.0	100.0
12.5 mm	-	90.0
2.36 mm	23.0	49.0
0.075 mm	2.0	8.0
Restricted Zone		
2.36 mm	34.6	34.6
1.18 mm	22.3	28.3
0.6 mm	16.7	20.7
0.3 mm	13.7	13.7

Any trial blend gradation has to pass between the control points established on the five sieves. In addition, it has to be outside of the area bounded by the limits set for the restricted zone (see figure 6.1).

Any number of trial blends can be attempted, but three is the standard number of blends. Trial blending consists of varying stockpile percentages of each aggregate to obtain a blend gradation meeting the gradation requirements for that particular mixture. In this example, three trial blends are attempted: an intermediate blend, a coarse blend, and a fine blend.

The intermediate blend is combined to produce a gradation that is not close to either the gradation limits for the control sieves or to the restricted zone. The stockpile percentages and combined gradation for the intermediate blend (labelled trial blend 1) are shown in table 6.9.

The coarse blend is combined to produce a gradation that is close to the minimum criteria for the nominal maximum sieve, the 2.36 mm sieve, and the 0.075 mm sieve. The stockpile percentages and combined gradation for the coarse blend (labelled trial blend 2) are presented in table 6.9.

The fine blend is combined to produce a gradation that is close to the maximum criteria for the nominal maximum sieve and to the restricted zone. The stockpile percentages and combined gradation for the fine blend (labelled trial blend 3) are indicated in table 6.9.

All three of the trial blends are shown graphically in figure 6.2. All three trial blends pass below the restricted zone. This is not necessarily a requirement. It is possible to have a trial gradation that passes above the restricted zone.

Once the trial blends are selected, a preliminary determination of the aggregate blend properties is necessary. These can be estimated mathematically from the aggregate properties determined in tables 6.3 to 6.7. Estimated values are shown in table 6.10.

Table 6.9. Estimated Aggregate Blend Properties

Property	Criteria	Trial Blend 1	Trial Blend 2	Trial Blend 3
Coarse Ang.	95%/90% min.	96%/92%	95%/92%	97%/93%
Fine Ang.	45% min.	48%	50%	54%
Thin/Elongated	10% max.	0%	0%	0%
Clay Content	45% min.	59%	58%	54%
Combined G_{sb}	n.a.	2.699	2.697	2.701
Combined G_{sa}	n.a.	2.768	2.769	2.767

Figure 6.1. Superpave Gradation Control Points and Restricted Zone for a 19.0 mm Nominal Maximum Size Aggregate Gradation

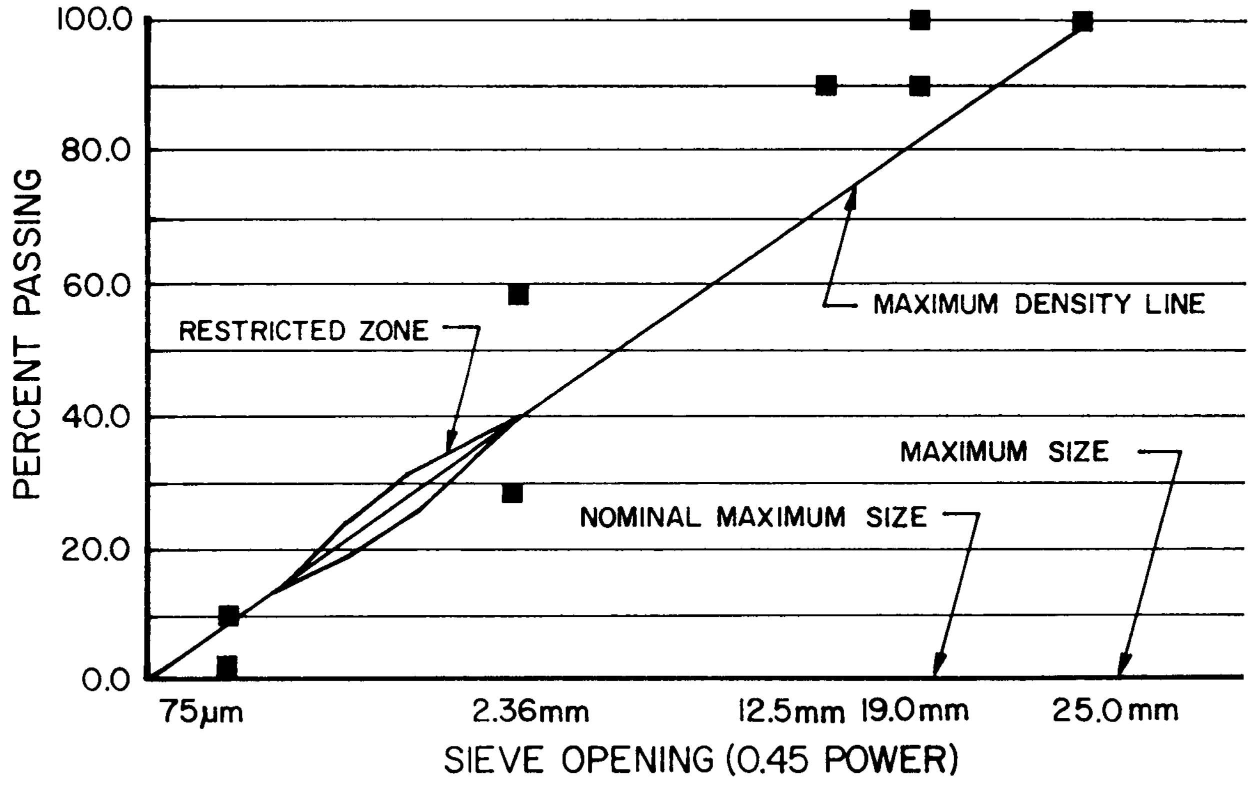
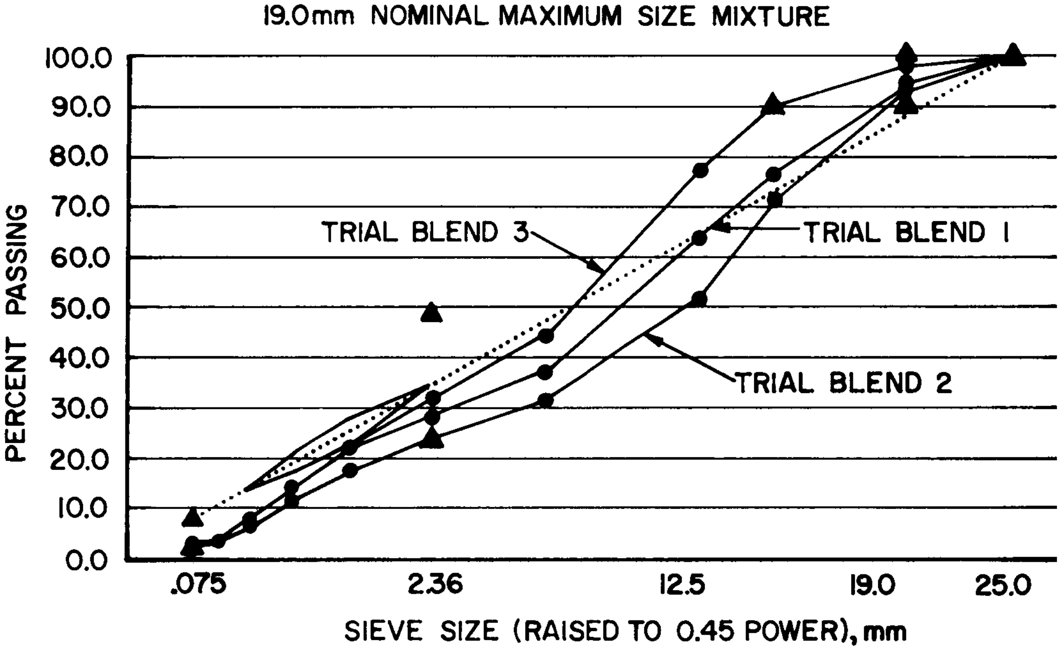


Table 6.10. Aggregate Blending Table for Trial Blends 1, 2 and 3

	#1 Stone	½" Chip	3/8" Chip	Manufactured Sand	Screened Sand			
Blend 1	25.0%	15.0%	22.0%	18.0%	20.0%			
Blend 2	30.0%	25.0%	13.0%	17.0%	15.0%			
Blend 3	10.0%	15.0%	30.0%	31.0%	14.0%			
Sieve Size						Trial Blend 1	Trial Blend 2	Trial Blend 3
25.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0 mm	76.1	100.0	100.0	100.0	100.0	94.0	92.8	97.6
12.5 mm	14.3	87.1	100.0	100.0	100.0	76.6	71.1	89.5
9.5 mm	3.8	26.0	94.9	100.0	99.8	63.7	51.9	77.7
4.75 mm	2.1	3.1	4.8	95.5	89.5	37.1	31.7	44.3
2.36 mm	1.9	2.6	3.0	63.5	76.7	28.3	23.9	31.9
1.18 mm	1.9	2.4	2.8	38.6	63.5	21.1	17.6	22.2
0.6 mm	1.8	2.3	2.6	21.9	45.6	14.4	12.0	14.5
0.3 mm	1.8	2.2	2.5	11.0	23.1	7.9	6.8	7.9
0.15 mm	1.7	2.1	2.4	5.7	8.4	4.0	3.6	4.1
0.075 mm	1.6	1.9	2.2	5.7	4.7	3.1	2.9	3.5

AS PER ED HARRIGAN AND Ron Kaminski
THESE NUMBERS ARE CORRECT. 8/30/95

Figure 6.2. Aggregate Gradations of Three Trial Blends



Values for coarse aggregate angularity are shown as the percentage of one or more fractured faces followed by the percentage of two or more fractured faces.

Based on the estimated properties, all three blends appear acceptable. When the design aggregate structure is selected, the blend aggregate properties will be verified by testing.

The next step is to evaluate the trial blends by compacting specimens and determining the volumetric properties of each blend. A minimum of two specimens per blend is compacted using the SHRP gyratory compactor.

The trial asphalt binder content is determined for each trial blend by estimating the effective specific gravity of the blend and using the calculations given in chapter 3.

The effective specific gravity, G_{se}, of the blend is estimated from its bulk (G_{sb}) and apparent (G_{sa}) specific gravities by using the following equation:

$$G_{se}=G_{sb}+0.8(G_{sa}-G_{sb}) \tag{6-1}$$

The multiplier, 0.8, can be changed at the discretion of the designer. Absorptive aggregates may require values closer to 0.6 or 0.5. The calculation for each trial blend is shown below:

Trial Blend 1:	$G_{se} = 2.699 + 0.8(2.768 - 2.699) = 2.754$
Trial Blend 2:	$G_{se} = 2.697 + 0.8(2.769 - 2.697) = 2.755$
Trial Blend 3:	$G_{se} = 2.701 + 0.8(2.767 - 2.701) = 2.754$

The volume of asphalt binder absorbed into the aggregate is estimated using the following equations:

$$V_{ba}=W_s(1/G_{sb}-1/G_{se}) \tag{6-2}$$

$$W_s=P_s\times\frac{(1-V_a)}{\frac{P_b}{G_b}+\frac{P_s}{G_{se}}} \tag{6-3}$$

where W_s = weight of aggregate,
P_b = percent of binder (assumed 0.05),
P_s = percent of aggregate (assumed 0.95),
G_b = specific gravity of binder (assumed 1.02), and
V_a = volume of air voids (assumed 0.04).

Using these equations the following values of V_{ba} are calculated for each trial blend:

Blend 1:

$$V_{ba}=[\frac{\frac{0.95(1-0.04)}{0.05}}{1.02}]+[(\frac{0.95}{2.754})(\frac{1}{2.699}-\frac{1}{2.754})]=0.017 \qquad \textbf{(6-4)}$$

Blend 2:

$$V_{ba}=[\frac{\frac{0.95(1-0.04)}{0.05}}{1.02}]+[\frac{0.95}{2.755}(\frac{1}{2.697}-\frac{1}{2.755})]=0.018 \qquad \textbf{(6-5)}$$

Blend 3:

$$V_{ba}=[\frac{\frac{0.95(1-0.04)}{0.05}}{1.02}]+[\frac{0.95}{2.755}(\frac{1}{2.697}-\frac{1}{2.755})]=0.016 \qquad \textbf{(6-6)}$$

The volume of the effective binder can be determined from the equation below:

$$V_{be}=0.091-0.02931\ln(0.039S_n) \qquad \textbf{(6-7)}$$

where S_n = the nominal maximum sieve size of the aggregate blend (in mm).

Using this equation the value of V_{be} for trial blends 1-3 is:

$$V_{be}=0.091-0.02931\ln(19.0\times0.039)=0.099 \qquad \textbf{(6-8)}$$

Finally, the initial trial asphalt binder content is calculated from the following equation:

$$P_{bi}=\frac{G_b(V_{be}+V_{ba})}{(G_b(V_{be}+V_{ba}))+W_s} \qquad \textbf{(6-9)}$$

This equation yields a value of 4.4 percent for P_{bi} for trial blends 1, 2 and 3.

Next, a minimum of two specimens for each trial blend are compacted using the SHRP gyratory compactor. Two additional specimens are prepared for determining the mixture's maximum theoretical specific gravity. An aggregate weight of 4500 grams is usually sufficient for the compacted specimens. An aggregate weight of 1500 grams is usually sufficient for the specimens used to determine maximum theoretical specific gravity (G_{mm}).

Specimens are mixed at the appropriate mixing temperature which is 165°C to 173°C for the selected PG 58-34 binder. The specimens are then short-term aged[2] by placing the loose mix in a flat pan in a forced draft oven at 135°C for 4 hours. The specimens are then brought within the compaction temperature range (150°C to 157°C) by placing them in another oven for a short time (generally less than 30 minutes). Finally, the loose mix is removed and either compacted or allowed to cool loose (for maximum theoretical specific gravity determination).

The number of gyrations used for compaction is determined based on the design high air temperature of the paving location (35°C) and the traffic (level of $>10^7$ ESALs). For these two conditions, the number of gyrations are identified as (see table 3.4):

N_{init} = 8 gyrations;
N_{design} = 109 gyrations; and
N_{max} = 174 gyrations.

Each specimen is compacted to the maximum number of gyrations, with data collected during the compaction process. During compaction, the height of the specimen is continually monitored. Knowing the initial weight of the mix, the fixed volume of the mold, and the measured height, the density can be continually monitored.

After compaction, the final density of the specimens are determined by AASHTO T 166. The G_{mm} of each blend is also determined. From this data, the air voids of the specimen at each gyration can be determined. Finally, the final calculated density of the compacted specimens are corrected to match the final measured density. The density at each gyration is subsequently adjusted. There is generally a difference of one to four percent between the calculated density and the measured density.

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[2] All specimens of paving mix compacted in the Superpave mix design method are conditioned as *loose mix* according to the short-term aging procedure in SHRP Standard Method of Test M-007.

The densification curves are plotted for each trial blend. The percent of the maximum theoretical density is determined for N_{init} (8 gyrations), N_{design} (109 gyrations), and N_{max} (174 gyrations) for each compacted specimen of each trial blend. The air voids content and the VMA are estimated (see table 6.11). An estimated asphalt binder content to achieve 4% air voids (96% G_{mm}) is determined for each trial blend. The mixture properties are then estimated at this asphalt binder content (see table 6.12). Estimated properties are compared to the Superpave level 1 (volumetric) criteria (see table 6.13). For the design traffic and nominal maximum particle size, the volumetric criteria are as follows:

% Air Voids	4.0
% VMA	≤13.0 (19.0 mm nominal maximum size mix)
% VFA	65 - 75

There are also criteria for densification that are constant for values at N_{init} (8 gyrations), N_{design} (109 gyrations), and N_{max} (174 gyrations). They are as follows:

% G_{mm} at N_{init} (8 gyrations)	< 89%
% G_{mm} at N_{design} (109 gyrations)	96%
% G_{mm} at N_{max} (174 gyrations)	< 98%

Table 6.11. Summary of Trial Blends

Blend	% AC	% G_{mm} @ N=8	% G_{mm} @N=174	% G_{mm} @N=109	% Air Voids	% VMA
1	4.4	87.1	97.6	96.2	3.8	12.7
2	4.4	85.6	97.4	95.7	4.3	13.0
3	4.4	86.3	96.5	95.1	4.9	13.5

Table 6.12. Estimated Values for Trial Blends

Blend	Trial % AC	Est. % AC	% G_{mm} @ N=8	% G_{mm} @ N=174	% Air Voids	% VMA	% VFA
1	4.4	4.3	86.9	97.4	4.0	12.7	68.5
2	4.4	4.5	86.0	97.7	4.0	13.0	69.1
3	4.4	4.7	87.2	97.4	4.0	13.4	70.1

Table 6.13. Mixture Criteria

% G_{mm} at N = 8 gyrations	< 89%
% G_{mm} at N = 174 gyrations	< 98%
% Air Voids	4.0%
% VMA (19.0 mm nominal maximum size mix)	≤ 13.0%
% VFA (< 10^7 ESALs design traffic)	65 - 75%

Finally, the dust-to-asphalt binder ratio criterion is considered. This criterion is constant for all levels of traffic. It is calculated as the percent by weight of the material passing the 0.075 mm sieve (by wet sieve analysis) divided by the effective asphalt binder content (expressed as percent by weight of mix). The dust-to-asphalt ratio must be between 0.6 and 1.2. Table 6.15 presents the results for the three trial blends.

Table 6.14. Dust-to-Asphalt Ratio of Trial Blends

Blend	Dust/Asphalt Ratio	Criteria
Trial Blend 1	0.84	0.6 - 1.2
Trial Blend 2	0.81	
Trial Blend 3	0.95	

After establishing all the estimated mixture properties, the data for the three trial blends are reviewed and a decision is made if one or more are acceptable, or if further trial blends require evaluation.

Table 6.15. Comparison of Trials Blends

Property	Blends That Meet Criterion
%G_{mm} @ N= 8 gyrations	1, 2, 3
%G_{mm} @ N= 174 gyrations	1, 2, 3
% Air Voids	1, 2, 3
% VMA	2, 3
% VFA	1, 2, 3

Trial blend 1 is unacceptable based on its failure to meet the minimum % VMA criterion. Trial blend 2 is acceptable, but the % VMA is at the lower limit. Trial blend 3 has an acceptable % VMA and meets the criteria for % VFA, dust-to-asphalt ratio, and the densification criteria. From these data, trial blend 3 is selected as the design aggregate structure.

6.3 Select Design Asphalt Binder Content

Selecting the design aggregate structure is the difficult step. Once the structure is selected (Trial Blend 3), specimens are compacted at several asphalt binder contents. The mixture properties are then evaluated with respect to the asphalt binder content.

A minimum of two specimens are compacted[3] at each of the following asphalt contents: estimated asphalt binder content, the estimated asphalt binder content ±0.5%, and the estimated asphalt binder content +1.0%. For trial blend 3, the binder contents for the mix design are thus 4.2%, 4.7%, 5.2%, and 5.7%. A minimum of four asphalt binder contents are evaluated. A minimum of two specimens are also prepared for determination of the maximum theoretical specific gravity. Specimens are prepared and tested in the same manner as the specimens in section 6.2.

Mixture properties are evaluated for the selected blend at the different asphalt binder contents. From these data points, plots of % air voids, % VMA, % VFA and density versus asphalt binder content are prepared. The design asphalt binder content is established at 4% air voids. All other mixture properties are checked at that asphalt binder content to verify that they meet the volumetric criteria. The design values for a 19.0 mm nominal maximum size mix (trial blend 3) are presented in table 6.16:

Table 6.16. Design Mix Properties @ 4.7 % Asphalt Content

Mix Property	Result	Criteria
% Air Voids	4.0	4.0
% VMA	13.2	13.0 min.
% VFA	70.0	65 - 75
Dust-to-Asphalt Ratio	0.97	0.6 - 1.2
% G_{mm} @ $N_{init} = 8$	87.1	< 89
% G_{mm} @ $N_{max} = 174$	97.5	< 98

6.4 Evaluate Moisture Sensitivity

The final step in the level 1 mix design is to evaluate the moisture sensitivity of the design mixture. This step is accomplished by performing AASHTO Method of Test T 283 on the design aggregate structure at the design asphalt binder content. Specimens are compacted to approximately 7 percent air voids. One subset of three specimens is the control subset. The other subset of three specimens is the conditioned subset. The

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[3] All specimens of paving mix compacted in the Superpave mix design method are conditioned as *loose mix* according to the short-term aging procedure in SHRP Standard Method of Test M-007.

conditioned subset is subjected to partial vacuum saturation followed by an optional freeze cycle, followed by a 24 hour thaw cycle at 60°C. All specimens are tested to determine their indirect tensile strengths. The moisture sensitivity is determined as a ratio of the tensile strengths of the conditioned subset divided by the tensile strengths of the dry (control) subset (table 6.17). The minimum criterion is 80 percent retained tensile strength. The design blend met the minimum requirement with an 83 percent retained tensile strength ratio.

Table 6.17. Moisture Susceptibility of Design Asphalt Blend by AASHTO T 283

Sample Number	1	2	3	4	5	6
Dry Strength (kPa)				890.1	859.0	870.8
Wet Strength (kPa)	713.5	704.5	745.2			
Average Dry Strength: 873.3 kPa Average Wet Strength: 721.1 kPa Tensile Strength Ratio: 83%						

6.5 Superpave Level 3 Mixture Design Example

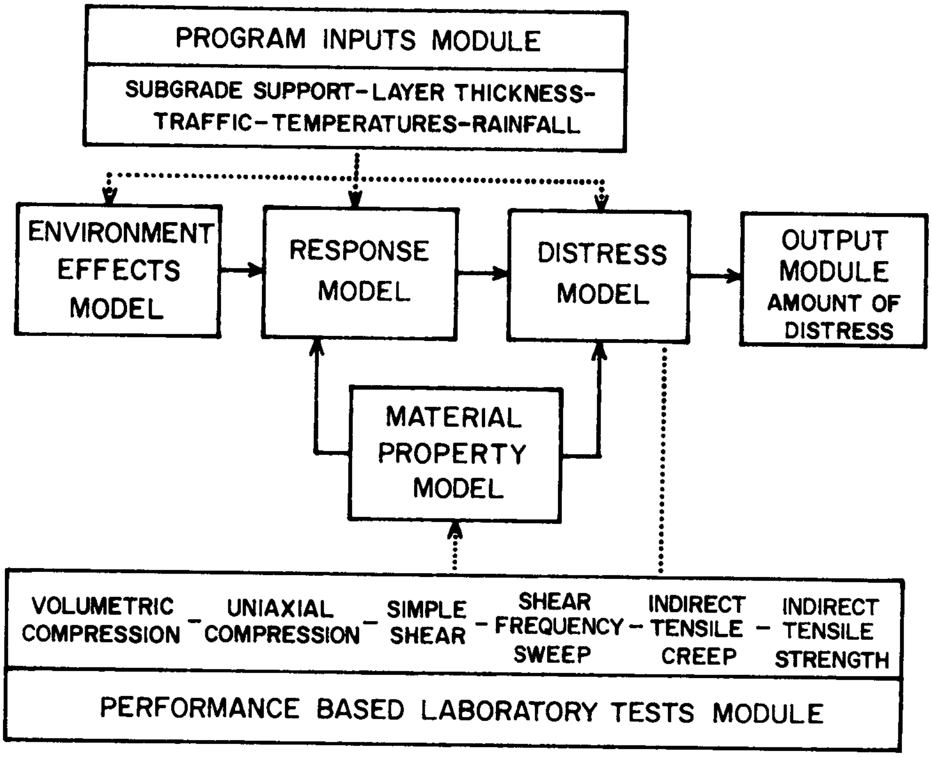
6.5.1 Introduction

The following example describes the use of the Superpave accelerated performance tests and performance models to support the level 3 mix design described in chapter 5 of this manual. Only one asphalt content is considered for discussion purposes. The examples consider only permanent deformation. Similar examples could be shown for fatigue cracking and low-temperature cracking with the Superpave pavement performance model.

The Superpave pavement performance model is composed of four parts (Figure 6.3) as follows:

- Mixture characterization or Material Property Model;
- Environmental Effects Model;
- Pavement Response Model; and
- Pavement Distress Model.

Figure 6.3. Flow Diagram of the Different Parts of the Superpave Pavement Performance Model



The mixture characterization program calculates the non-linear elastic, viscoelastic, plastic and fracture properties of a mixture from the performance-based laboratory tests. These properties are used with the pavement response program to evaluate the behavior of a mixture subjected to traffic and/or environmental loads. Some of these material properties are also used directly in the pavement distress model. The pavement response program, which is a finite element program, calculates the stresses and strains in the asphalt-aggregate mixture from wheel loads and environment loads. The pavement distress program takes the relevant mixture properties and the appropriate stresses and strains calculated with the finite element program and calculates the amount of cracking (from wheel loads and environmental loads) and rutting with time.

6.5.2 Level 3 Mix Design and Pavement Performance Prediction Approach

The general steps to performing a level 3 mix design are as follows:

(1) Perform level 1 mix design as described in chapter 3 and illustrated in the level 1 example problem of this chapter. The output from the design includes the following:

- selected asphalt binder grade;
- design asphalt binder content;
- selected aggregate materials; and
- design aggregate percentages.

(2) Define project where mix is to be used:

- design life;
- expected traffic;
- select climatic region;
- select weather files;
- select design level;
- define pavement cross section;
- select seasonal adjustment factors; and
- select asphalt contents for analysis.

(3) Perform repeated shear screening test for tertiary creep.

(4) Perform performance based tests.

(5) Run performance prediction models.

(6) Determine acceptability and select job mix.

6.5.2.1 Define Project Where Mixture is to be Used

The design life for the project is specified to determine the number of years of weather data required to drive the performance models. Design traffic is defined as the expected number of ESALs which will be applied over the pavement life. Within the performance models the design number of ESALs is divided by the design life to obtain the number of axle passes which will be stimulated by the performance models. The performance models do not escalate annual traffic to simulate traffic growth rate.

Climatic region of the project is selected using the Environmental Effects Model map shown in figure 6.4. Associated with each of the nine environmental effects regions are default parameter files for sunshine, rainfall, wind, etc. which will be used in the environmental model.

Temperature files which will be used to drive the environmental effects program are selected. A data base of weather data is available with the Superpave software. These weather stations have ten years of historical daily minimum/maximum temperatures.

Next, the desired level of design is selected. Independent selections can be made with Superpave for low temperature cracking and permanent deformation/fatigue cracking. Options include level 3, level 2, or level 1. In the example that follows, permanent deformation and the level 3 mix design are considered for illustrative purposes.

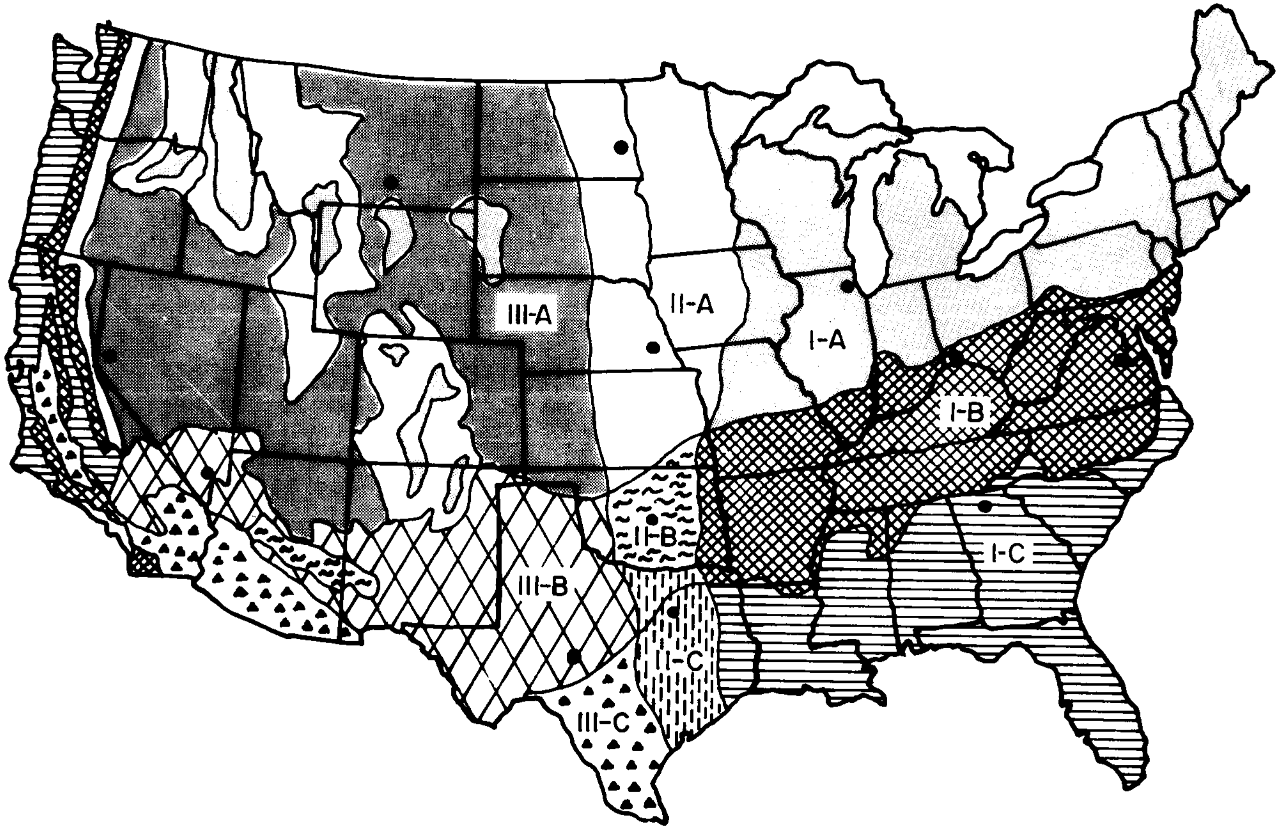
The pavement cross section in which the mixture is to be located must be defined. The entire cross section can include up to seven pavement layers including subgrade. A maximum of two new asphalt layers may be used.

Seasonal adjustment factors can be selected for traffic and lower layer moduli. The designer can define month-to-month variations in traffic level if desired. Lower layers with moduli affected by thaws weakening, desiccation, etc. can be simulated by using monthly adjustment factors.

6.5.2.2 Select Asphalt Contents for Analysis

Performance prediction can be done for a range of asphalt contents. For each mix design in the pavement cross section asphalt content can be selected as low, medium or high. Medium asphalt content is the percent asphalt binder obtained from the level 1 mix design. High asphalt content is the percent asphalt binder which produces 3% air voids at the design number of gyrations. Low asphalt content is the percent which produces 6% air voids.

Figure 6.4. FHWA Environmental Effects Model Map of U.S. Climatic Regions



The number of selected asphalt contents has a direct impact on the amount of required testing and a multiplying effect on the amount of computer analysis time. If two new asphalt layers are used, each with three asphalt contents there is a total of six combinations which must be analyzed for performance prediction.

6.5.2.3 Perform Repeated Shear Screening Test

The repeated shear at constant stress ratio screening test is performed as discussed in sections 5.6 and 5.7 at the highest selected asphalt content. Mixtures which fail are excluded from performance based testing.

6.5.3 Performance-Based Tests and Results

The tests discussed below are required for the prediction of permanent deformation in the level 3 design. The performance-based tests are as follows:

- Volumetric;
- Uniaxial Strain;
- Simple Shear at Constant Height; and
- Frequency Sweep at Constant Height.

The procedures presented in this section determine material properties by appropriate test methods for use in predicting the mixture's potential for permanent deformation.

(1) Prepare duplicate sets of specimens (150mm diameter by 50mm high) compacted at N_{design} by SHRP Method of Test M-002 to 7% air voids at the high, design and low asphalt contents. The total number of specimens prepared for permanent deformation testing is 12 (4 specimens per asphalt content times 3 asphalt contests = 12).

Note - All specimens of paving mix compacted in the Superpave mix design method are conditioned as *loose mix* according to the short-term aging procedure in SHRP Standard Method of Test M-007.

(2) Frequency Sweep at Constant Height: Six of the twelve specimens (2 specimens at three asphalt contents = 6) prepared above are tested by performing the constant height frequency sweep in accordance with SHRP Standard Practice P-005. Nine frequency sweeps are conducted at 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, and 0.02 Hz. Each series of sweeps, at each asphalt content, is conducted at 4°C, 20°C and 40°C for a total of 27 sweeps. Axial deformation, shear deformation, axial load and shear load is recorded at a rate of about 50 data points per load cycle in a format suitable for analysis by the Superpave software. Table 6.18 is an illustration of the data output generated

from this test for one asphalt content.

(3) Simple Shear at Constant Height: On the same six specimens tested in the frequency sweep procedure, conduct the simple shear test at constant height in accordance with SHRP Standard Practice P-005. The test is conducted at each asphalt content at 4°C, 20°C and 40°C. After preconditioning, the shear stress on the specimen is increased at a rate of 70 kPa/s to a level determined by the test temperature. The shear stress is maintained for 10 seconds while the compressive load is controlled by feedback to maintain the specimen at constant height. The shear stress is then reduced at a rate of 25 kPa/s to 0 kPa and held for an additional 10 seconds. The axial deformation, shear deformation, axial load and shear are recorded at a rate of 10 data points per second in a format suitable for analysis by the Superpave software. Table 6.19 presents an example of a portion of the test output developed from this test for one asphalt content.

(4) Volumetric Test: On the remaining six specimens (2 specimens at three asphalt contents = 6) prepared above, conduct the volumetric test in accordance with SHRP Standard Practice P-005. Perform the test for each asphalt content at 4°C, 20°C and 40°C. The axial deformation on both sides of the specimens, the radial deformation and the hydrostatic (confining) pressure are recorded in a format suitable for analysis by the Superpave software. Table 6.20 presents an example of the data output from this test for one asphalt content.

Table 6.18. Example Output Data from the Frequency Sweep Test

Frequency (Hz)	Period (sec)	Shear Stress (kPa)	Shear Strain (mm/mm × 10^{-5})	Complex Modulus in Shear (10^6 kPa)	Phase Angle (°)	Storage Modulus (10^6 kPa)	Loss Modulus (10^5 kPa)
10	48.5	429.1793	8.9699	4.7848	10.537	4.7039	8.7515
5	45	395.5252	8.8294	4.4800	11.082	4.3964	8.6120
2	18.5	334.1318	8.0578	4.1474	11.609	4.0624	8.3474
1	18.5	322.1555	8.2914	3.8861	12.421	3.7950	8.3613
0.5	5.5	300.0334	8.3231	3.6053	12.982	3.5131	8.1000
0.2	5.5	270.1702	8.3752	3.2257	14.217	3.1269	7.9228
0.1	5.5	249.3225	8.4957	2.9349	15.458	2.8287	782108
0.05	3	229.1290	8.5748	2.6722	17.014	2.5552	7.8191
0.02	3	202.7551	8.8133	2.3005	19.425	2.1696	7.6512
0.01	3	183.5207	9.0254	2.0338	21.230	1.8957	7.3649

Table 6.19. Example Test Data From Simple Shear at Constant Height Test

Time (sec)	Axial Load (N)	Shear Load (N)	LVDT #1 Axial Deformation (mm)	LVDT #1 Shear Deformation (mm)
0	34.27	5.23	-0.0290	0.5016
0.1	32.11	124.41	-0.0291	0.5016
0.2	27.79	243.58	-0.0290	0.5016
0.3	25.64	368.16	-0.0291	0.5020
0.4	23.48	481.92	-0.0290	0.5013
0.5	21.32	601.09	-0.0291	0.5010
0.6	21.32	736.51	-0.0291	0.5010
0.7	23.48	850.26	-0.0290	0.5010
0.8	23.48	969.43	-0.0290	0.5013
0.9	21.32	1094.02	-0.0291	0.5010
1	19.16	1213.19	-0.0289	0.5007
1.1	21.32	1337.77	-0.0290	0.5010
1.2	21.32	1467.78	-0.0291	0.5007
1.3	23.48	1586.94	-0.0291	0.5007
1.4	23.48	1706.11	-0.0289	0.5004
1.5	23.48	1836.12	-0.0292	0.5007

(5) Uniaxial Strain Test: On the same six specimens tested the volumetric test, conduct the uniaxial strain test in accordance with the SHRP Standard Practice P-005. The test is conducted for each asphalt content at 4°C, 20°C and 40°C. The specimen is covered around its circumference with a close-fitting rubber membrane. After a preconditioning step, the shear stress applied to the specimen is increased at a rate of 70 kPa/s to a level determined by the test temperature. The shear stress is held for 10 seconds and then reduced to 7 kPa/s to a level of 25 kPa where it is held for 30 seconds. During this cycle of shear stress, the confining pressure is adjusted through a feedback loop to maintain the circumference of the specimen at a constant value. The axial deformation on both sides of the specimens, the radial deformation, the axial load and the confining pressure are recorded at a rate of 10 data points per second in a format suitable for analysis by the Superpave software. Table 6.21 presents data output from this test for one asphalt content.

Table 6.20. Example Test Data from the Volumetric Test

Time (sec)	Sequence	LVDT #2 Axial Deformation (mm)	LVDT #4 Axial Deformation (mm)	Confining Pressure (kPa)	Radial Deformation (mm)
0	1	0.08942	-0.30270	13.11	-0.38115
0	2	0.10634	-0.29967	27.60	-0.35571
0.088	2	0.10665	-0.29967	28.29	-0.35515
0.176	2	0.10757	-0.29899	32.43	-0.35405
0.264	2	0.10880	-0.29866	37.26	-0.35294
0.352	2	0.11003	-0.29764	42.78	-0.35073
0.44	2	0.11157	-0.29764	47.61	-0.34852
0.528	2	0.11341	-0.29697	53.82	-0.34630
0.616	2	0.11495	-0.29596	59.34	-0.34298
0.704	2	0.11649	-0.29461	65.55	-0.33911
0.792	2	0.11864	-0.29461	71.07	-0.33634
0.88	2	0.12049	-0.29326	77.97	-0.33247
0.968	2	0.12233	-0.29293	83.49	-0.32915
1.056	2	0.12387	-0.29124	89.70	-0.32473
1.144	2	0.12572	-0.29057	95.91	-0.32030
1.232	2	0.12756	-0.28955	101.43	-0.31643

Table 6.21. Example Data from the Uniaxial Strain Test

Time (sec)	LVDT #2 Axial Deformation (mm)	LVDT #4 Axial Deformation (mm)	Axial Load (N)	Confining Pressure (kPa)	Radial Deformation (mm)
0	0.13894	-0.23056	266.934	8.28	-0.22792
0.078	0.13679	-0.23191	88.978	8.28	-0.22792
0.156	0.13709	-0.23124	151.263	8.28	-0.22792
0.234	0.13863	-0.23056	275.832	8.28	-0.22792
0.312	0.13956	-0.23023	338.117	8.28	-0.22792
0.39	0.14109	-0.22854	444.892	8.28	-0.22792
0.468	0.14263	-0.22719	542.768	8.28	-0.22792
0.546	0.14417	-0.22585	667.336	8.28	-0.22847
0.624	0.14540	-0.22450	774.110	8.28	-0.22847
0.702	0.14601	-0.22382	800.803	8.28	-0.22847
0.78	0.14724	-0.22248	907.576	8.28	-0.22847
0.858	0.14847	-0.22113	1023.247	8.28	-0.22847
0.936	0.15001	-0.21944	1165.611	8.97	-0.22847
1.014	0.15093	-0.21809	1263.486	8.28	-0.22847
1.092	0.15155	-0.21708	1290.180	8.97	-0.22847
1.17	0.15278	-0.2154	1414.753	8.28	-0.22902
1.248	0.15401	-0.21405	1530.424	8.97	-0.22902
1.326	0.15493	-0.21236	1637.197	8.28	-0.22902
1.404	0.15555	-0.21135	1663.890	8.97	-0.22902

6.5.4 Material Properties and Material Property Model

Figure 6.3 shows that the test data from the the frequency sweep, simple shear, volumetric and uniaxial strain tests are input to the material property model for each asphalt content. The frequency sweep is used to determine the linear viscoelastic properties (i.e. complex modulus) and the parameters of the power law. When the log of the complex modulus is plotted against the log of the frequency, the slope of the resulting line gives the parameter *S*. This S can be related to another mixture property, m, which is the slope of the log creep compliance curve. The parameter m is used in both the calculation of the fatigue cracking (in determining a Paris' law coefficient) and the permanent deformation.

Data from the volumetric, uniaxial strain, and simple shear at constant height tests are used concurrently to determine the elastic or resilient and plastic (Vermeer) properties of the mixture. The resilient (elastic) properties of the asphalt concrete are determined from the components k_1, k_2, k_3, k_6; the Poisson's ratio is determined from the components k_4 and k_5. The plastic components (α, χ, ϕ_p, ϕ_{cv}) are used in the Vermeer model in the determination of the permanent deformation characteristics of the asphalt concrete.

Table 6.22 illustrates the computed material properties developed from the test data input to the material property model. These properties relate to the resilient and plastic parameters identified previously.

Referring to figure 6.3, the input through the Superpave software to the Environmental Effects Model is the following:

- Average minimum/maximum pavement temperature for each day of the year.
- Rainfall, solar radiation, cloud cover and wind speed based upon geographic regions.

6.5.5 Environment Effects Model

The output from the Environmental Effects Model is divided into blocks of similar temperatures defined as a season. The minimum season length is defined as one month. The temperatures are calculated as average pavement temperatures (°C) at one-third depth for each season. Table 6.23 illustrates example average pavement temperatures at one-third depth for estimated seasons calculated with the Environmental Effects Model.

Table 6.22. Examples of Material Property Parameters Calculated from Superpave Material Property Model

	Elastic or Resilient Components					
Test Temperature (°C)	k_1	k_2	k_3	k_4	k_5	k_6
4	0.1835	0.3897	0.0000	1.6210	-0.3945	2.2060
(Multiplying factor)	10^4	10^2	-	-	-	-
20	1.7280	0.2273	0.0000	0.0000	-2.2130	3.8130
(Multiplying factor)	10^3	10^2	-	-	-	-
40	2.0610	0.2529	0.0000	0.0000	-2.7990	1.3900
(Multiplying factor)	10^3	10^2	-	-	-	-
	Plastic Components					
	α	χ	ϕ_p	ϕ_{cv} ($x10^{-2}$)		
4	32.4500	369.3000	20.4200	0.5556		
20	20.7500	277.200	20.5700	0.5556		
40	14.4500	70.9600	22.9400	0.5556		

Table 6.23. Average Pavement Temperatures at Depth Calculated by the Environmental Effects Model

Number of Months in Season	Average Pavement Temperature (°C) at 1/3 Depth
2	5.91
1	13.22
1	20.98
2	29.55
3	31.63
1	22.54
1	15.53
1	9.38
Total = 8 seasons	

6.5.6 Response and Distress Models to Predict Rutting

Superpave allows the mix designer to identify and input the thickness of the total pavement structure. The designer also provides the input for the material properties for all layers (subgrade, subbase, base, etc) below the asphalt layer. These material properties are entered as "default values" which are moduli values. The material properties (table 6.22) calculated by the Material Property Model are interpolated to the average pavement temperature at 1/3 depth for each season. The finite element model associated with the response model then calculates the stresses and strains in the asphalt layer associated with the material properties of the structural layers and the rate of traffic loading.

The calculated stresses and strains are then used by the distress model to predict the amount of rutting or permanent deformation. Table 6.24 shows example results provided as output from these two models. The traffic identified in table 6.24 is the traffic estimated by the response and distress models at the end of the seasons calculated by the Environment Effects Model. The rut depth is expressed in millimeters. This same series of calculations would also be made for the two other asphalt contents as discussed in chapter 5, and would be extended to the prediction of fatigue cracking and (or) low-temperature cracking as necessary for a given project.

Table 6.24. Example of Predicted Rut Depth Data from Distress Model

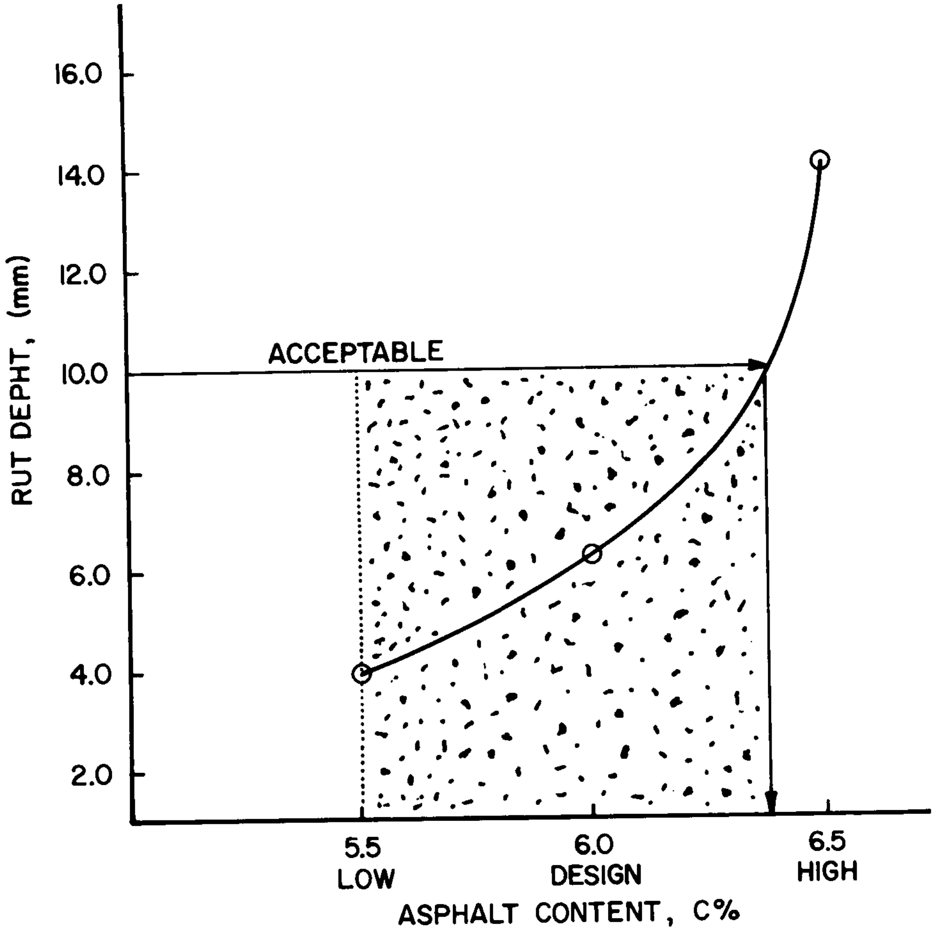
Estimated Traffic (ESALs × 10^6)	Rut Depth (mm)
0.08333	0.65
0.12500	0.86
0.16667	0.50
0.25000	0.74
0.37500	0.93
0.41667	1.02
0.45834	1.02
0.50000	1.02

6.5.7 Selection of the Optimum Asphalt Content

The procedures discussed previously are followed for the remaining asphalt contents identified in chapter 5 and the rut depths are predicted. The predicted values of rut depth (permanent deformation) are used to select the optimum asphalt content. The magnitudes of the predicted rut depths are plotted against the asphalt contents. Figure 6.5 illustrates the graphical plot. Table 5.3 of chapter 5 presents a suggested acceptable level for rutting of 10 mm. This value is shown in figure 6.5 on vertical axis as the acceptable level and is projected to the right to intersect with the plot. At this point of intersection a vertical line is projected perpendicular to the horizontal axis as shown in figure 6.5.

Asphalt contents to the left of the vertical line in figure 6.5 as shown by the shaded area satisfy the rutting or permanent deformation requirement. The optimum asphalt content may be selected within this range identified by the shaded area. If a range of acceptable asphalt binder contents cannot be established from which to select an optimum asphalt content that satisfies the rutting or permanent deformation requirement, the mix proportioning must be adjusted or a modifier included in the mix design.

Figure 6.5. Selection of an Optimum Asphalt Content Range Satisfying Permanent Deformation (Rutting) Requirements



Appendix A Superpave Aggregate Gradation Control Points and Restricted Zones

Table A-1. 37.5 mm Nominal Maximum Size

	Control Point (Percent Passing)	
Sieve Size	Minimum	Maximum
75 µm	0	6
2.36 mm	15	41
25.0 mm	-	90
Nominal maximum (37.5 mm)	90	100
Maximum (50.0 mm)	100	-

Table A-2. 25.0 mm Nominal Maximum Size

	Control Point (Percent Passing)	
Sieve Size	Minimum	Maximum
75 µm	1	7
2.36 mm	19	45
19.0 mm	-	90
Nominal maximum (25.0 mm)	90	100
Maximum (37.5 mm)	100	-

Table A-3. 19.0 mm Nominal Maximum Size

	Control Point (Percent Passing)	
Sieve Size	Minimum	Maximum
75 µm	2	8
2.36 mm	23	49
12.5 mm	-	90
Nominal maximum (19.0 mm)	90	100
Maximum (25.0 mm)	100	-

Table A-4. 12.5 mm Nominal Maximum Size

	Control Point (Percent Passing)	
Sieve Size	Minimum	Maximum
75 µm	2	10
2.36 mm	28	58
9.5 mm	-	90
Nominal maximum (12.5 mm)	90	100
Maximum (19.0 mm)	100	-

Table A-5. 9.5 mm Nominal Maximum Size

	Control Point (Percent Passing)	
Sieve Size	Minimum	Maximum
75 µm	2	10
2.36 mm	32	67
4.75 mm	-	90
Nominal maximum (9.5 mm)	90	100
Maximum (12.5 mm)	100	-

Table A-6. Boundaries of Aggregate Restricted Zone

Sieve Size Within Restricted Zone	Minimum And Maximum Boundaries of Sieve Size For Nominal Maximum Aggregate Size (Minimum/Maximum Percent Passing)				
	37.5 mm	25.0 mm	19.0 mm	12.5 mm	9.5 mm
4.75 mm	34.7/34.7	39.5/39.5	-	-	-
2.36 mm	23.3/27.3	26.8/30.8	34.6/34.6	39.1/39.1	47.2/47.2
1.18 mm	15.5/21.5	18.1/24.1	22.3/28.3	25.6/31.6	31.6/37.6
600 μm	11.7/15.7	13.6/17.6	16.7/20.7	19.1/23.1	23.5/27.5
300 μm	10.0/10.0	11.4/11.4	13.7/13.7	15.5/15.5	18.7/18.7

Appendix B Superpave Specimen Numbers, Test Codes and Temperature Codes for Level 2 and Level 3 Mix Designs

Tables B-1 and B-2 present the quantity of test specimens and their code numbers required for each performance test in the level 2 and level 3 mix design procedures (exclusive of the specimens required for the initial volumetric design procedure). The specimen code numbers, and the test and temperature codes, correspond to those employed by the Superpave software in guiding the performance testing and analysis. Each table presents the requirements for one asphalt binder content; generally, a level 2 or level 3 mix design will evaluate specimens prepared at a minimum of three asphalt binder contents.

Table B-1. Requirements for Superpave Level 2 Mix Design

		Specimen Quantity and Code Numbers at Test Temperature (°C) / Temperature Code				
Test Code	Test	-20/A	-10/B	0/C	T_{eff}(FC)/H	T_{eff}(PD)/G
H	Volumetric	-	-	-	-	-
J	Uniaxial Strain	-	-	-	-	-
S	Simple Shear at Constant Height	-	-	-	1, 2	1, 2
F	Frequency Sweep at Constant Height	-	-	-	1, 2	1, 2
T	Indirect Tensile Strength (50 mm/min Loading Rate)	-	-	-	3, 4	-
C	Indirect Tensile Creep	5, 6, 7	5, 6, 7	5, 6, 7	-	-
X	Indirect Tensile Strength (13 mm/min Loading Rate)	-	5, 6, 7	-	-	-
R	Repeated Shear At Constant Stress Ratio	-	-	-	-	8, 9

Table B-2. Requirements for Superpave Level 3 Mix Design

		Specimen Quantity and Code Numbers at Test Temperature (°C) / Temperature Code						
Test Code	Test	-20/A	-10/B	0/C	4/D	20/E	40/F	T_{eff}(PD)/G
H	Volumetric	-	-	-	10, 11	10, 11	10, 11	-
J	Uniaxial Strain	-	-	-	10, 11	10, 11	10, 11	-
S	Simple Shear at Constant Height	-	-	-	12, 13	12, 13	12, 13	-
F	Frequency Sweep at Constant Height	-	-	-	12, 13	12, 13	12, 13	-
T	Indirect Tensile Strength (50 mm/min loading rate)	-	14, 15	-	16, 17	18, 19	-	-
C	Indirect Tensile Creep	20, 21, 22	23, 24 25	26, 27, 28	-	-	-	-
X	Indirect Tensile Strength (13 mm/min loading Rate)	20, 21, 22	23, 24, 25	26, 27, 28	-	-	-	-
R	Repeated Shear at Constant Stress Ratio	-	-	-	-	-	-	8, 9

Appendix C Standard Method of Test for Determining the Percentage of Crushed Fragments in Gravel[1]

C.1. Purpose and Scope

This method of test covers the procedure for determining the percentage of crushed fragments contained in a sample of crushed gravel.

The percentage of crushed fragments specified in Publication 408 is the minimum amount considered necessary to provide adequate strength and stability in subbase and the required voids ratio in bituminous and portland cement concretes.

C.2. Sampling

Obtain the sample in accordance with PTM 607. It is recommended that the washed and dried aggregate resulting from the procedure of PTM 100, "Amount of Material Finer than No. 100 or No. 200 Sieve in Aggregate," be used. Select a test portion of the sample in accordance with PTM 625 and of sufficient size to be not less than the weights specified in the following table. Do not select samples of an exact, predetermined weight.

Gradation	Approx. Min. Weight	
	kg	lb
#8	0.5	1.0
#57, #67, #7	1.2	2.5
2A, #3, #5, 0GS	2.5	5.0

C.3. Apparatus

Sieves must have square openings of the sizes required in section C.4 conforming to be requirements of PTM 117, for sieving the samples in accordance with section C.4.

A general-purpose balance is also needed, which meets the requirements of AASHTO M 231 for the weight range in which the principal sample weight (see section C.2) is located.

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[1] Pennsylvania Test Method No. 621, reproduced with permission of the Pennsylvania Department of Transportation.

C.4. Procedure

Separate the material on the #4 sieve. Discard all material passing the #4 sieve. When determining the crush count of AASHTO #3 material, separate on the ½ inch sieve and discard all material passing.

Determine to the nearest gram the weight of the crushed fragments in the sample obtained above. A crushed fragment is one having one or more fractured faces. Nicked fragments will not be considered as crushed. A fractured face is a face that exposes the interior of the gravel particle.

C.5. Calculations

The percentage of crushed fragments shall be determined as follows:

$$\frac{A}{B} \times 100 = \% Crushed$$

where: A = weight of crushed fragments

B = total weight of sample retained on the sieve in section A.4.

C.6. Report

Report the amount crushed to the nearest percent.

C.7. References

Pennsylvania Test Method No. 117
AASHTO M 231

Appendix D Superpave Paving Mix Designation

Within the Superpave mix design method, paving mixes are designated based upon the key characteristics of: nominal maximum size; location of the gradation above or below the restricted zone; traffic level; and intended location in the pavement structure.

An example paving mix designation is

100-C-12.5-B

where

100 = traffic level expressed in millions of 80 kN ESALs;

C = below the restricted zone, coarse;

12.5 = nominal maximum size, mm; and

B = paving mix located below 100 mm depth, base course.

The possible mix designators are presented in tables D-1 through D-4.

Table D-1. Traffic Level Designator

Designator	Traffic Level (ESALs)
0.3	$< 3 \times 10^5$
1	3×10^5 to 1×10^6
3	1×10^6 to 3×10^6
10	3×10^6 to 1×10^7
30	1×10^7 to 3×10^7
100	3×10^7 to 1×10^8
300	$> 1 \times 10^8$

Table D-2. Gradation Designator

Designator	Gradation
C	Coarse, below the restricted zone
F	Fine, above the restricted zone

Table D-3. Nominal Maximum Size Designator

Designator	Nominal Maximum Size
9.5	9.5 mm
12.5	12.5 mm
19.0	19.0 mm
25.0	25.0 mm
37.5	37.5 mm

Table D-4. Paving Mix Depth Designator

Designator	Depth of Paving Mix
blank	Within top 100 mm of pavement
B	Base, below top 100 mm of pavement