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Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP Asphalt Research Program

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Abstract

The Strategic Highway Research Program was a highly focused, ambitious research effort which targeted four specific areas for intense study over the time frame from 1987 to 1993.

Asphalt was one of the four study areas. This report describes the Superpave system, the final product of the asphalt research program; and the various parts which comprise its operational characteristics. In all, the final report of the SHRP asphalt research program consists of five parts, the contents of which are briefly described in this report. Reference is made within this report to specific details within the other four parts for readers who want a more detailed description of the methodology, test methods and theory behind Superpave.

Executive Summary

The Superpave (Superior Performing Pavement) mix design method provides a complete, comprehensive means for the design of paving mixes that will achieve a level of performance commensurate with the unique demands of traffic, climate, pavement structure and reliability (or conversely, risk) for the project. It facilitates the selection and combination of asphalt binder, aggregate and, where 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, and to a variety of specialized pavement mixes such as stone matrix asphalt (SMA), for use in the construction of new surface, binder and base layers and of overlays on existing pavements. It directly addresses the reduction and control of:

- permanent deformation,
- fatigue cracking, and
- low-temperature cracking

through materials selection and mix design, and explicitly considers the effects of aging and moisture sensitivity in promoting or arresting the development of these three distresses.

The Superpave Mix Design Concept

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 for durability;
- sufficient voids in the mineral aggregate and the paving mix as a whole;
- sufficient workability; and
- satisfactory performance characteristics over the service life of the pavement.

The Superpave mix design system contains three distinct levels of design, termed *level 1*, *level 2*, and *level 3*. This permits the selection of a design process that is appropriate for the traffic loads and volume (expressed as total 80 kN ESALs over the service life of the pavement) expected at the paving project.

All three levels of design explicitly consider the effects of climate (environment) on pavement performance. Selection of the performance grade (PG) of asphalt binder is guided by the high and low pavement design temperatures at the project location. Candidate paving mixes are evaluated for acceptable moisture sensitivity. Asphalt binders and paving mixes are aged in the laboratory to simulate the effects of short and long-term aging on performance.

Evaluation of the Performance Capabilities of Asphalt Binders in the Superpave System

In the Superpave system, selection of a *performance grade (PG)* of asphalt binder is guided primarily by the high and low pavement design temperatures at the actual location of the pavement. Evaluation of the (unmodified or modified) asphalt binder is based on a comparison of the results of the performance-based tests listed in table 1 to limits contained in the Superpave performance-based asphalt binder specification (AASHTO Provisional Standard Specification MP1, *Performance Graded Asphalt Binder).* This permits the capabilities of any asphalt binder to be objectively measured and gauged against those of any other asphalt binder.

Table 1. Superpave Asphalt Binder Performance Tests

Test Method	Measure Property	Relevant Pavement Distress
Bending Beam Rheometer Test	• Creep stiffness • Slope of log stiffness versus log time curve	• Low-Temperature Cracking
Dynamic Shear Rheometer Test	• Shear stiffness • Phase angle	• Permanent Deformation • Fatigue Cracking
Direct Tension Test	• Failure strain	• Low-Temperature Cracking

The contribution of the asphalt binder to permanent deformation is controlled by specifying a minimum value of 2.2 kPa for the stiffness parameter, $G^*/\sin\delta$ (= 1/J", the inverse of the loss compliance), at a maximum pavement design temperature. This parameter is correlated to that portion of the accumulated, non-recoverable deformation occurring in a pavement that is attributable to the asphalt binder. Comparison of the value of $G^*/\sin\delta$ for asphalt binders to this specification limit will indicate how well they will perform with respect to permanent deformation.

The contribution of the asphalt binder to low-temperature cracking is controlled by specifying limits for the creep stiffness (< 300 MPa), the slope of the stiffness-time relationship (> 0.300), and the tensile strain at failure (> 1.0 percent) at test temperatures related to the lowest expected pavement design temperature. These properties affect the ability of the pavement to dissipate the tensile strains that result from rapid reductions in temperature or continual low-temperature cycling. Comparison of the measured values of these three properties for asphalt binders with these specification limits will indicate how well they will perform with respect to low-temperature cracking.

The contribution of the asphalt binder to fatigue cracking is governed by specifying a maximum value of 5,000 kPa for the stiffness parameter, $G^*\sin\delta$ (= G", the loss modulus), at the average pavement design temperature. This parameter is related to the contribution of the asphalt binder to the dissipation of energy in a pavement during each loading cycle. Comparison of the measured value of $G^*\sin\delta$ for asphalt binders with this specification limit will indicate how well they will perform with respect to fatigue cracking.

Performance Evaluation and Design of Paving Mixes in the Superpave System

The Superpave *level 1* mix design method employs a performance-based asphalt binder specification, empirical, performance-related aggregate specifications, and the principles of volumetric mix design, to obtain paving mixes with satisfactory performance for low traffic paving projects without the need for accelerated performance 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.

The *level 1* design method does not provide specific estimates of pavement performance with regard to permanent deformation, fatigue cracking and low-temperature cracking. It does provide reasonable assurance of adequate performance if all the specified criteria are met.

The Superpave *level 2* mix design method 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 high and low asphalt binder contents bracketing this design value, are subjected to a series of accelerated performance tests selected for use in ordinary mix designs.

These test results are used in the Superpave software to estimate the development of permanent deformation, fatigue cracking and low-temperature cracking over the service life of the pavement. The reliability of these estimates is consistent with the choice of the *level 2* method for routine mix designs. Selection of the optimum asphalt binder content is based upon these performance estimates and volumetric requirements for air voids content, voids in mineral aggregate and voids filled with asphalt.

The Superpave *level 3* mix design method also 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 high and low asphalt binder contents bracketing the design value, are subjected to an extended series of accelerated performance tests. These test results aid in the selection of 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 a considerably greater time and a greater number of specimens than *level 2* designs.

These test results are used in the Superpave software to estimate the progress of permanent deformation, fatigue cracking and low-temperature cracking over the service life of the pavement. The reliability of these estimates is consistent with the designation of *level 3* as the method of choice for mix designs where superior performance is mandatory. Selection of the optimum asphalt binder content is based upon these performance estimates and volumetric requirements for air voids content, voids in mineral aggregate and voids filled with asphalt.

Compaction and Performance Testing in the Superpave Mix Design Method

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 *accelerated performance tests* 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 tests and procedures, and the equipment required for each, are presented in table 2.

Table 2. Superpave Mix Design Tests and Equipment

Method or Procedure	Test Equipment	Relevant SHRP or Other Test Designation
Gyratory or Rolling Wheel Compaction	SHRP Gyratory Compactor *or* Rolling Wheel Compactor	M-002 *or* M-008
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	Shear Test Device	M-003, P-005
Simple Shear	Shear Test Device	M-003, P-005
Uniaxial Strain	Shear Test Device	M-003, P-005
Volumetric Test	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	Shear Test Device	M-003, P-005
Indirect Tensile Creep Test	Indirect Tensile Test Device	M-005
Indirect Tensile Strength Test	Indirect Tensile Test Device	M-005

The SHRP gyratory compactor effectively simulates the field compaction process to ensure that engineering properties of laboratory compacted specimens are equivalent to those of in-place paving mix.

This unit is equally capable of central laboratory and field control operations. It permits real-time determination of bulk specific gravity and air voids content during compaction; this capability is required for the *level 1* (volumetric) mix design.

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. The unit operates at an angle of gyration of 1.25°, a speed of 30 gyrations per minute, and a vertical ram pressure of 0.6 MPa.

All compacted specimens used in the mix design process are short-term aged. This procedure consists of placing loose mix 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 through HMA production and about 3 years of pavement service. A long-term (> 10 years) aging procedure is also provided.

All trial mix designs are screened for adequate moisture sensitivity using either AASHTO Standard Method of Test T 283 or SHRP Method of Test M-006.

Accelerated Performance Testing with the Shear Test Device and the Indirect Tensile Test Device

The ability of a paving mix to resist the development of permanent deformation is estimated through the use of the *shear test device*. The series of tests listed in table 2 provides 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 pavement structure for specific traffic and climatic conditions.

The shear test device simulates the comparatively high shear stresses that exist near the pavement surface at the edges of the tires and that lead to lateral and vertical deformation. It is distinguished by the capability 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. It accommodates standard Superpave specimens of 150 mm diameter.

The ability of a paving mix to resist the development of low-temperature cracking is estimated through the use of the *indirect tensile test device*. The series of tests listed in table 2 provides material properties that are used in the Superpave pavement performance prediction models. The development over time of low-temperature cracking is predicted for the trial mix design in a pavement for specific traffic, climatic and structural 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 the same as those presented in ASTM Standard Test Method D 4123.

Test results from both devices are required to estimate the ability of a paving mix to resist the development of fatigue cracking.

The Superpave Software

The Superpave software integrates specification, mix design and support routines into one program. It is designed to be used in conjunction with *The Superpave Mix Design Manual for New Construction and Overlays* (Cominsky et al. 1994) to guide the mix design process from beginning to end. It provides an orderly, self-contained means for the recording of all test data and analysis results, performance predictions, and other information 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.

At the conclusion of the mix design, an individual computer file is available for archiving that contains all essential information about the project design, from the initial selection of materials to field control during HMA production and pavement construction.

The Superpave software consists of the *program core* containing:

- 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.

In addition, several complete, independent programs are *embedded* in the Superpave software and accessed automatically by its direction and control routines:

- algorithms that calculate fundamental material properties used in performance prediction models from the results of the load and non-load related performance tests described previously;
- performance prediction models 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 specially tailored for use with the Superpave software that generates seasonal pavement temperature files used by the performance prediction models.

1

Introduction to the Superpave System

1.1 Introduction

Superpave (*Sup*erior *Per*forming Asphalt *Pave*ments) is the final product of the Strategic Highway Research Program (SHRP) Asphalt Research program. Superpave

- is a comprehensive system for the design of paving mixes that are tailored to the unique performance requirements dictated by the traffic, environment (climate), and structural section at a pavement site. It enhances pavement performance through the selection and combination of the most suitable asphalt binder, aggregate, and, where necessary, modifier from all the possible choices;
- represents the integration of more than twenty-five products of the SHRP asphalt research program into a single system for the design and analysis of paving mixes. It encompasses new material specifications, test methods and equipment, a mixture design method, and a software system in a comprehensive, coordinated package;
- was devised to replace the diverse material specifications and mixture design methods now used by the fifty states with a single system that can provide results tailored to the distinct environmental and traffic conditions found at any given pavement location in the United States and Canada;
- is applicable to virgin and recycled, dense-graded, hot-mix asphalt, with or without modification, for use in new construction and overlays.

It was developed to address and minimize permanent deformation, fatigue cracking, low temperature cracking, and it considers how the effects of aging and moisture damage contribute to the development of these three distresses.

1.2 Organization

This final report is one of a series of five reports that describes the final products of the SHRP Asphalt Research Program and their development, validation and use.

- Superior Performing Asphalt Pavement (Superpave): The Product of the SHRP Asphalt Research Program;
- Technical Summary: Level 1 Mixture Design (Cominsky, Harrigan, and Leahy 1994);
- Validation of Relationships Between Specification Properties and Performance (Leahy, Harrigan, and Von Quintus 1994);
- The Superpave Mix Design System Manual of Specifications, Test Methods and Practices (Harrigan et al. 1994);
- Superpave Mix Design Manual for New Construction and Overlays (Cominsky et al. 1994);
- Superpave Software: A Users Manual (Deighton et al. 1994)

The first report presents the Superpave system, with emphasis on explaining its main features and how it can be merged into routine state highway agency operations.

The second report offers a concise, comprehensive discussion of the development and validation of the performance-based specifications, test methods, practices, equipment and the software in the Superpave system.

The third report contains all of the Superpave test methods, standard equipment specifications, practices, and protocols.

The fourth report describes the three-level Superpave mix design method which replaces existing methods such as Marshall and Hveem.

The fifth report is the user's manual for the Superpave software.

This report is in large measure a synthesis of results obtained and products developed during the SHRP Asphalt Research Program. Detailed supporting data and information are contained in research reports and working papers from the individual SHRP research contracts and other research reports and manuals that are referenced throughout the five reports. A glossary of terms utilized in the Superpave system is contained in appendix A of this report. A list of major reports produced by each contract is in section 1.5 of this report.

1.3 Program Background

The SHRP Asphalt Research Program was developed in the early 1980s because of an increasing number of premature asphalt pavement failures. In recognition of this problem, the states initiated the development of a coordinated, well-funded, national research effort to develop improved specifications for asphalts and, ultimately, asphalt mixtures. The importance of and need for specification development in the SHRP Asphalt Research Program originated in Transportation Research Board Special Report 202, *America's Highways: Accelerating the Search for Innovation* (TRB 1986a) popularly called the "Blue Book", which presented the conclusions and recommendations of the Strategic Transportation Research Study (STRS). The authors of the Blue Book stated the objective of the asphalt research program as follows:

> To improve pavement performance through a research program that will provide increased understanding of the chemical and physical properties of asphalt cements and asphalt concretes. The research results would be used to develop *specifications, tests*, ... needed to achieve and control *the pavement performance desired* (emphasis added).

This emphasis was reinforced and further defined in the May 1986 Transportation Research Board report, *Strategic Highway Research Program Research Plans* (TRB 1986b) popularly called the Brown Book. This report stated a specific constraint or guideline for the asphalt program: "... the final product will be *performance-based specifications for asphalt*, with or without modification, and *the development of an asphalt-aggregate mixture analysis system* (AAMAS)." (Emphasis added).

The Brown Book further described the program's Project 1-4, "Preparation of Performance-Based Specifications for Asphalt and Asphalt-Aggregate Systems." This project consisted of two tasks: to develop the asphalt specification and to develop the AAMAS.

Finally, the SHRP Executive Committee in 1987 approved *A Contracting Plan for SHRP Asphalt Research* (SHRP 1987). This contracting plan became the strategic plan for the SHRP Asphalt Research Program, and took precedence over earlier research plans when issues of proper technical direction arose. The contracting plan combined the many tasks identified in the 1986 Brown Book into a coordinated, manageable structure of eight main contracts. The original A-002 and A-003 contracts were divided into three and two parts, respectively. The A-006 contract was incorporated into the A-001 contract.

The responsibility for the development of the Superpave performance-based asphalt binder specification, performance-based asphalt-aggregate mixture specification and mix design system, and for the technical direction and coordination of the entire program was assigned to the A-001 contractor, The University of Texas at Austin, in October 1987.

Between 1987 and 1993, the asphalt research program was established and carried out through the award of the eight major research contracts and an additional 15 supporting studies. Throughout this time, the goals of the program remained substantially unchanged from those originally articulated in the Blue Book, although details were changed as the program evolved.

Four significant changes to the research and contracting plans evolved through an ongoing dialogue among those in the highway community who participated in the development, conduct, management and oversight of the program.

1. The term *asphalt* was broadened to *asphalt binder* in recognition of the fact that the specification encompasses modified binders as well as unmodified asphalt cements.

2. The original concept of a SHRP specification for an AAMAS[1] evolved to a performance-based specification for asphalt-aggregate mixtures supported by a distinct mixture design system.

3. The term Superpave was chosen in 1991 to signify the integrated structure of performance-based specifications, test methods, equipment and protocols, and a mixture design system. The Superpave system is the principal product of the SHRP asphalt research program.

4. Also in 1991, the Superpave software was developed to provide a unifying framework for the entire system.

The eight major contracts of the SHRP asphalt research program are listed in table 1-1.

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[1] The term *asphalt-aggregate mix analysis system,* or AAMAS, was introduced by NCHRP Project 9-6 (Von Quintus et al. 1991). SHRP adopted the term Superpave in order to distinguish the two research efforts and to better describe the specific goal of the SHRP research.

Table 1-1. The Eight Major Contracts of the SHRP Asphalt Research Program

SHRP Contract No.	Contract Title (Contractor)
A-001	SHRP Asphalt Research Program: Technical Direction, Specification and Superpave Development (The University of Texas at Austin)
A-002A	Binder Characterization and Evaluation (Western Research Institute)
A-002B	Novel Approaches for Investigation of Asphalt Binders (University of Southern California)
A-002C	Nuclear Magnetic Resonance Investigation of Asphalt (Montana State University)
A-003A	Performance-Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures (University of California at Berkeley)
A-003B	Fundamental Properties of Asphalt -Aggregate Interaction Including Adhesion and Adsorption (Auburn University)
A-004	Asphalt Modification Practices and Modifiers (Southwestern Laboratories)
A-005	Performance Models and Validation of Test Results (Texas Transportation Institute)

1.4 Superpave

The major products of the SHRP asphalt research program were:

1. A performance-based specification for asphalt binders and the supporting test methods and equipment (chapter 2);

2. A performance-based mixture design system with supporting test methods and equipment (chapter 3 and 4);

3. A modifier evaluation protocol (chapter 5); and

4. The Superpave specification, design, and support software (chapter 6).

These products are an integrated, coordinated system and are tied together by the Superpave software. The Superpave system provides a means for rational design of asphalt paving mixtures and provides a framework and mechanism to tie mixture and structural design together.

Superpave was developed to replace the diverse specifications and mix design methods used by the 50 states and other transportation agencies. Superpave provides a single, performance-based system that can account for the distinct traffic and environmental conditions found throughout the United States, Canada, and other parts of the world.

Thus, changes or modifications needed in the future should be undertaken by American Association of State Highway and Transportation Officials (AASHTO), not on an agency-by-agency basis. Failure to follow this procedure will quickly return the industry to fragmented, widely-varying specifications and procedures which may not be performance-based.

It must also be emphasized that Superpave is a system, and users are cautioned against selectively choosing certain components of the system for use and rejecting other components.

1.4.1 Specifications

Performance-based specifications for both asphalt binders and asphalt-aggregate mixtures have been developed. These specifications apply equally to modified and unmodified materials, and allow selection of materials and design of mixtures on the basis of pavement performance requirements for predicted traffic and environmental conditions. In addition, a modifier evaluation protocol is provided that allows proposed modifiers to be evaluated without the need for lengthy field trials. The modifier evaluation protocol involves the evaluation of the modified binder or mixture to determine whether the performance-based specifications are satisfied. It also includes specialized techniques to measure time and heat stability, phase separation, and stability.

1.4.2 Test Methods and Equipment

The Superpave test methods and equipment required to support specifications, the modifier evaluation protocol, and the mixture design system are described in chapters 2, 3 and 4 of this report. Complete test methods and equipment specifications are contained in Harrigan et al. 1994.

The new test methods, equipment, and practices for asphalt binders are:

- test method for determining the flexural creep stiffness of asphalt binders using the Bending Beam Rheometer (AASHTO TP1);
- test method for determining rheological properties of asphalt binders using a dynamic shear rheometer (AASHTO TP5);
- test method for determining the fracture properties of asphalt binders using a direct tension test. (AASHTO TP2);
- practice for accelerated aging of asphalt binder using a pressurized aging vessel, (PAV) (AASHTO PP1).

The above AASHTO designations are provisional. In addition, the asphalt binder specification requires use of the rolling thin film oven test (AASHTO T240); the Cleveland open cup flash point test (AASHTO T48); and measurement of viscosity with the Brookfield Thermosel Viscometer (ASTM D4402) or capillary viscometer (AASHTO T201).

The new test methods, equipment and practices for asphalt-aggregate mixtures involve:

- laboratory and field control compaction by the Superpave gyratory compactor (SHRP M-002);

- asphalt-aggregate compatibility and moisture sensitivity by the net adsorption test (SHRP M-001);

- short- and long-term aging by the forced draft oven (SHRP M-007);

- Characterization of permanent deformation and fatigue cracking behavior for high traffic volume mixes by the Superpave shear and indirect tensile equipment, include the following tests (SHRP M-003, M-005 and P-005):

    - volumetric (hydrostatic state of stress) test,
    - uniaxial strain test,
    - simple shear test at constant height,
    - frequency sweep at constant height test,
    - repeated shear test at constant stress ratio test (a screening test for plastic flow or tertiary creep),
    - repeated shear test at constant height test, and
    - indirect tensile strength test (50 mm/min).

- Characterization of low-temperature cracking behavior by the indirect tensile test device (SHRP M-005):

    - indirect tensile creep test, and
    - indirect tensile strength test (12.5 mm/min).

- Characterization of permanent deformation and fatigue cracking behavior for lower traffic volumes (e.g. less that 10^7 ESALs) involves only

    - simple shear test at constant height,
    - frequency sweep at constant height,
    - repeated shear test at constant stress ratio (a screening test for plastic flow or tertiary creep), and
    - indirect tensile strength test (50 mm/min).

It is anticipated that the repeated shear test at constant stress ratio may not always be necessary for routine design. These tests are described in chapter 4.

In addition, moisture sensitivity is evaluated using either the indirect tensile test (AASHTO T-283) or the Environmental Conditioning System (SHRP M-006).

1.4.3 Mixture Design System

The Superpave mix design system is described in chapters 3 and 4. The step-by-step procedures are described by Cominsky et al. (1994). This system provides a step-by-step procedure for the design of mixtures to provide a specified level of performance in terms of rut depth and cracking frequency for the predicted traffic and environmental conditions. The distresses considered are:

- permanent deformation,
- fatigue cracking, and
- low temperature cracking.

The method also recognizes and accounts for the effects of aging and moisture in the development of these distresses.

The mix design method is structured so that the user may add other distresses (e.g., reflective cracking, ravelling and studded tire damage) when appropriate test methods and analytical procedures are identified.

1.4.4 Field Control Tests and Protocols

The mix design system includes test methods and protocols for field control of paving mixtures (chapter 4). These are suitable for use with any type of state highway agency specification and quality control/quality assurance program. The volumetric properties of the plant-produced mix compacted with the Superpave gyratory compactor and the in-situ density of the compacted pavement are the primary controls of the asphalt-aggregate mix.

1.4.5 Modifier Evaluation Protocol

The modifier evaluation protocol and associated tests provide a means of assessing the probable performance of modified asphalt binders and asphalt-aggregate mixtures without the need for lengthy field trials. The performance-based specifications and test methods apply equally to modified and unmodified materials, and thus they can be used to estimate the performance of modified materials directly. In addition, specialized tests and procedures in the protocol address considerations in the use of modified materials (storage stability, phase separation, heat sensitivity, toxicity, etc.). The protocol is described in chapter 5.

1.4.6 Superpave Software

The Superpave Specification, Design and Support Software is described in chapter 6 and in the Users Manual (Deighton et al. 1994). The software contains an extensive database of environmental parameters based on 20- to 80-year observations from approximately 7,000 weather stations in the United States and Canada. Additional environmental data may be incorporated to make the software and the system applicable to other regions of the world. Extension of the system and its specification limits to climates outside of the extremes found in the United States and Canada should be done with some caution until further validation is performed with field pavement performance data.

1.4.7 Performance Models

The performance models which are utilized in the Superpave software are described briefly in chapter 4 and appendix C, and in detail by Lytton et al. (1993). These are the models that are included in the Superpave mix design system.

1.4.8 Summary

The SHRP Asphalt Program was an unparalleled mission-oriented research and development program which delivered the products briefly described above and will be described in greater detail in subsequent chapters. A substantial effort was devoted to:

1. developing a well-coordinated system related to the design and specification of material for both modified and unmodified asphalt mixtures;

2. developing performance-based specifications that can be used throughout the United States and Canada; and

3. developing an understanding of the products throughout the industry while simultaneously developing the products.

Thus, the myriad specifications of various transportation agencies can be eliminated, which will benefit not only the states but also hot-mix asphalt contractors, oil companies, and specialty asphalt binder companies that have had to produce materials in response to numerous, and sometimes meaningless, specifications.

1.5 Primary SHRP Reports

The following are the major reports produced by each contract:

A-001 **Superpave and Asphalt Research Program Final Reports**

- Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP Asphalt Research Program (SHRP-A-410)
- Level 1 Mix Design: Materials Selection, Compaction, and Conditioning (SHRP-A-408)
- Validation of Relationships Between Specification Properties and Performance (SHRP-A-409)
- Superpave Mix Design System Manual of Specifications, Test Methods, and Practices (SHRP-A-379)
- Superpave Mix Design Manual for New Construction and Overlays (SHRP-A-407)
- Superpave Superior Performing Asphalt Pavement System (SHRP-A-411)

A-002A **Asphalt Binder Studies Reports**

- Binder Characterization and Evaluation Volume 1 (SHRP-A-367)
- Binder Characterization and Evaluation Volume 2: Chemistry (SHRP-A-368)
- Binder Characterization and Evaluation Volume 3: Physical Characterization (SHRP-A-369)
- Binder Characterization and Evaluation Volume 4: Test Methods (SHRP-A-370)

A-003A **Asphalt Mixture Studies Reports**

- Stage 1 Validation of the Relationship between Asphalt Properties and Asphalt-Aggregate Mix Performance (SHRP-A-398)
- Accelerated Performance-Related Tests for Asphalt-Aggregate Mixes and Their Use in Mix Design and Analysis Systems (SHRP-A-417)
- Low-Temperature Cracking: Binder Validation (SHRP-A-399)
- Low-Temperature Cracking: Test Selection (SHRP-A-400)
- Low-Temperature Cracking: Field Validation of the Thermal Stress Restrained Specimen Test (SHRP-A-401)
- Aging: Binder Validation (SHRP-A-384)
- Selection of Laboratory Aging Procedures for Asphalt-Aggregate Mixtures (SHRP-A-383)
- Laboratory Aging of Asphalt-Aggregate Mixtures: Field Validation (SHRP-A-390)
- Water Sensitivity: Binder Validation (SHRP-A-402)
- Water Sensitivity of Asphalt-Aggregate Mixes: Test Development (SHRP-A-403)
- Field Validation of the Environmental Conditioning System (SHRP-A-396)
- Fatigue Response of Asphalt-Aggregate Mixes (SHRP-A-404)
- Permanent Deformation Response of Asphalt-Aggregate Mixes (SHRP-A-415)
- Stiffness of Asphalt-Aggregate Mixes (SHRP-A-388)

A-003B **Adhesion-Absorption Study Reports**

- Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Absorption (SHRP-A-341)

A-005 **Performance Model Reports**

- Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixes (SHRP-A-357)

2

Performance-Based Binder Specifications

2.1 Asphalt Binder Specification

The performance-based asphalt binder specification (table 2-1) is applicable to both modified and unmodified asphalt binders including binders with modifiers dispersed, dissolved or reacted with base asphalt cements. The specification is based on stiffness of the aged binder for a specific combination of traffic loading and environmental conditions. Thus, asphalt binder grades are specified primarily with respect to pavement temperatures which allows one binder to be selected for a specified design combination of high and low temperatures. The loading condition related to high temperature performance is a vehicle speed of 100 km/hr and a traffic volume of less than 10^7 equivalent single axle loads (ESALs).

Environmental conditions are specified in terms of

- average 7-day maximum pavement design temperature and
- minimum pavement design temperature.

The average 7-day maximum pavement design temperature is the average of the highest daily pavement temperatures for the 7 hottest consecutive days in a year. The lowest annual pavement temperature is the coldest temperature of the year.

The asphalt binder specification uses the designation *PG x-y*

where *PG* = Performance Graded,
x = high pavement design temperature, and
y = low pavement design temperature.

The pavement design temperatures and corresponding grades are given in table 2-2.

Table 2-1. Performance-Graded Asphalt Binder Specification (AASHTO MP1)

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 (T240) OR THIN FILM OVEN RESIDUE (T179)																					
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.

Table 2-1. 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

Table 2-2. Pavement Design Temperatures and Corresponding Grades

High Design Temperature (°C)	PG Grade Designation x	Low Design Temperature (°C)	PG Grade Designation (y)
< 46	46-	> −10	-10
< 52	52-	> −16	-16
< 58	58-	> −22	-22
< 64	64-	> −28	-28
< 70	70-	> −34	-34
< 76	76-	> −40	-40
< 80	80-	> −46	-46

Hence, an asphalt binder that is graded PG 64-28 would meet the specification for an average high 7-day pavement temperature of less than 64°C, and a low annual pavement temperature greater than −28°C. However, because of the intermediate temperature requirements which are related primarily to fatigue, an asphalt binder may not satisfy the next lower high temperature grade, i.e., an asphalt binder graded PG 64-28 may not meet the requirement for a PG 58-28 grade.

2.1.1 Calculation of Design Pavement Temperatures

Design pavement temperatures can be obtained from direct measurement or can be calculated from air temperature data. The process of calculating pavement temperature from air temperature is as follows:

- convert average 7-day maximum air temperature to pavement surface temperature.
- calculate 7-day maximum pavement temperature at design depth.
- convert minimum air temperature to minimum pavement surface temperature.
- calculate minimum pavement temperature at design depth.

The method allows the estimation of the pavement surface temperature and the temperature at specified depths from the surface.

Convert Maximum Air Temperature

The maximum air temperature can be converted to a pavement surface temperature using equation 2.1 which is based on theoretical energy balance at the pavement surface. The solution of equation 2.1 requires the techniques of numerical analysis:

$$1331\ \alpha\tau_a^{\frac{1}{Cosz}} \cdot CosZ + \varepsilon_a\sigma T_a^4 - h_c(T_s - T_a) - 164k - \varepsilon\sigma T_s^4 = 0 \tag{2.1}$$

where

α = Pavement surface absorptivity
τ_a = Transmission Coefficient for Air
z = Latitude – 20°
ε = Pavement surface emissivity
σ = Stefan–Boltzman Constant (5.67×10^{-8} watts per $m^{2\circ}K^4$)
h_c = Surface coefficient of heat transfer (watts per m^2 °C)
k = Thermal conductivity coefficient (watts per m °C)
T_a = Air temperature (°K)
T_s = Surface temperature (°K)

The calculations for maximum pavement temperature were performed for sunny days (no cloud cover), assume an 8°C difference between the surface temperature and the temperature at a depth of 50 mm, and use the following default values:

$\tau = 0.80$ $\alpha = 0.9$ $k = 1.38$ watts/m °C
$\varepsilon = 0.9$ $h_c = 19.88$ watts/m^2 °C

To simplify calculations the pavement surface temperature can be calculated using the following regression equation (Huber 1994):

$$T_s = T_a + 0.00618\phi^2 + 0.2289\phi + 24.4 \tag{2.2}$$

where T_s= surface temperature, °C
T_a= air temperature, °C
ϕ = latitude, degrees

Calculate Maximum Pavement Temperature at Depth

The design depth for calculation of maximum pavement temperature used in the Superpave system is 20 mm below the top of the pavement layer. Consider, for example, a 50-mm-thick surface mixture over a base mixture. Design depth for the surface mixture is 20 mm below the pavement surface. Design depth for the base mixture is 20 mm below the top of the base mixture, that is, 70 mm below the pavement surface.

The maximum pavement temperature at specified depths is calculated using the following equation:

$$T_{d(max)} = [T_{s(max)} + 17.8][1 - 2.48(10^{-3})d + 1.085(10^{-5})d^2 - 2.441(10^{-8})d^3] - 17.8 \qquad (2.3)$$

where $T_{d(max)}$ = pavement temperature at depth, °C
$T_{s(max)}$ = pavement surface temperature, °C
d = depth from surface, mm

For a surface mixture where the design depth is 20 mm, equation 2.3 simplifies to

$$T_{20(max)} = 0.955\ T_{s(max)} - 0.8 \qquad (2.4)$$

where $T_{20(max)}$ = temperature at 20 mm, °C
$T_{s(max)}$ = temperature at surface, °C

Convert Minimum Air Temperature

The minimum pavement surface temperature is defined as the minimum air temperature.

Calculate Minimum Pavement Temperature at Depth

The design depth for calculation of minimum pavement temperature is at the surface of the pavement layer. Consider then the example of a 50 mm surface layer over a base layer. Design depth for the surface layer is at the pavement surface. Design depth for the base mixture is at the top of the base layer, which is 50 mm below the pavement surface.

The minimum pavement temperature at depth d is calculated using the following equation:

$$T_{d(min)} = T_{s(min)} + 5.1\ (10^{-2})\ d - 6.3\ (10^{-5})\ d^2 \qquad (2.5)$$

where

$T_{d(min)}$ = pavement temperature at depth d, °C
$T_{s(min)}$ = pavement temperature at the surface, °C
d = depth below the surface, mm

2.1.2 Superpave Weather Database

The Superpave software contains a database of statistical weather data that can be used to determine high and low pavement temperatures. All weather stations in Canada and the United States that contained at least 20 years of records were used to generate statistical air temperature data. Approximately 7,000 weather stations, included in the Superpave software, have the following data elements.

High Air Temperature — A moving 7-day average of air temperature was calculated and the maximum value of each year was selected. A data set containing the maximum value for each year of record was analyzed statistically to determine the mean and standard deviation of the high-temperature data set.

Low Air Temperature — The minimum value of air temperature was selected for each year of record. A data set containing the minimum value for each year was analyzed statistically to determine the mean and standard deviation of the low-temperature data set.

These mean and standard deviations are summarized in the Superpave weather database and can be used to calculate design high and low pavement temperatures in the following fashion:

- select mean and standard deviation for high and low air temperatures;
- select desired reliabilities for high and low air temperatures;
- select design depths; and
- calculate the high and low pavement design temperature.

2.2 Description of the Performance-Based Asphalt Binder Specification

The performance-based asphalt binder specification is a principal product of the SHRP asphalt research program. A major objective of the asphalt research program was to identify and validate engineering properties that could be directly linked to the performance (that is, the response to traffic and environmental loading) of asphalt binders. The performance-based asphalt binder specification shown in table 2-1 incorporates performance-based engineering properties.

The asphalt binder specification requires tests on unaged, short-term aged and long- term aged asphalt binder. This specification represents a different approach to specifying criteria than do existing specifications. The specification is based on pavement temperature and performance-based engineering properties. Instead of changing engineering property requirements for different grades, the specification calls for the same engineering properties for all grades but specifies different temperatures at which the properties must be met.

The flash point of the unaged asphalt binder is specified for safety considerations; its viscosity as measured by ASTM D4402 is specified to ensure pumpability. Note that the viscosity requirement may be waived at the discretion of the specifying agency if the supplier warrants satisfactory pumpability and mixability.

Performance-related requirements are as follows:

- A minimum stiffness (1.0 kPa) is specified on the unaged binder to guard against mixture tenderness.

- A minimum stiffness (2.2 kPa) is specified on the short-term aged binder to ensure adequate permanent deformation resistance immediately after construction.

- A maximum stiffness (5,000 kPa) is specified on long-term aged material to guard against fatigue cracking caused by excessively stiff asphalt binders.

- A maximum stiffness (300 MPa) and minimum slope (0.30) of the creep deformation are specified to limit excessive stiffness at low temperature.

- A higher creep stiffness is allowed by the specification if a minimum tensile strain (1 percent) at failure is achieved. (It is anticipated that this will apply primarily for modified binders which have high stiffnesses at low temperature, but exhibit large failure strains as shown in figure 2-1).

2.2.1 Asphalt Binder Aging

The specification requires asphalt binder aging to simulate:

- short-term aging — aging during construction; and
- long-term aging — aging during the first 5 to 10 years of service life.

Short-term aging is achieved using the rolling thin film oven test (RTFOT, AASHTO T240; ASTM D2872). The test was developed in the western United States for use with the AR viscosity grading system. A specified amount of asphalt binder is poured into a specially designed bottle. The bottle is placed in a rack that rotates around a horizontal axis. The rotating bottle causes fresh films of asphalt binder to be continuously exposed. Heated air is blown into the bottle to purge vapors from the bottle once each rotation. The test is conducted at 163°C with a test time of 85 minutes.

The primary reasons for the inclusion of the RTFOT in the Superpave system are that the temperature control is more precise and modified binders do not tend to "skin over." Additionally, the RTFOT can accommodate more samples and the test time is significantly shorter than the traditional and more widely used thin film oven test (TFOT).

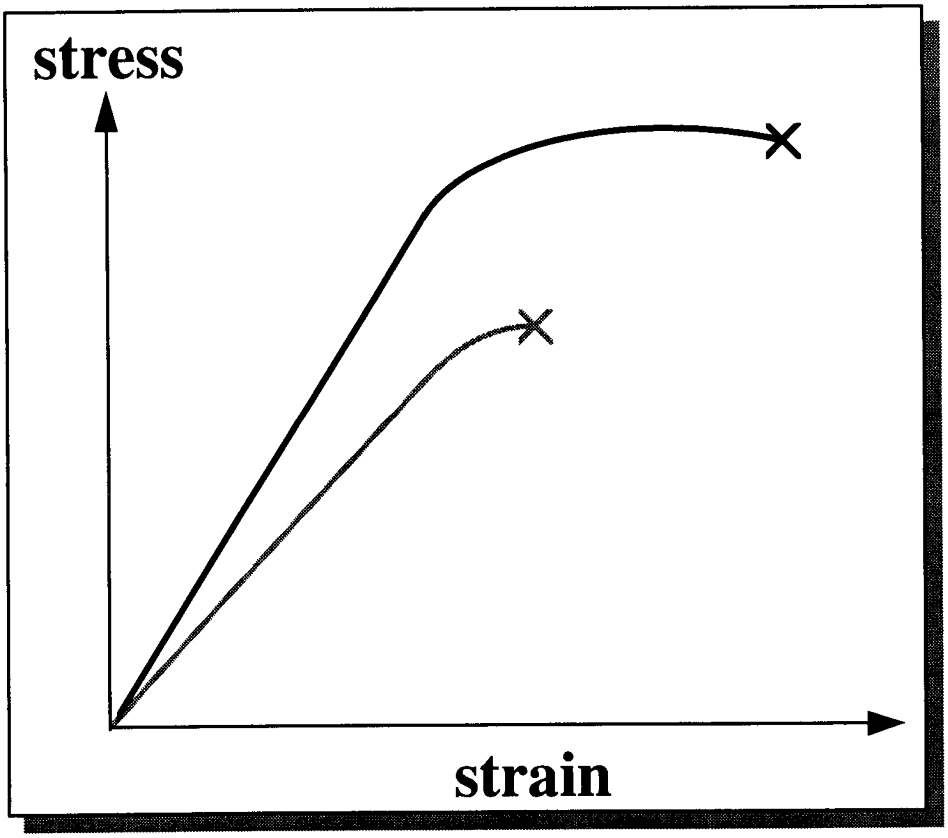


Figure 2-1. **Typical Relationships Between Failure Stress and Failure Strain for Unmodified (*lower*) and Modified (*upper*) Asphalt Binders in the Direct Tension Test**

This reduction in time is offset by the need to transfer the asphalt from the bottles to the pans for PAV aging. While an improved short-term aging procedure is needed and, when developed, can be easily incorporated, *the RTFOT and TFOT procedures should not be specified interchangeably* since this would double the number of grades and lead to the development of state-dependent specifications. *It should be noted that scraping of the residue from the RTFOT bottles is allowed in the Superpave system.*

Long-term aging, which simulates field aging during the first 5 to 10 years of service, is achieved by additional aging of the binder using the pressure aging vessel (PAV) (AASHTO PP1, Harrigan et al. 1994). The asphalt binder from the RTFOT is placed in pans which are loaded into the PAV (figure 2-2). The depth of the binder is 3.2 mm ± 0.1 mm (approximately 50 g). The binder is then subjected to an air pressure of 2100 ± 100 kPa for 20 hours at a temperature of 90, 100, or 110°C, depending on the mean maximum weekly pavement temperature (table 2-1). Most of the states require an aging temperature of 100°C except when the binder will actually be used in a desert region, defined as having a high pavement design temperature greater than 64°C. High temperature grades being used in non-desert regions are aged at 100°C. In northern regions of North America, where temperatures generally are lower, the pressure aging temperature is 90°C.

Figure 2-3 illustrates these primary performance-based tests and the temperatures at which they are used.

2.2.2 Performance-Based Binder Tests

Three performance-based test methods are used to grade the asphalt binders and are the primary basis of the specification. These methods utilize the following test equipment which can test modified as well as unmodified asphalt binders, including those binders in which the modifiers are dispersed, dissolved or reacted in the base asphalt cements:

- bending beam rheometer,
- dynamic shear rheometer, and
- direct tension test.

2.2.2.1 Bending Beam Rheometer

The bending beam rheometer (figure 2-4) measures the low-temperature stiffness characteristics of the asphalt binder. The test equipment and test procedure (AASHTO TP1) are described by Harrigan et al. (1994).

A beam of asphalt binder 125 mm long, 12.5 mm wide and 6.25 mm thick is formed by pouring the asphalt binder into a mold and allowing it to cool (figure 2-5). The beam is then placed in the cooling bath until it achieves the designated testing temperature.

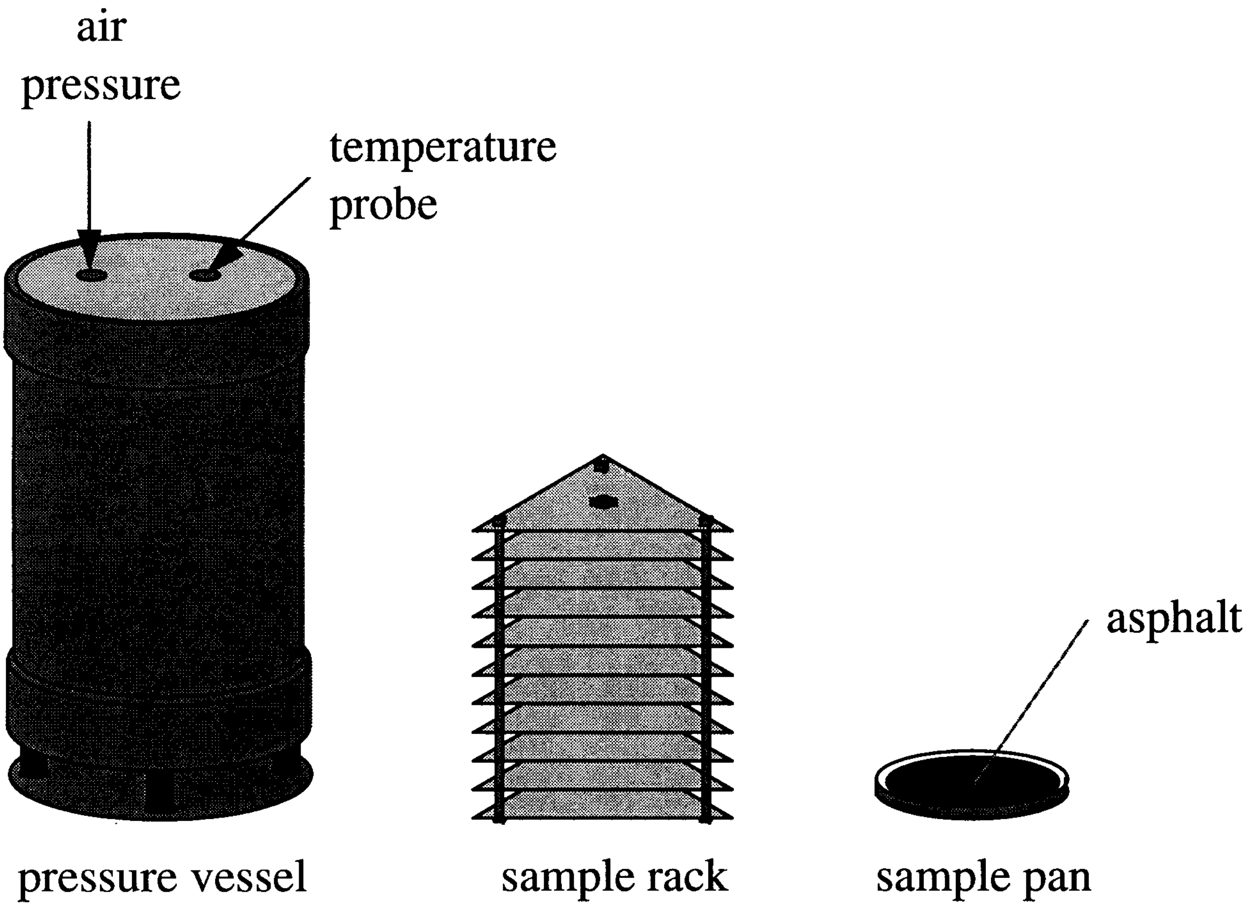


Figure 2-2. Schematic View of the Superpave Pressure Aging Vessel

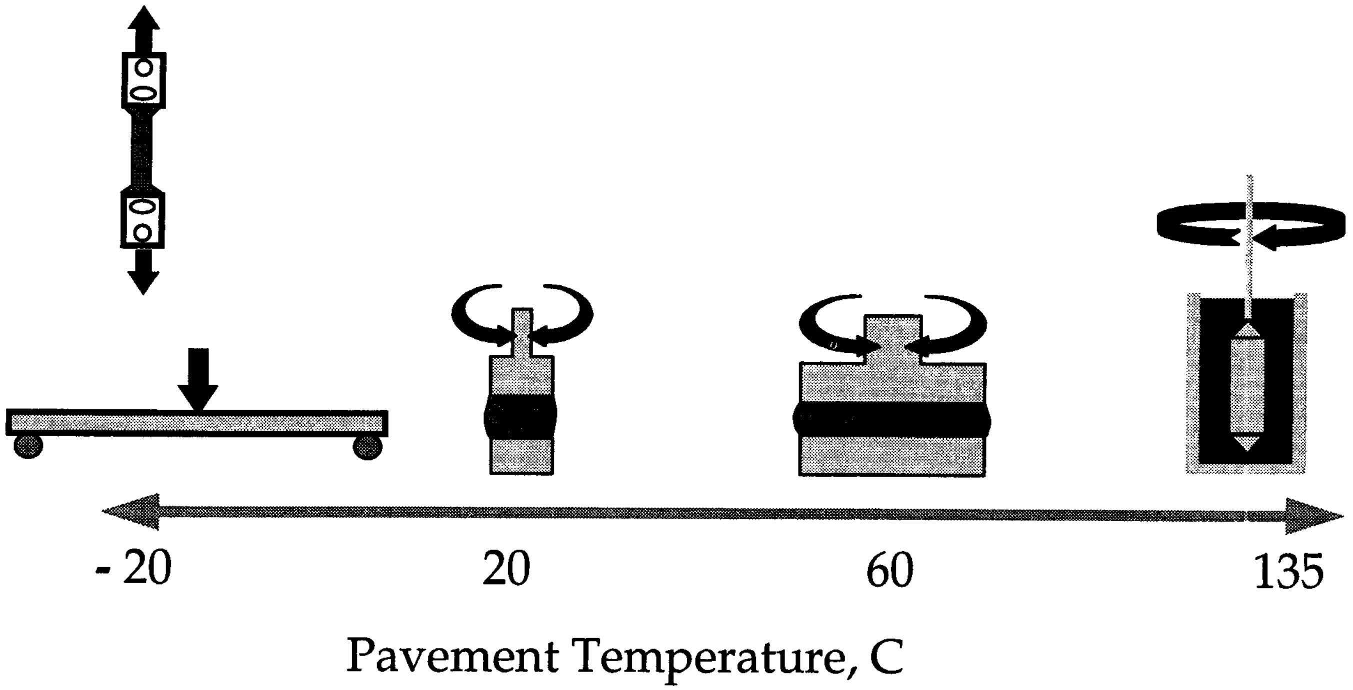


Figure 2-3. **The Superpave Primary, Performance-Based Test Methods for Asphalt Binders**

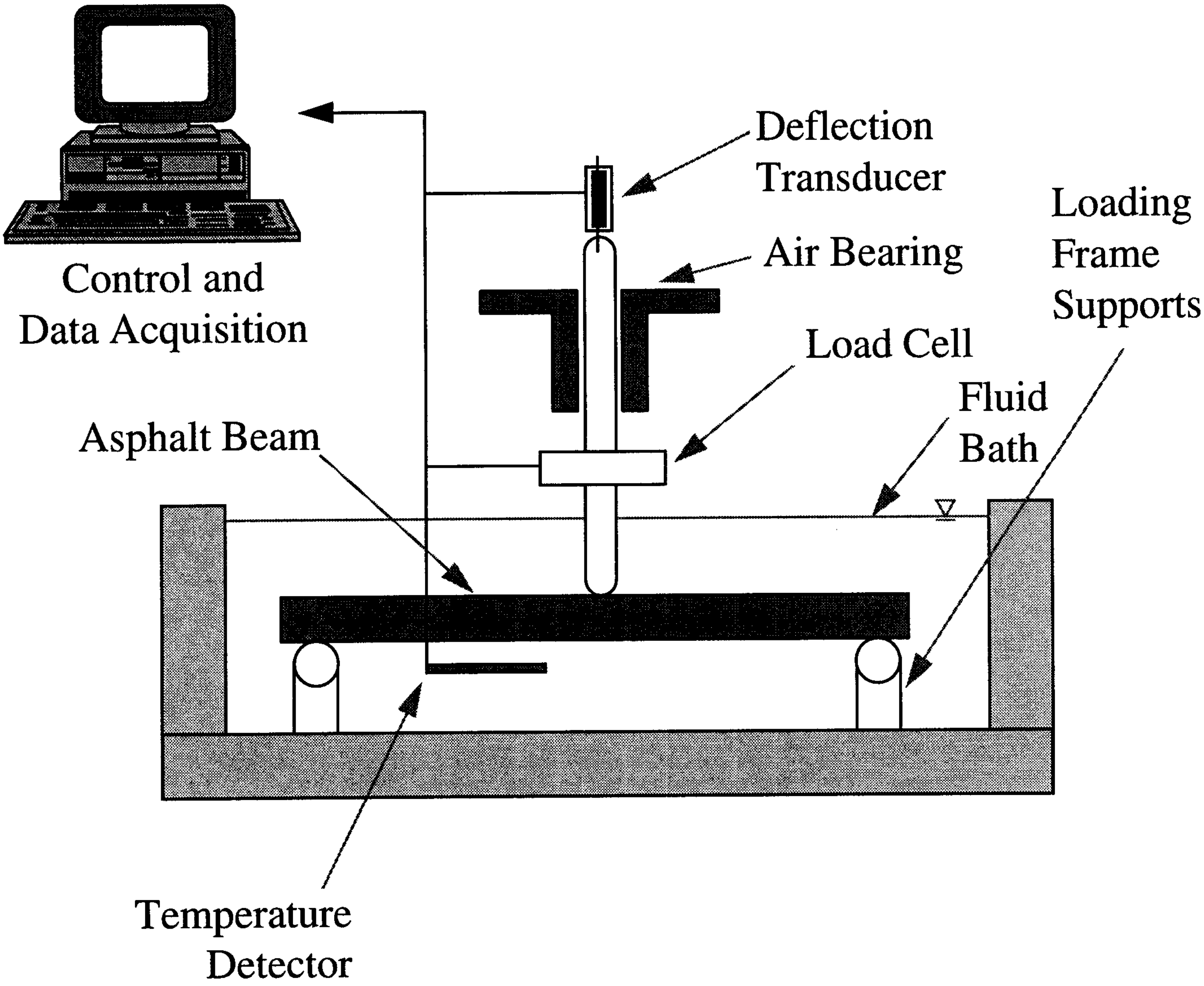


Figure 2-4. Schematic View of the Superpave Bending Beam Rheometer

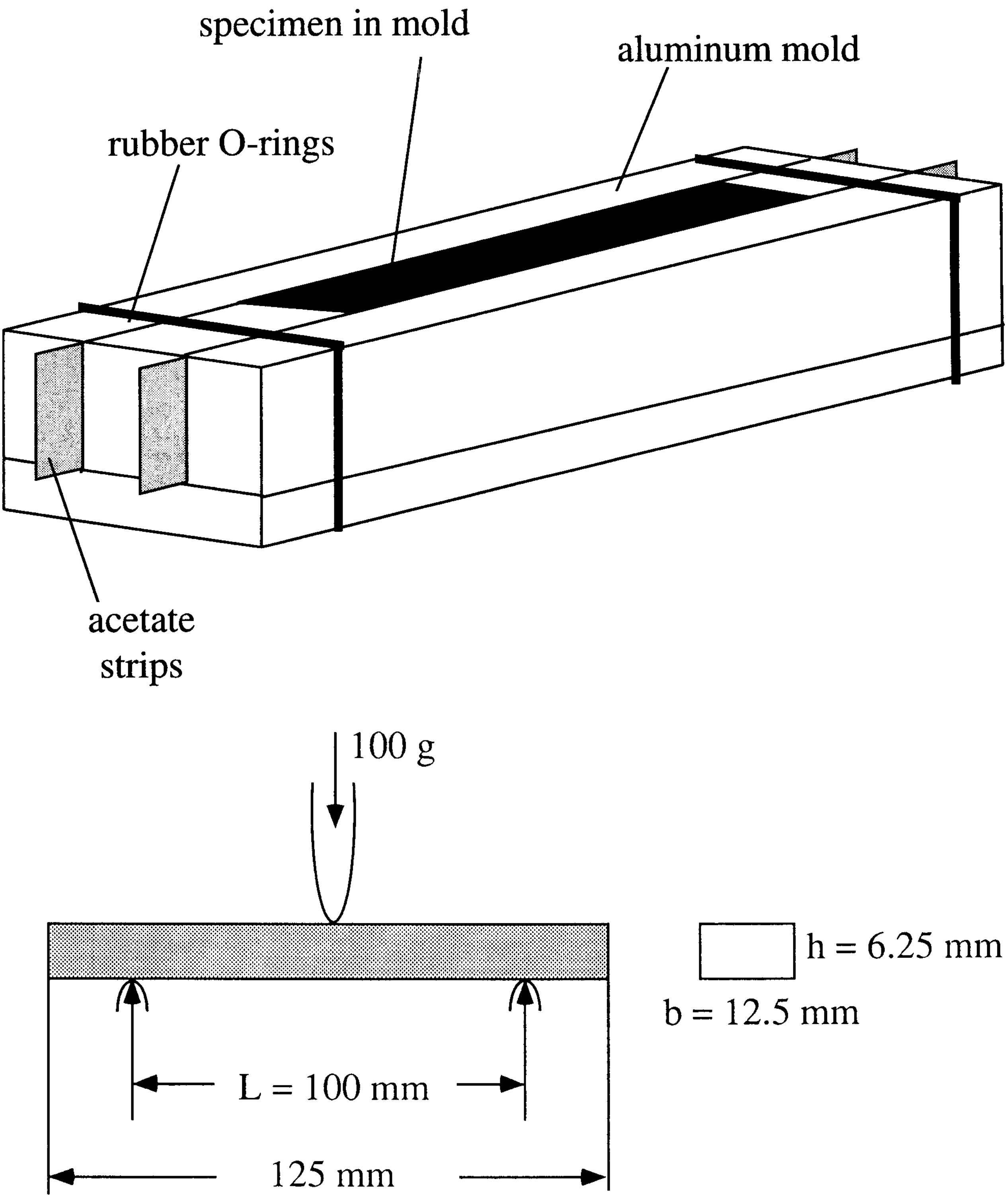


Figure 2-5. **Details of Specimen Mold for Bending Beam Rheometer (upper) Bending Beam Rheometer Specimen (lower)**

Testing must be conducted within 60 ± 5 minutes to minimize stiffening effects which occur with time.

During testing, the loading platform and beam are submerged in a cooling bath. The bath liquid maintains the test temperature and at the same time provides buoyancy to the specimen, which minimizes deflections caused by the mass of the beam. The beam is placed on supports, 100 mm apart, and is loaded at the midspan with a constant load of 95 to 100 g. The deflection of the beam at the midspan is measured continuously over a period of 240 seconds (figure 2-6).

The deflection is related to the span length and geometry of the beam according to the following equation:

$$\delta_t = \frac{PL^3}{48S_tI} \tag{2.6}$$

where

δ_t = deflection at time t.
L = the span length, mm
S_t = stiffness at time t, kpa
I = moment of inertia = $1/12\ b\ h^3$
h = beam height, mm
b = beam width, mm
P = concentrated center load, g

Therefore,

$$S_t = \frac{PL^3}{4bh^3\delta_t} \tag{2.7}$$

Thus for the specified beam geometry (figure 2-5), the flexural stiffness can be calculated using the following equation:

$$S_t = \frac{908.3P}{\delta_t} \tag{2.8}$$

Since the deflection increases with time, the stiffness will decrease as a function of time (figure 2-6).

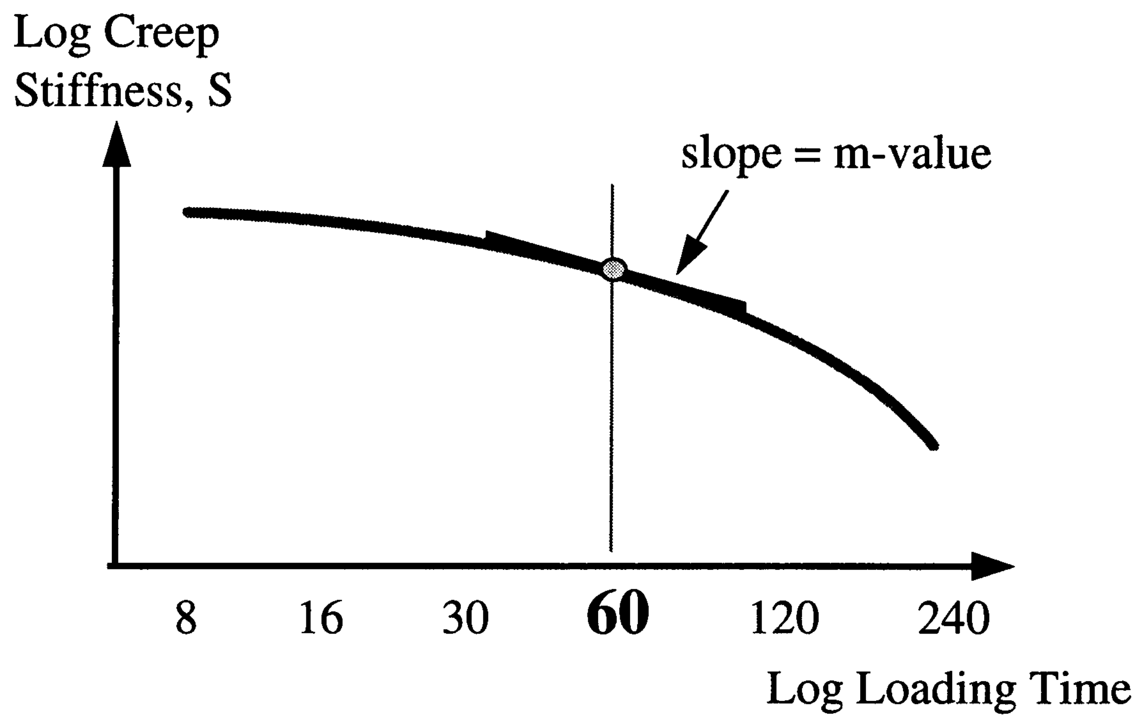


Figure 2-6. **Relationship of Creep Stiffness (*S*) and Slope (*m*) To Bending Beam Rheometer Loading Time**

Specification values are:

- a maximum stiffness value at the minimum pavement temperature plus 10°C after 60 seconds of loading time which, by time-temperature superposition, is equivalent to the stiffness at the minimum pavement temperature at 2 hours' loading time. The specified maximum creep stiffness value at 60 seconds is 300 MPa.

- a minimum value for the slope (*m*) of the relationship between log stiffness and log time after 60 second loading time at the minimum pavement temperature plus 10°C. The specified minimum *m*-value is 0.30.

- a physical hardening index is included in the specification to obtain information needed to access its importance. The phenomenon is discussed in volume 3 of the final report for SHRP contract A-002A (Andersen et al. 1994).

2.2.2.2 Dynamic Shear Rheometer

The dynamic shear rheometer (AASHTO TP5, figure 2-7) measures the high-temperature shear stiffness and phase angle. A 1- to 2-mm thick sample of asphalt is placed between two parallel circular plates (8 or 25 mm in diameter). The actual thickness is dependent on the stiffness of the binder. The bottom plate is fixed and the top plate is oscillated by a computer-controlled electronic motor. Oscillations typically are less than 0.1 degree and occur at a range of frequencies. For specification purposes, the frequency is 10 radians per second which has been related to a traffic speed of 100 km/hr. The temperature of the sample must be within ± 0.1 °C of the specified test temperature. The sample is conditioned for 10 cycles prior to actual testing.

For slower moving traffic, a lower frequency could be used for evaluation of a proposed product. For example, with city street traffic a frequency of 5 radians per second could be used (corresponding to 50 km/hr); for standing traffic, a very low frequency, such as 1 radian per second might be appropriate. An alternative procedure is used in the specification. Rather than changing the test procedure, an increase in the high temperature performance grade is recommended for low traffic speeds, heavy loads and/or very high traffic volumes. This recommended procedure is presented in detail in section 2.2 of Cominsky et al. 1994.

The angular rotation (Θ) and applied torque (τ) is measured, and the shear stiffness (complex modulus), *G**, is calculated using the following equation:

$$G* = \frac{\tau_m}{\gamma_m} \qquad (2.9)$$

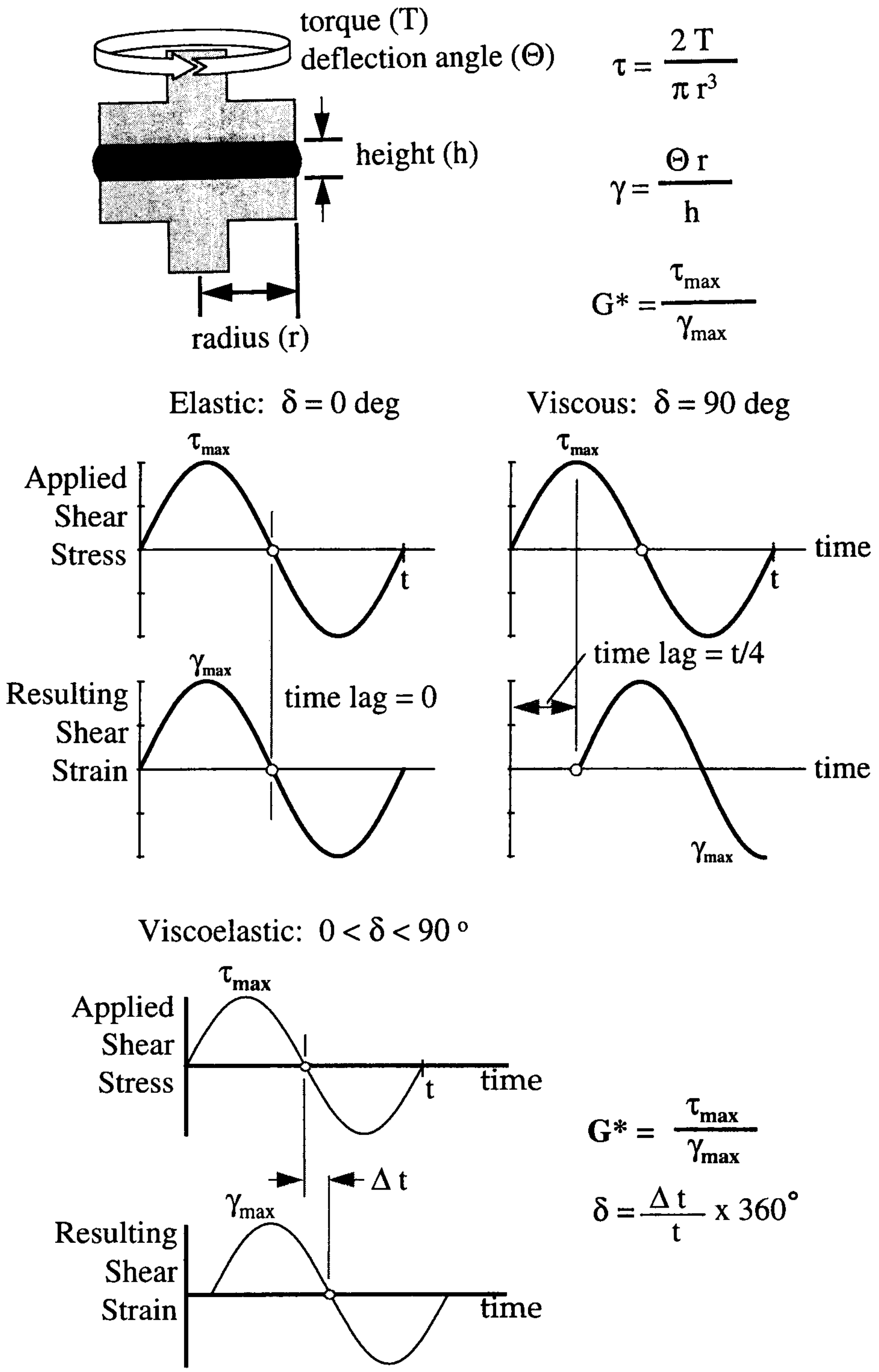


Figure 2-7. **Dynamic Shear Rheometer**

a) principle of operation.

b) relationship of shear stress and shear strain for elastic (δ = 0°) and viscous (δ = 90°) materials.

c) relationship of shear stress and shear strain for viscoelastic (0° < δ < 90°) materials.

where

G^* = the complex shear stiffness modulus, kPa,
τ_m = maximum shear stress (peak to peak, figure 2-7), kPa, and
γ_m = maximum shear strain (peak to peak, figure 2-7).

The shear stress (τ) is calculated using the following equation:

$$\tau = \frac{2T}{\pi r^3} \tag{2.10}$$

where

T = applied torque
r = radius of the plate.

The shear strain (γ) is calculated using the following equation:

$$\gamma = \frac{\theta r}{h} \tag{2.11}$$

where θ = deflection or angle of rotation.

The phase angle δ is determined from the time lag between the applied shear stress (torque) and the resulting shear strain (angular rotation) in a controlled stress test, or between the induced shear strain and the required shear stress in a controlled strain test. It is calculated using the following equations:

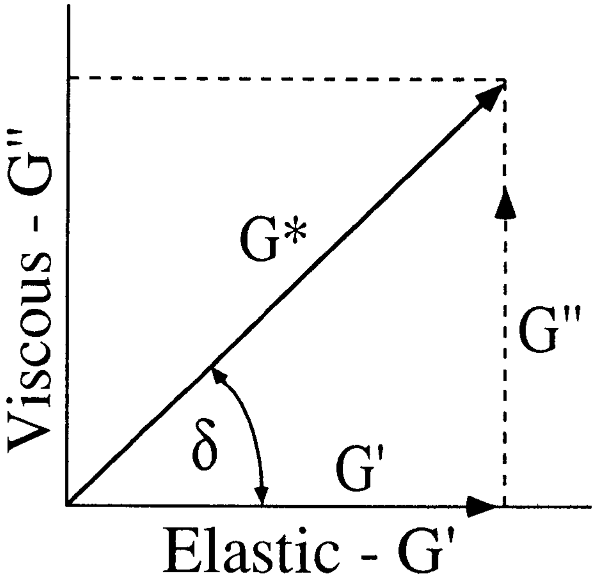
$$\delta = 360\frac{\Delta t}{t},\ \textit{degrees} \tag{2.12}$$

or

$$\delta = 2\pi\frac{\Delta t}{t},\ \textit{radians} \tag{2.13}$$

where

Δt = time shift
t = cycle time.



$$\text{Sin}\,\delta = \frac{G''}{G^*}$$

Figure 2-8. **Graphical Representation of the Components of the Complex Shear Modulus *G****

The angle is expressed in radians or degrees (figures 2-7b and 2-7c), and is a measure of the loss and storage moduli, G'' and G' which make up the complex modulus G^* as shown in figure 2-8. The values of G'' and G' can also be considered to be an estimate of the viscous component and the elastic and delayed elastic components of the complex stiffness modulus G^*. A perfectly elastic material would exhibit a phase angle equal to zero, while a viscous material would exhibit an angle of 90°. Thus an elastic material would exhibit maximum shear stress and maximum shear strain at the same time, while for a perfectly viscous material maximum shear stress would occur at the same time as minimum shear strain. Asphalt tend to be elastic ($\delta = 0$) at cold temperatures and viscous ($\delta = 90°$) at very high temperatures.

Specification values are:

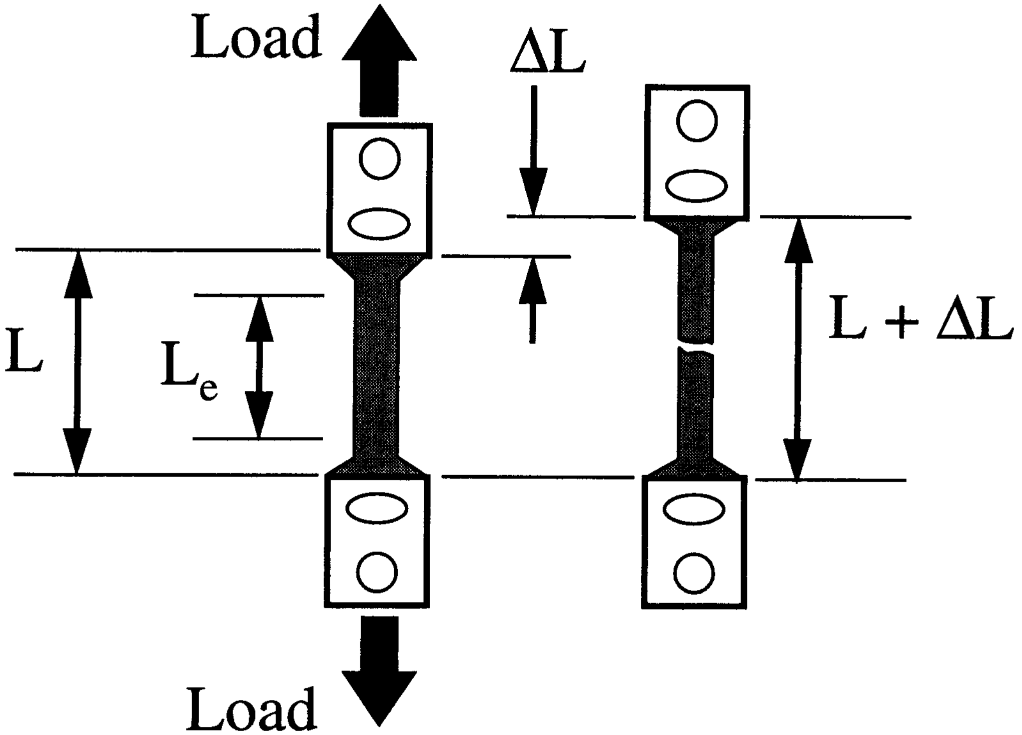
- To minimize rutting, the stiffness value, $G^*/\sin\delta$, of the binder after the RTFOT must be greater than 2.2 kPa at the maximum 7-day average pavement design temperature. To control possible tenderness, if aging does not occur during construction, the stiffness value $G^*/\sin \delta$, of the tank or original unaged asphalt must be greater than 1 kPa at the same pavement temperature.

- To control fatigue, the stiffness value, $G^* \sin\delta$, of the binder after the RTFOT and PAV aging must be less than 5,000 kPa at the approximate average (termed "intermediate") pavement temperature. Since the average temperature will decrease as the maximum pavement temperature decreases, this requirement may cause a given asphalt binder which satisfies a PG 58- criteria to fail the PG 52- criteria because of the intermediate temperature requirements, though not the high temperature requirements.

2.2.2.3 Direct Tension Test

The direct tension test (AASHTO TP3, figure 2-9) measures the low temperature fracture properties of the asphalt binder. A dogbone-shaped specimen is tested at a constant rate of elongation of 1.0 mm/min at a specified temperature ±0.2°C until it fractures.

The stress and strain at failure are calculated using the initial cross-sectional area (A) and effective gauge length (L_e) of the specimen, the load at failure (P_f) and elongation at failure (ΔL_f). Thus, failure stress is the tensile stress on the test specimen when the load reaches a maximum value with or without fracture during the test. The failure shown is the tensile strain corresponding to the failure stress. A typical load-elongation relationship is shown in figure 2-10.



$$\text{failure strain } (\varepsilon_f) = \frac{\text{change in length } (\Delta L)}{\text{effective gauge length } (L_e)}$$

Figure 2-9. **The Direct Tension Test Specimen**

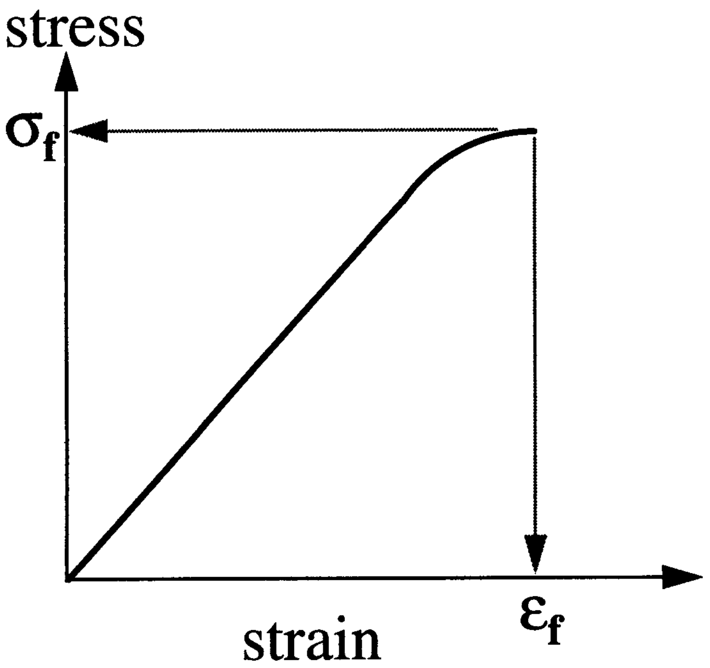


Figure 2-10. **Typical Relationship of Load (Stress) and Elongation (Strain) to Failure for the Direct Tension Test**

Thus,

$$\text{Failure stress, } \sigma_f = \frac{P_f}{A} \tag{2.14}$$

and

$$\text{failure strain, } \varepsilon_f = \frac{\Delta L_f}{L} \tag{2.15}$$

The direct tension device is used to determine failure characteristics at low temperatures, which can cause low temperature cracking to occur. To control low temperature cracking, the binder specification requires that the failure strain must be greater than 1 percent at the minimum pavement temperature plus 10°C. At these temperatures the strain at failure can be expected to range from 1 to 10 percent. A laser-based extensometer provides precise measurements of specimen elongation (figure 2-11). A video extensometer can also be utilized to measure deformation of the specimen.

The specification value is:

- It is not necessary to perform the direct tension test if the creep stiffness of the binder is less than 3×10^5 kPa at the minimum pavement design temperature. If the creep stiffness of the binder is between 3×10^5 and 6×10^5 kPa, the direct tension failure strain requirement can be used for acceptance in lieu of the creep stiffness requirement. In either case, the *m*-value requirement must be satisfied. It is anticipated that the use of the direct tension test will be primarily for modified binders which exhibit high stiffness at low temperature, but which exhibit large failure strains (figure 2-1).

2.3 Other Binder Tests

2.3.1 Rotational Viscometer

The rotational viscometer (figure 2-12) described in ASTM D4402, "Measurement of Asphalt Viscosity Using a Rotational Viscometer," measures the high temperature viscosity of asphalt binders. The test is conducted by rotating a spindle immersed in the asphalt binder at a specified temperature.

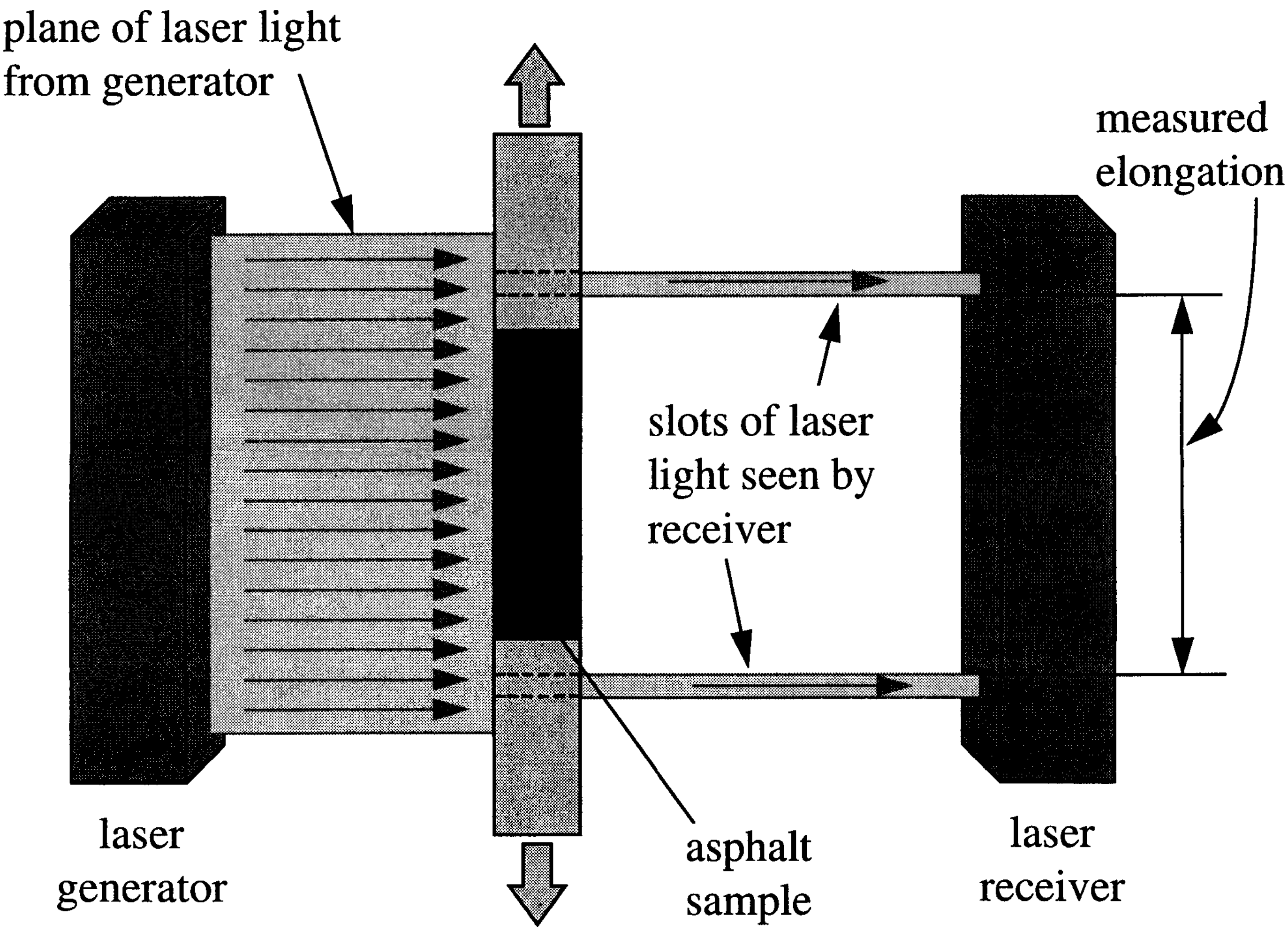


Figure 2-11. Schematic View of a Laser Extensometer

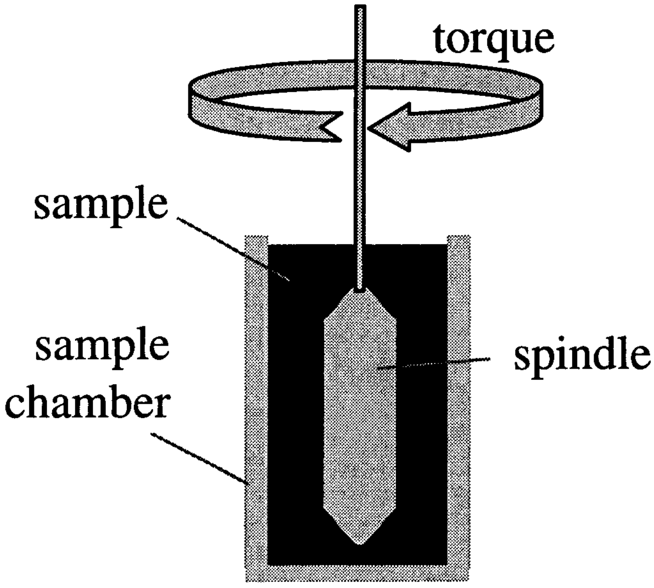


Figure 2-12. Principle of Operation of the Rotational Viscometer

To ensure pumpability, the specification stipulates that the binder must have a maximum viscosity of 3Pa·s at a test temperature of 135°C. The specification requirement may be waived if the supplier warrants that the asphalt binder can be pumped and mixed at temperatures that satisfy safety standards.

The rotational viscometer can also be used to establish the viscosity-temperature relationship for the binder. This relationship can be used as a guideline to determine mixing and compaction temperatures. For some modified binders, however, excessively high temperatures may be indicated. These high temperatures, which may damage the asphalt binder, often will not be required for mixing and compaction because of shear thinning. Thus, the supplier's recommendations concerning mixing and compaction temperatures should be followed.

2.3.2 Flash Point Test

The flash point is measured by the Cleveland Open Cup flash point test (ASTM D92) in which a brass cup is filled with a specified volume of asphalt binder and heated at a specified rate. A small flame is passed over the surface of the binder. The temperature at which sufficient volatiles are released to cause an instantaneous flash is the flash point. The specification requires that all grades have a minimum flash point value of 230°C.

2.3.3 Mass Loss

The mass loss indicates the amount of volatile loss that occurs when a tank binder is aged in accordance with the RTFOT (AASHTO T240). The mass of the sample is measured before and after the RTFOT. The maximum loss permitted is 1 percent.

3

Level 1 Mixture Design System

3.1 Introduction

The Superpave mix design method is hierarchical and vertically integrated. It encompasses the performance-based tests and performance prediction models developed in the SHRP asphalt research program as well as elements of volumetric mix design technology. Superpave has been developed for ready application to all classes of roadway, from rural or urban residential streets to heavily travelled interstate highway routes.

The Superpave hierarchical approach is illustrated conceptually in figure 3-1. It matches the appropriate level of mix design effort and technology to the pavement being designed. Three levels of design are defined based on traffic and the importance of the pavement. Suggested boundary values are 1 million and 10 million ESALs; however, the actual traffic levels are established by the user. Thus, the user determines which level of design is appropriate for any given project or project type. As shown, all three design levels include a volumetric mix design phase. Thus, depending on the traffic, the mix design may be complete after the volumetric design (level 1). In level 2 and level 3, mechanical performance-based tests are conducted to allow the mix design to be optimized for resistance to permanent deformation, fatigue cracking, and low temperature cracking.

A general flow chart of the Superpave mix design system is shown in figure 3-2. Aggregates and binder are selected using criteria specific to design conditions that the mixture will experience in service. An optional test, the net adsorption test (SHRP M001), is available to screen potential aggregate or asphalt-aggregate combinations for compatibility and potential moisture susceptibility.

For level 1 the laboratory mixture design involves only volumetric design, which evaluates aggregates and asphalt binders in order to select an gradation and asphalt binder content that satisfy specified criteria for air voids, voids in mineral aggregate, and voids filled with asphalt. For levels 2 and 3, performance-based tests are conducted and estimates of distress with time are made. This allows the mixture design to be optimized with regard to one or more of three distresses: permanent deformation, low temperature cracking, and fatigue cracking. Subsequent to completion of the mix design, modifications may be required because of changes to the material properties once the mixture is produced in a plant. These modifications may or may not require retesting.

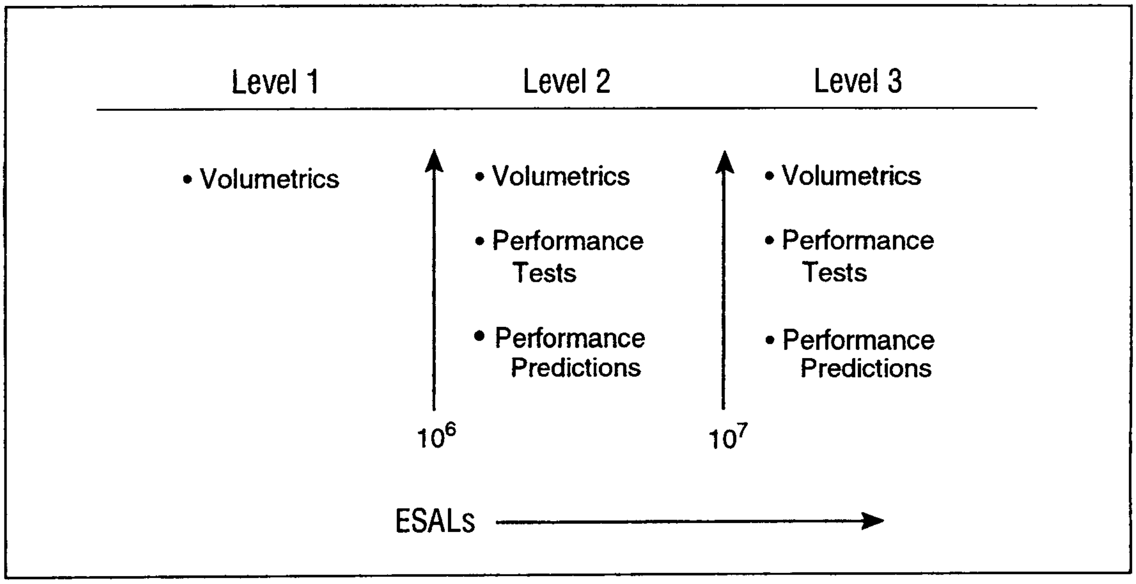


Figure 3-1. **Hierarchical Organization of the Superpave Mix Design System: Level of Mix Design versus Suggested Traffic Level (ESALs)**

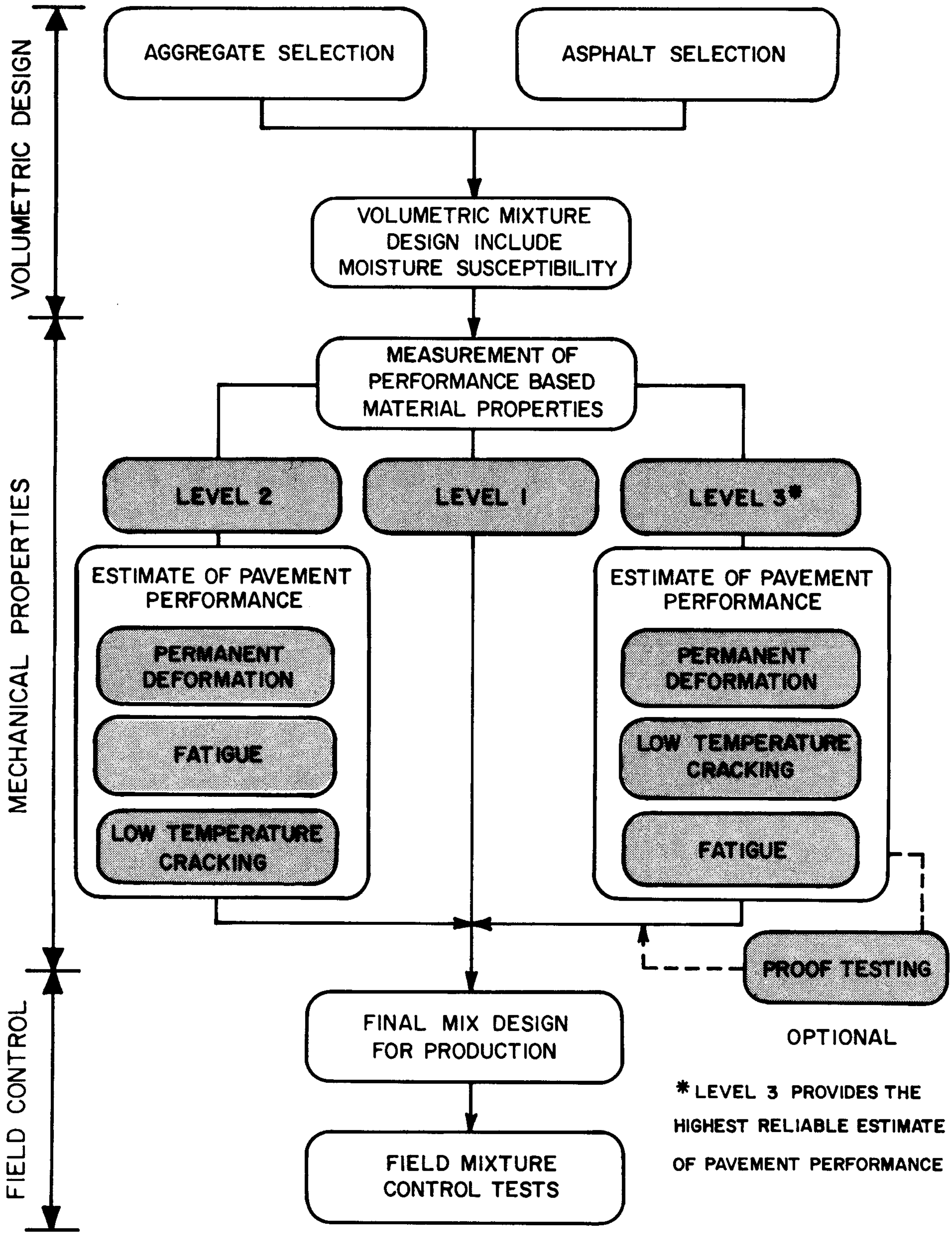


Figure 3-2. Flow Chart of the Superpave Mix Design System

Finally, during construction, field control tests are run at the hot mix asphalt (HMA) plant to verify that the mixture is being produced to the laboratory design. The field control tests and procedures are applicable to any quality control/quality assurance system.

It is anticipated that a majority of the mixture designs will use the level 1 and level 2 procedures, while level 3 will be used for mix designs of pavements to carry very heavy traffic loads (> 10^7 ESALs over the anticipated service life) or roadways of critical importance.

Level 3 also includes an optional proof testing scheme that allows the mixture to be subjected to tests which simulate the actual traffic and environmental conditions to confirm that the mixture actually performs at the desired level.

Again it must be emphasized that the level of design and the use of proof testing is a policy or engineering design decision. The actual number of ESALs can vary from organization to organization and exceptions can be made on the basis of potential risks and consequences of failure.

In level 2 mixture design, fewer tests are performed at fewer temperatures than for level 3 mixture design. Performance-based tests for permanent deformation are done at a single effective temperature for permanent deformation. Likewise, tests used to predict fatigue cracking are performed at a single effective temperature for fatigue cracking. Effective temperatures for permanent deformation and fatigue are defined as the single test temperature at which the amount of permanent deformation or fatigue cracking which occurs is equivalent to that obtained by considering each season separately throughout a year. These two temperatures will be different from each other and can be calculated using equations contained in chapter 4 of Cominsky et al. 1994. Low temperature tensile strength is measured at a single temperature in level 2 design.

Level 3 mixture design simulates the entire year by breaking it into representative seasons. Performance-based tests for permanent deformation and fatigue cracking are performed at a range of temperatures. A larger slate of tests are conducted to more rigorously evaluate mixture response across a greater range of stress. Permanent deformation and fatigue cracking are predicted using mixture properties in each of the representative seasons.

A summary comparison of level 2 and level 3 is shown in table 3-1.

Table 3-1. Comparison of Level 2 and Level 3 Mix Design Methods

	Permanent Deformation/ Fatigue Cracking	**Low-Temperature Cracking**
Test Types	Level 3 considers more states of stress, and requires two additional test methods.	No difference between level 2 and level 3.
Test Temperatures	Level 3 considers range of temperatures from 4 to 40°C. Level 2 uses one effective temperature for fatigue cracking and one for permanent deformation.	Level 3 considers three temperatures. Level 2 considers tensile strength at one temperature only.
Performance Prediction	Level 3 breaks the year into seasons. Level 2 considers the entire year as a single season.	No difference between level 2 and level 3.

3.2 Guidelines and Requirements

Throughout the design process, aggregate and asphalt mix properties are compared to guidelines and criteria in the mix specification. Depending upon specific design conditions, primarily traffic level, a property may be either a guideline or a requirement.

- A *guideline* is a suggested specified value; compliance is not mandatory.

- A *requirement* is a specified value which must be satisfied.

For mix design levels 2 and 3, all aggregate properties are considered to be guidelines to achieve satisfactory performance. The final design is controlled by the performance tests. Thus, rather than specifying the individual properties of the aggregate, the emphasis is placed on the performance of the mix. For level 1 designs, performance tests are not considered. Thus, aggregate properties which would otherwise be considered guidelines may need to be considered as requirements.

For example, *crushed faces* is an aggregate property which may be either a guideline or a requirement. At traffic levels less than 10^6 ESALs, where a level 1 design would be used, the risk of permanent deformation is not as great as at higher traffic levels. Since level 1 design is appropriate, the accelerated performance-based tests for permanent deformation are not required. Instead, permanent deformation resistance is obtained with crushed aggregate faces and satisfactory air voids, both of which are requirements. For level 2 and 3 mix designs, accelerated performance-based tests for permanent deformation are required, in which case aggregate crushed faces will be considered only as a guideline.

The aggregate properties considered by the Superpave mix design system are shown below under the headings of consensus properties or agency source properties.

Consensus Properties
gradation
coarse aggregate angularity
fine aggregate angularity
clay content
thin elongated particles
dust proportion

Agency Source Properties
toughness
soundness
deleterious materials

Agency source properties are local standards that are established by the agency and may vary depending on local conditions and experience. Consensus standards, however, were developed by a group of experts from the aggregate and paving industry, who established recommended values. The Superpave method considers these values to be fixed for North America; it is recommended that they not be changed by individual agencies. Rather, if changes are needed, such changes should be initiated through AASHTO and adopted nationwide.

3.3 Compaction

The entire mix design system, including field control, is based on the use of the Superpave gyratory compactor. The compactor is relatively inexpensive, portable, and capable of quickly molding specimens with minimal specimen-to-specimen variation. The performance properties of the compacted specimen simulate the performance properties of cores from pavements constructed with the same asphalt aggregate combination. The compactor also allows the compactibility of the mix to be evaluated, including an estimate of the final air voids content under traffic (the probability of the mix becoming plastic under traffic) and a measure of the structuring of the aggregate in the mix.

The Superpave gyratory compactor (figure 3-3) has the following characteristics:

- an angle of gyration of 1.25 ± 0.02°;
- a rate of 30 gyrations per minute;
- a vertical pressure during gyration of 600 kPa; and
- the capability of producing 150 × 150 mm specimens.

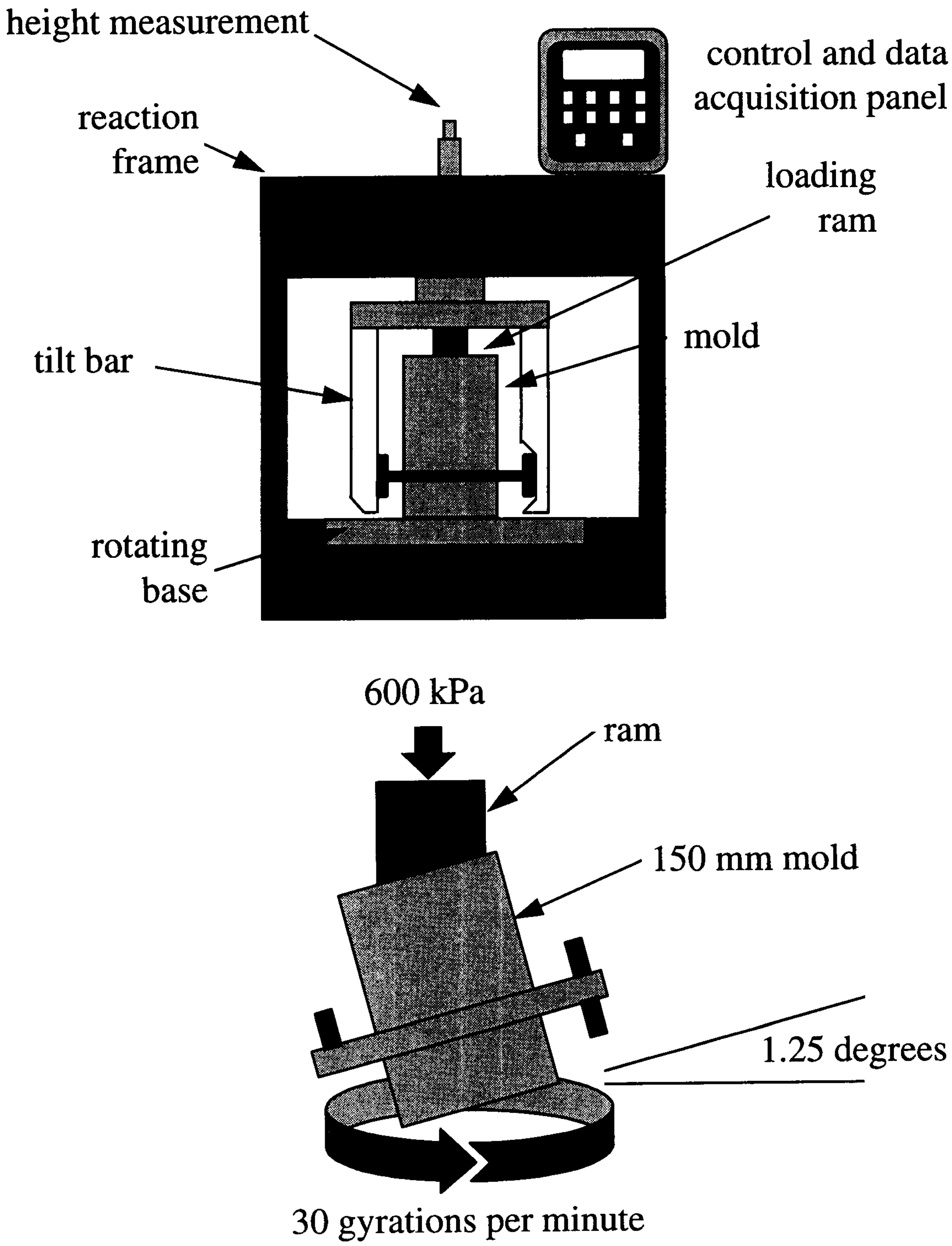


Figure 3-3. **The SHRP Gyratory Compactor**
a. Schematic
b. Principle of Operation

Other gyratory compactors can be utilized if capable of meeting the specified requirements (SHRP Method of Test M002, Harrigan et al. 1994).

During the compaction process, the relative density of the specimen is monitored and displayed. Typical results are shown in figure 3-4. Density as a percent of maximum theoretical specific gravity (AASHTO T209) can be plotted against either the number of gyrations or the log of the number of gyrations. This process allows the compactibility and the aggregate structure of the mix to be evaluated.

Three compactive efforts are specified in the Superpave mix design procedure:

- N_{init}, the initial compactive effort;
- N_{design}, the design compactive effort; and
- N_{max}, the maximum compactive effort.

The compactive efforts N_{init} and N_{max} are used to evaluate the compactibility of the mix, while N_{design} is used to select the asphalt content. Corresponding to these compactive efforts are densities:

- C_{init}
- C_{design}
- C_{max}

which are expressed as a percent of maximum theoretical specific gravity (AASHTO T209).

Values of N_{design} are a function of average design air temperature and ESALs, and vary from 68 to 172 as shown in table 3-2. The design high air temperature can be obtained from weather data in the Superpave software and user-defined reliability.

The number of gyrations for N_{init} varies from 7 to 10 according to equation 3.1:

$$\log N_{init} = 0.45 \log N_{design} \tag{3.1}$$

The number of gyrations for N_{max} varies from 104 to 287 according to the following equation:

$$\log N_{max} = 1.10 \log N_{design} \tag{3.2}$$

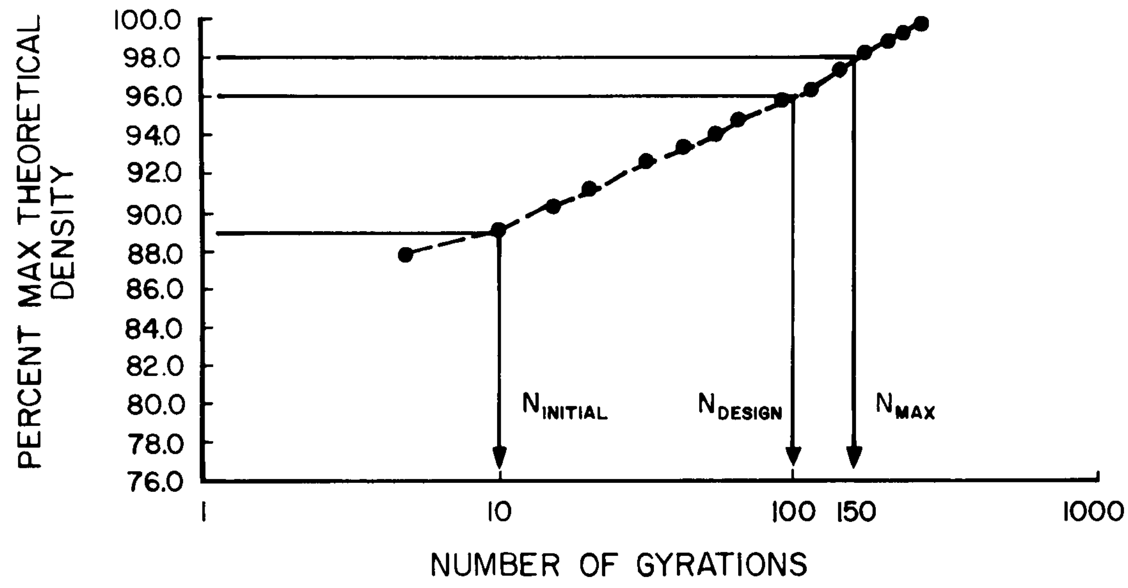


Figure 3-4. Typical Densification Curve Obtained with the SHRP Gyratory Compactor

Table 3-2 Design Gyrations (N_{design})

Traffic (ESALs)	Average Design Air Temperature (°C)			
	< 39	39 - 41	41 - 43	43 - 45
< 3 × 10^5	68	74	78	82
< 1 × 10^6	76	83	88	93
< 3 × 10^6	86	95	100	105
< 1 × 10^7	96	106	113	119
< 3 × 10^7	109	121	128	135
< 1 × 10^8	126	139	146	153
> 1 × 10^8	143	158	165	172

Typical compaction curves for two different aggregate structures with the same asphalt content are shown in figure 3-5. Mixes exhibiting relatively steep slopes and low C_{init} values are indicative of mixes that have developed good aggregate structure or internal resistance to densification. Steeper curves indicate better aggregate structuring. While it is possible to select a design asphalt content for a mix with a weak aggregate structure, the design will result in poorer performance, especially its resistance to permanent deformation. To ensure adequate structure the specifications require that

$$C_{init} \leq 89\%$$

where the number of gyrations, N_{init}, varies from about 7 to 10 according to equation 3.1.

A maximum density requirement at N_{max} insures that the mix will not compact excessively under the anticipated traffic, become plastic, and produce permanent deformation. Thus, the specification requires that

$$C_{max} \leq 98\%$$

In other words, the air voids content must be 2 percent or greater. Since N_{max} represents a compactive effort which would be equivalent to traffic which greatly exceeds the design traffic (ESALs), excessive compaction under traffic will not occur. Thus, the air voids will not drop below 2 percent and the mix will not become plastic.

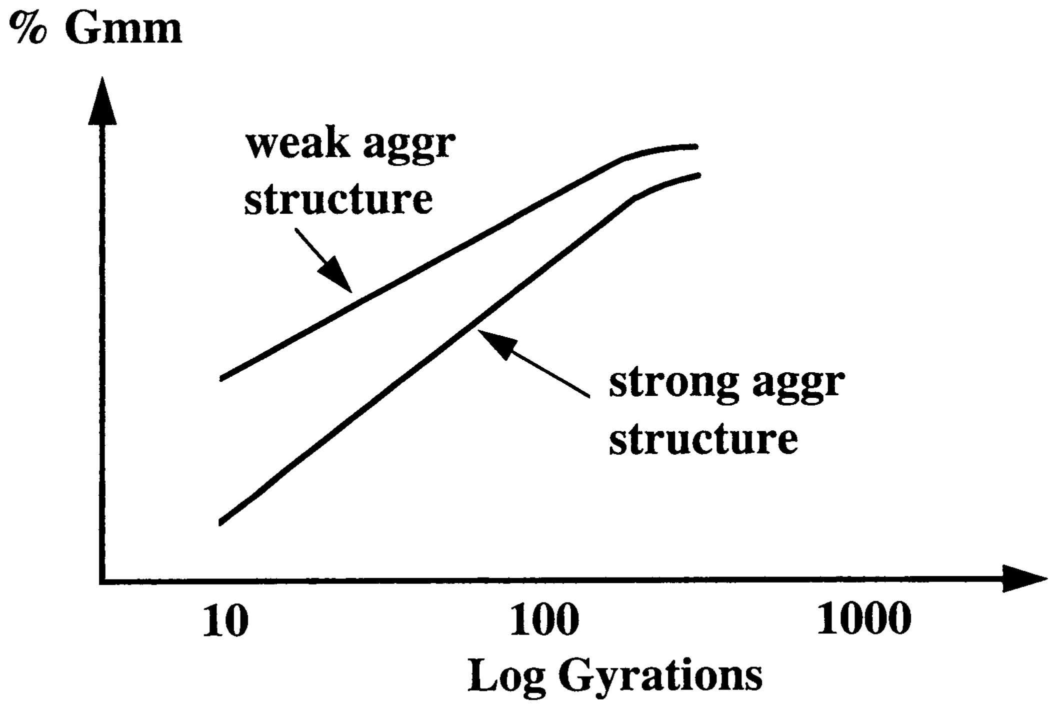


Figure 3-5. Densification Curves Illustrating Different Characteristics of Strong and Weak Aggregate Structures.

3.4 Level 1 Mix Design

Level 1 mix design, which is based upon volumetric mix design principles, includes the following steps:

- select asphalt binder grade;
- select aggregate sources/products;
- measure compactibility of asphalt binder and aggregate;
- determine design aggregate structure;
- determine design asphalt binder content; and
- check moisture damage resistance.

3.4.1 Select Asphalt Binder Grade

Asphalt binder grade is selected according to pavement temperature and traffic. A secondary method involves agency designation of geographic regions or zones based upon pavement temperatures and traffic.

The primary method of selecting the required binder grade is based upon design pavement temperatures and traffic (chapter 2, Cominsky et al. 1994). The high and low pavement design temperatures can be calculated by using information contained in the Superpave software or can be supplied directly by the mix designer.

The Superpave weather database contains parameters for:

- high air temperature, defined as the average 7-day maximum air temperature for the year; and
- low air temperature, defined as minimum air temperature for the year.

Statistical parameters in the database define the distribution of these temperatures over many years rather than storing individual records for each weather station. The statistical temperature parameters are:

Low Temperature	High Temperature
Mean	Mean
Standard deviation	Standard deviation

Selected design air temperatures are converted to pavement design temperatures, and the appropriate grade of asphalt binder is selected.

In the secondary method, the mix designer determines the geographic zone in which the project is located and selects the required grade of binder on the basis of the expected traffic level over the service or design life of the pavement.

Figure 3-6 illustrates the relative importance of the binder to the various types of distress. As shown, the binder plays an extremely important role in low-temperature cracking.

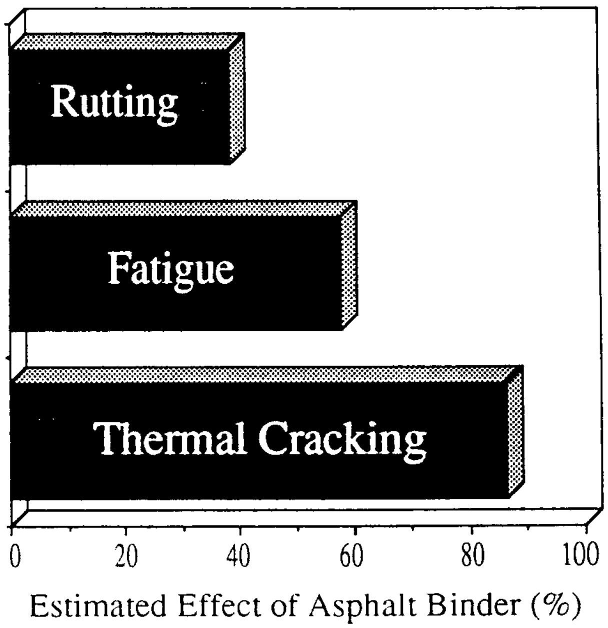


Figure 3-6. **Relative Effect of the Asphalt Binder on the Development of Permanent Deformation, Fatigue Cracking and Low-Temperature Cracking**

For fatigue cracking, the aggregate properties, the mix properties, and the pavement structure are more important; for permanent deformation, the properties of the aggregate and the asphalt mix are dominant.

It must be recognized that the asphalt binder, while important, cannot make up for poor aggregates, poor mix characteristics, poor construction or inadequate structural design. The users of Superpave are cautioned to use the entire system and not selected pieces.

3.4.2 Select Aggregate Sources/Properties

The selection of the aggregate must consider many factors:

- Climate
- Traffic
- Availability
- Cost
- Skid resistance
- Moisture sensitivity
- Local experience
- Other

The importance of any one of these will vary with the agency and the specific region in which a given project is located. *While availability may relate directly to first cost it does not necessarily relate to life-cycle cost or to the design and construction of cost- effective asphalt pavements.*

Because of the importance of the aggregate and the resulting mix, recommendations regarding specific aggregate characteristics have been included later in this chapter.

The characteristics included are:

Consensus Properties	Agency Source Properties
Aggregate gradation	Toughness (AASHTO T96)
Coarse aggregate angularity	Soundness (AASHTO T104)
Fine aggregate angularity	Deleterious materials (AASHTO T112)
Clay content	
Thin elongated particles	

Recommended consensus properties values were developed by industry experts using a modified Delphi process. The resulting recommendations are considered to be the best practice currently available. The actual process by which these values were finalized is described in Cominsky, Harrigan and Leahy 1994 and Leahy, Harrigan, and Von Quintus, 1994. These cannot be changed in the Superpave software by individual specifying agencies. If changes are needed due to new findings, new tests, or field experience, the changes should be made nationally through the American Association of State Highway and Transportation Officials (AASHTO).

No recommended values for the source properties are specified. The agency should specify the source properties for their local conditions or preapprove aggregate sources.
While conformance to these recommendations for level 2 and 3 designs is not mandatory, conformance will increase the probability of passing the performance-based tests and producing a good-performing pavement. Conformance to these recommendations is critical for level 1 designs, which do not involve performance testing.

3.4.2.1 Determine Design Traffic

An initial step in the design process is to determine the project design traffic level with the agency's usual procedure. Traffic is defined as expected ESALs on the design lane during the design life of the pavement structure. Design ESALs can be estimated using traffic information from any source or may be calculated using the average annual daily traffic (AADT), FHWA vehicle type distributions (W-4 tables), and lane distribution factors (AASHTO 1993).

3.4.2.2 Aggregate Gradation

Different sets of sieve sizes are currently used by various North American agencies. The Superpave mix design method specifies the use of the AASHTO standard sieves (AASHTO T27) for gradation determinations (table 3-3). Gradation is expressed in terms of percent passing these specified sieves. Other sieves should not be used because of the effect on gradations, maximum aggregate size determinations and the volumetric design of the mix.

Table 3-3. Sieve Sizes

Sieve Size and Designation	Appropriate English Equivalent
63.0 mm	2 1/2 in.
50.0 mm	2 in.
37.5 mm	1 1/2 in.
25.0 mm	1 in.
19.0 mm	3/4 in.
12.5 mm	1/2 in.
9.5 mm	3/8 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

The nominal maximum sieve size is defined as one sieve larger than the first sieve to retain more than 10 percent of the aggregate. Maximum sieve size is defined as one sieve larger than the nominal maximum size.

Mixes are specified primarily according to the nominal maximum sieve size. The selection of the nominal maximum size of the aggregate should account for the layer thickness and the depth of the mix in the pavement structure. As general guidelines, the layer thickness should be 2.5 times the nominal maximum size, and the nominal maximum size should increase with depth.

Aggregate gradation specifications include control points and a restricted zone for each nominal maximum size. Figure 3-7 shows the specifications for a 12.5-mm nominal maximum size gradation plotted on a 0.45 power chart. Eight gradation control points are used which control minimum and maximum percent passing the 75 μm (dust), the 2.36 or 4.75 mm (sand), and the nominal maximum sieve size, and also defines the maximum sieve size. The restricted zone shown in figure 3-7 as a shaded area represents an area through which the gradation should not pass.

The restricted zone has two purposes:

The restricted zone has two purposes:

1. It limits inclusion of large amounts of natural sand that cause "humps" in the gradation curve in the 600 μm range.

2. It discourages gradations which fall on the maximum density line and thus often will have inadequate voids in mineral aggregate (VMA).

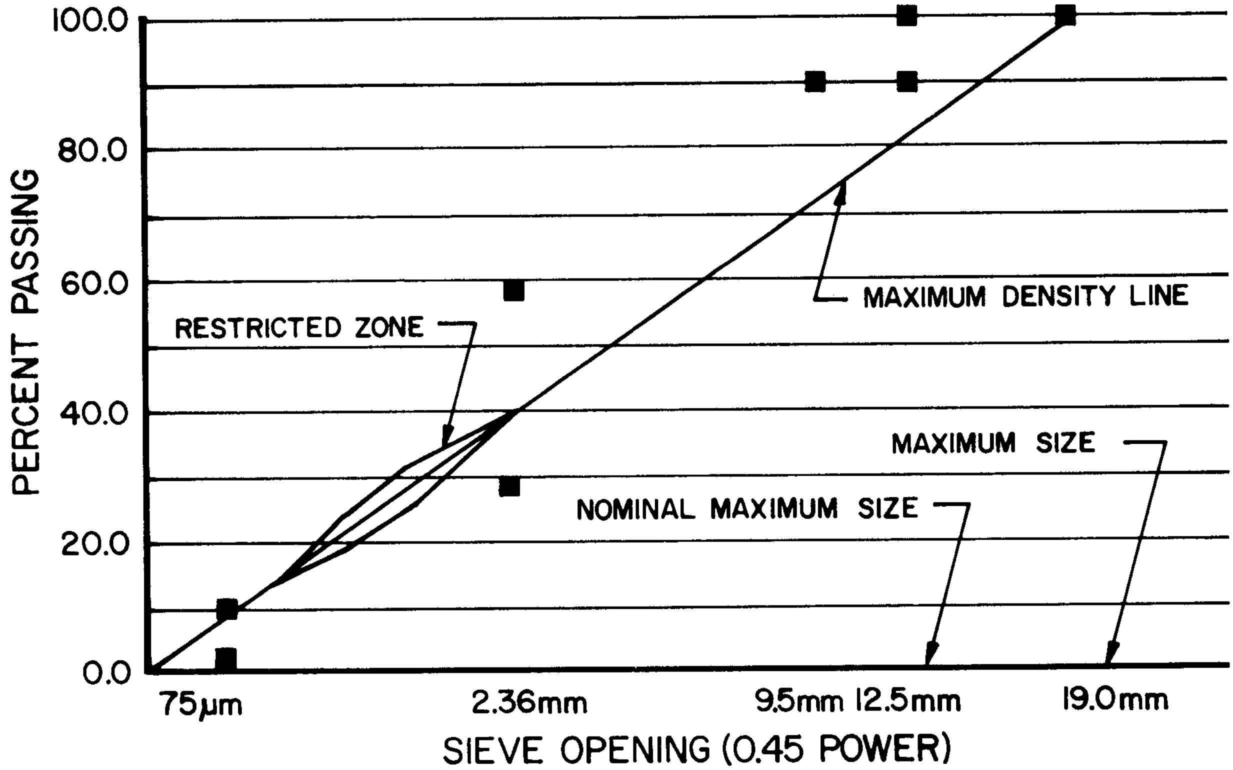


Figure 3-7. **Superpave Gradation Control Points and Restricted Zone for a 12.5-mm Nominal Maximum Size Aggregate Gradation**

The mix designer is encouraged to develop gradations that pass below rather than above the restricted zone. This will produce a coarser gradation and maximize the development of a robust aggregate structure.

3.4.2.3 Coarse Aggregate Angularity

Aggregate crushed faces is defined as the number, in percent, of particles larger than the 4.75-mm sieve that have mechanically induced fractured faces. Aggregate crushed faces ensure an adequate aggregate skeleton to resist shear forces that cause rutting. The requirement for crushed faces is dependent on traffic volume and on the pavement layer. High traffic volumes typically call for more crushed faces. Upper pavement layers, particularly surface courses, require more crushed faces than lower layers.

Suggested values of crushed faces are listed in table 3-4 according to traffic level and location in the pavement structure.

Mixes to be used on high traffic volume pavements are judged on their engineering properties, hence crushed faces are considered as guidelines in the volumetric proportioning phase of the Superpave mix design method.

Table 3-4. Coarse Aggregate Angularity Recommendations

Traffic Level (ESALs)	**Surface Mixes (< 100 mm from surface)**	**Lower Mixes (> 100 mm from surface)**
$< 3 \times 10^5$	55/-	-/-
$< 10^6$	65/-	-/-
$< 3 \times 10^6$	75/-	-/-
$< 10^7$	85/80	65/-
$< 3 \times 10^7$	95/90	80/75
$< 10^8$	100/100	95/90
$> 10^8$	100/100[1]	100/100

Note: Coarse aggregate angularity is the percentage by weight of material retained on the 4.75-mm sieve which has one or more fractured faces. The first number in the second and third columns denotes percentage crushed on one face, the second number denotes the percentage crushed on two faces, e.g., 85/80 is 85 percent particles with at least one crushed face and 80 percent particles with at least two crushed faces.

3.4.2.4 Fine Aggregate Angularity

Fine aggregate, defined as material passing the 2.36-mm sieve, must possess sufficient internal friction to resist permanent deformation of the mix. Rounded natural sands are considered undesirable. Fine aggregate angularity is measured using ASTM Standard Method of Test C 1252, "Uncompacted Void Content of Fine Aggregates." Recommended values are dependent upon the amount of traffic and the depth at which the pavement layer is located (table 3-5).

Table 3-5. Fine Aggregate Angularity Recommendations

Design ESALs	Surface Mixes (< 100 mm from surface)	Lower Mixes (> 100 mm from surface)
$< 3 \times 10^5$	-	-
$< 3 \times 10^6$	40	-
$< 3 \times 10^7$	45	40
$\geq 3 \times 10^7$	45	45

3.4.2.5 Aggregate Clay Content

The sand equivalent test measures the proportion of clay materials in fine aggregate; these can create problems with pavement performance.

None of the performance tests developed by SHRP to characterize engineering properties of asphalt-aggregate mixes will directly evaluate the effect of clay content. Therefore, limiting values of sand equivalent are recommended as shown in table 3-6.

Table 3-6. Limiting Values For Sand Equivalent

Traffic Level (ESALs)	Sand Equivalent Minimum %
$< 3 \times 10^6$	40
$< 10^7$	45
$> 10^7$	50

3.4.2.6 Aggregate Elongated Particles

Thin, elongated aggregate particles have reduced strength when load is applied to the flat side of the particle; they also can contribute to segregation and aggregate breakdown during compaction. Elongated particles are defined as having a ratio of maximum dimension to minimum dimension of greater than 5. ASTM Standard Method of Test D4791, "Flat or Elongated Particles in Coarse Aggregate," is the test method to be used. Recommended limits for elongated particles is a maximum of 10 percent by weight for traffic levels greater than 10° ESALs.

3.4.2.7 Aggregate Toughness

Aggregate toughness is defined as the resistance to fracture from impact as measured in the Los Angeles Abrasion Test (AASHTO T96). The Los Angeles abrasion test is a measure of the toughness of an aggregate particle and its resistance to degradation during construction and service of the pavement. Aggregate particles should be able to resist degradation during handling and mixing, or else they could produce significant changes in the aggregate gradation.

In addition, surface pavement layers must be able to withstand the abrasive action of traffic. Insufficient toughness could lead to disintegration of the pavement surface due to erosion or wear of the aggregate particles.

Aggregate toughness is defined by the agency. Suggested values for Los Angeles abrasion are listed in table 3-7 according to traffic level and location within the pavement structure.

Table 3-7. Suggested Limiting Values of Los Angeles Abrasion Limits

Traffic Level (ESALs)	Los Angeles Abrasion Loss (Wearing Course)	Los Angeles Abrasion Loss (Non-Wearing Course)
$< 10^6$	50	50
$< 10^7$	45	50
$< 10^8$	40	50
$\geq 10^8$	35	50

3.4.2.8 Aggregate Soundness

Aggregate soundness is the resistance of aggregate to weathering cycles, including wetting and drying, heating and cooling, freezing and thawing, and combinations of the three. The test most often used to evaluate aggregate soundness is the Soundness of Aggregate by use of Sodium Sulfate or Magnesium Sulfate (AASHTO T104).

While the applicability of this test to aggregates for use in asphalt mixes is questionable it has been included as an agency source specification for which specification values are established by the agency.

3.4.2.9 Deleterious Materials

Deleterious materials are controlled to prevent aesthetic problems. Small quantities of shale do not effect structural performance, but pop-outs may be aesthetically undesirable and could trap water.

Other deleterious materials are clay, coal or other soft materials. These are typically controlled by placing a limit on the percent by weight of these materials that can be accepted in the total aggregate.

The specification values for deleterious materials are defined by the agency. A suggested limiting value for deleterious materials is 2 percent by weight of the aggregate.

3.4.3 Compatibility of Asphalt Binder and Aggregate

The net adsorption test (SHRP M-001, Harrigan et al. 1994) is an optional screening test to estimate the chemical compatibility and moisture sensitivity of any specific combination of aggregate and asphalt binder. The net adsorption test measures the amount of asphalt cement dissolved in toluene which is adsorbed onto the aggregate surface and the amount which is removed by addition of water to the toluene. If more than 90 percent of asphalt is retained, the asphalt binder and aggregate are considered compatible. If less than 70 percent is retained, the combination is incompatible. If between 70 and 90 percent is retained, the compatibility is questionable.

3.4.4 Volumetric Mix Definitions

Volumetric properties are defined according to the volume diagram shown in figure 3-8. The following terms are defined:

Air voids is the percent by volume of air between coated aggregate particles in the compacted paving mix.

Voids in mineral aggregate (VMA) is the volume of compacted paving mix not occupied by the aggregate when aggregate volume is calculated using the aggregate bulk specific gravity.

Absorbed asphalt volume is the volume of asphalt binder absorbed into the aggregate. It is equal to the difference in aggregate volume calculated with its bulk specific gravity and with its effective specific gravity. Absorbed asphalt volume is represented by the overlap of volume of asphalt binder and volume of bulk aggregate shown in figure 3-8.

Effective asphalt volume is the volume of asphalt binder that is not absorbed into the aggregate. It is represented by the asphalt volume above bulk aggregate volume shown in figure 3-8.

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.

3.4.5 Aggregate Gradation Selection

The aggregate gradation is selected to provide an aggregate structure that satisfies compactibility requirements and provides sufficient voids in mineral aggregate.

Voids in the mineral aggregate (VMA) and compactibility are influenced predominantly by aggregate characteristics such as gradation, angularity and surface texture.

Using aggregate stockpiles selected by the designer, a blending analysis is conducted and the results of the blending analysis are plotted on 0.45 power gradation analysis charts. From the blending analysis, at least three gradations should be chosen for evaluation (figure 3-9).

An initial trial asphalt content is calculated based on the desired VMA, 4 percent air voids, and an estimated asphalt absorption of the aggregate using the bulk and apparent specific gravities of the aggregates. The method of calculation is described in section 3.7.2 of Cominsky et al. 1994, and is included in the Superpave software. Duplicate specimens are mixed and compacted at the trial asphalt content for each gradation. The required compaction effort, N_{design}, is selected on the basis of traffic level and high design air temperature. The densities (C_{init} and C_{max}) occurring at N_{init} and N_{max} and the VMA are determined at the estimated asphalt content. Acceptable gradations have densities less than 89 and 98 percent at N_{init} and N_{max}, respectively, and VMA values that exceed the minimum VMA given in figure 3-10.

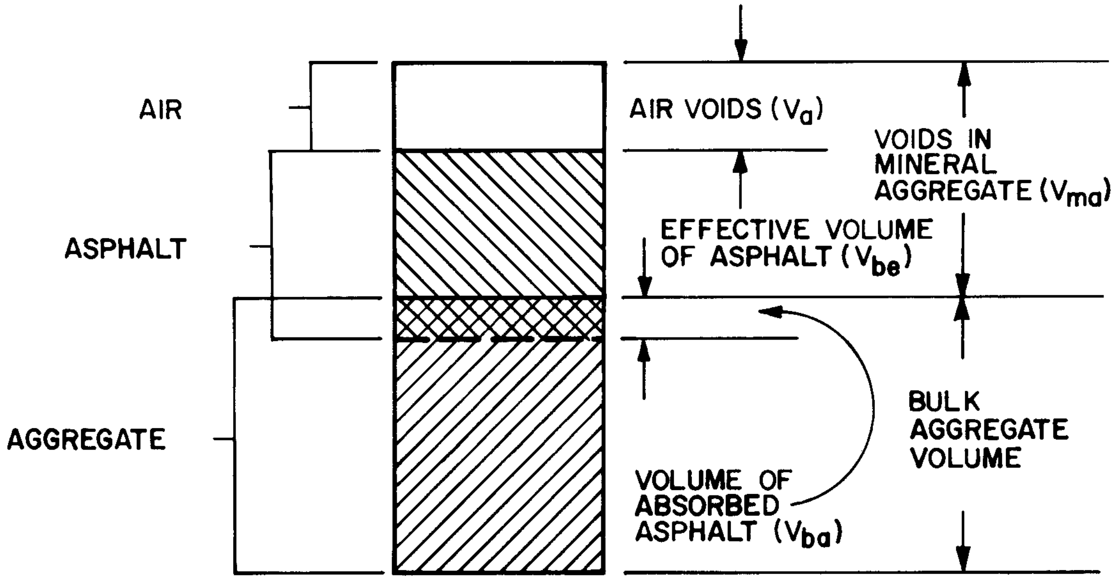


Figure 3-8. Definitions of the Volumetric Properties of Compacted Asphalt Paving Mix

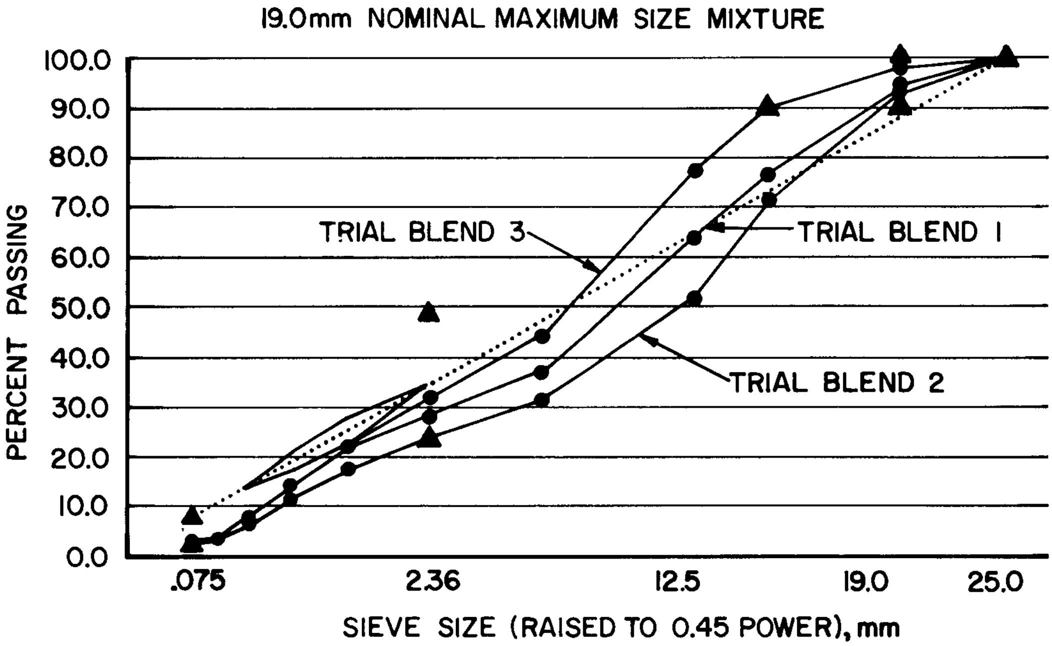


Figure 3-9. Evaluation of the Aggregate Gradations of Three Trial Blends

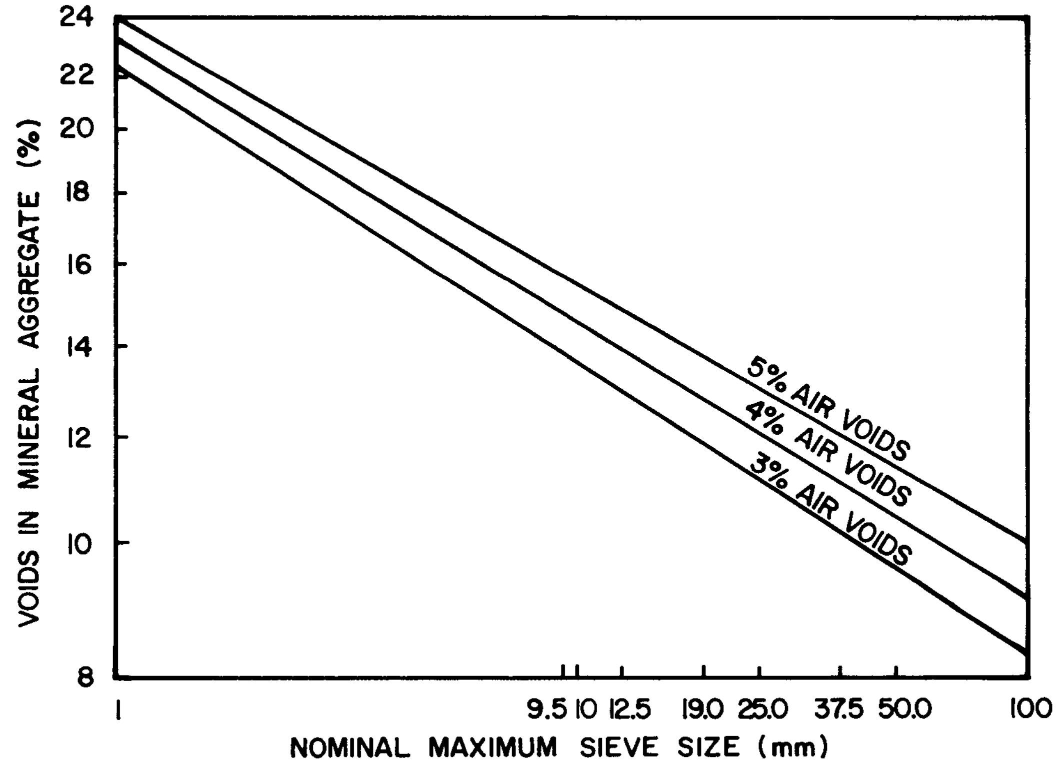


Figure 3-10. Minimum Percent Voids in Mineral Aggregate (VMA) for 3, 4 and 5 Percent Air Voids

3.4.6 Asphalt Binder Content Determination

The Superpave approach to asphalt binder content determination is to mix different percentages of asphalt binder with the selected aggregate structure to determine the effect on air voids, VMA, and VFA. 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 volumetric design. *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.*

Duplicate specimens are compacted at each of four asphalt contents, eight specimens in total. Typical densification curves are shown in figure 3-11. Mixes with higher asphalt contents compact to a higher terminal density.

Volumetric characteristics, that is, air voids, VMA, VFA and density are determined for each specimen at N_{design} gyrations. Plots of the volumetric properties versus binder content are made as shown in figure 3-12 and the asphalt binder content at 4 percent air voids is determined. VMA and VFA are checked to ensure that specification values are met.

Next, density is checked against specification values at N_{init} and N_{max}. An estimated densification curve is used as shown in figure 3-13 for this purpose. In figure 3-14, a densification curve is estimated at an asphalt binder content at which the air voids content would be 4 percent at N_{design} gyrations. Using the estimated densification curve, density is estimated at N_{init} and N_{max} and checked against specification values.

Several outcomes of the level 1 mix design are possible:

- All the guidelines and specification values are satisfied. The design asphalt content and design aggregate gradation are selected as the final mix design. If a level 2 or level 3 mix design is to be done, the results of the level 1 design are used as the starting point in the measurement of mechanical properties.

- All guidelines are not satisfied but the mix designer decides to use a level 2 or 3 mix design to determine final mix acceptability.

- Some guidelines and criteria have not been satisfied. The volumetric design is repeated. Different aggregates or another blend of the same aggregate stockpiles may be required.

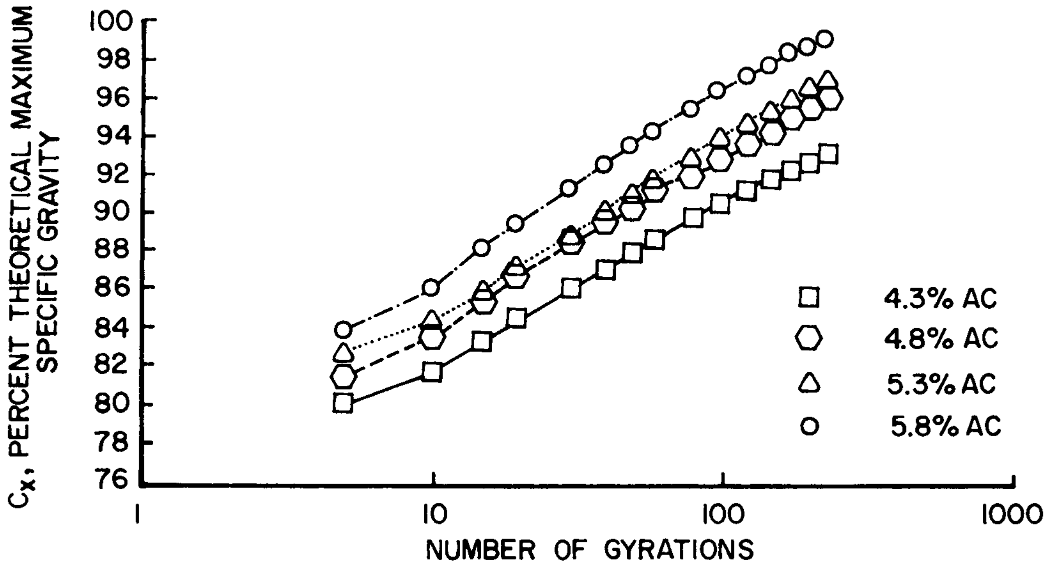


Figure 3-11. Gyratory Compaction Densification Curves for Four Asphalt Binder Contents

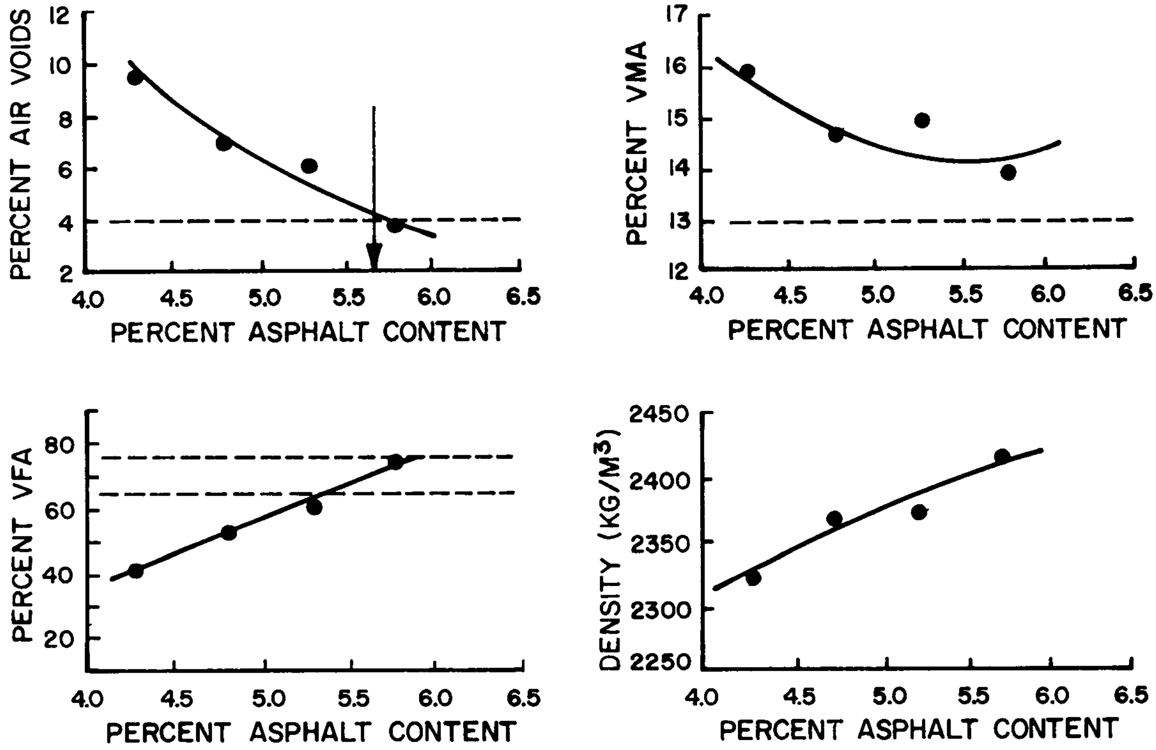


Figure 3-12. Plots of Percent Air Voids, Percent VMA, Percent VFA and Density versus Percent Asphalt Content

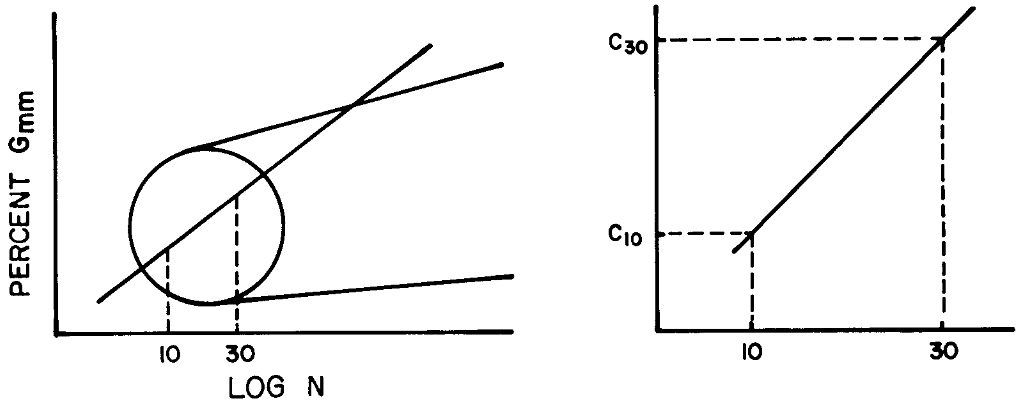


Figure 3-13. Calculating the Slope of a Densification Curve

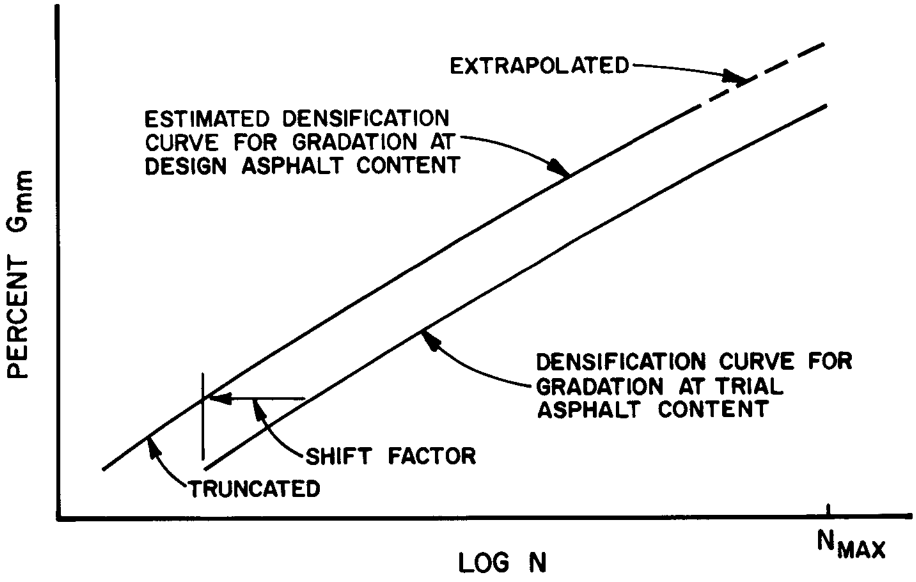


Figure 3-14. Shifting the Densification Curve of a Trial Asphalt Content

4

Level 2 And Level 3 Mix Designs

4.1 Introduction

The tests utilized to predict performance in both level 2 and level 3 mix designs are discussed in section 4.4. Level 2 mixture design is expected to be the most predominant Superpave design type used in typical highway applications. The level 2 mix design should be used for projects with design traffic having greater than 10^6 but less than 10^7 equivalent single axle loads (ESALs). Figures 4-1 and 4-2 identify the performance tests required of a level 2 mix design.

The Superpave level 2 mix design utilizes the volumetric (level 1) and optimizes that design with respect to permanent deformation, fatigue cracking and low-temperature cracking. Repeated shear at constant stress ratio, simple shear at constant height, frequency sweep at constant height and indirect tensile strength tests are conducted to predict permanent deformation and fatigue cracking, and the low-temperature indirect tensile creep and indirect tensile strength tests are used to predict low temperature cracking.

Predictions of permanent deformation require results from two tests: frequency sweep at constant height, and simple shear at constant height; both are conducted at an effective temperature for permanent deformation. Predictions of fatigue cracking require three tests: frequency sweep at constant height, simple shear at constant height, and the indirect tensile strength, all conducted at an effective temperature for fatigue.

The effective temperature for permanent deformation, T_{eff} *(PD)*, is defined as the single test temperature at which the amount of permanent deformation produced would be equivalent to that measured by considering each season throughout the year.

Similarly, the effective temperature for fatigue cracking, T_{eff} *(FC)*, is defined as the single test temperature at which the amount of fatigue cracking would be equivalent to that measured by considering each season throughout the year. The effective temperatures for permanent deformation and fatigue are calculated from historical temperature data at the project site. The calculation is described in Cominsky et al. 1994, sections 4.6 and 4.7.

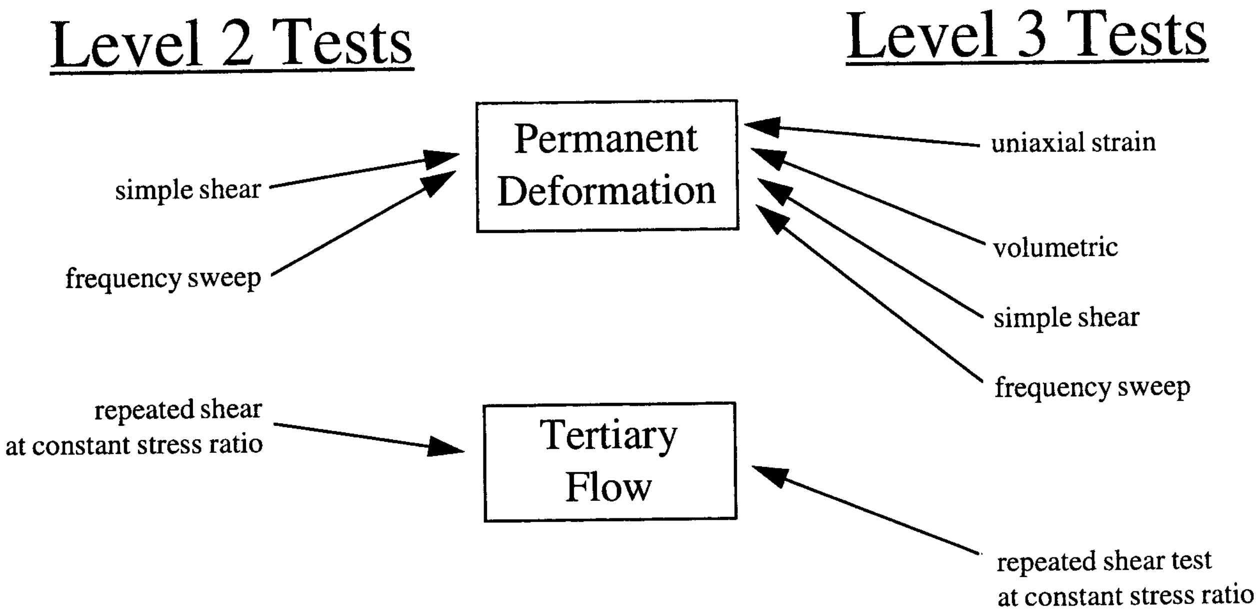


Figure 4-1. **Performance-Based Test Requirements for Superpave Level 2 and Level 3 Mix Designs for Overlays**

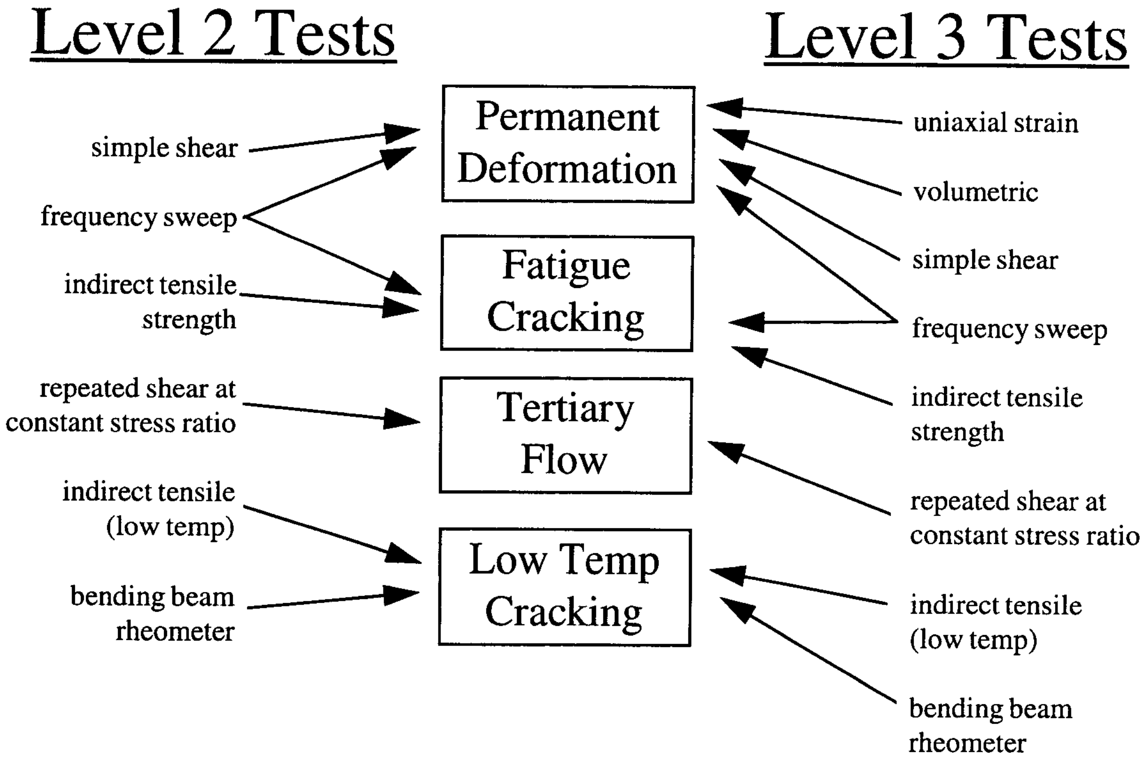


Figure 4-2. **Performance-Based Test Requirements for Superpave Level 2 and Level 3 Mix Designs for New Construction**

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

The repeated load shear at a constant stress ratio is included as a screening test to identify mixtures that exhibit tertiary plastic flow leading to instability and premature rutting. While this test as well as the repeated load shear at constant height provides a tool for mixture evaluation and analysis, it is anticipated that it will not be often needed in the Superpave design procedure as a guard against catastrophic mix failure since the compactibility phase of the volumetric level 1 design should eliminate mixtures that will compact to very low levels of air voids (< 2 percent). It should also be noted that the Superpave system does not predict fatigue and low-temperature cracking for overlay mixtures. This significantly reduces the amount of testing (figure 4-1)

The Superpave level 3 mix design is similar in form to the level 2 mix design procedure, but utilizes a more complete set of performance-based mixture properties and yields more reliable predictions for fatigue cracking, permanent deformation, and low-temperature cracking.

To complete the characterization of material properties in level 3 designs, two additional tests are used with the level 2 tests already described (figures 4-1 and 4-2). The following tests are performed for level 3 mix designs:

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

The volumetric (hydrostatic state of stress) test, the uniaxial strain test and the simple shear at constant height test are used to measure the nonlinear elastic behavior of the aggregate skeleton and are related to the permanent deformation of the mix. As the aggregate particles move in contact with each in response to traffic loads, the stiffness of the aggregate skeleton increases; this in turn enhances the resistance of the pavement to deformation.

Mixture performance prediction for level 3 mix design is done essentially the same as in level 2. The main differences from level 2 are the following:

- Material property characterization is more complete including nonlinear elastic behavior.

- Weather data and lower layer moduli are evaluated in a more rigorous manner by dividing the year into seasons, each with specific pavement temperatures and lower layer moduli.

The use of the tertiary creep (repeated shear test at constant stress ratio) test and the limitations for overlays in level 2 design also apply to level 3 mix design.

4.2 Role of Pavement Structure

The unique ability of level 2 and level 3 mix designs to predict pavement performance by using fundamental engineering properties requires an evaluation of the entire pavement structure. It is no longer possible to evaluate the suitability of a mix design without considering the pavement into which the paving mix is to be placed. The thrust of mix performance prediction is to calculate stresses within the in-place paving mix and predict mix response. Pavement structure including subgrade support (along with pavement temperature and applied load) effects stresses which are imposed upon a paving mix.

Thus, the Superpave mix design method links pavement structural design and mix design. Pavement performance predictions depend upon structural thickness and material properties. For example, a mix that is placed in two pavements—one thicker than the other—will be subjected to two different levels of stress; hence, its predicted performance will be different. Alternately, if two paving mixes with different material properties are used in the same pavement section, their predicted performance will differ.

It is theoretically possible to design a pavement section or adjust a proposed pavement cross section with the Superpave system using a trial and error approach with different layer thicknesses or different material properties. However, the pavement performance model incorporated into the Superpave software is not sufficiently robust to be used as a stand-alone structural design system. Certain simplifying assumptions were necessary to efficiently package the finite element analysis program into the Superpave software. For example, lower layer moduli are *estimated* based on qualitative decisions made by the mix designer. *Measurement* of lower layer material properties and thicknesses (if required), would allow a more realistic performance prediction to be made, but would complicate the Superpave mix design system beyond a practical limit. However, the better the structural data used in the mix design calculations, the more robust the mix design will be.

Therefore, Superpave can link structural and mix design, but an automated process of balancing structural thickness and material properties is not yet available.

The Superpave method can be used for either new construction or overlays of existing pavements. The structural design model included in Superpave software is able to handle existing asphalt hot mix asphalt (HMA), and portland cement concrete layers. Therefore, mix designs to be used for an overlay can be evaluated the same way as new construction.

4.3 Constraints on Performance Prediction Models

The Superpave performance prediction models predict permanent deformation, fatigue cracking and low temperature cracking for any defined pavement cross section. The following constraints have been imposed because of the need to package the prediction models contained in the Superpave software in a form suitable for routine mix design. Such constraints may be eased and the capabilities expanded in the future.

1. A maximum of two new asphalt concrete layers can be evaluated.
2. Fatigue cracking prediction is based upon the material properties of the lowest new asphalt concrete layer. These properties are attributed to the entire thickness of all layers.
3. Low temperature cracking prediction is based upon the material properties of the top layer. These properties are attributed to the total thickness of new asphalt concrete layers.
4. Low temperature cracking cannot be predicted accurately for mix designs which are overlays of existing pavements due to the interference of reflection cracking.
5. Fatigue cracking cannot be predicted for mix designs that overlay existing pavements.

Thus mix designs for overlays are limited to minimizing or controlling permanent deformation. This limitation is not generally important since fatigue cracking would normally not occur when the underlying structure is sound. This fact greatly simplifies the tests requirements and the sophistication of the test equipment needed for overlay design.

4.4 Performance-Based Tests

A slate of performance-based tests are included in the Superpave mix design system. For the most part, they may be considered nondestructive tests to measure material response to various states of stress. The notable exception is the tensile strength test, which is measured at failure in an indirect tensile mode.

4.4.1 Load Induced Distress

4.4.1.1 Superpave Shear Test Device

The material model used in the Superpave software to predict permanent deformation and fatigue cracking includes non-linear elastic, viscoelastic and plastic characterizations.

In nonlinear elastic behavior, the resilient modulus (elastic behavior) is dependent upon the state of stress in the material. In hot mix asphalt, the nonlinearity of resilient modulus arises from the aggregate particles contained in the mix. As bulk (confining) stress increases, hot mix asphalt becomes stiffer. Three tests were developed to measure nonlinear elastic properties and plastic properties:

- volumetric (hydrostatic state of stress) test;
- uniaxial strain test; and
- simple shear at constant height test.

Figure 4-3 illustrates the biaxial shear test device developed to perform these tests. It consists of

- a closed loop, servohydraulic loading system,
- two perpendicular load actuators, and
- a environmental chamber.

The environmental chamber controls temperature and allows the specimen to be rapidly subjected to confining pressure. The reaction frame is extremely rigid so that precise displacement measurements can be made without frame compliance. The shear table holds specimens and can be actuated to impart shear loads.

A test control unit consists of the system hardware and software. The hardware interfaces with the testing apparatus through input and output transducers. It consists of controllers, signal conditioners, and a computer and its peripherals. The software consists of the algorithms required to control the testing apparatus and to acquire data during a test.

Linear variable differential transducers (LVDTs) are affixed to specimens and measure the response of specimens to applied testing loads. The LVDTs make it possible for the system to operate in a closed loop feedback mode, i.e., the LVDT signals are used to control the applied testing loads. For example, the compressive (axial) load can be continually controlled by feedback from the shear deformation.

The environmental control unit is required to control the temperature and air pressure inside the testing chamber at a constant level. The unit is capable of providing temperatures within a wide range from 1° to 80°C. Air pressure and the rate of pressure change within the chamber is precisely controlled. Air pressure is normally applied at a rate of 70 kPa per second up to a maximum value of 840 kPa. This is achieved by storing compressed air in separate storage tanks that can be emptied into the testing chamber at the required rate. Air pressure provides specimen confinement for two of the tests, viz., the volumetric and uniaxial strain test. Testing is done at an effective temperature as high as 63°C in level 2 designs, and at 4, 20 and 40°C in level 3 designs.

A suitable hydraulic system provides the required force to load specimens for different testing conditions. A hydraulic pump powers the two actuators, each with a capacity of approximately 32 kN. The vertical actuator applies an axial force to test specimens. The horizontal actuator drives the shear table, which imparts shear loads on the specimen.

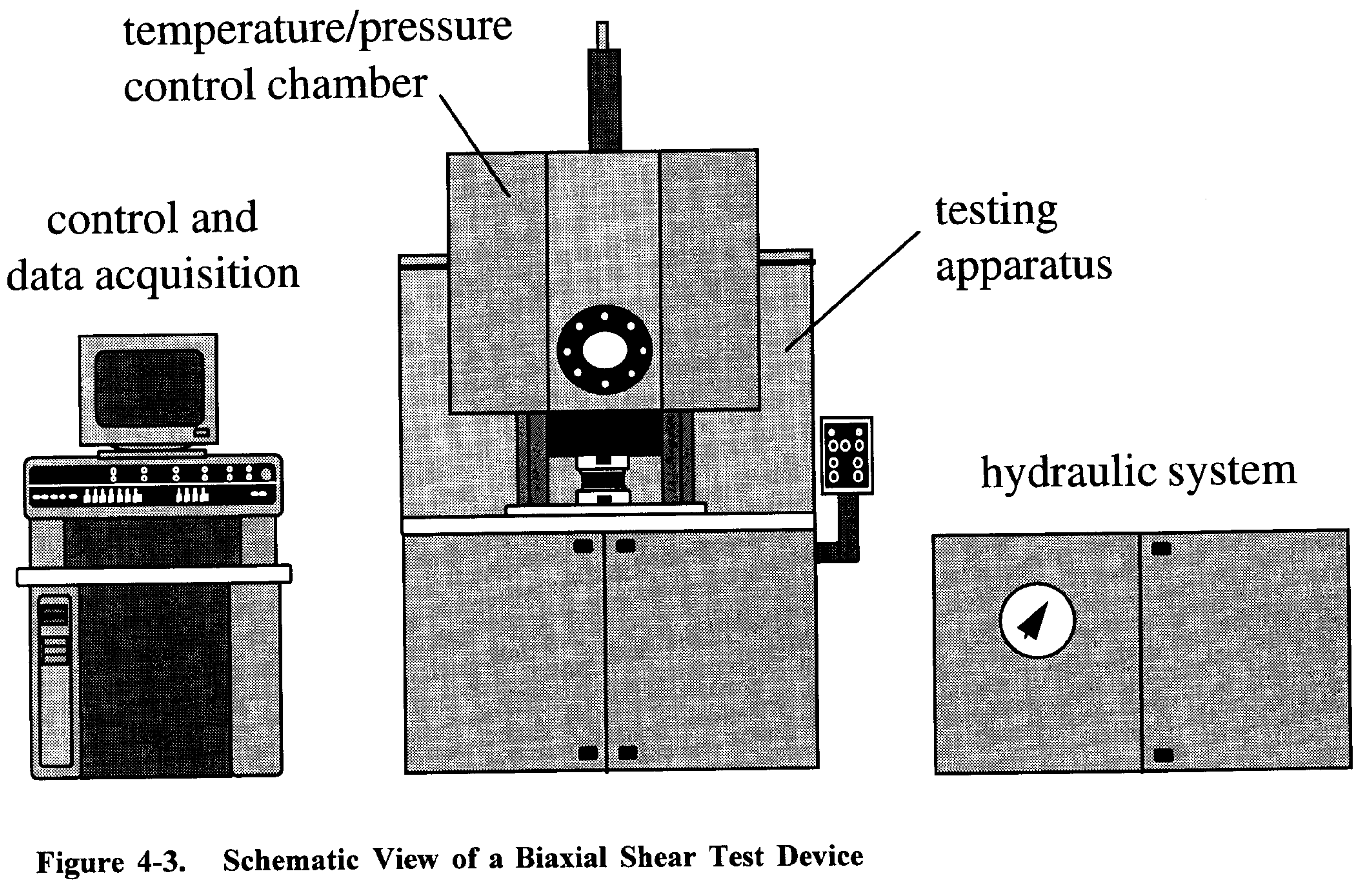


Figure 4-3. Schematic View of a Biaxial Shear Test Device

4.4.1.2 Specimen Preparation and Instrumentation

This procedure is described in detail in SHRP Method of Test M-003 (Harrigan et al. 1994). The first step in specimen preparation is to trim test specimens to a thickness of 50 mm. For the four tests that require no confining pressure, the specimen is glued between two platens. A gluing device (figure 4.4) is used to squeeze the specimen between the platens while the glue cures. An epoxy-type glue such as Devcon Plastic Steel is employed for this purpose. The gluing device rigidly holds the platens and specimen to ensure that the platens are parallel. After the glue has cured, four screws are affixed to the side of the specimen using a gap filling variety of cyanoacrylate glue. These screws are used to affix the bracket that holds the horizontal LVDT (figures 4-5 and 4-6). Axial LVDTs are affixed to the platens.

A different specimen configuration is used for confined tests. Test specimens are still placed between platens, however, no glue is used. A rubber membrane surrounds the specimen. A radial LVDT is affixed by a collar that surrounds the perimeter of the specimen (figure 4-7). Axial LVDTs are affixed to the platens.

The volumetric and uniaxial strain tests use confining pressure in their protocol. These two tests are performed only for a level 3 mix design. Levels 2 and 3 designs use repeated shear at constant stress ratio, simple shear at constant height, and frequency sweep at constant height tests. The repeated shear test at constant height is a stand-alone test that can be used for rut depth estimation.

4.4.1.3 Tests Conducted with the Shear Test Device

The following tests are performed using the Superpave shear test device; detailed procedures are presented in SHRP Method of Test M-003 and Practice P-005 (Harrigan et al. 1994):

- volumetric test,
- uniaxial strain test,
- simple shear test at constant height,
- frequency sweep test at constant height,
- repeated shear test at constant stress ratio, (a screening test not used with the Superpave performance prediction models), and
- repeated shear test at constant height (not used in the Superpave system).

The repeated shear test at constant height was developed through the SHRP asphalt research program, but is not a part of the Superpave system. It can be used for quick estimation of rut depth.

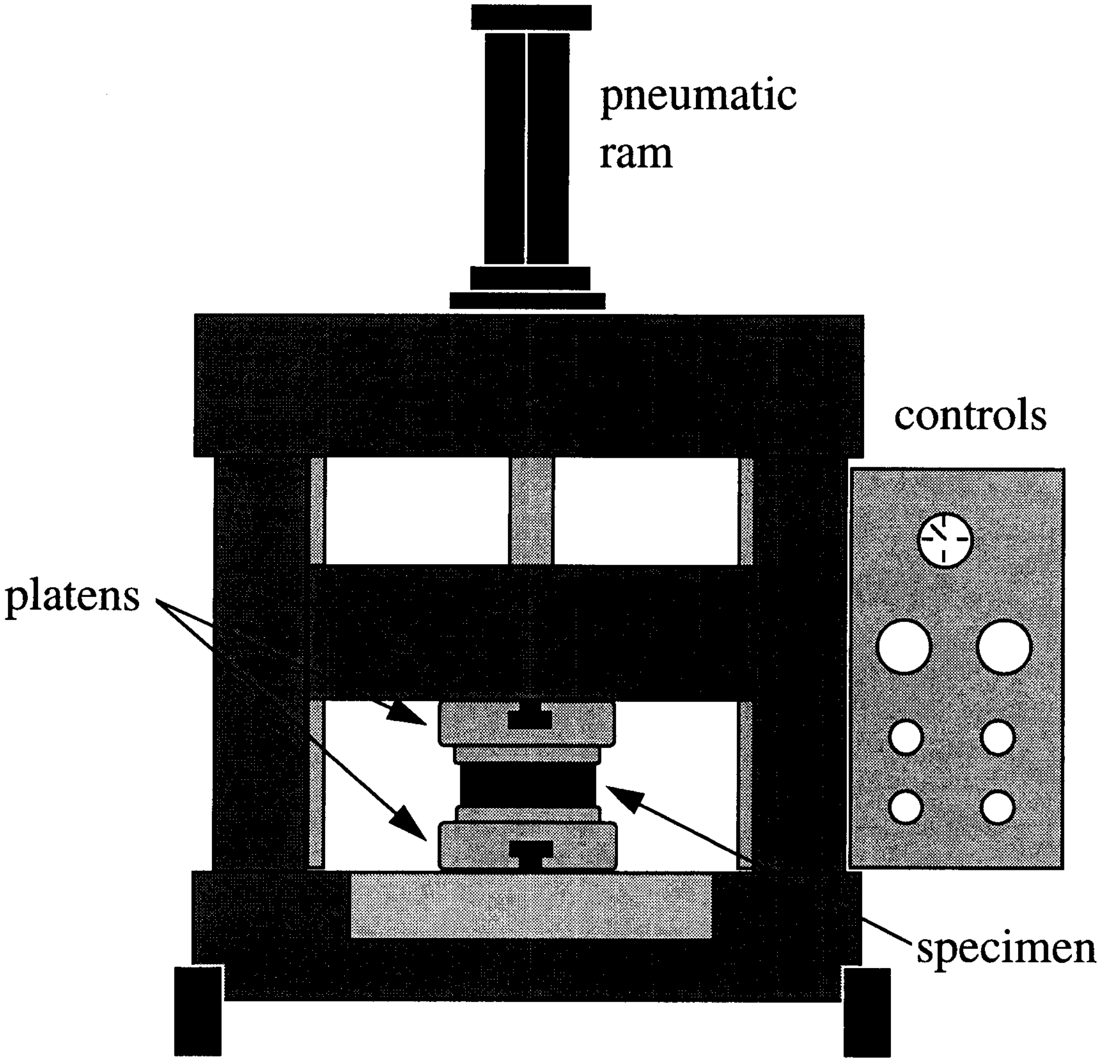


Figure 4-4. Conceptual View of a Platen Gluing Device for Shear Test Specimens

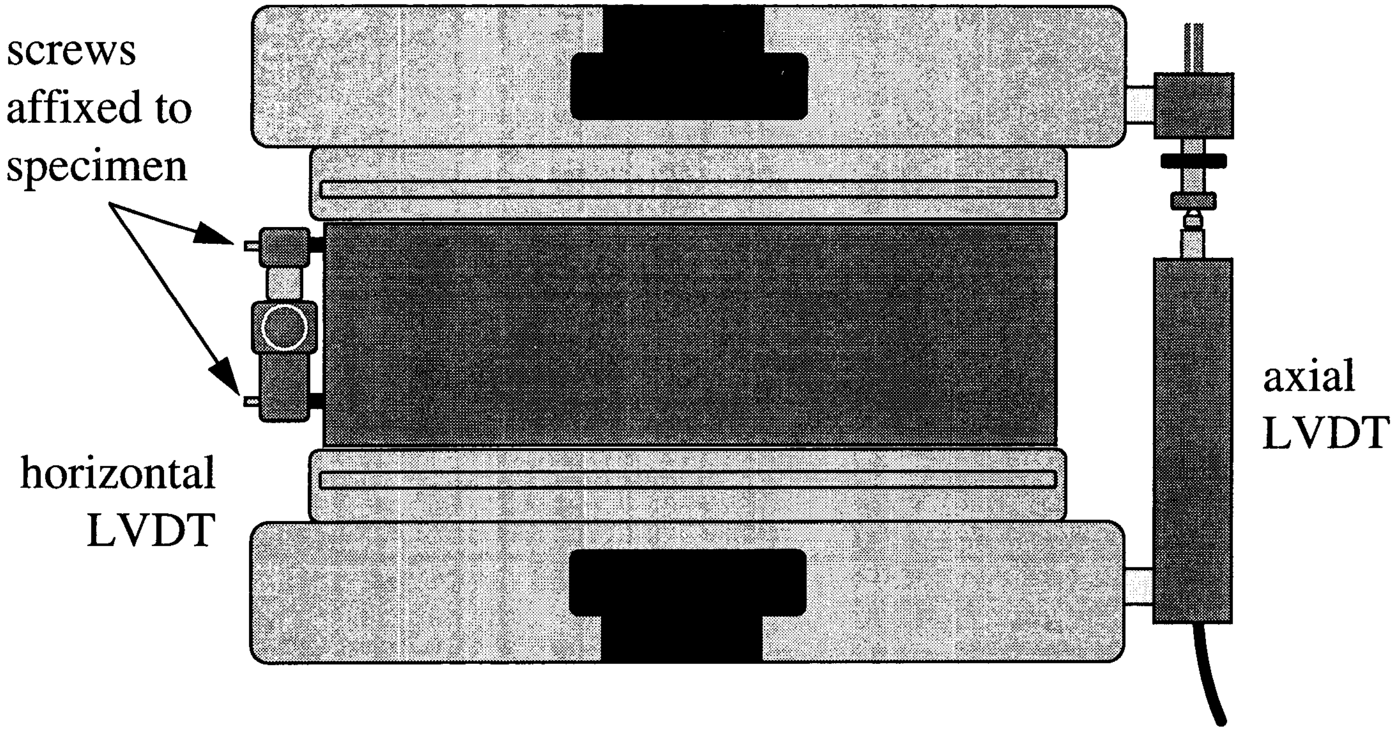


Figure 4-5. **Front View: LVDT Set-Up for Unconfined Specimens Tested in the Shear Test Device**

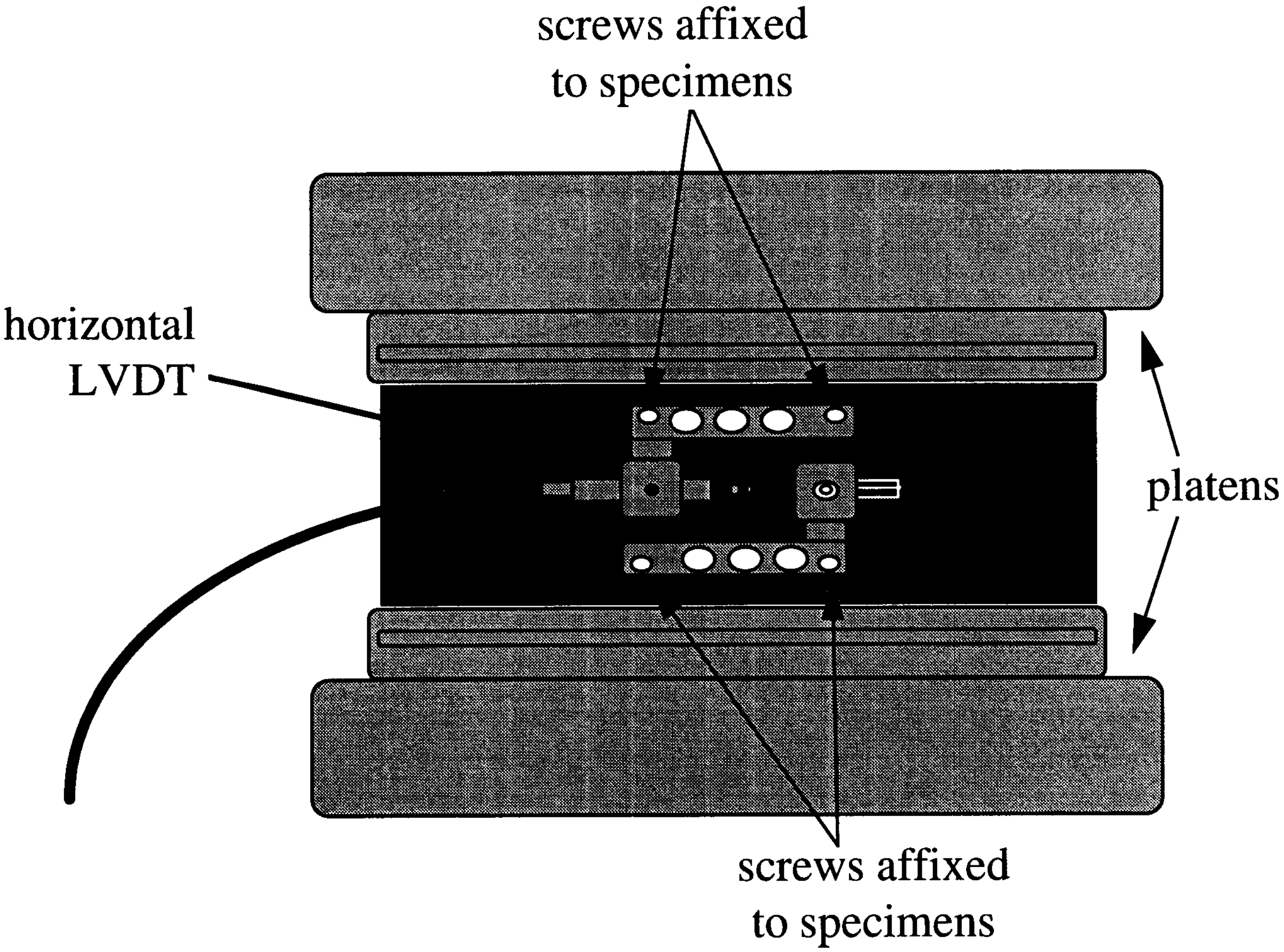


Figure 4-6. **Side View: LVDT Set-Up for Unconfined Specimens Tested in the Shear Test Device**

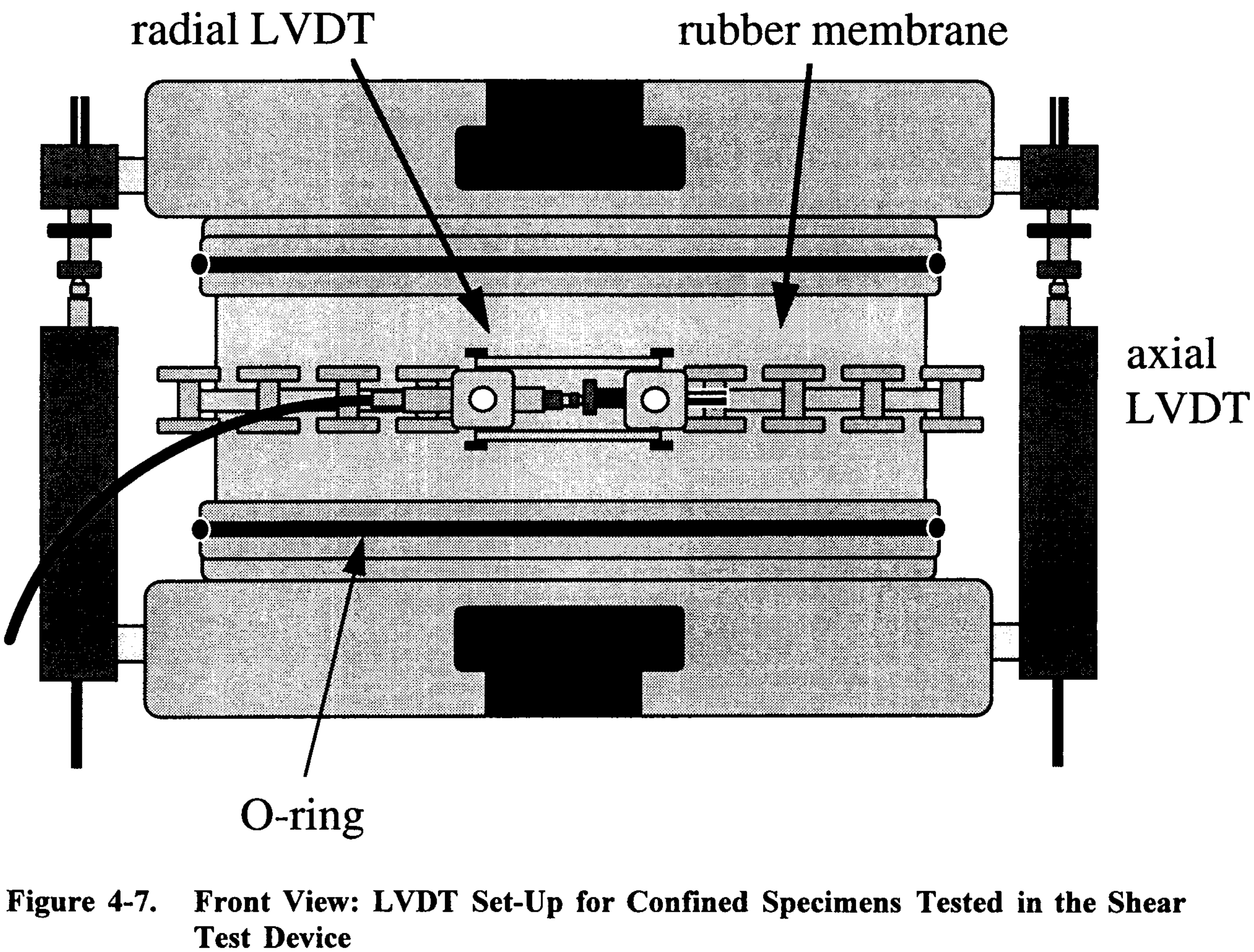


Figure 4-7. **Front View: LVDT Set-Up for Confined Specimens Tested in the Shear Test Device**

Volumetric Test (Hydrostatic State of Stress). In this test the specimen is subjected to a hydrostatic stress state and the associated volume change is determined. Figure 4-8 illustrates schematically the key parameters of this test.

A fast confining pressure ($\sigma_{11} = \sigma_{22} = \sigma_{33}$) is applied at a constant rate. Since the top and bottom platens are not fixed to the specimen, the specimen will decrease both axially and in perimeter or circumference. The following response variables are measured:

σ_{11} = $\sigma_{22} = \sigma_{33}$ = confining pressure, kPa.
P_o = original perimeter of specimen, mm.
P_c = perimeter of specimen under confinement, mm.
δ_p = $P_o - P_c$,mm.
r = radius of specimen, mm.
ε_0 = $\delta_p / 2\pi r$

Figure 4-9 illustrates the change in confining pressure versus time during the volumetric test at 20°C.

Uniaxial Strain Test. In this test, the axial load is applied and the confining pressure necessary to maintain a constant diameter of the specimen is measured. Figure 4-10 shows schematically the main parameters of this test.

A confining pressure ($\sigma_{22} = \sigma_{33}$) is applied at a constant rate. As the specimen deforms inward due to the confining pressure, the axial load (σ_{11}) increases to counteract this effect and maintain a constant perimeter or circumference. The following response variables are measured:

σ_{11} = variable axial load to maintain constant perimeter/circumference, kPa.
σ_{22} = σ_{33} = confining pressure, kPa.
δ_v = vertical displacement of specimen, mm.
h = height of specimen, mm.
ε_0 = δ_v / h

Figure 4-11 illustrates the application of the axial stress during the test.

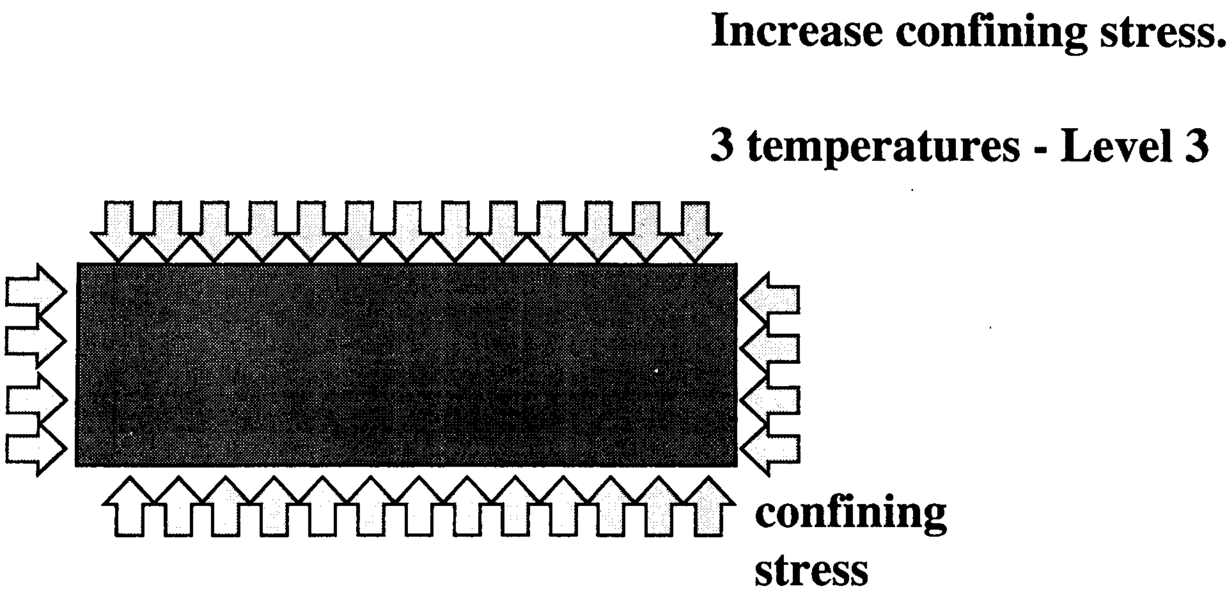


Figure 4-8. Conceptual View of the Volumetric Test

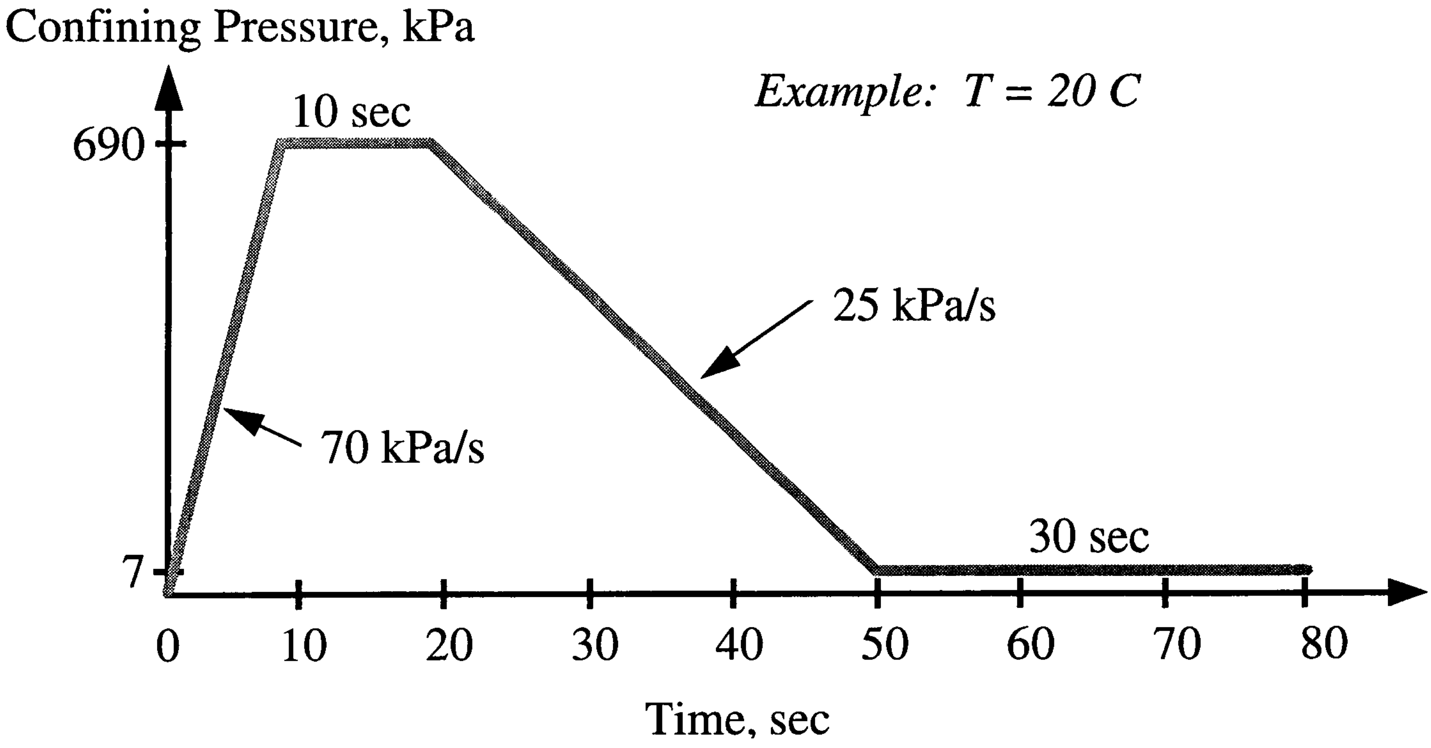


Figure 4-9. Ramping of Confining Pressure in the Volumetric Test

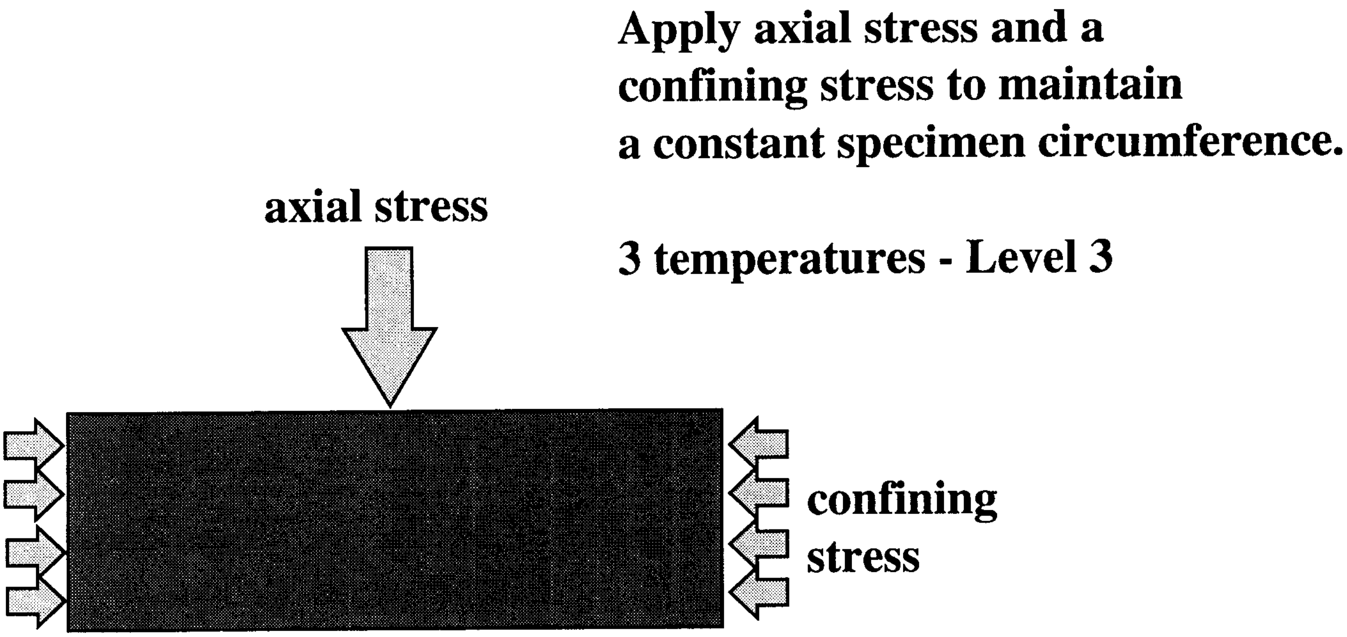


Figure 4-10. Conceptual View of the Uniaxial Strain Test

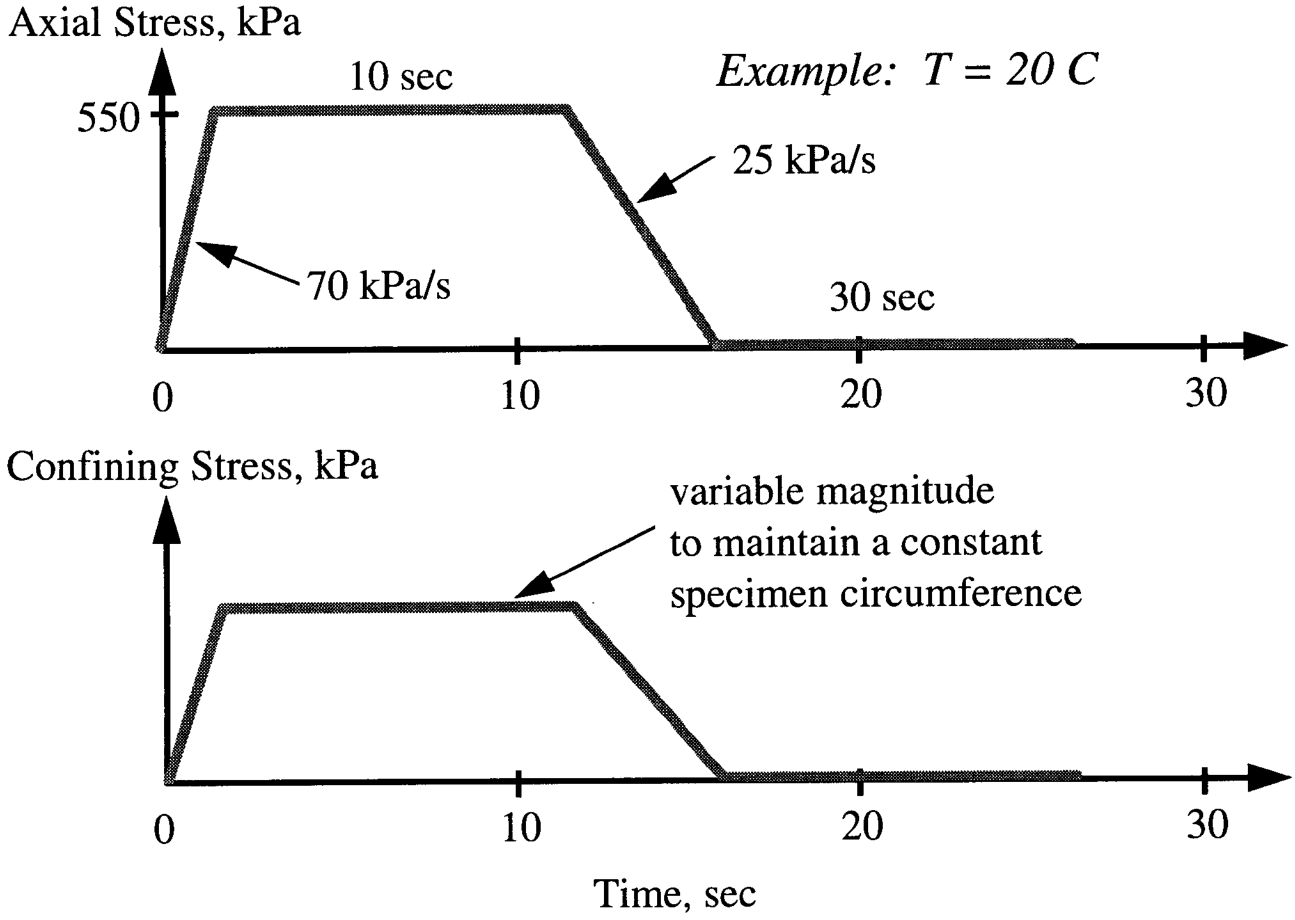


Figure 4-11. Variation of Axial Stress and Confining Pressure (Stress) in the Uniaxial Strain Test

Simple Shear Test at Constant Height. In this test a shear stress is applied while maintaining the specimen at constant height and the corresponding shear strain is measured. A controlled shearing stress is applied to a test specimen. As the specimen is sheared, it dilates, which increases its height. An axial stress is continually applied to keep the specimen height constant.

Figure 4-12 shows the application of stresses during the test. During the test, axial and shear loads and deformations are measured and recorded. Figure 4-13 provides the parameters of this test.

A shear stress (σ_{22}) is applied at a constant strain rate. A variable axial load or stress (σ_{11}) is applied to maintain a constant height specimen as the specimen is horizontally displaced or deformed. The following response variables are measured:

σ_{11} = variable axial stress applied to maintain a constant height, kPa.
σ_{22} = shear stress applied, kPa.
δ_H = horizontal displacement, mm.
h = height of specimen, mm.
ε_0 = $\delta_H/2h$

Frequency Sweep at Constant Height. This is a frequency sweep test in the shear mode. The simple shear test set-up is used, however, the load is applied at a series of frequencies and different temperatures. From these results the phase angle (ϕ) and the complex modulus (G^*) are measured. No confining pressures are applied. The shear stress is adjusted to provide a small shear strain and an axial stress is applied to maintain constant height. The following are measured:

σ_{11} = variable axial stress applied to maintain a constant height, kPa.
σ_{22} = shear stress applied, kPa.
ϕ = phase angle, degrees.
G^* = Complex shear modulus, kPa.

Figure 4-14 provides the key parameters of this test in schematic form. Figure 4-15 illustrates the application of shearing and axial stresses during test.

4.4.1.4 Indirect Tensile Test Device

Indirect tensile testing involves applying a compressive load along the vertical diametral axis of a cylindrical specimen. The mechanics of the test are such that a nearly uniform state of tensile stress is achieved across the vertical diametral plane. This test is used to obtain fatigue cracking analysis data for the mix. In this test the specimen is loaded at a constant deformation rate (50 mm/min). The specimen is loaded until failure, which is the peak load. Load and deformation characteristics are measured throughout the test.

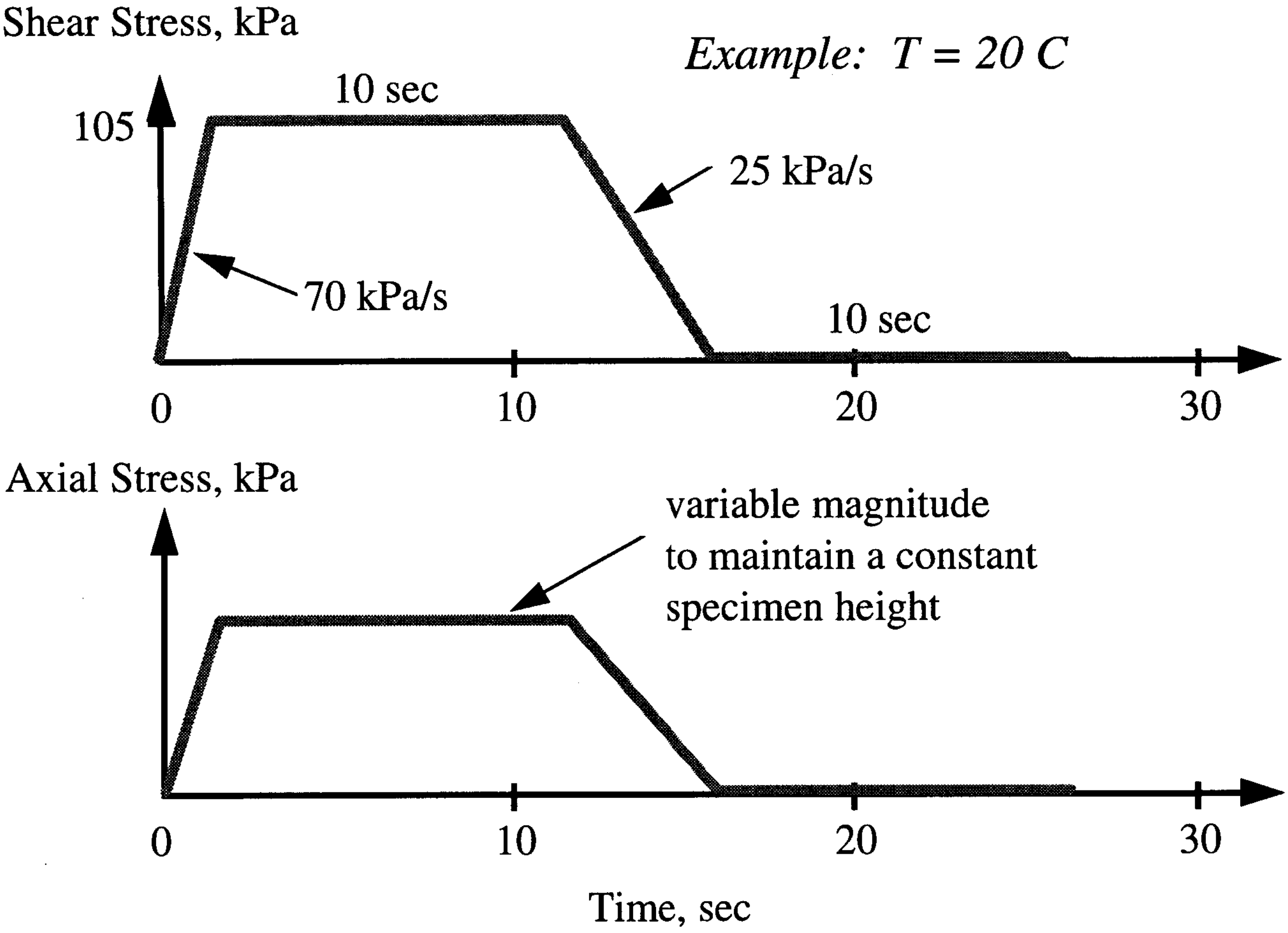
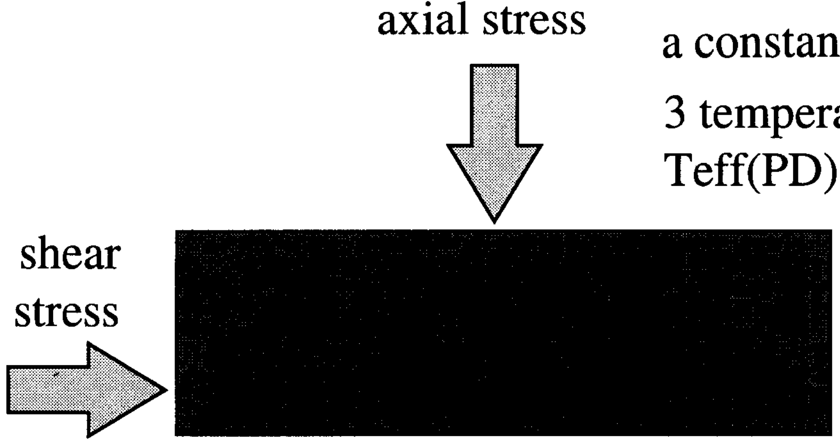


Figure 4-12. Variation of Axial Stress and Shear Stress in the Simple Shear at Constant Height Test

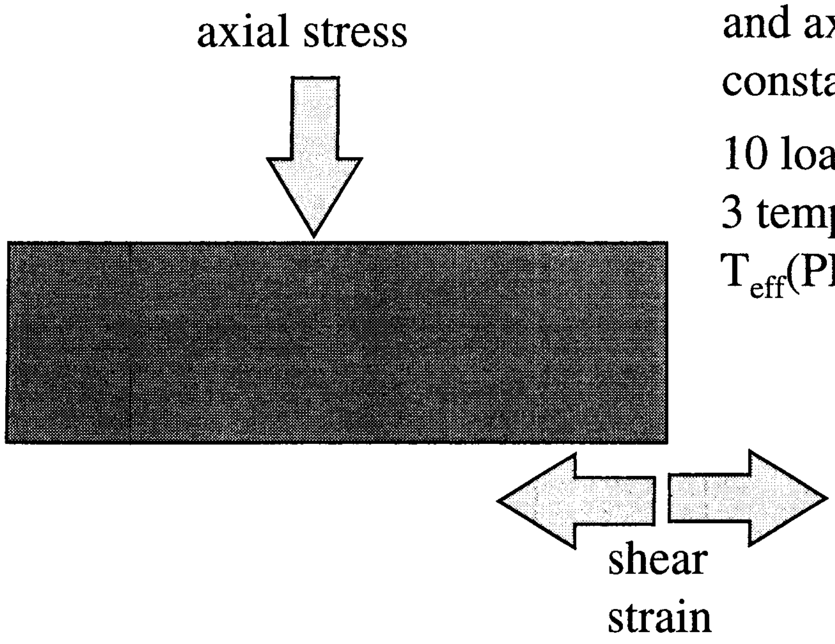


Apply horizontal shear stress and an axial stress to maintain a constant specimen height.

3 temperatures - Level 3

Teff(PD) - Level 2

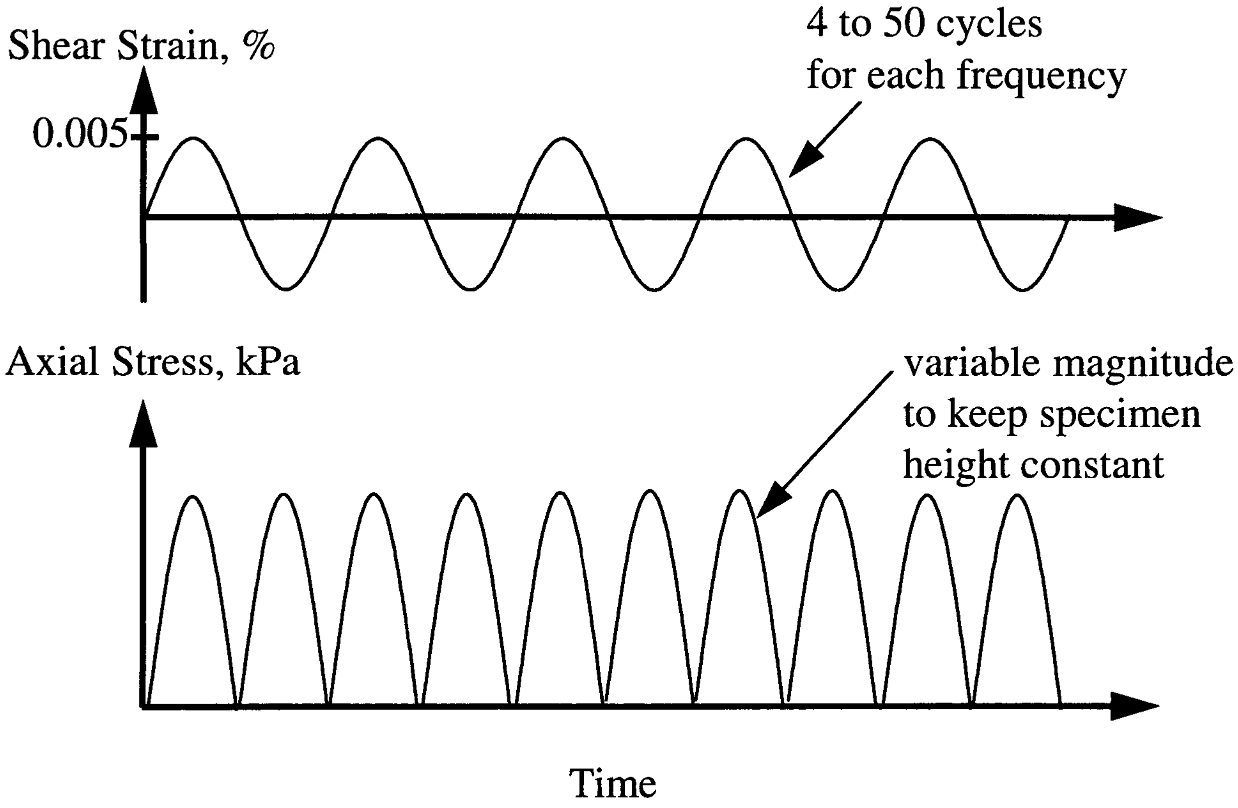
Figure 4-13. Conceptual View of the Simple Shear at Constant Height Test



Apply horizontal shear strain and axial stress to maintain a constant specimen height.

10 load frequencies,
3 temperatures - Level 3
T_{eff}(PD) and T_{eff}(FC) - Level 2

Figure 4-14. Conceptual View of the Frequency Sweep at Constant Height



4 to 50 cycles
for each frequency

variable magnitude
to keep specimen
height constant

Figure 4-15 Variation of the Shear Strain and Axial Stress in the Frequency Sweep at Constant Height

Figure 4-16 illustrates schematically the indirect tensile test. Figure 4-17 illustrates the load and deformation characteristics of this test.

4.4.2 Non-Load Induced Stress

The material model used in Superpave software to predict low temperature cracking is based upon a linear viscoelastic characterization. The lower test temperatures used for low temperature cracking allow a simpler material property model to be used than the model required for permanent deformation and fatigue cracking. Two tests are used to obtain required material properties. The tests are:

- low temperature tensile creep
- low temperature tensile strength

The equipment used for both of these tests is the indirect tensile test device (IDT). The test measures the creep compliance and strength of asphalt mixes using indirect tensile loading techniques at intermediate to low temperatures. Figure 4-18 illustrates the instrumentation needed for the IDT testing.

The IDT Creep Compliance and Strength test is used to analyze mixes for low temperature cracking. Tests are performed at 0, −10 and −20°C for both the level 2 and level 3 mix designs.

In the first phase of the test, a static creep load of fixed magnitude is placed on the specimen (figure 4-19). The magnitude of the load should produce a prescribed level of horizontal microstrain in the test specimen during the defined duration of the creep phase of the test. Vertical and horizontal deformations are measured on both sides of the specimen throughout the test.

At the conclusion of the creep loading period, the specimen is loaded until failure (peak load) by applying additional load. Vertical and horizontal movements and load are measured. Measurements are taken until the load has decreased to a value of at least 10 percent less than peak load. Figure 4-20 shows the controlled deformation portion of the test.

4.5 Performance Prediction

Comprehensive pavement performance models that predict the development of permanent deformation, fatigue cracking and low temperature cracking with time were developed and are included in the Superpave software. A detailed discussion of the models can be found in appendix B of this report and in Lytton et al. 1993. A worked example is presented in chapter 6 of Cominsky et al. 1994.

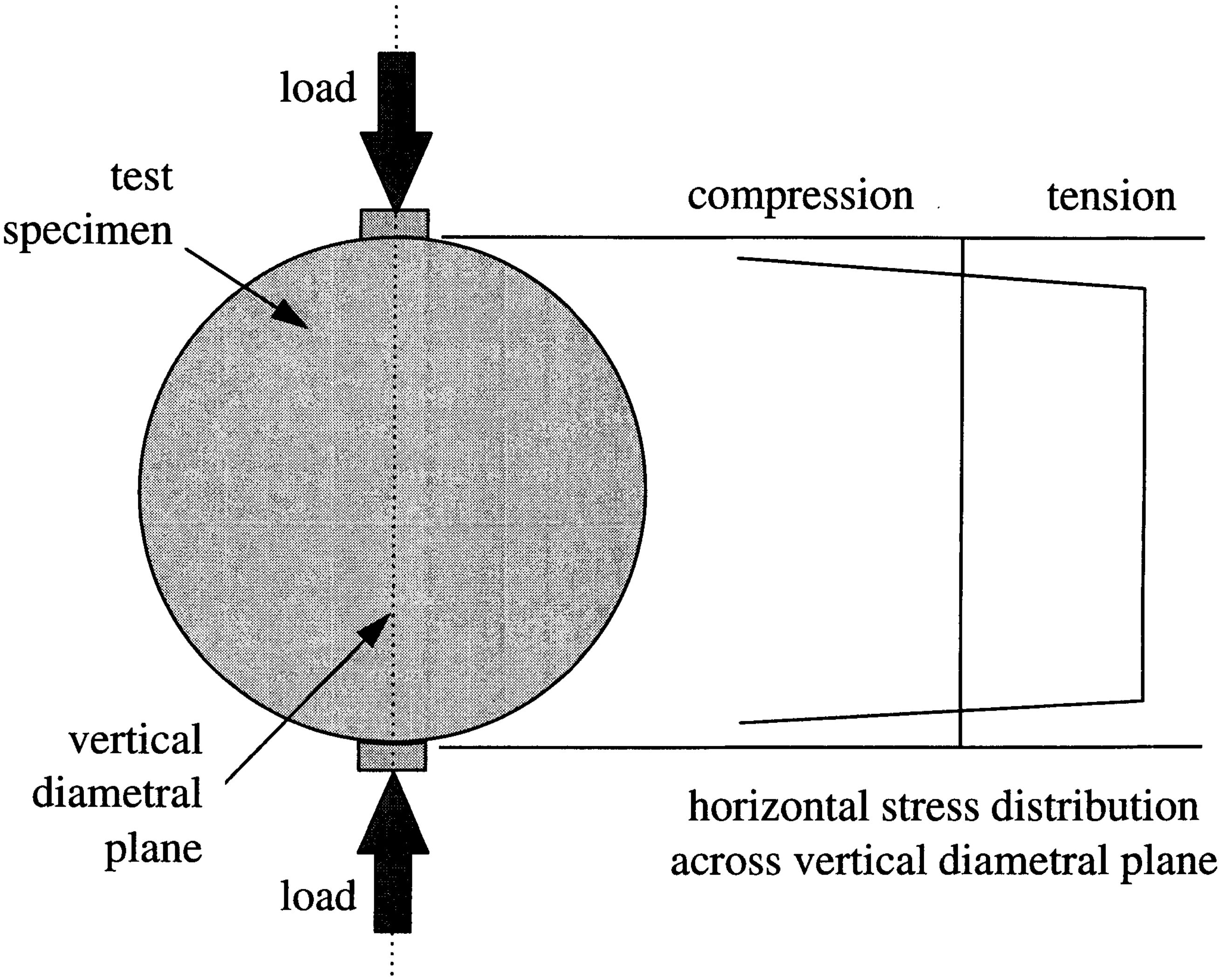


Figure 4-16. Schematic View of the Indirect Tensile Test

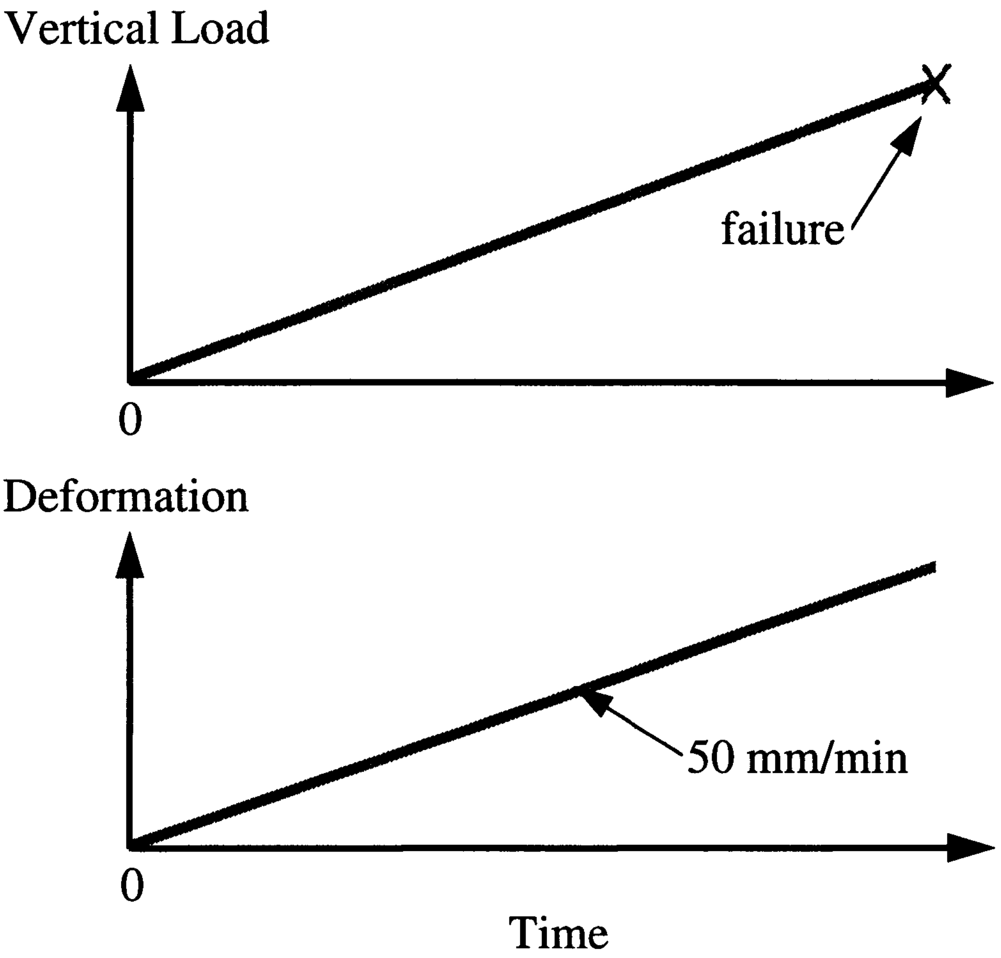


Figure 4-17. Indirect Tensile Test: Specimen Loading and Deformation Characteristics (Shown for Loading Rate of 50 mm/min)

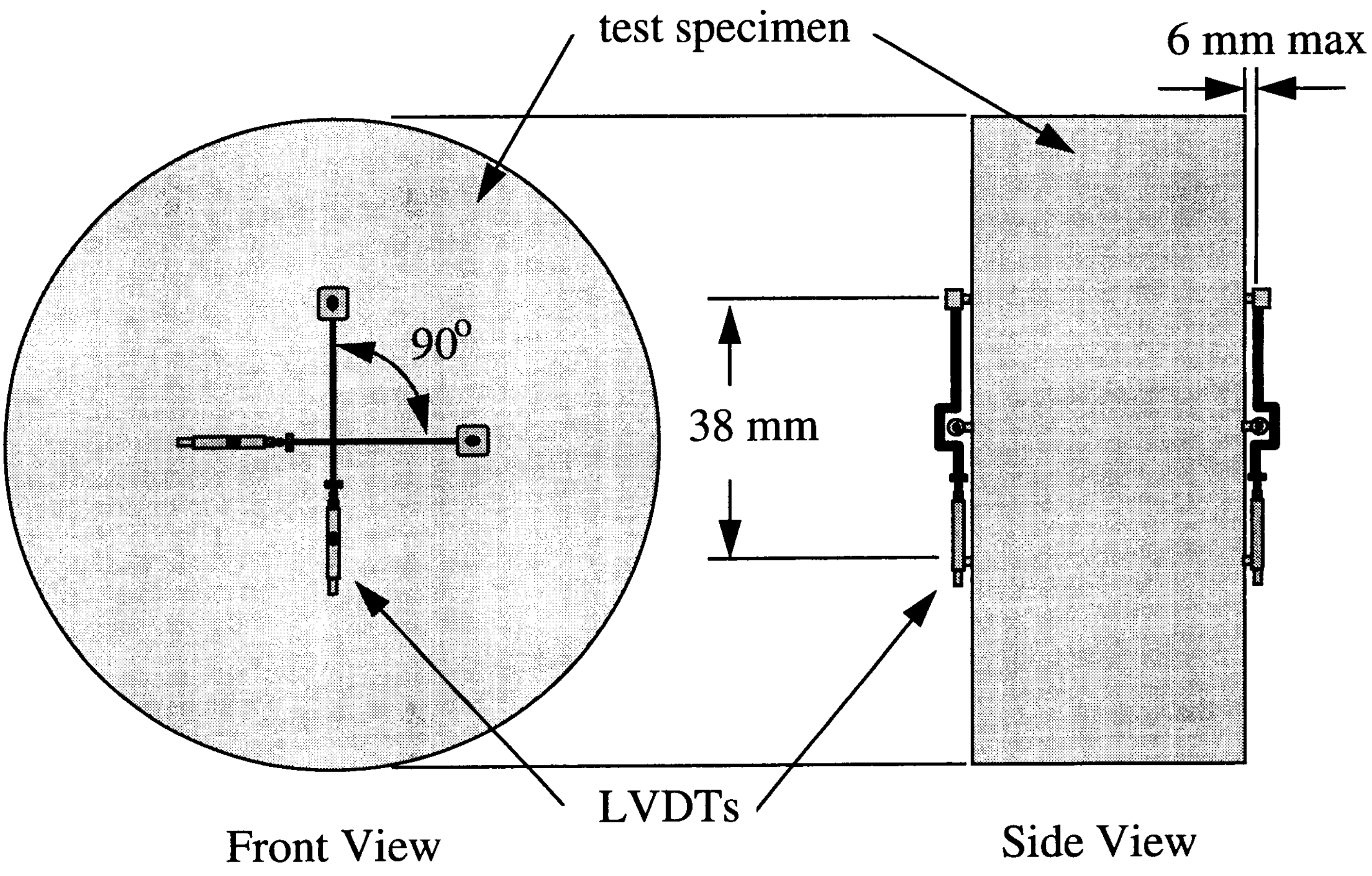


Figure 4-18. Typical Specimen Instrumentation for the Indirect Tensile Creep and Strength Tests

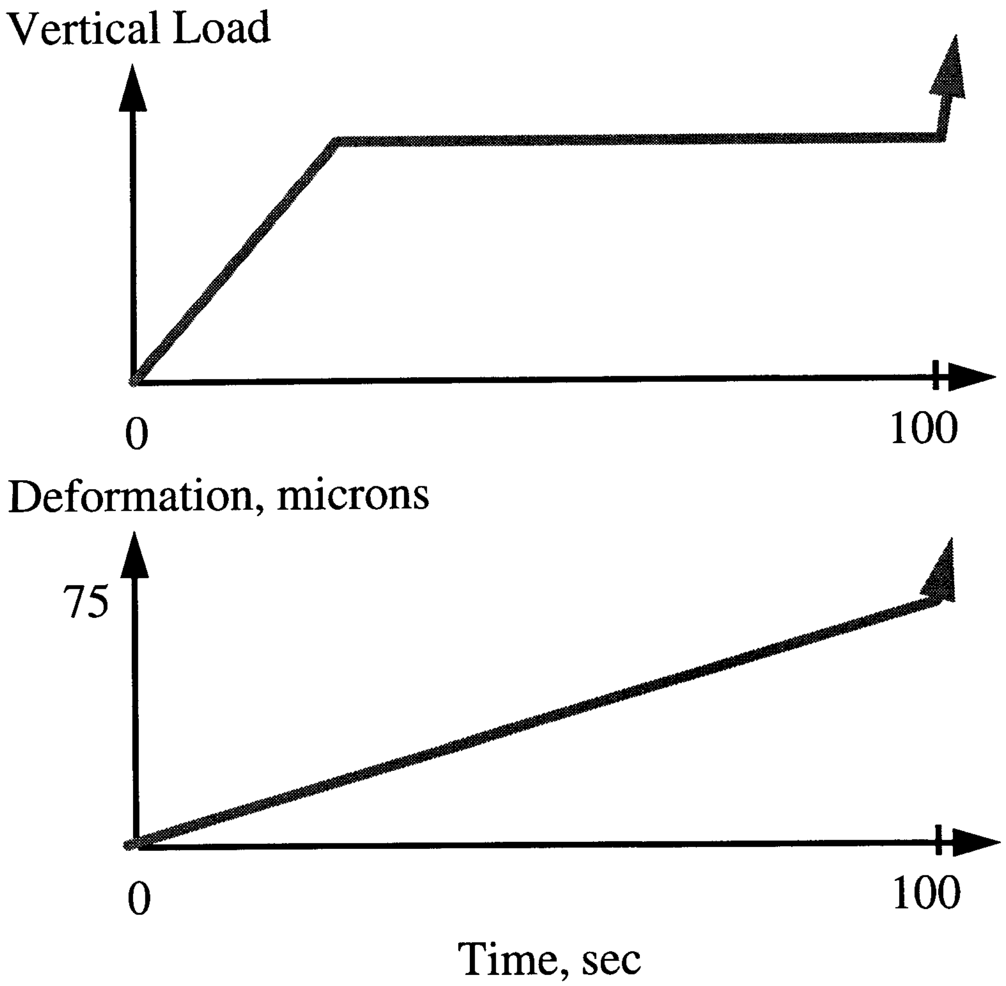


Figure 4-19. Variation of Load and Deformation in the Indirect Tensile Creep Test

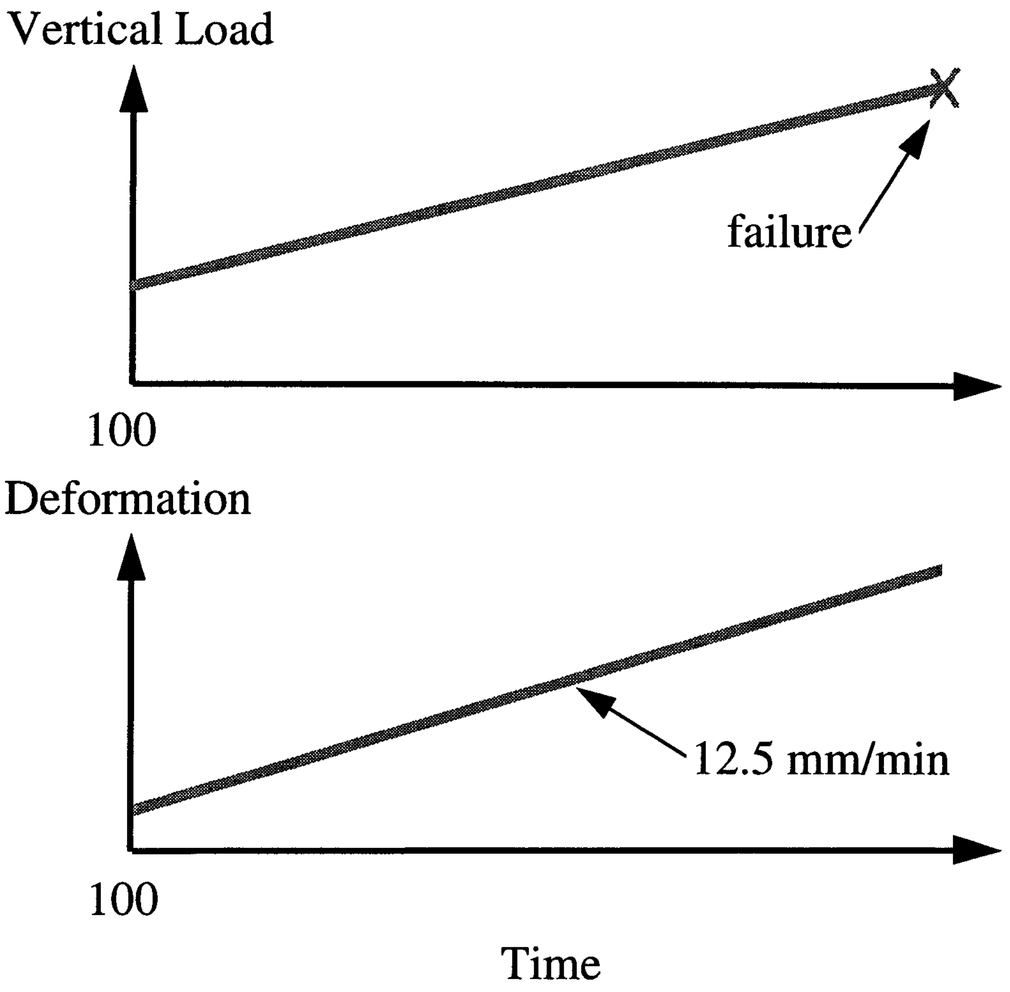


Figure 4-20. Variation of Load and Deformation in the Indirect Tensile Strength Test (12.5 mm/min Loading Rate)

The pavement performance model can evaluate or design asphalt concrete paving mixes to minimize a specific distress or combinations of different distresses. The model is composed of four parts (see figure 4-21):

- material property model;
- environmental effects model;
- pavement response model; and
- pavement distress model.

The mix characterization program calculates the non-linear elastic, viscoelastic, plastic and fracture properties of a mix from the performance-based laboratory tests.

The frequency sweep data is used to determine the linear visco-elastic properties (i.e., complex modulus and phase angle) and the parameters of the power law. The hydrostatic, uniaxial, and simple shear tests are used concurrently to determine the resilient (k_1 through k_6) and plastic (Vermeer) properties of the mix. The frequency sweep test provides the complex modulus. When the log of the complex modulus is plotted against the log of the frequency the slope of the resulting lines is *S*. This *S* can be related to another mix property, *m*, which is the slope of the log creep compliance curve. The parameter *m* is used in both the fatigue and the permanent deformation calculations.

The uniaxial, volumetric (hydrostatic), and simple shear at constant height test provide the same information but employ different stress paths. The resilient (elastic) components, k_1, k_2, k_3, and k_6, are used in the calculations of the elastic modulus, while the Poisson's ratio of the asphalt concrete is calculated with 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.

The non-load related portion of Superpave software models predicts crack spacing as a function of age (number of seasonal cycles) and is based upon parameters obtained from the indirect tensile creep and failure tests. The material parameters needed for the thermal cracking model are *m*, as mentioned previously, and the undamaged tensile strength of the mix. The parameters are used in determining a Paris' Law coefficient.

The properties are used with the pavement response program to predict the behavior of a mix subjected to traffic and environmental loads. Some of these material properties are also used in the pavement distress model. The pavement response program, which is a finite element program, calculates the stresses and strains in the asphalt-aggregate mix from wheel loads and environmental loads. The pavement distress program takes the relevant mix properties and the appropriate stresses (from wheel loads and environmental loads), and calculates the permanent deformation with time. Each of these models are briefly discussed in appendix B.

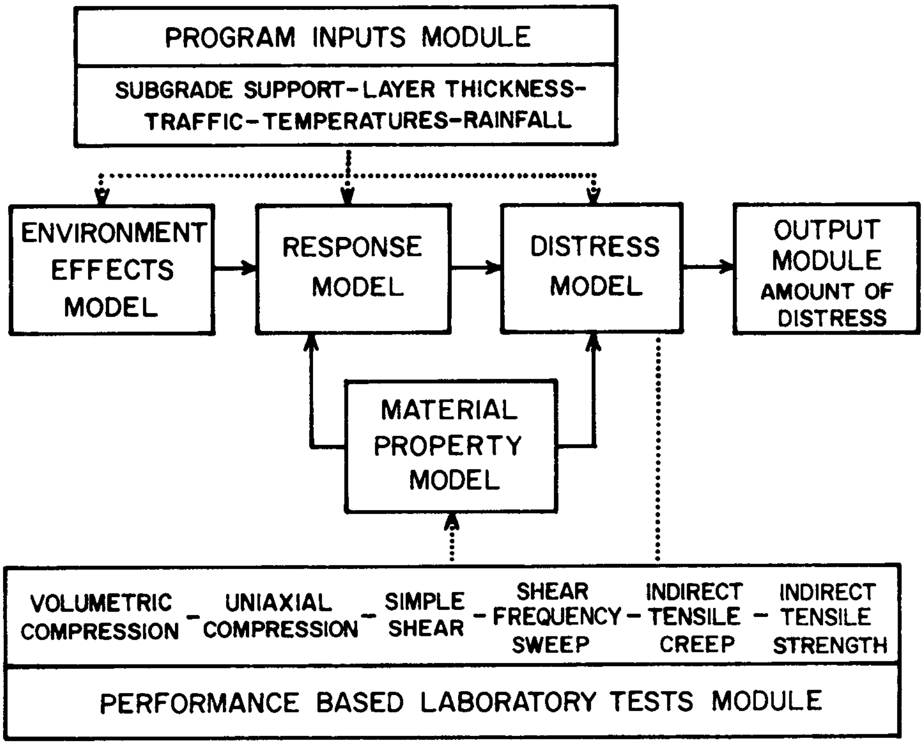


Figure 4-21. Flow Diagram of the Superpave Performance Prediction Model

4.6 Screening for Tertiary Permanent Deformation

The Superpave performance prediction models do not predict tertiary permanent deformation. Tertiary creep is illustrated in figure 4-22 and defined as the point after which permanent deformation will begin to accelerate rapidly, leading to pavement failure. The material property models used in the Superpave software characterize initial creep and steady state secondary creep and do not predict when the point of inflection will occur.

The repeated shear at constant stress ratio test provides information related to tertiary creep evaluation. The repeated shear at constant stress ratio resembles the simple shear test at constant height previously discussed; however, the loading is repeated for 20,000 cycles (4 hours). Test conditions must be specific to the location in the pavement structure, the temperature of the environment, and the amount of traffic to be carried.

The process for performing the repeated shear constant stress ratio test is:

- calculate effective temperature for permanent deformation $T_{eff}\,(PD)$;
- determine control temperature (T_c) and number of repetitions from the expected traffic and effective temperature;
- select state of stress from the asphalt content and pavement structure;
- test and determine if tertiary creep is encountered.

A plot of the log of plastic strain versus the log of number of repetitions is made as shown in figure 4.22. Material parameters are not specifically calculated from this test, but the results are used in Superpave as a pass/fail screening procedure. If the mix remains in steady state secondary creep the mix “passes”. When the mix “passes” the screening requirements, the mix may be subjected to the battery of tests for the characterization of permanent deformation, fatigue cracking and low temperature cracking. If the plastic strain enters the tertiary creep phase, the mix “fails” the screening test. When the mix fails the screening test, it will be necessary either to make adjustments to the mix proportioning or to redesign the mix completely.

4.7 Performing a Level 2 or Level 3 Mix Design

This section provides an overview of the process used to perform either a level 2 or level 3 mix design, which incorporates the performance-based tests and performance prediction models.

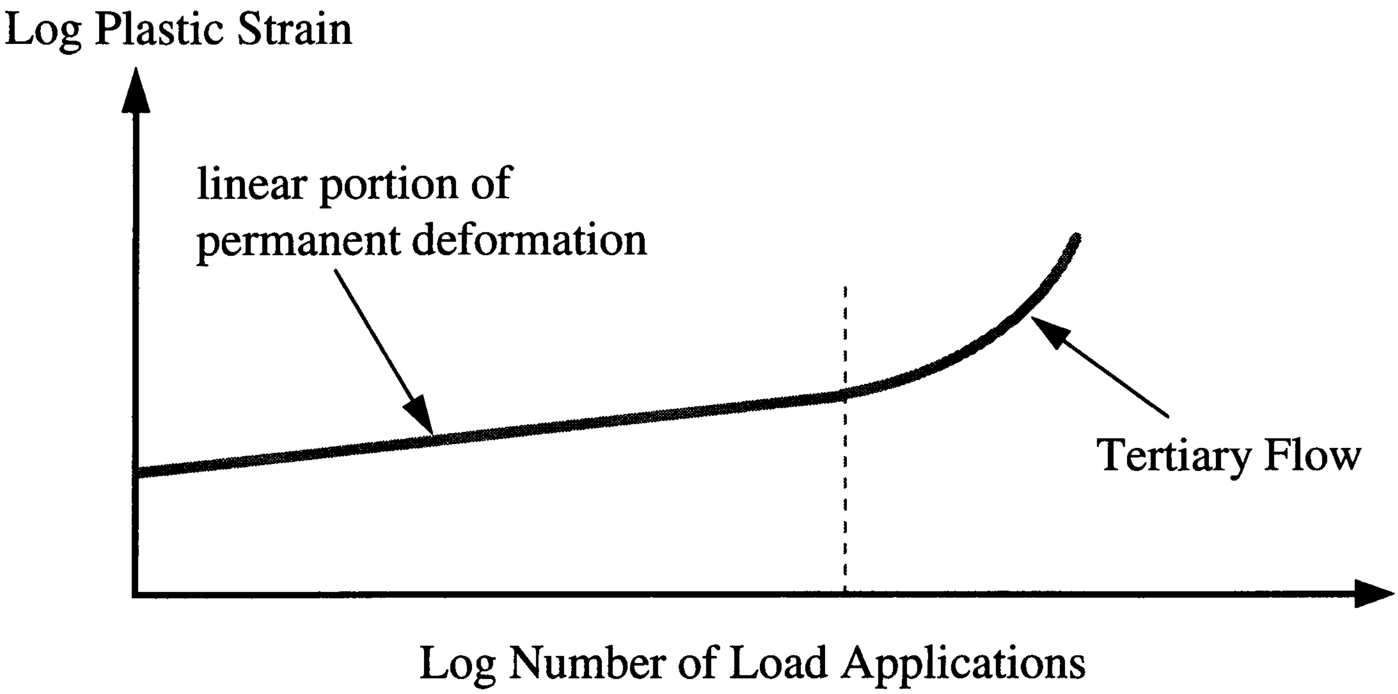


Figure 4-22. **The Development of Tertiary Creep or Flow as a Function of Repeated Shear Loading**

The general steps to performing a level 2 or level 3 mix design are:

1. Perform level 1 mix design.
2. Define the design life and expected traffic for the project where the mix will be used.
3. Select climatic region and weather files.
4. Select design level and define pavement cross section.
5. Select seasonal adjustment factors.
6. Select asphalt contents for analysis.
7. Perform repeated shear screening test for tertiary creep test.
8. Perform performance-based tests.
9. Run performance prediction models.
10. Determine acceptability and select job mix.

Step 1. Perform level 1 Mix Design. A level 1 mix design is done as discussed in chapter 3. Output from the design includes:

- selected asphalt binder grade;
- design asphalt binder content;
- selected aggregate materials; and
- design aggregate structure.

Steps 2-5. Define Project Where Mix is to be Used

2. The *design life* for the project is specified to establish the design traffic and to determine the number of years of weather data required for the performance models. Design traffic is defined as the expected number of ESALs per lane during the design life of the pavement. Within the performance models, the design number of ESALs is divided by the design life to obtain the number of ESALs per lane per year which will be simulated by the performance models. *The performance models do not escalate annual traffic to simulate traffic growth rate.*

3. The *climatic region* for the project is selected using the Environmental Effects Model map shown in figure 4-23. 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.

The *temperature files* which drive the environmental effects program are selected. A state-by-state database of weather data is available with the Superpave software. These weather stations have 10 years of historical daily minimum/maximum temperatures.

4. The *desired level of design* is selected. Independent selections can be made for low temperature cracking and permanent deformation/fatigue cracking. Options include level 3, level 2 or level 1. Level 1 indicates that no additional analysis is to be done. Hence, if low temperature cracking is of no interest to the mix designer, level 1 can be selected. Finally, fatigue cracking analysis can be excluded. Note that "Exclude Fatigue" must be set to "Y" in the Superpave software if the mix design is an overlay of existing asphalt concrete or portland cement concrete. Similarly, if fatigue cracking is not a concern for new construction, it can be eliminated.

   The *pavement cross section* in which the mix is to be located is defined. The entire cross section can include up to seven pavement layers including the subgrade. A maximum of two new asphalt layers may be used.

5. The *seasonal adjustment factors* are 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 freeze-thaw weakening, desiccation, etc., can be simulated by using monthly adjustment factors.

Step 6. Select Asphalt Binder Contents for Analysis. Performance predictions 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 (design asphalt content). High asphalt content is the percent asphalt which produces 3 percent air voids at the design number of gyrations. Low asphalt content is the percent which produces 6 percent air voids.

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.

Step 7. Perform Repeated Shear Screening Test. The repeated shear screening test is performed as discussed in section 4.6 at the highest selected asphalt content. If plastic flow occurs, redesign of the mix must be considered.

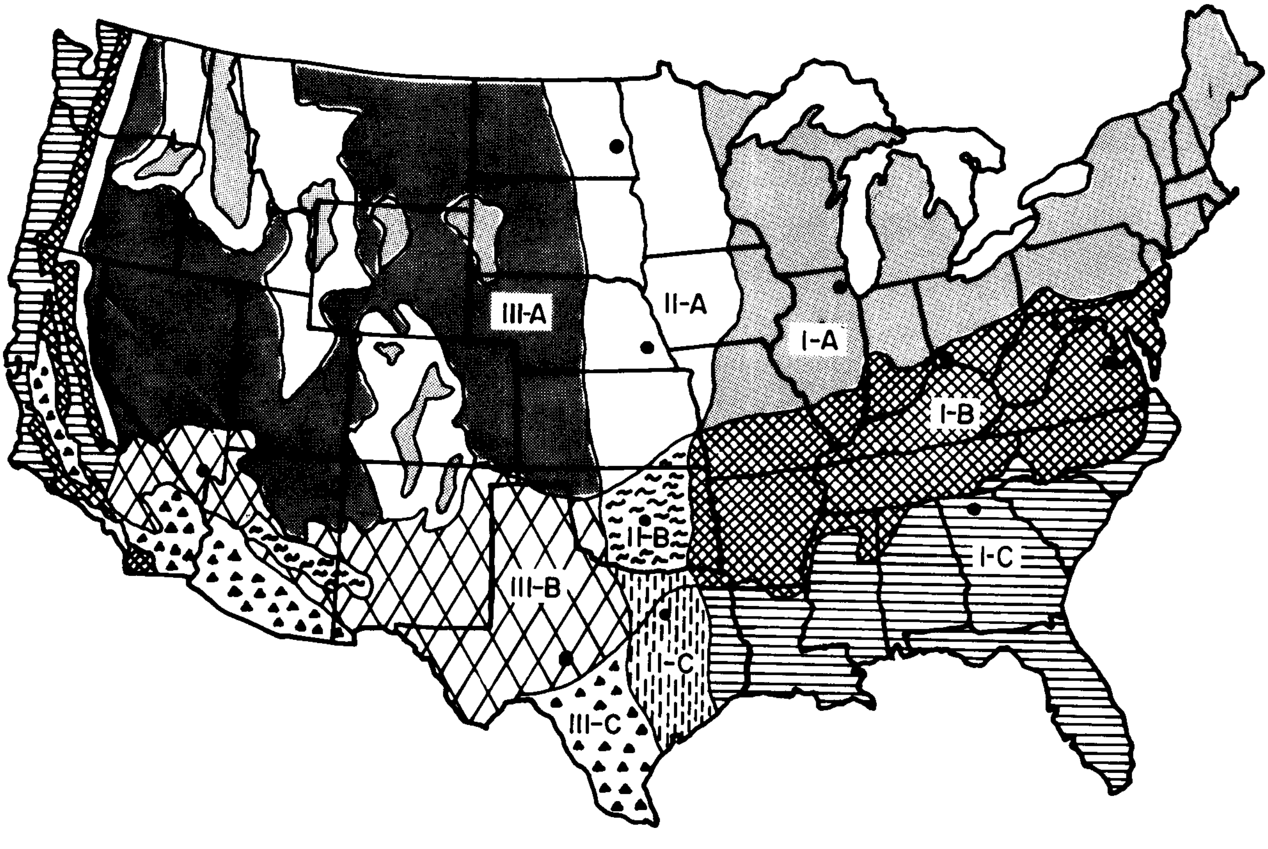


Figure 4-23. FHWA Environmental Effects Model Map of U.S. Climatic Regions

Step 8. Perform Performance-Based Tests. A list of performance-based tests and required information is provided by the Superpave software based on design level. Included on the list is the layer number, the test type, the test temperature, asphalt content and test data file name.

Step 9. Run Performance Prediction Models. The performance models are run using data files obtained from the required performance-based tests. The Superpave performance models operate in a batch mode under the control of the Superpave software shell.

Step 10. Determine Acceptability and Select Job Mix. Predicted performance levels are compared to agency specification values. The mix design is selected which meets the requirements.

Plots of predicted performance versus time (figures 4-24, 4-25 and 4-26) are used to select a mix that offers the desired level of performance. In these figures, materials A, B, and C may be three entirely different combinations of materials, or the same aggregate gradation prepared at three asphalt contents. The test methods are suited to evaluating the effect on performance of aggregate types and proportions, asphalt modifiers, or any other hot mix asphalt ingredient or characteristic.

For the materials represented in figures 4-23, 4-24, and 4-25, no material meets all the distress criteria at the design number of ESALs. Both materials A and B meet the rutting criterion, but fail the cracking criteria. If distress such as fatigue and low temperature cracking are of primary importance, material C would be the clear choice.

Consider the case when materials A, B, and C represent the same aggregate blend with varying asphalt content; material A has the lowest asphalt content and material C the highest. Material B has a middle value of asphalt content. In this case, the performance prediction would be considered a *design* procedure and three additional design plots would be useful (figure 4-27). These design plots define the range of asphalt contents meeting performance standards. In this specific example, an asphalt content approximately two-thirds between B and C would optimize pavement performance. This type of information would be useful too in selecting the optimum asphalt content as well as establishing job control tolerances.

4.8 Field Control of Hot Mix Asphalt

The Superpave mix designs system extends beyond the scope of existing mix design systems. The Superpave method is the first mix design system to integrate elements of field control into the mix design system.

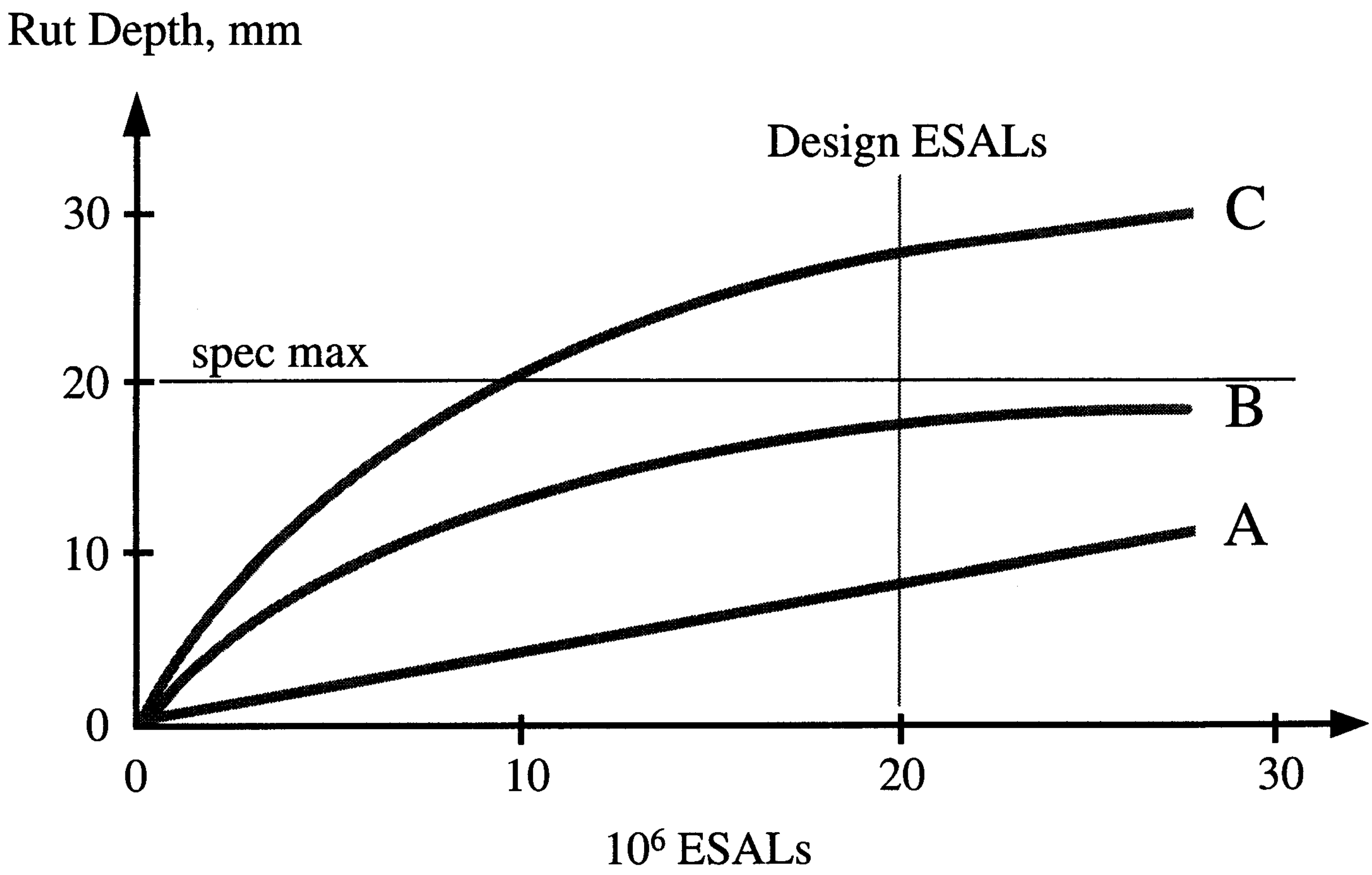


Figure 4-24. Predicted Development of Rut Depth Versus Number of ESALs

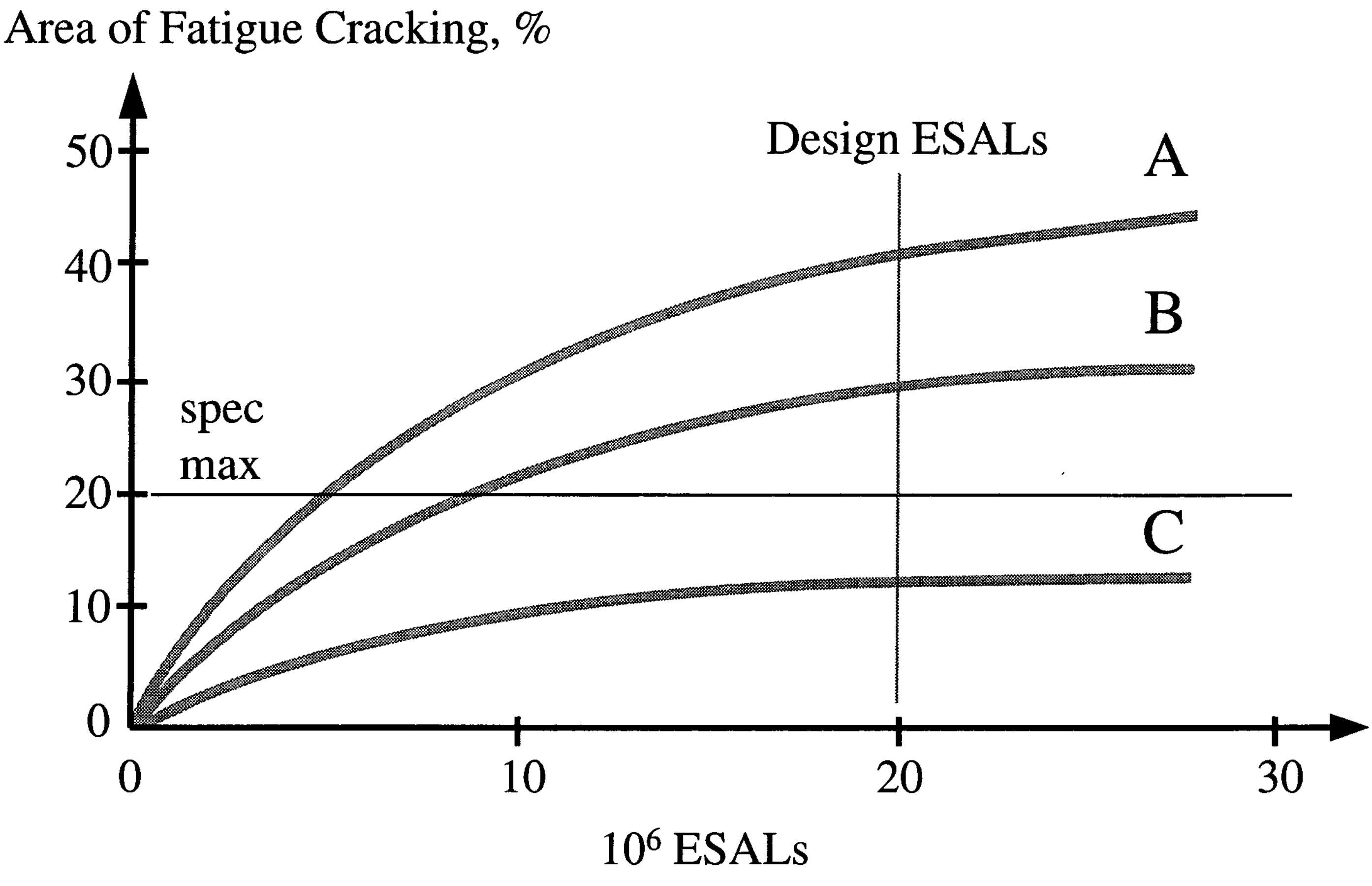


Figure 4-25. Predicted Development of Area of Fatigue Cracking Versus Number of ESALs

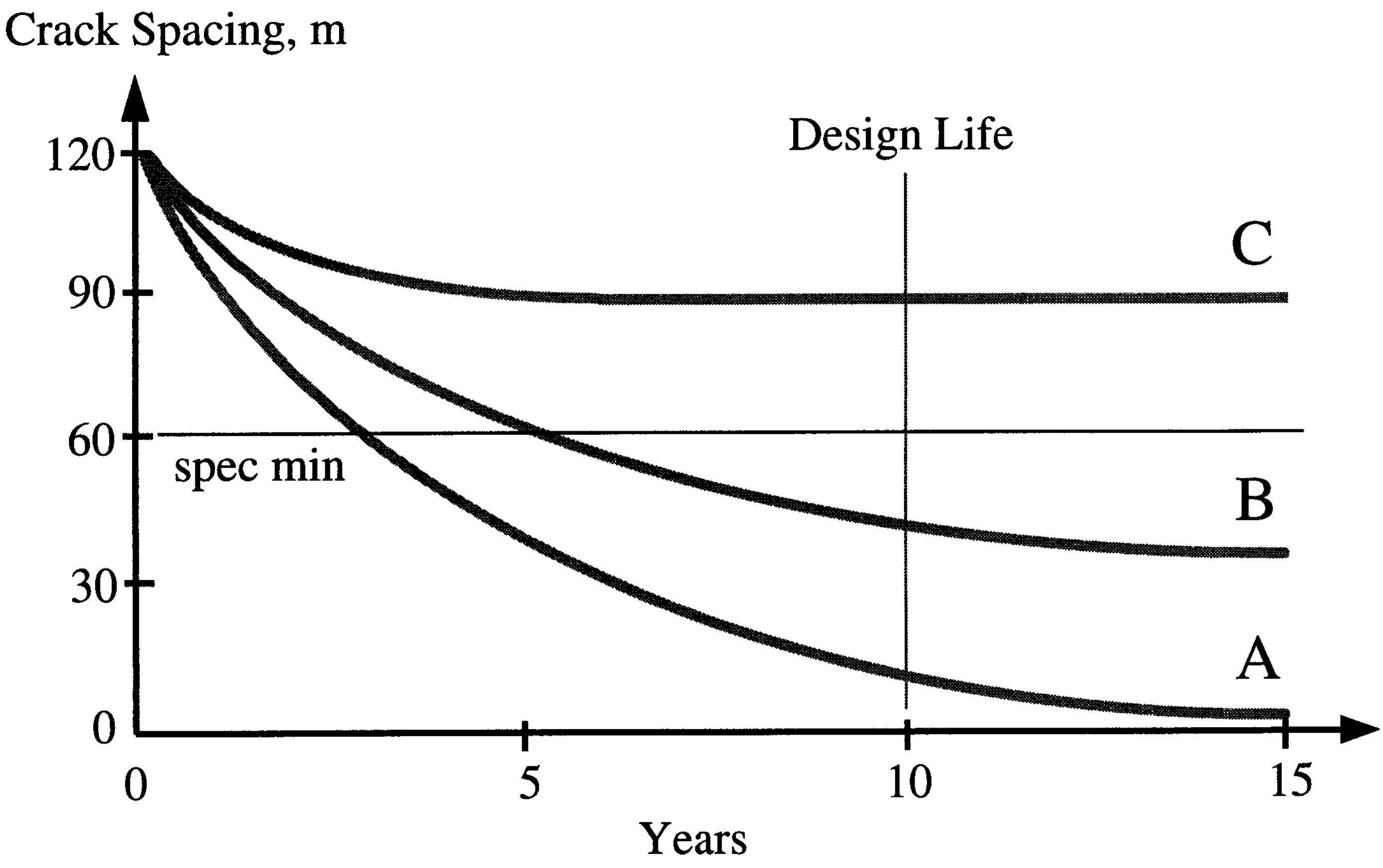


Figure 4-26. Predicted Development of Low Temperature Crack Spacing Versus Time

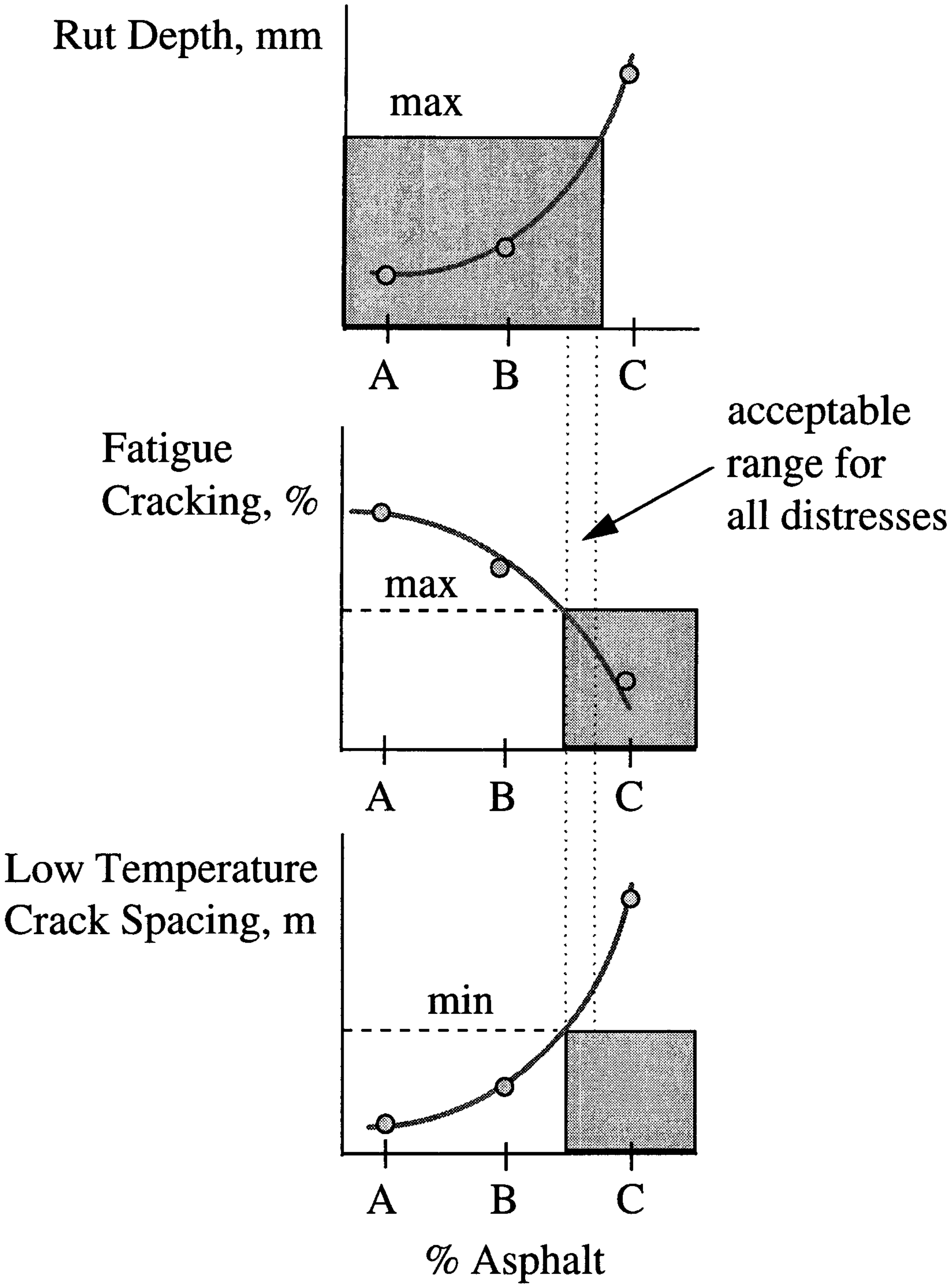


Figure 4-27 Selection of an Acceptable Range of Asphalt Content to Minimize the Development of Three Pavement Distresses

Currently, field control of hot-mix asphalt construction is typically specified by the highway agency. Existing field control systems vary greatly from mix design validation to limited material proportion control. The Superpave method formalizes field control systems by incorporating a selection of tests and tools to validate the mix design in the field. As such, the Superpave method provides components that can be incorporated into an agency-defined Quality Control/Quality Assurance system.

Four general levels of field control are available in the Superpave method:

1. gyratory compaction control;
2. volumetric property control;
3. performance-based property control; and
4. in situ pavement property control.

4.8.1 Gyratory Compaction Control

Gyratory compaction control is achieved by compacting mix samples and measuring the bulk density of the sample after the design number of gyrations. If the type of aggregate and asphalt binder, aggregate gradation, amount of each aggregate and asphalt binder content do not change, then the density should remain constant. A change in the type of materials or the amount will cause a change in density.

This approach minimizes the amount of testing required for quality control by the agency or contractors. Periodically, or if a change in density is detected, it will be necessary to determine the volumetric properties and/or the performance properties as measured by the frequency sweep and simple shear tests at constant height. Information obtained from these two performance tests will provide an estimate of the amount of rutting which can be expected due to the changes in the mix. If deemed necessary, however, a more detailed level 3 analysis could be performed on mixtures or specimens sent to a central laboratory.

4.8.2 Volumetric Property Control

Volumetric property control is based on confirming mix properties from a level 1 mix design on plant-mixed material. Hot mix sampled from plant production is compacted in the Superpave gyratory compactor. Specification values for air voids, voids in mineral aggregates, and voids filled with asphalt should be met at the design number of gyrations. Density at N_{init} and N_{max} should meet specification values. Aggregate properties as well as gradation and asphalt content can also be used.

Volumetric property controls include:

- asphalt content;
- gradation;
- coarse aggregate angularity;
- fine aggregate angularity;
- clay content;
- elongated particles;
- deleterious materials;
- percent air voids;
- percent voids in mineral aggregate (VMA); and
- percent voids filled with asphalt (VFA).

Asphalt content can be monitored by:

- solvent extraction;
- nuclear asphalt gauge;
- plant meter readings; and
- maximum (Rice) theoretical specific gravity determination.

Gradation can be monitored by sieve analysis using:

- extracted aggregate; and
- aggregate cold feed sampling.

Percent air voids, VMA, and VFA are measured on plant mix samples compacted to the design number of gyrations with the Superpave gyratory compactor. The air voids are calculated using the bulk specific gravity of the compacted specimen. The maximum theoretical specific gravity is measured on a companion sample.

VMA is calculated using the compacted specimen bulk specific gravity, and the aggregate bulk specific gravity. The VFA is calculated using the air voids and VMA for that specimen.

Applicable tests for volumetric property control include a subset of the following possible tests:

- asphalt content by solvent extraction;
- sieve analysis of extracted aggregate;
- fractured faces;
- fine aggregate angularity;
- elongated particles;
- sand equivalent;
- deleterious materials;

- asphalt content by nuclear gauge;
- asphalt content by plant meter readings;
- asphalt content by maximum theoretical specific gravity;
- sieve analysis of cold feed belt samples;
- gyratory compaction of specimen;
- compacted specimen bulk specific gravity;
- maximum theoretical specific gravity; and
- aggregate bulk specific gravity.

4.8.3 Performance-Based Property Control

The objective of performance-based property control is to confirm that the performance-based properties which were used to predict acceptable performance during the mix design are being achieved during construction. Conceptually the Superpave method can accommodate the entire battery of performance-based tests used during mix design. In reality, limitations regarding portability of mix design test equipment and length of testing time render complete verification of performance predictions impractical.

Performance-based properties should be measured periodically or when the density or gyratory compacted specimens indicate a change in the mix. A subset of the performance-based tests can be conducted and values compared to the original mix design. The simple shear and frequency sweep at constant height tests will be used to monitor mix conformance to design and to estimate the amount of rutting which can be expected due to a mix variable.

Performance-based properties would be measured using samples of plant mix material compacted with the Superpave gyratory compactor.

4.8.4 In Situ Pavement Property Control

The objective of in situ pavement property control is to confirm that the in-place pavement has satisfactory binder content and air voids. This can be done non-destructively with nuclear gages, or through appropriate laboratory testing of pavement core specimens.

5

The Superpave Practice for Modifier Evaluation

5.1 Introduction

5.1.1 Objective and Purpose

The Superpave mix design system provides the means to evaluate proposed modifiers added to the asphalt on to the mix by measuring performance properties using the performance based tests. In the case of binders (and, to a lesser extent, mixtures) *the desired grade of material for the pavement temperatures and traffic is specified by the user agency; the method of achieving the necessary properties is left to the supplier.* Thus, many current practices for the specification and quality control of modified materials are no longer needed by user agencies. Nevertheless because the interest in and use of modifiers are increasing, a set of guidelines has been prepared, principally for the use of material vendors and suppliers.

The Superpave practice for modifier evaluation (AASHTO Provisional Practice PP5) provides the means to:

- pinpoint the need for modifier use during the mix design process;
- estimate the performance capability of modified asphalt binders and paving mixes under specific climatic and traffic conditions;
- perform simple cost comparisons of modified versus unmodified asphalt binders and paving mixes over extended periods of service; and
- suggest an appropriate modifier for a given situation.

5.1.2 Significance and Use

The Superpave specifications and test methods encompass and apply equally to unmodified and modified asphalt binders and paving mixes. This transparency was achieved because all test methods and equipment were checked with a variety of modified materials, and because the specifications and test methods are applicable to all current types of modifiers. The applicability of properties and limits contained in the Superpave binder and mixture specifications to modified asphalts was verified through blind testing of a variety of different materials for which field performance data were available (Cominsky, Harrigan, and Leahy 1994; Leahy, Harrigan, and Von Quintus, 1994).

Thus, adoption of the Superpave system automatically provides an agency with the opportunity to use many types of modifiers in construction without relying on special requirements, qualified materials lists, unique equipment or test methods. In these circumstances, a distinct practice for modifier evaluation is unnecessary in the Superpave system since its specifications, test methods and mix design system can be applied to any asphalt material, without regard for the details of modification. Decisions on the use of a modifier can be made by weighing performance estimates against projected cost.

The Superpave system includes a separate practice for modifier evaluation (AASHTO PP5) that provides two additional capabilities to material suppliers:

- special methods and procedures to facilitate the routine use of modifiers in mix design; and
- a complete scheme for the evaluation and classification of new modifiers.

In the first instance, the practice for modifier evaluation is a recognition of the fact that, while the use of modifiers presents special opportunities, it may sometimes bring about special concerns. For example, many modifiers are dispersed into asphalt cement under conditions of high shear and elevated temperature, forming blends that will separate over time. Failure to measure the *storage stability* of the blended binder could lead to major construction and performance problems. Storage stability is not a criterion in the Superpave binder specification but is included in the practice for modifier evaluation.

In the second instance, material suppliers have long had a need for a complete, comprehensive method of *objectively* classifying and rating new modifiers. The Superpave practice for modifier evaluation provides a complete procedure, independent of the mix design process, for:

- estimating the effect of a new modifier on asphalt pavement performance;
- judging the compatibility of modifiers and asphalt cements; and
- comparing the performance characteristics of different classes of modifiers—for example, recycled tire rubber (CRM) versus styrene-butadiene-styrene (SBS) block copolymer—without the need for extended field tests.

5.1.3 Caveats and Cautions

The Superpave specifications, test methods and equipment were initially developed through research on 42 conventional asphalt binders and 11 aggregates in the Materials Reference Library. They were then evaluated with a wide variety of modified asphalt binders and paving mixes in the Materials Reference Library and adapted as necessary to insure their *transparency* to both unmodified and modified materials.

This process established the applicability of the Superpave system to binders and paving mixes containing examples of the main classes of asphalt modifiers. These modifiers include anti-stripping agents, various families of polymers, rubber latexes, reclaimed tire rubber, fibers, and natural asphalts.

The user of this practice is cautioned that the population of modifiers evaluated during the development of the Superpave system was of limited size and composed exclusively of materials commercially available from 1989 through 1991. New modifiers which are members of a novel class of materials should be carefully evaluated before use with Superpave. This caution applies especially to the screening for asphalt compatibility, determination of storage stability, and safety issues.

5.1.4 Summary of the Practice

The Superpave practice for modifier evaluation provides a complete procedure for the measurement of the performance characteristics of modified asphalt binders and paving mixes for hot mix asphalt pavements. It uses performance-based specifications and laboratory binder and mixture tests, and the performance models incorporated in the Superpave software.

Materials can be evaluated as a single component and/or as a multiphase system in the final paving mix produced for roadway placement. The same performance criteria are used for both unmodified and modified materials.

The practice provides guidance, or specific test methods, for special properties or characteristics of modifiers or modified asphalt binders such as purity, toxicity, storage stability, and compatibility.

The practice can be used as an integral part of the overall Superpave mix design system, or alone, to compare the effectiveness of different modifiers, to evaluate novel materials, or to relate the expected benefits of a modified system to its incremental costs.

5.2 Materials Selection and Characterization

The Superpave system addresses the design of paving mixes to minimize permanent deformation, fatigue cracking and low-temperature cracking for a particular set of climatic, traffic and structural conditions. The effects of asphalt aging and moisture susceptibility on paving mix performance are explicitly considered.

Materials selection criteria for asphalt binders and aggregates in the Superpave system are discussed in chapters 2 and 3 of this report. The large majority of commercially-available modifiers are designed as additives to asphalt cement. Thus, the Superpave asphalt binder specification is a primary source of guidance for selection of an appropriate modifier. However, the Superpave mix design system (Cominsky et al. 1994) and its specification and related test methods provide critical information necessary to judge the efficacy of modifiers that are intended to improve the properties of as aggregate in HMA (such as hydrated lime) or that are blended into the paving mix during HMA production (such as carbon black).

Figures 5-1 and 5-2 present the distribution of the 42 unmodified asphalt binders in the SHRP Materials Reference Library within the high and low temperature performance grade ranges defined by the Superpave asphalt binder specification (chapter 2). Within the high temperature range, only a very small percentage of unmodified asphalt binders are adequate for use in areas of the United States where the PG-70 grades are needed. Within the low temperature range, the available unmodified asphalt binders are satisfactory for preventing the development of low-temperature cracking only in those areas of the United States and Canada where winter pavement temperatures do not fall below −28°C (a PG-28 grade). *If the Superpave software recommends the use of a binder performance grade outside of these ranges, an appropriate modified asphalt binder must immediately be considered by the material supplier or HMA contractor.*

5.2.1 Modifiers

The effect of adding a variety of typical modifiers to unmodified asphalt binders is illustrated in tables 5-1, 5-2 and 5-3.

Laboratory and field test results (Coplantz et al. 1994; AASHTO 1991; Wardlaw and Schuler 1992) suggest that the use of asphalt binders containing polymers that exhibit rubber-like elasticity may reduce the susceptibility of paving mixes to permanent deformation at high pavement temperatures. For example, table 5-1 shows that adding either EVA or polyethylene increases the high temperature performance range of an asphalt binder from PG-58 to PG-64 or -70, permitting its use in appreciably hotter climates. Reacting SBS with unmodified asphalt binder also accomplishes a two-grade increase in high temperature performance.

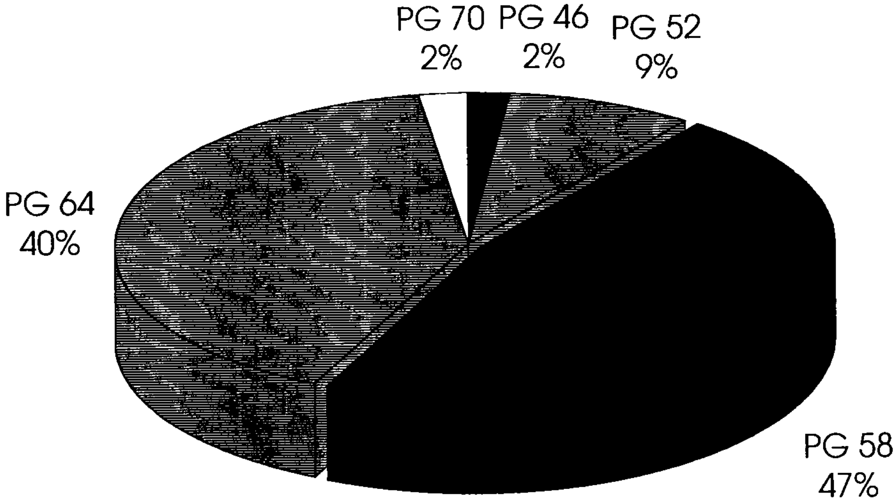


Figure 5-1. Distribution of Unmodified Asphalt Binders in the SHRP Materials Reference Library Within the High Temperature Performance Grades (AASHTO MP1)

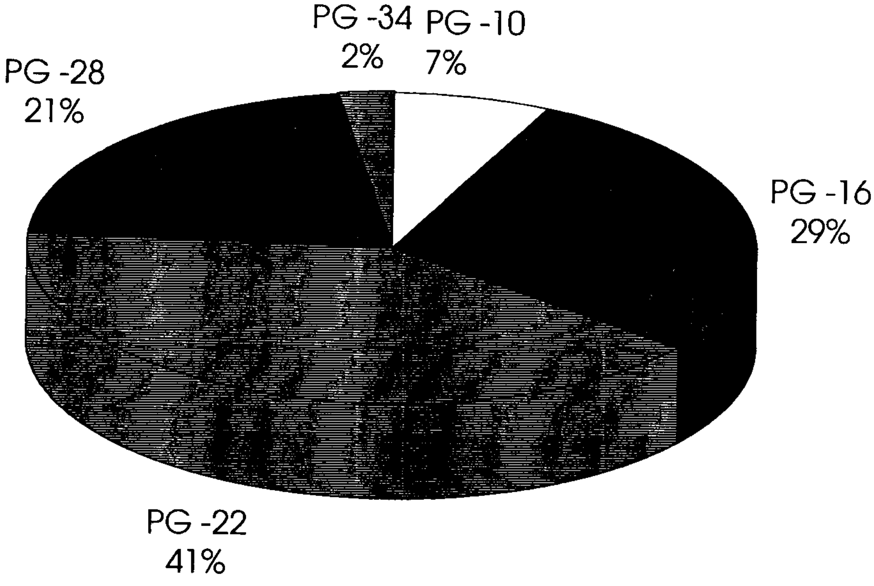


Figure 5-2. Distribution of Unmodified Asphalt Binders in the SHRP Materials Reference Library Within the Low Temperature Performance Grades (AASHTO MP1)

The literature also suggests that more amorphous, less crystalline polymers are preferable when the primary concern is the reduction of fatigue or low-temperature cracking. In Table 5-2, the addition of an SBR latex product provided the largest effect on the resistance to fatigue cracking, as measured by the largest *decrease* in the temperature (-6°C) at which the stiffness parameter, $G^{*}\sin\delta$, reaches 5,000 kPa, the specification limit. A temperature change of this magnitude is equivalent to a gain of nearly two performance grades at intermediate temperatures.

The results in table 5-3 show how the same series of asphalt modifiers affect the ability of the asphalt binder to resist low temperature cracking. The low temperature performance grade of an asphalt binder improves as the creep stiffness measured in the bending beam rheometer decreases, and the slope, *m*, of the log creep stiffness versus log time curve increases. Reclaimed tire rubber provided the largest positive changes in both the stiffness and the slope for an unaged binder.

For modified binders aged in the pressure aging vessel (PAV), as required in the Superpave binder specification, the results are less dramatic. Both EVA and an organic filler material have a positive effect on both stiffness and slope, with EVA addition improving the low temperature performance of the asphalt binder by one grade, from PG-22 to PG-28. The addition of a latex rubber and the reaction of an SBS with an asphalt cement have mixed results, improving the creep stiffness but having relatively little effect on the slope.

Tables 5-1, 5-2 and 5-3 also demonstrate that the modifier concentration of the asphalt binder has a substantial effect upon its performance characteristics. The addition of 5 percent EVA to a base PG 58-22 asphalt cement improves both the high and low temperature performance by one grade, to a PG 64-28, but a concentration of 2 percent EVA is sufficient only to change the low temperature performance grade, yielding a PG 58-28 modified asphalt binder.

Trends drawn from these illustrative results should be used with caution. They show the effect of modifier addition or reaction *alone*. This generally results in better high, intermediate *or* low temperature performance, but never all three, and two of the three infrequently. In practice, however, *both the modifier and the performance grade of the base asphalt cement can be varied* to achieve a required performance grade. For example, in a situation where better high and low temperature performance is needed than is provided by an unmodified asphalt binder, a modifier selected to improve high temperature performance can be combined with a base asphalt cement with good low temperature performance to provide a modified binder that improves upon the unmodified binder at both extremes of temperature.

Another practical strategy is to use more than one modifier. For example, a polymer providing improved high temperature performance could be combined with a base asphalt cement and with a second modifier with good low temperature behavior to expand the performance envelope at both temperature extremes.

Table 5-1. Effect of Modifier Addition on Resistance to Permanent Deformation (As Characterized by Dynamic Shear Rheometer Determination of $G^*/\sin\delta$ at High Temperature)

Grade of Unmodified Asphalt Cement	Modifier	Test Temperature (°C)	Aging Method	Ratio of $G^*/\sin\delta$ (Modified/Unmodified)	Superpave High Temperature Performance Grade	
					Unmodified	Modified
AC-20	Cellulose fibers	65	TFO[1]	1.2	-	-
150-200	EVA (2%)	65	TFO	0.9	58	58
150-200	EVA (5%)	65	TFO	3.0	58	64
AR-4000	Inorganic filler	45	Unaged	1.3	-	-
AC-30	Organic filler	60	Unaged	1.1	-	-
AC-20	Polyethylene	70	TFO	2.9	58	70
AC-20	Polyfunctional polyolefin	65	TFO	3.1	-	-
AC-30	Reclaimed tire rubber	45	Unaged	1.8	-	-
AR-4000	Reclaimed tire rubber	45	Unaged	1.2	-	-
AC-20	Reacted SBS	65	TFO	2.9	-	-
AC-20	Reacted SBS	70	TFO	3.8	58	70
AR-4000	SBS copolymer	60	Unaged	2.9	-	-

[1] Measurements made on residues aged in the thin film oven or rolling thin film oven.

Table 5-2. Effect of Modifier Addition on Resistance to Fatigue Cracking (As Characterized by Dynamic Shear Rheometer Determination of $G^{*}\sin\delta$ at Intermediate Temperatures)

Grade of Unmodified Asphalt Cement	Modifier	Test Temperature (°C)	Aging Method	Ratio of $G^{*}\sin\delta$ (Modified/Unmodified)	ΔT(°C) at $G^{*}\sin\delta = 5$ MPa (Modified/Unmodified)
AC-20	EVA	25	Recovered from Field Core	1.0	-4
150-200	EVA (2%)	20	PAV[1]	0.7	-2
150-200	EVA (5%)	20	PAV	0.7	-4
AC-20	Polyethylene	20	PAV	1.9	-
AC-20	Reacted SBS	20	PAV	0.8	-
AC-20	SBR Latex	25	Recovered from Field Core	0.6	-6

[1] Measurements made on residues aged in the pressure aging vessel (PAV), SHRP Method B-005.

Table 5-3. Effect of Modifier Addition on Resistance to Low-Temperature Cracking (As Characterized by Bending Beam Rheometer Determination of Creep Stiffness at Low Temperature)

Grade of Unmodified Asphalt Cement	Modifier	Test Temperature (°C)/Aging Method	Ratio of Creep Stiffness (Modified/Unmodified)	Ratio of Slope[1], m (Modified/Unmodified)	Superpave Low Temperature Performance Grade	
					Unmodified	Modified
AC-20	Cellulose fibers	-20/PAV[2]	1.1	1.0	-	-
150-200	EVA (2%)	-20/PAV	0.7	1.2	-22	-28
150-200	EVA (5%)	-20/PAV	0.6	1.1	-22	-28
AC-20	Latex	-15/PAV	0.9	1.0	-	-
AC-30	Organic filler	-15/PAV	0.6	1.1	-	-
AC-20	Polyfunctional Polyolefin	-20/PAV	1.1	0.8	-	-
AR-4000	Reclaimed tire rubber	-15/Unaged	0.2	1.4	-	-
AC-20	Reacted SBS	-20/PAV	0.7	0.9	-	-

[1] m is the slope of the log creep stiffness versus log time curve after 60 seconds' loading time in the bending beam rheometer.

[2] Measurements made on residues aged in the pressure aging vessel (PAV), SHRP Method B-005.

The Superpave modifier practice recommends the development of fact sheets to classify and categorize candidate modifiers for specific applications. Table 5-4 provides a guide for their development. Much of the information in the fact sheets will initially be available only from vendors, but as new modifiers are evaluated in the laboratory and used in field projects, the specifying agency will be able to incorporate its own performance data and other critical information.

Table 5-4. Modifier Selection and Characterization

Selection
- Target pavement distress(es)
- Effect on other performance areas
- Historical performance (laboratory and field)
- Health and safety data
- Handling and storage requirements
- Production procedures
- Construction (laydown) procedures
- Asphalt recommendations or requirements
- Aggregate recommendations or requirements

Characterization
- Physical properties
- Chemical properties
- Quality control properties
- Performance characteristics of modified asphalt binders and paving mixes

The Superpave system also encourages the user agency to transfer the selection of a specific modifier to the HMA contractor, requiring only that the modified asphalt binder meet the relevant binder specification criteria. The advantages of this approach to the specifying agency are twofold: it eliminates the need for modifier specifications or criteria; and it delegates the burden of selecting modifiers that are compatible with available asphalt cements, and that achieve the necessary performance levels, entirely to the HMA contractor and material suppliers. The specifying agency need only consider the quality control/quality assurance aspects of the selection.

5.2.2 Asphalt

The principal criterion used by a material supplier for selection of a base asphalt cement is compatibility with the modifier. This implies several considerations:

- In terms of chemical reactivity with asphalt cements, modifiers can vary from those that are completely inert to those which are intentionally reacted to achieve the desired performance.

Reactivity can be determined through specific chemical characterization techniques discussed in section 7.2 of the modifier evaluation practice (AASHTO PP5) or preferably, by measuring the change in the rheological properties of the modified binder over time.

From a practical standpoint, the preferable modifiers are chemically unreactive with asphalt cement or completely react for an intended purpose within a definite time period. The generation of reaction by-products, such as heat or gaseous compounds, will be scrutinized carefully by the material supplier to avoid serious safety and environmental problems.

- The storage stability of a modified asphalt binder refers to the tendency of the modifier to separate from the base asphalt cement over time when held at high temperature without agitation.

Chemically reacted modified asphalt binders should generally be stable, although they may be sensitive to damage by excessive heating.

Modified asphalt binders formed by the dispersion of an unreactive modifier in a base asphalt cement will exhibit varying levels of storage stability. The stability will be determined by the affinity of asphalt cement molecules to compounds on the surface of the modifier particles, and by the storage temperature.

Chemical characterization of the base asphalt cement by the material supplier may be helpful to guide formulation of stable modified binders. The separation tests in AASHTO PP5 provide a semi-quantitative measure of storage stability.

- Modified asphalt binders are subject to the same aging processes as occur for unmodified asphalt binders.

The chemical composition of the base asphalt cement determines its susceptibility to aging, i.e., irreversible physicochemical change resulting from loss of volatiles, oxidation, and, to a lesser extent, thermal degradation. Asphalt aging occurs both in the HMA production process and with time in the pavement.

Similarly, modified asphalt binders age during HMA production and pavement service. The precise degree of aging depends upon the chemical composition of the modifier as well as the characteristics of the base asphalt cement. For example, polymeric modifiers with saturated bonds resist thermal degradation, which reduces the performance characteristics of the modified binder over time to a far greater degree than similar polymers containing unsaturated bonds (Collins and Bouldin 1992).

The rolling thin film oven test and the pressure aging vessel test will assess the degree of aging expected for modified binders during HMA production and in long-term pavement service. These test methods were validated principally with unmodified asphalt binders. Test results for modified binders should be used carefully. For example, it has been found that the thin film oven test does not yield comparable results for sulfur-extended asphalt binders as for unmodified asphalts. The advice of modifier vendors on thermal and oxidative stability should also be considered in the selection process.

These three factors—reactivity, stability, and aging—make it imperative that the base asphalt cement used in the modified HMA production be *chemically identical* to that employed in the laboratory formulation or evaluation of the modified binder. This requires that the performance grade, crude oil slate, and refining process remain constant. Analytical techniques, such as ion exchange chromatography and size exclusion chromatography, can be used by the material supplier to confirm the similarity of base asphalt cements.

5.2.3 Aggregate

The Superpave system has no special requirements for aggregates used with modified asphalt binders. The net adsorption test (SHRP Method M-001, Harrigan et al. 1994) is not an accurate measure of the compatibility of *modified asphalt binders* and unmodified aggregate, since it does not account for differences in reactivity of the modifier and the base asphalt with the aggregate surface. In general, the behavior of modified HMA specimens in the Superpave aging and moisture susceptibility procedures and accelerated performance tests should be used to decide if changes in aggregate type, gradation, etc., would benefit the paving mix performance.

With the exception of treatment with hydrated lime slurry to reduce stripping, routine processes that modify aggregate to improve HMA performance are uncommon. The net adsorption test may be used to evaluate the compatibility of unmodified asphalt cement with *modified aggregates.*

5.3 Health and Safety Precautions

The types of materials commonly used to produce modified asphalt binders (Button 1992) are not considered extremely hazardous to handle because of toxicity or flammability. However, as discussed above, many are sensitive to heat and can thermally degrade to toxic or flammable byproducts. In this respect, the handling of modified asphalt binders exactly parallels that of unmodified asphalt binders: overheating or prolonged storage at high temperature must be avoided. In addition, susceptibility to chemical irritations, such as contact dermatitis, varies considerably from person to person. The proper level of protective clothing and equipment must be used to prevent worker contact with any modifier material.

When using a modifier, the specifying agency and/or the HMA contractor must carefully consult the Material Safety Data Sheet (MSDS) supplied with the modifier. The MSDS will present the *known* health and safety hazards associated with the material as well as precautions for its use. Review of the MSDS and consultation with the modifier vendor will allow users to develop an effective, practical plan to ensure worker health and safety. This plan must explicitly address the ramifications of the chemical reaction or blending of the modifier and base asphalt cement and the handling of the modified binder at the elevated temperatures used in HMA production.

5.4 Performance-Based Test Methods and Equipment

The Superpave system uses the same test methods and equipment for modified and unmodified materials.

5.4.1 Asphalt Binder Testing

Table 5-5 recapitulates the performance-based laboratory binder tests that are discussed in more detail in chapter 2. A wide range of modified asphalt binders were tested with these methods and equipment during the Superpave development and validation process in order to confirm that the methods are equally applicable to unmodified and modified binders.

Table 5-5. Performance-Based Laboratory Binder Tests

Tests	Measured Properties	Pavement Distress
Dynamic Shear Rheometer (DSR)	High Temperature Shear Stiffness	• Permanent Deformation • Fatigue Cracking
Bending Beam Rheometer (BBR)	Low Temperature Creep Stiffness	• Low Temperature Cracking
Direct Tension (DT)	Stress, Strain, and Energy to Failure	• Low Temperature Cracking
Rolling Thin Film Oven Test (RTFOT)	• Mass Loss • Shear and Creep Stiffness of Aged Residue	• Short-Term Aging
Pressure Aging Vessel Test (PAV)	Shear and Creep Stiffness of Aged Residue	• Long-Term Aging

The test temperatures used for the rheological and direct tension measurements in table 5-5 highlight differences in performance at service temperatures that arise from the use of modified binders. Moreover, the direct tension test is specifically included in the testing protocol because rheological measurements alone are not always sufficient to emphasize the improved strain-to-failure behavior demonstrated by some modified binders.

Both the rolling thin film oven test and the pressure aging vessel test are capable of simulating the aging in service of *most* modified binders. Vendors should be consulted to determine the likelihood that either of these procedures would give unreliable results for a particular modifier (e.g., sulfur-extended asphalt binder).

The Superpave practice for modifier evaluation also addresses several test methods unique to modified asphalt binders:

Homogeneity refers to the uniform distribution of the modifier throughout the modified asphalt binder. This can be monitored by the material supplier during binder and HMA production by periodic sampling of the binder and measurement of its rheological properties.

Storage stability refers to the rate at which the modifier separates from the base asphalt cement during unagitated storage at elevated temperatures. Storage stability affects the homogeneity of the modified asphalt binder.

Workability is a measure of the viscosity or stiffness of the modified binder at the temperature at which the production and laydown of hot mix asphalt take place. Extremely stiff binders can render asphalt pumps at hot mix asphalt plants inoperative or inaccurate, impede gravity-induced flow where required, or make it impossible to achieve a satisfactory level of pavement compaction.

5.4.2 Mixture Compaction

The Superpave mix design system uses the Superpave gyratory compactor. Compaction of modified paving mix specimens is conducted by the same procedure used for unmodified paving mix specimens. The suitability of this compactor was verified by SHRP for a wide range of common modifiers.

Care should be taken during the compaction process to confirm that a satisfactory level of compaction is achieved for modified binders that exhibit exceptionally high stiffness at typical mixture and compaction temperatures at a reasonable number of gyrations (typically 4 percent air voids at 90 to 110 gyrations). The workability test results will provide guidance to adjust the mixing and compaction temperatures to achieve satisfactory in-place air voids.

5.4.3 Mixture Testing

Table 5-6 recapitulates the performance-based laboratory mixture tests that are discussed in earlier chapters of this report.

Table 5-6. Performance-Based Laboratory Mixture Tests

Pavement Distress	Equipment & Tests	Measurements
Permanent Deformation	Shear Test Device: • Uniaxial Strain Test • Volumetric Test • Simple Shear Test at Constant Height • Frequency Sweep at Constant Height • Repetitive Shear Test at Constant Stress Ratio • Repetitive Shear Test at Constant Height (optional)	• Dilatancy • Damage Accumulation in Repetitive Shear • Stiffening under Confining Stress • Shear Modulus and Phase Angle
Low Temperature Cracking	Indirect Tensile Test Device: • Indirect Tensile Creep Test • Indirect Tensile Strength Test	• Creep Compliance • Tensile Strength
Fatigue Cracking	Shear Test Device: • Frequency Sweep • Indirect Tensile Strength Test	• Shear Modulus • Phase Angle • Tensile Strength
Water Sensitivity	AASHTO T 283: • Tensile Strength in Dry and Wet Condition	• Change in Tensile Strength
Aging (Short Term)	Forced Draft Oven Aging of Loose Mix	• Change in Performance Properties
Aging (Long Term)	Forced Draft Oven Aging of Compacted Mix	• Change in Performance Properties

Modified paving mixes were tested with the methods and equipment presented in table 5-6 during the Superpave development and validation process. The methods and equipment were found to yield reasonable test results for modified paving mixes.

No full-scale field pavements were constructed with modified paving mixes for use in the field validation of Superpave. Therefore, initial validation of these methods for modified paving mixes was accomplished primarily by reference to historical data on the performance of similar materials in uncontrolled experiments.

5.5 The Superpave Mix Design System

Using the Superpave mix design system (Cominsky et al. 1994), paving mixes can be designed that will satisfy objective performance criteria dictated by the particular set of traffic, climatic, and structural factors to which the pavement will be exposed. The mix design system is *transparent* to the use of modifiers; its component test methods and specifications apply equally to modified as well as unmodified materials.

The mix design system encompasses five main steps:

1) materials selection
2) volumetric mixture design
3) performance-based mixture testing
4) performance estimates and comparison with specifications
5) field control

The practice for modifier evaluation interacts with the mix design system in several of these steps:

- During *materials selection*, the system guides the choice of an asphalt binder with a performance grade that will satisfy performance criteria over the entire range of pavement design temperatures. Experience indicates that only modified asphalt binders will satisfy the specification requirements of several performance grades intended for use in very hot or very cold climates.

- When the *pavement performance of the trial design is estimated and compared with the specifications* through the use of the performance prediction models in the Superpave software, the trial design may be found lacking in one or more performance areas. One possible response might be to reexamine the materials selected and evaluate whether a modified asphalt binder would bring the predicted performance up to satisfactory levels.

- When modified paving mixes are used, *field control* procedures may include special sampling and testing requirements, e.g., binder homogeneity and binder storage stability.

5.6 Possible Applications of the Superpave Practice for Modifier Evaluation

5.6.1 Pinpoint the need for modifier use during the mix design process.

As discussed in previous sections, this is an inherent function of the Superpave mix design system. In this application, specific use of the practice for modifier evaluation is not required except to provide specialized information relevant to modifier handling, storage and safety.

5.6.2 Estimate the performance capability of modified asphalt under specific climatic and traffic conditions.

This is another inherent function of the Superpave mix design system. Specific use of the practice for modifier evaluation is *not* required.

5.6.3 Perform simple cost comparisons of modified versus unmodified asphalt materials over extended periods of service.

This application is accomplished with AASHTO PP5. Suppose that a specifying agency wished to estimate the cost-benefit ratio of using a hypothetical polymer modifier to reduce permanent deformation. Using the practice, it would follow these steps:

1. Select an unmodified mix design with which the agency has pavement performance experience.

2. Prepare paving mix specimens with both the unmodified asphalt binder and the polymer-modified binder at the same binder content and volumetric properties.

   Note: Some modifiers may require adjustments in the mix design parameters (asphalt content or gradation). In those instance, the material supplier's recommendations should be followed.

3. Test both sets of specimens in the simple shear test device; determine damage accumulation in repetitive shear, dilatancy, and stiffening under confining stress for each paving mix.

4. Using the Superpave software with the Superpave shear test results, estimate permanent deformation over a service life of the agency's choosing, e.g., 15 years for pavements constructed with each paving mix.

5. Estimate the cost-benefit of using the polymer-modified paving mix in place of the unmodified paving mix using the first costs of the hot mix asphalts. The exact details of this calculation will depend upon agency policies, e.g. whether maintenance and rehabilitation is scheduled on a periodic basis or triggered by a specific level of rutting.

5.6.4 Choose an appropriate modifier for a given situation.

Asphalt modifiers are produced to address specific types of pavement distress, particularly permanent deformation, low-temperature cracking and moisture sensitivity. This application of the practice for modifier evaluation makes use of the Superpave binder and paving mix tests, and the specification criteria which they support, to provide objective, performance-based measures against which different materials may be compared.

For example, if two modifiers are marketed to reduce the development of rutting, their rheological properties (as measured with the dynamic shear rheometer) can be compared at a realistic pavement temperature and contrasted with properties measured for the unmodified asphalt cement commonly used in the same circumstances. At any given pavement temperature, the binder with the highest value of $G^*/\sin\delta$ (see chapter 2) will make the greatest contribution to the rutting resistance of the pavement.

An even more stringent comparison can be made by preparing equivalent paving mixes with the two modified binders and the unmodified asphalt binder and testing them with the shear test device. The test results can be used as input data in the Superpave pavement performance prediction model for permanent deformation. This will yield quantitative estimates of the development of rutting with time for each of the binders.

5.6.5 Estimate the effect of a new modifier on asphalt pavement performance.

This application is addressed by use of the practice for modifier evaluation in the same way as discussed in the previous section. Predicted estimates of pavement performance, coupled with cost data, permit specifying agencies to identify modifiers that are cost-effective in any given pavement situation.

5.6.6 Judge the compatibility of modifiers and asphalt cements.

The practice for modifier evaluation identifies specific chemical and physical test procedures for materials suppliers to evaluate the compatibility of modifiers with asphalt cements.

5.6.7 Compare the performance characteristics of different classes of modifiers.

The *validated*, performance-based binder and mixture tests and performance prediction models in the Superpave system permit specifying agencies to assign any modifier to performance and cost classes without the need for costly and time-consuming field experiments. The examples in sections 5.6.3 and 5.6.4 suggest how this could be done on a systematic basis using the practice for modifier evaluation. Of course, an agency's field experience can be used to calibrate and support the conclusions drawn from the time-expedient laboratory analysis.

6

The Superpave Specification, Design, and Support Software

6.1 Introduction

The Superpave specification, design, and support software was developed for the final user of these research results: the mix designer. The intent is to provide the mix designer all the computational tools to perform a mix design using the Superpave mix design method.

The Superpave mix design system has three vertically integrated levels of mix design. Level 1 design is a volumetric mix design where aggregate characteristics and mixture volumetric properties, such as air voids and VMA, are the basis for the selection of gradation and asphalt binder content. Level 2 design includes volumetric design and key performance-based mixture tests from which performance is predicted. Level 3, the highest level, includes an expanded series of performance-based tests. A more rigorous prediction of performance is made in level 3.

Databases are a key component of the Superpave software. The mix designer is able to maintain information regarding both raw materials, such as aggregates and asphalt binders, and mix design results. Results include aggregate blending analysis, compacted specimen densification curves, performance-based test results, and performance predictions. Field verification testing, whether used by a contractor for quality control or by an agency for quality assurance, can be stored within the Superpave software. The software encompasses all aspects of mix design, from the time a mix is conceived as aggregate stockpiles and an asphalt binder to when it is in place on the roadway.

The Superpave software provides all the tools needed to perform all three levels of mix design. The software contains a weather database for selection of design temperature requirements. Data analysis sheets store raw test data, perform calculations, and save test results. The software interfaces with the performance-based tests to store results and provide input into performance prediction models. Likewise, Superpave software controls the performance prediction models and stores performance predictions.

The Superpave system uses field control tests to ensure that mixtures designed with the performance-based asphalt binder and asphalt mixture specification perform as designed. These tests measure gradation, asphalt content, and volumetric properties.

Field control tests identify the processes, procedures, and tests for validating the job mix formula, as well as day-to-day field control to assure production of a mix that will perform as desired. The procedures include the testing of unprocessed materials (aggregates) as well as plant processed materials (HMA) (chapter 4).

Recommended tests at the hot mix plant include determination of asphalt content, gradation, and volumetric properties. In-place mixture properties, such as air voids and level of compaction, are also recommended.

The Superpave software operates on a computer with an 80386 or later processor, VGA graphics and sufficient hard disk space. An 80486 processor provides the most effective performance.

6.2 Superpave Interaction

The Superpave software integrates all tools needed for paving mix design. Not all of the software is contained directly in Superpave program, however: some software is embedded; other programs are associated with the Superpave program (figure 6-1). Generally, the embedded and associated programs are independent, special-purpose software designed for interaction with the Superpave structure.

Associated software are stand-alone programs and do not require the Superpave software to function. For example, software programs that control testing machines run as stand-alone programs. Files generated by the associated software are accessed by the Superpave software for use in predicting performance of the paving mix. Associated software includes programs to run and acquire data from the performance tests.

Embedded software is accessed only through a Superpave software screen, and control is returned to the Superpave software when the specialized software is exited. Embedded software includes material property models which convert performance-based test data into material properties used in pavement performance prediction. The environmental effects model generates temperature files, which are used in performance prediction. The performance prediction models for load-associated and non-load distresses are also embedded in the Superpave software.

The Superpave software maintains all of the information required by a mix designer. This includes specifications for asphalt binder and asphalt paving mixes, weather information to determine environmental conditions, as well as all of the data analysis forms needed to perform the required mix design.

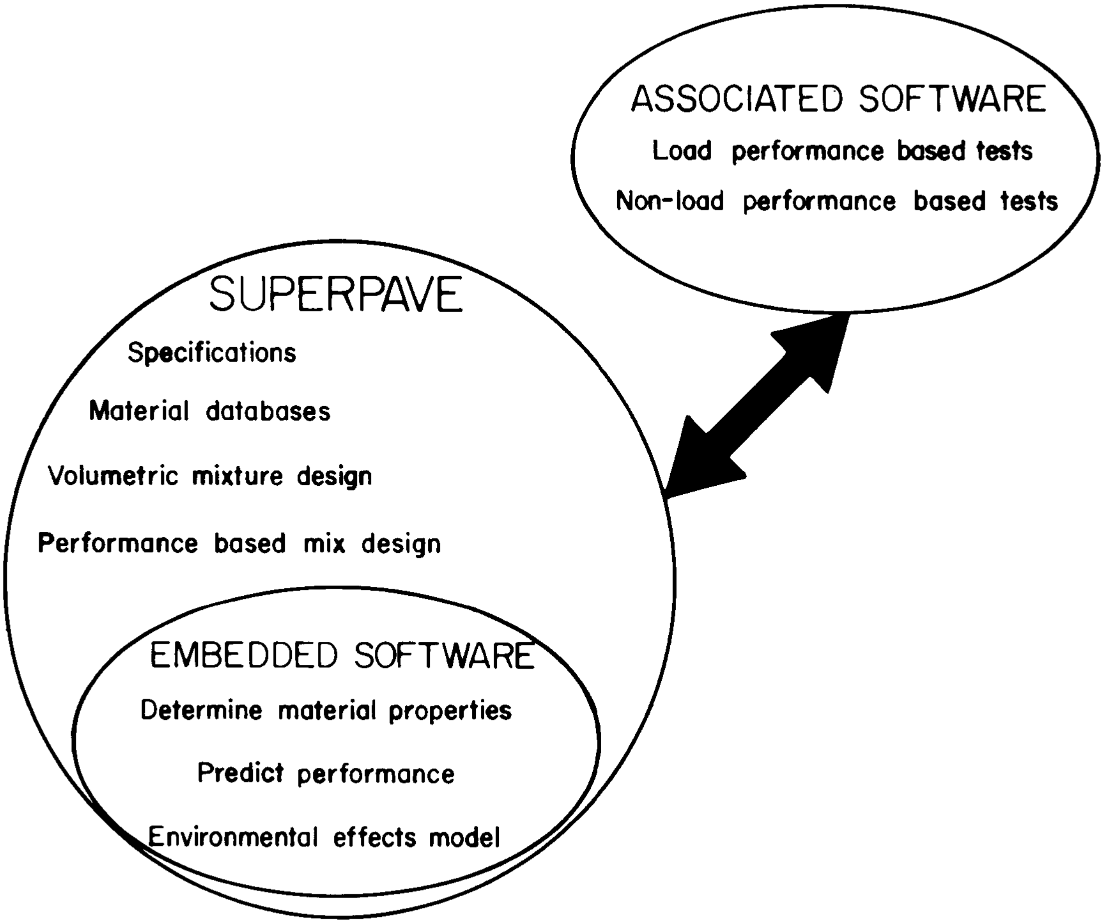


Figure 6-1. **Structure of the Superpave Specification, Mix Design and Support Software**

From the user's point of view, a significant portion of the software is devoted to user-defined databases of information, including asphalt binders, aggregates, mix designs, and construction history. Another portion of the software deals with specifications. The user has read-only access to the asphalt binder specifications, aggregate specifications, and environmental databases.

6.3 Superpave Menu Structure

The software is a stand-alone system using a windows-like user interface with drop-down menus. The system is designed for use with a mouse. Navigation through screens, opening and saving files, and routines such as plot and calculate are executed by pointing and clicking on appropriate buttons. The software can also be operated with function keys and arrow keys to perform file operations and execute commands.

The main menu is divided into the main areas of consideration during mix design (figure 6-2). Menus are structured as hierarchal options in which succeeding options are displayed as cascading menus. Options are displayed in drop-down lists. Menu options are numbered hierarchically, such as 1.1.3.0 (figure 6-3).

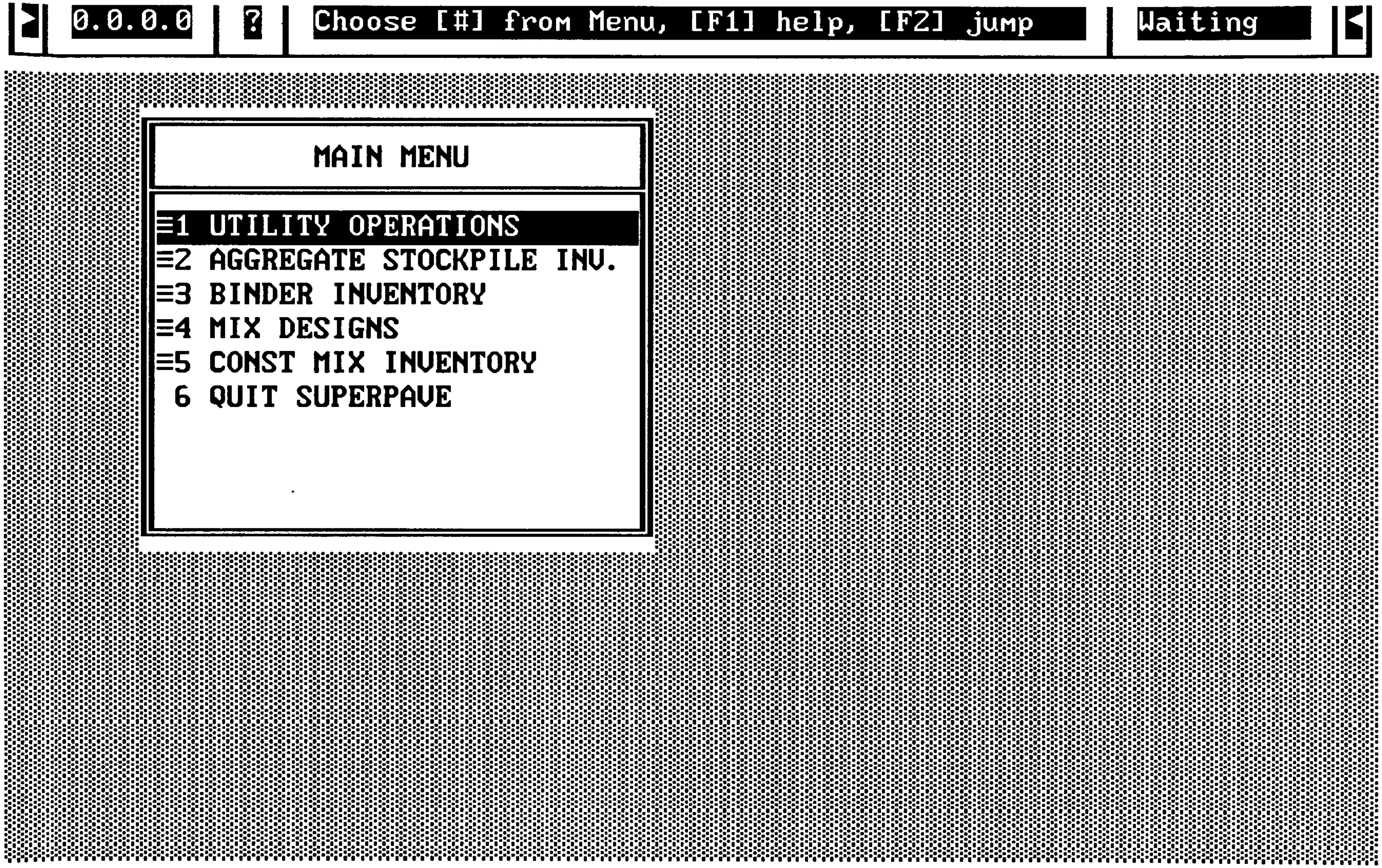
Option 1.1.3.0 refers to:

Option 1 on the main menu is Utility Operations.
Option 1 on the mix design menu is Consensus Standards.
Option 3 on the service conditions menu is Binder Specifications.
Option 0 on the environmental conditions menu is Modify Binder Grade.

6.4 Superpave Data Analysis Forms

The software has data analysis forms for routine tests. A data analysis form is analogous to a paper form used to record weights and measurements made during a test as well as the calculated test results.

In the Superpave software, weights, measurements, and results are recorded on the data analysis form. Results are displayed in the appropriate location as a part of the test method. Figure 6-4 shows part of a test screen for a compaction curve from the SHRP gyratory compactor. A field is shown for the maximum theoretical density, which is required as part of the compaction process. If the value of maximum theoretical density is known, the value is entered into the field. If a maximum theoretical density test must be done to obtain the value, the user can call up a test data sheet by selecting the upward-facing arrow. After filling in the appropriate weights, the maximum theoretical specific gravity is calculated and displayed on the compaction sheet. The data analysis sheet retains weight measurements and is visible only when the upward arrow is selected.



Choose [#] from Menu, [F1] help, [F2] jump

Figure 6-2. Superpave Specification, Mix Design and Support Software: Main Menu Screen

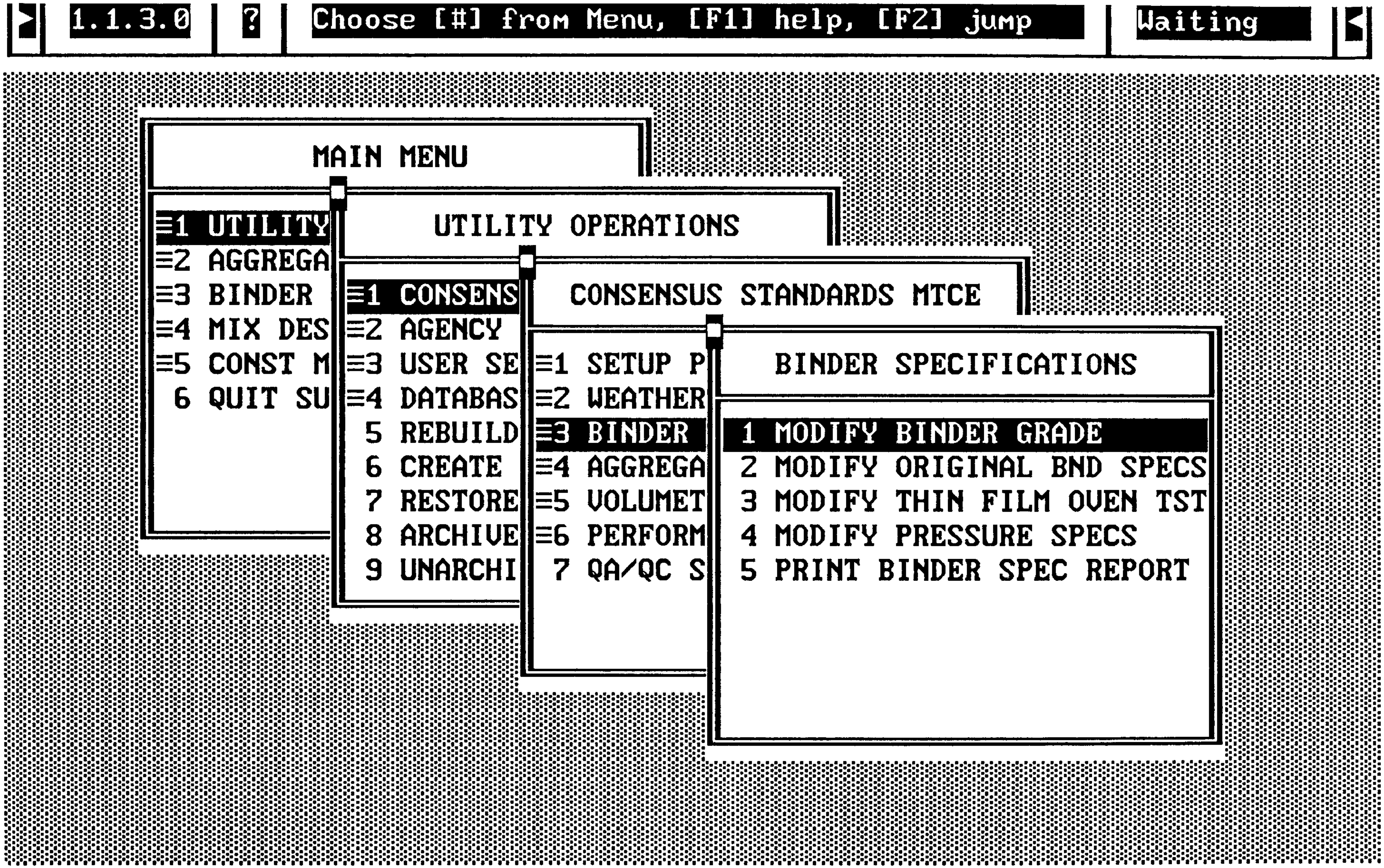
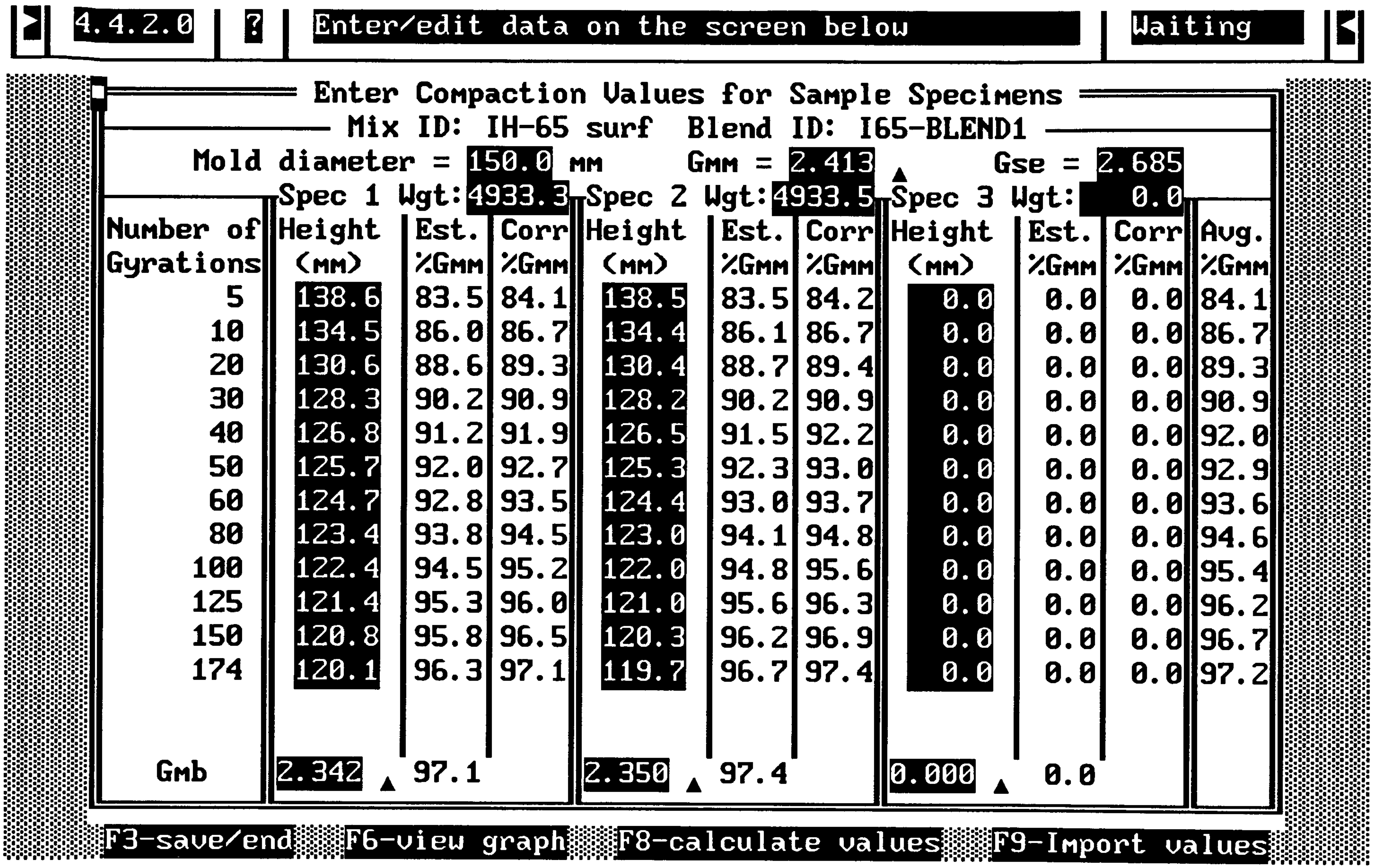


Figure 6-3. Superpave Specification, Mix Design and Support Software: Screen for Menu Option 1.1.3.0



Enter Compaction Values for Sample Specimens

Mix ID: IH-65 surf   Blend ID: I65-BLEND1

Mold diameter = 150.0 mm   Gmm = 2.413   Gse = 2.685

	Spec 1 Wgt: 4933.3			Spec 2 Wgt: 4933.5			Spec 3 Wgt: 0.0			
Number of Gyrations	Height (mm)	Est. %Gmm	Corr %Gmm	Height (mm)	Est. %Gmm	Corr %Gmm	Height (mm)	Est. %Gmm	Corr %Gmm	Avg. %Gmm
5	138.6	83.5	84.1	138.5	83.5	84.2	0.0	0.0	0.0	84.1
10	134.5	86.0	86.7	134.4	86.1	86.7	0.0	0.0	0.0	86.7
20	130.6	88.6	89.3	130.4	88.7	89.4	0.0	0.0	0.0	89.3
30	128.3	90.2	90.9	128.2	90.2	90.9	0.0	0.0	0.0	90.9
40	126.8	91.2	91.9	126.5	91.5	92.2	0.0	0.0	0.0	92.0
50	125.7	92.0	92.7	125.3	92.3	93.0	0.0	0.0	0.0	92.9
60	124.7	92.8	93.5	124.4	93.0	93.7	0.0	0.0	0.0	93.6
80	123.4	93.8	94.5	123.0	94.1	94.8	0.0	0.0	0.0	94.6
100	122.4	94.5	95.2	122.0	94.8	95.6	0.0	0.0	0.0	95.4
125	121.4	95.3	96.0	121.0	95.6	96.3	0.0	0.0	0.0	96.2
150	120.8	95.8	96.5	120.3	96.2	96.9	0.0	0.0	0.0	96.7
174	120.1	96.3	97.1	119.7	96.7	97.4	0.0	0.0	0.0	97.2
Gmb	2.342 ▲	97.1		2.350 ▲	97.4		0.000 ▲	0.0		

Figure 6-4. Superpave Specification, Mix Design and Support Software: Screen for Densification Curve From Gyratory Compaction

6.5 Types of Standards Stored in Superpave

The Superpave software contains two levels of standards: consensus standards and agency standards. Consensus standards cannot be changed without changing the mixture design method. For example, the gyratory compactor characteristics cannot be changed without changing the entire basis for the mix design method.

Agency standards are discretionary items that must be established by the policy of the specifying agency. For example, the level of reliability to be used when selecting design temperatures should be specified by the agency. Different agencies will specify different levels of risk. Another agency standard is the target level of performance. Agencies will specify how much rutting is allowable before the pavement condition is judged a failure. An agency may decide that 5 mm rutting is the maximum tolerable permanent deformation on an interstate highway; on a rural highway, 20 mm might be tolerable.

A partial list of consensus standards and agency standards is shown in table 6-1.

6.6 Asphalt Binder

The asphalt binder specification is stored within the software as a lookup table. The asphalt binder specification is used to categorize asphalt binders according to specification test results. The technician performs the specification tests at the prescribed temperatures and enters the results. The Superpave software checks the measured properties with required properties for conformance to the specification.

During mix design, the specification is used as a look-up table to determine the grade of asphalt binder required for a specific project. As part of the mix design, the designer will select high and low design pavement temperatures. These temperatures will be compared to temperatures in the specification to determine the grade of asphalt binder needed.

As noted in chapter 2, the asphalt binder specification tests are performed with a dynamic shear rheometer, a bending beam rheometer, and, if necessary, a direct tension device. Each of these tests is controlled by test software resident on a host computer attached to the respective testing device. To execute any of these tests, the operator must use the data collection and analysis software associated with the testing machine. When the test is completed, results may be saved within the Superpave software.

Table 6-1. Consensus Standards and Agency Standards for Superpave

Consensus Standards	Agency Standards
Aggregate Properties	Design Temperature Risk
• Gradation limits	• High temperature
• Coarse aggregate angularity	• Low temperature
• Fine aggregate angularity	Asphalt Binder Grade
• Clay content	• By geographic zone
• Thin elongated particles	Acceptable Performance Limits
Densification Curve Evaluation	• Permanent deformation
• Design gyrations	• Fatigue cracking
• N_{init} gyrations	• Low temperature cracking
• N_{max} gyrations	Aggregate Properties
Volumetric Proportions	• Nominal maximum size
• Air voids	• Aggregate toughness
• Voids in mineral aggregate	• Aggregate soundness
• Voids filled with asphalt	• Aggregate deleterious materials
• Dust Proportion	
Performance-Based Test Methods	
• Repeated shear tests	
• Frequency sweep	
• Uniaxial strain	
• Simple shear	
• Volumetric (hydrostatic state of stress)	
• Indirect tensile creep	
• Indirect tensile strength	

The database is structured to have one, or many, test results associated with an asphalt binder. For example, an asphalt binder entered in the database could have only one set of specification test data (which would be sufficient to grade the asphalt binder), or many sets of test data that are generated during quality control testing.

The asphalt binder database provides a user-defined inventory of asphalt binders available to the mix designer. During mix design, after the environmental conditions have been specified and the required grade of asphalt binder is known, the inventory of asphalt binders becomes a list of binders that could be selected for a mixture design. When the designer selects a binder, test data associated with the binder are used elsewhere in the software as part of the input required to estimate engineering properties of the mixture.

6.7 Selection of Asphalt Binder Grade

A design asphalt binder grade is selected as follows:

- Select applicable weather stations in the vicinity of the project.
- Select probability associated with risk to the pavement of actual temperatures falling below or exceeding mean low and high air temperatures.
- Select design air temperatures.
- Convert design air temperatures to pavement design temperatures.
- Select the applicable asphalt binder grade.

Superpave contains a statistical weather database for approximately 5,000 weather stations in the United States and 2,000 in Canada. Weather stations can be displayed on a map from which the user can select up to three stations for consideration. For each station, the software calculates a design high air temperature and a design low air temperature associated with various degrees of probable risk specified in the agency standards. The user then selects a design high and low air temperature. The Superpave software determines the pavement design temperatures and indicates the minimum required grade of asphalt binder. Alternately, the user can suggest an asphalt binder grade and the software will calculate the probable risk associated with its use.

6.8 Mixture Design and Analysis System

As described in the introduction to this chapter, the Superpave mix design method is a three-level, vertically integrated system. Level 1 of mix design is volumetric, levels 2 and 3 are performance-based. Higher levels produce a higher assurance that material properties meet the requirements of traffic and environment. Hence, higher mix design levels are desirable with higher levels of traffic. The three design levels fit as follows within the structure of the Superpave software.

Level 1. Volumetric Design Volumetric design is the lowest level of mix design available in Superpave. Design asphalt content is obtained by analyzing volumes of air voids, asphalt binder, and aggregate for mixtures that have been compacted using a standardized method of compaction.

Level 2. Intermediate Traffic Performance-Based Design The intermediate performance-based design consists of a volumetric design followed by a slate of performance-based tests from which pavement performance is predicted. Permanent deformation, fatigue cracking, and low temperature cracking levels are predicted with time.

Level 3. High Traffic Performance-Based Design The advanced performance-based design method begins with a volumetric design followed by performance-based tests. The slate of tests is expanded from level 2 mix design and is performed at a range of temperatures instead of a single effective temperature.

6.8.1 Level 1 Design

Volumetric mixture design as used within Superpave is similar to historical volumetric mix design methods. Volumetric proportions of compacted mixtures containing different amounts of asphalt binder are evaluated for air voids, voids in mineral aggregate (VMA), and void filled with asphalt (VFA). In addition, aggregate characteristics are specified. The design aggregate structure and the design asphalt binder content selected in the volumetric mix design will produce a densification curve which passes through 96 percent of maximum theoretical specific gravity at the design number of gyrations. At the maximum number of gyrations, the mixture must be less that 98 percent of maximum theoretical specific gravity. At the initial number of gyrations the mixture must be less than 89 percent of maximum theoretical specific gravity.

Steps to performing a level 1 (volumetric) mix design include:

- Determine design traffic.
- Select design weather conditions.
- Determine design high and low temperatures.
- Select asphalt binder to be used.
- Select aggregate stockpiles to be used.
- Blend one or more aggregate gradations.
- Calculate trial asphalt content and compact duplicate specimens.
- Select one gradation and compact at four asphalt contents.
- Determine design asphalt content.

The Superpave software provides the following functions for level 1 mix design:

- Calculates equivalent single axle loads from traffic data.
- Provides weather data to determine design temperatures.
- Provides a blending routine for combining aggregate stockpiles.
- Calculates trial asphalt content for gradation evaluation.
- Evaluates densification curves from gyratory compactor.
- Calculates and plots air voids, VMA and VFA at design gyrations.
- Calculates density at initial gyrations and maximum gyrations.

6.8.1.1 Calculate Equivalent Single Axle Loads (ESALs)

The Superpave software can calculate design ESALs from average annual daily traffic (AADT), lane distribution, vehicle type distribution, vehicle type equivalency, vehicle type growth rate and design life. The user also has the option to enter the design ESALs directly.

6.8.1.2 Provide Weather Data

The Superpave software contains statistical, historical weather information for almost 7,000 weather stations in the United States and Canada. The software calculates design air temperatures for specified risk levels or, conversely, determines the risk level for a selected design air temperature. Design air temperatures are converted into design pavement temperatures, which are used for asphalt binder selection.

6.8.1.3 Aggregate Blending Routine

The Superpave software contains a suite of blending routines that can combine selected aggregate stockpiles to meet a gradation control specification.

6.8.1.4 Calculate Trial Asphalt Content

The Superpave software calculates a trial asphalt content for the aggregate structure evaluation in which different blends of aggregates are compacted at a single asphalt content to estimate adequacy of the aggregate structure for VMA.

6.8.1.5 Evaluate Gyratory Compaction Data

The Superpave software stores data from the gyratory compactor and calculates and displays densification curves.

6.8.1.6 Design Volumetric Properties

The Superpave software calculates and plots air voids, VMA, and VFA at the design number of gyrations. Asphalt content is selected at 4 percent air voids. VMA and VFA are evaluated and checked against specification requirements.

6.8.2 Level 2 Design

Level 2 intermediate mix design builds upon the historical mix design practices found in the level 1 mixture design. The use of simple shear and frequency sweep testing to predict permanent deformation and fatigue cracking, and the use of indirect tensile creep and indirect tensile strength testing to predict low temperature cracking, measure validated material properties which have been tied to pavement performance.

Steps in performing a level 2 mix design include:

- Select three asphalt contents bracketing the level 1 design content.
- Compact performance-based test specimens to 7 percent air voids.
- Obtain historical pavement temperatures.
- Calculate effective temperatures.
- Run performance-based tests.
- Evaluate test data to obtain material properties.
- Obtain predicted traffic.
- Obtain structural layer information.
- Predict pavement response.

Superpave provides the following functions in support of the level 2 mix design:

- Historical air temperature
- Calculation of historical pavement temperatures
- Converts pavement temperature to effective temperature
- Embedded software converts test data into material properties
- Predicts pavement performance

6.8.2.1 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 the level 1 design, a database containing 10 years of historical daily minimum/maximum temperatures for all of the United States is impractical. A library of historical air temperatures for each state is available with Superpave software. Mix designers will install temperature files only for geographic areas of interest, thus reducing the volume of unneeded information.

6.8.2.2 Historical Pavement Temperature

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

6.8.2.3 Pavement Temperature Converted Into Effective Temperature

For permanent deformation and fatigue cracking, the level 2 mix design predicts performance 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. Effective temperature is different for permanent deformation than for fatigue cracking. The Superpave software calculates both effective temperatures for use as test temperatures for the performance-based tests.

6.8.2.4 Calculate Material Properties

The Superpave software accesses data files created by the associated data collection software. Testing machines have stand-alone software to control execution of the performance-based tests and to provide data collection files as an output of the test. The Superpave software processes the data files using embedded software to obtain material properties.

6.8.2.5 Predict Pavement Performance

The Superpave software predicts pavement performance using material properties, traffic, pavement temperature and pavement structure. Pavement distress versus time is displayed.

6.8.3 Level 3 Design

The level 3 advanced performance-based design builds upon the historical mix design practices found in a level 1 mix design and exceeds the capabilities of a level 2 mix design. The level 3 mix design uses a larger slate of performance-based tests and predicts performance using varying pavement temperatures instead of effective temperatures for permanent deformation and fatigue cracking. Level 3 mix design is the most rigorous approach in the Superpave system.

Steps in performing a level 3 mix design include:

- Select three asphalt contents bracketing the level 1 design content.
- Compact performance-based test specimens to 7 percent air voids.
- Run performance-based tests.
- Evaluate test data to obtain material properties.
- Obtain historical pavement temperatures.
- Obtain predicted traffic.
- Obtain structural layer information.
- Predict pavement performance.

The Superpave software provides the following functions in support of the level 3 mix design:

- Provides historical air temperatures
- Calculates historical pavement temperatures
- Embedded software converts test data into material properties
- Predicts pavement performance

6.8.3.1 Historical Air Temperature

The level 3 design procedure uses the same 10-year blocks of historical air temperatures used in a level 2 mix design.

6.8.3.2 Historical Pavement Temperature

Historical air temperatures are converted into historical pavement temperatures using the FHWA Environmental Effects Model embedded in the software. The output from the model used by level 3 is exactly the same pavement temperature used in level 2.

6.8.3.3 Calculate Material Properties

The Superpave software accesses data files created by the associated data collection software. Testing machines will have stand-alone software to control execution of the performance based tests and to provide data collection files as an output of the test protocol. The Superpave software processes the data files using embedded software to obtain material properties.

The process for obtaining material properties is the same in level 3 as in level 2. Unlike level 2, however, testing includes the volumetric and uniaxial strain tests; the frequency sweep is performed over a range of temperatures from which a master curve of mix stiffness is obtained.

6.8.3.4 Predict Pavement Performance

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

6.9 Superpave Configuration

The Superpave software can be installed on one computer as a stand-alone system, or it may be used in a local area network. In a local area network, computers could be installed at work stations in the laboratory. As tests are performed, data is entered directly into data analysis sheets as part of the mix design. For example, if a particular paving mix is being designed, a blending analysis can be done in one day. The next day another technician can recall the design and compact specimens, saving the densification results in the files. When the technician performs maximum theoretical specific gravity tests, weights would be entered directly into data analysis forms.

When the mix design is completed, the Superpave software can generate a summary file containing all information and tests results assembled during the design. The summary file can be transmitted by modem to a field laboratory computer, and field control testing can be added to the file. Hence, a comprehensive file exists of all data associated with the mix design, all the way from blending analysis to the last field control test performed during construction.

6.10 Summary

The Superpave software is an extremely powerful, integrated tool for materials engineers and pavement designers. It performs all the necessary functions to implement the Superpave mix design system, the asphalt binder, and asphalt-aggregate mix specifications.

Appendix A Glossary of Terms for the Superpave Mix Design System

Absorbed Asphalt Volume The volume of asphalt binder which is absorbed into the aggregate. It is equal to the difference between the aggregate volume when calculated with the bulk specific gravity and with the effective specific gravity.

Aggregate Control Points Maximum and (or) minimum limits which are established at specified sieve sizes for each set of aggregate gradation controls, including the maximum size, the nominal maximum size, and the restricted zone.

Aggregate Restricted Zone A zone which lies on the maximum density line and extends from the 300 μm sieve to the 2.36 mm sieve through which it is usually undesirable for the gradation to pass. For 25 and 37.5 mm nominal maximum size gradations, the restricted zone extends to the 4.75 mm sieve.

Air Voids The total volume of air between coated aggregate particles in a compacted asphalt mixture.

Asphalt-Aggregate Compatibility The ability of an asphalt binder, as measured by the net adsorption test (SHRP Test M-001, *Measurement of Initial Asphalt Adsorption and Desorption in the Presence of Moisture*), to adhere to the surface of the fine aggregate portion of the total aggregate and to maintain this adherence in the presence of moisture.

Asphalt Binder An asphalt-based cement that is produced from petroleum residue either with or without the addition of organic modifiers.

Asphalt (Binder) Content The percent by weight of asphalt binder in the total paving mix including both the asphalt binder and aggregate.

Asphalt Modifier Any organic material of suitable manufacture, used in either virgin or recycled condition, which is dissolved, dispersed or reacted in asphalt cement to enhance its performance.

Bending Beam Rheometer A low temperature test device which measures the mid-point deflection of a simply-supported prismatic beam of asphalt binder subjected at low temperature to a constant load applied at the mid-point of the beam.

Clay content A measure of the amount of clay material which is present in the portion of aggregate that passes the 4.75 mm sieve.

Coarse Aggregate Aggregate which is retained on the 2.36 mm sieve.

Coarse Aggregate Angularity The percent by weight of aggregate particles larger than 4.75 mm with one or more fractured faces.

Critical Temperature (T_c) A test temperature higher than the effective temperature (T_{eff}) for permanent deformation which is selected to reduce testing time to reasonable levels for projects with very high predicted ESALs.

Deleterious Materials Undesirable contaminants, such as soft shale, coal, wood, or mica, which is found in a blended aggregate.

Design Aggregate Structure An aggregate gradation selected through the Superpave level 1 (volumetric) mix design procedure which meets all aggregate and volumetric requirements at an initial trial asphalt content.

Design Asphalt Content The asphalt content determined for the design aggregate structure through the Superpave level 1 (volumetric) mix design procedure which produces compacted specimens with four percent air void at N_{design} and which meets relevant air void requirements at N_{init} and N_{max}.

Direct Tension Test Device A low temperature, non-contact test device which measures the strain and stress at failure of an asphalt binder specimen pulled at a constant rate of elongation.

Dust Proportion The ratio of the percent by weight of aggregate passing the 75 μm sieve to the percent effective binder content.

Dynamic Shear Rheometer A high and intermediate temperature test device which measures the complex shear modulus and phase angle of a binder specimen placed between two parallel plates which are oscillated with respect to each other at pre-selected frequencies and rotational deformation amplitudes.

Effective Asphalt Volume The volume of asphalt binder which is not absorbed into the aggregate.

Effective Temperature (T_{eff}) A single test temperature at which an amount of permanent deformation or fatigue cracking would occur equivalent to that which would be measured by considering the seasonal fluctuation of temperature throughout the year.

Environmental Conditioning System 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.

ESAL Equivalent single axle load.

Federal Highway Administration Grading Chart An aggregate 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.

Filler or Mineral Filler Aggregate, predominately mineral dust, which passes the 75 μm sieve.

Fine Aggregate Aggregate which passes the 2.36 mm sieve.

Fine Aggregate Angularity The percent of air voids of loosely compacted aggregate as measured in the National Aggregate Association Test Method A. This test is done on the portion of blended aggregates passing the 2.36 mm (No. 8) sieve.

Fractured Face An angular, rough, or broken surface of an aggregate particle created by crushing, by other artificial means, or by nature. A face is considered a fractured face 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.

Frequency Sweep at Constant Height Test A test in which employs a specimen and loading configuration identical to that of the Simple Shear at Constant Height test in the shear test device. 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.

Guideline A specification value which is provided as design guidance, but to which conformance is not mandatory.

High Air Temperature The maximum annual 7-day average air temperature recorded at a weather station.

Indirect Tensile Creep Test A test in which a 150 mm diameter specimen is subjected in the indirect tensile test device to a diametral preconditioning load to obtain uniform deformation. A fixed static load is then applied for 100 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 test in which a compressive load is applied along the diametral axis of 150 mm diameter specimen in the indirect tensile test device at a controlled vertical deformation rate until failure occurs.

Long-Term Aging An optional procedure for paving mixes in which 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 mix designer's discretion.

Low Air Temperature The minimum annual air temperature recorded at a weather station.

Material Property A characteristic of a material which does not depend upon the testing apparatus, procedure or condition, and from which its behavior under load can be predicted.

Maximum Density Line A line which is 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.

Maximum Pavement Design Temperature Maximum pavement temperature at 20 mm depth determined from *high air temperature* for any given location.

Maximum (Aggregate) Size A sieve size which is one size larger than the nominal maximum size.

Minimum Pavement Design Temperature Minimum pavement temperature at the surface, equal to the *low air temperature* for any given location.

Nominal Maximum (Aggregate) Size A sieve size which is one size larger than the first sieve to retain more than 10 percent of the aggregate.

Optimum Binder Content The asphalt content determined for the design aggregate structure through Superpave level 2 or level 3 performance testing of compacted specimens which satisfies agency requirements for acceptable, predicted levels of permanent deformation, fatigue cracking and (or) low-temperature cracking at the designated pavement design life.

Pavement Performance Prediction Model A computer algorithm which provides realistic predictions of future pavement performance from the material properties of the paving mix; the predicted traffic; the climatic history of the pavement site; and the pavement structure.

Pressure Aging Vessel A pressurized, heated vessel which accelerates the aging of asphalt binder samples to simulate their in-situ aging in pavements.

Requirement A specification value which a material must always meet.

Repeated Shear at Constant Height Test A test in which a specimen is subjected in the shear test device 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. This test is not a formal part of the Superpave system.

Repeated Shear at Constant Stress Ratio Test A screening test in which a specimen is subjected in the shear test device 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.

Rock Predominately coarse aggregate which is retained on the 2.36 mm sieve.

Sand Predominately fine aggregate which passes the 2.36 mm sieve.

Shear Test Device A biaxial, closed-loop servohydraulic test device which can simultaneously subject paving mix specimens to simultaneous horizontal and axial loads over a wide range test temperatures and confining pressures.

Short-Term Aging A procedure for paving mixes in which 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 material compacted. This procedure simulates the aging that takes place during HMA production and the pavement construction process.

Simple Shear at Constant Height Test A test in which a specimen (typically 150 mm in diameter and 65 mm in height) is maintained in the shear test device at constant height while a shear load of 70 kPa/s is applied. 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 load causes a horizontal displacement, and the axial load is varied to maintain the specimen at constant height.

Soundness The weight percent of degradation which is experienced by a blended aggregate during the sodium or magnesium soundness test.

Tertiary Creep Plastic flow of a paving mix due to gross instability under repetitive shear and compressive loading which leads to catastrophic pavement failure.

Thin, Elongated Particle A coarse aggregate particle which has a ratio of maximum to minimum dimensions greater than five (5).

Toughness The weight percent of material which is lost from the blended aggregate during the Los Angeles Abrasion Test.

Uniaxial Strain Test A test in which a specimen encased in a rubber membrane is subjected in the shear test device 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.

Voids Filled with Asphalt (VFA) The percentage of the VMA which is filled with asphalt binder. It is the effective asphalt volume divided by the voids in the mineral aggregate.

Voids in Mineral Aggregate (VMA) The volume of effective asphalt binder and air voides in a compacted mix.

Volumetric (or Hydrostatic State of Stress) Test A test in which a specimen is completely surrounded in the shear test device 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 kPa/s, and the change in its perimeter is recorded.

Appendix B Pavement Performance Predictions

An important result of the SHRP research program was the development of a comprehensive pavement performance model that predicts the development of permanent deformation, fatigue cracking and low temperature cracking with time. The pavement performance model can be used to evaluate or design asphalt concrete paving mix to minimize a specific distress or combinations of different distresses. The model is composed of four parts (figure B.1): 1) a material property model, 2) an environmental effects model, 3) a pavement response model, and 4) a pavement distress model. The mixture characterization program calculates the non-linear elastic, viscoelastic, plastic and fracture properties of a mixture from the performance-based laboratory tests. The properties are used with the pavement response program to predict the behavior of a mixture subjected to traffic and environmental loads. Some of these material properties are also used 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 environmental loads. The pavement distress program takes the relevant mixture properties and the appropriate stresses (from wheel loads and environmental loads), and calculates the permanent deformation with time. Each of these models are briefly discussed in the following sections.

Environmental Effects Model

The environmental effects model is based upon the program developed at the Texas Transportation Institute for the FHWA, and is used to calculate temperatures within the pavement system using daily air temperature data and material thermal properties. It uses the minimum and maximum daily air temperatures recorded at site-specific weather stations as input, and predicts hourly pavement temperatures with depth. The thermal-cracking prediction model uses a detailed temperature distribution with depth; the fatigue cracking and permanent deformation models use the average seasonal temperatures calculated at one third the depth of the asphalt concrete layer. The number and length of each season is based upon this pavement temperature distribution calculated for each month. The number of seasons can vary from 1 to 12.

Mixture Characterization Model

One of the most important steps in the pavement performance analysis is the selection of a suitable constitutive equation to model the behavior of a mixture under some load. Stated

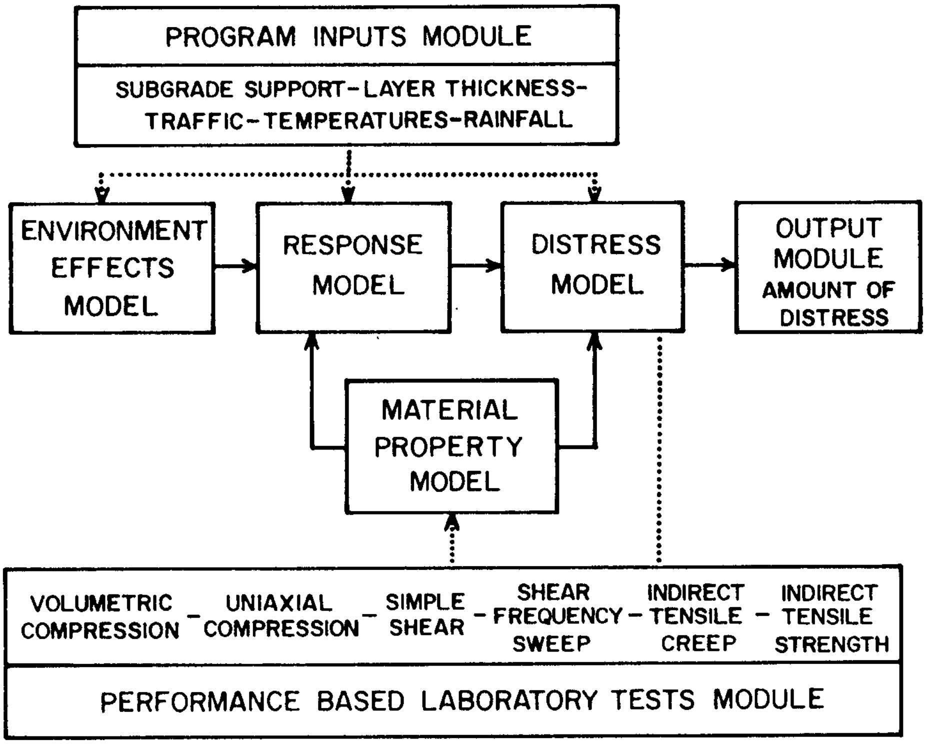


Figure B.1 Flow Diagram of the Different Parts of the Pavement Performance Model simply, constitutive or stress/strain laws of engineering materials play a vital role in providing reliable results for predicting how the material will perform. Six basic tests are used to determine the required material properties. These are a hydrostatic state of stress (volumetric compression) test, a uniaxial strain (confined compression) test, a constant height simple shear test, a shear frequency sweep test, an indirect tensile creep test, and an indirect tensile strength test. The indirect tensile creep and strength tests are needed for low temperature cracking predictions; the other four tests are needed for permanent deformation and fatigue cracking predictions. To estimate the material properties from these accelerated laboratory tests, a linear viscoelastic formulation was adopted for the low temperature cracking model; whereas, an elastoplasticity formulation was used within the rutting and fatigue cracking (load related) models. For the load related models, the specimen deformation is separated into two parts: an elastic and plastic (inelastic) component. The nonlinear elastic properties are defined by the constitutive equation developed directly as a simple modification of the isotropic linear relation (generalized Hook's Law) with the elastic constant replaced by scalar functions associated with the stress. In the resilient modulus model, any scalar function of stress can be used for the isotropic nonlinear elastic modulus. The constitutive models formulated on this basis are the Cauchy elastic type in which the state of strain is determined uniquely by the current state of stress. The elastic or resilient modulus, is defined as:

$$E_R = K_1 P_a \left(\frac{\Theta + K_6}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a}\right) K_3$$

where: K_1, K_2, K_3, K_6 = material properties or constants determined by regression analyses from the results of the accelerated laboratory tests

Θ = I_1 = first stress invariant $(\sigma_1 + \sigma_2 + \sigma_3)$

τ_{oct} = Octahedral shear stress

P_a = Atmospheric pressure

An important component of the elasto-plastic approach is the failure law. This law, which constitutes an upper limit of the yield function, determines the shape of the yield function and the plastic potential. In the pavement performance model, the Vermeer model (2) was adopted. In the Vermeer model, the total strain increments are divided into two inelastic components: a plastic cone component and plastic cap component. Each strain component is calculated separately.

The non-load related model is based upon a one-dimensional constitutive equation that includes an approximate means for modeling the two-dimensional stress distribution within the asphalt concrete layer. The model developed for thermal stress predictions is based upon Boltzmann's superposition principle for linear viscoelastic materials:

$$\sigma(\xi) = \int_0^{\xi} E(\xi - \xi') \frac{d\epsilon}{d\xi'} d\xi'$$

where: $\sigma(\xi)$ = stress at reduced time ξ
$E(\xi - \xi')$ = relaxation modulus at reduced time $\xi - \xi'$
$d\varepsilon$ = total strain increment
ε = strain at reduced time ξ (= $\alpha(T(\xi') - T_o)$)
α = linear coefficient of thermal contraction
$T(\xi')$ = pavement temperature at reduced time ε'
T_o = pavement temperature when $\sigma = 0$
ξ' = variable of integration

Pavement Response Models

The pavement response model predicts the stresses and strains within the pavement system using the material properties, pavement structure information and pavement temperature predictions from the environmental effects model. For the low temperature cracking prediction model, a Maxwell model was selected because the assumption of a linear viscoelastic material is reasonable at cold temperatures. The constitutive equation given above essentially models the asphalt layer as a uniaxial rod, and is written in terms of reduced time, σ, because time-temperature superposition is being used to represent the creep compliance and relaxation modulus curves. The master relaxation modulus curve is determined from the indirect tensile test. The use of time-temperature superposition means that the asphalt concrete mixture is modeled as a thermorheologically simple material. With a change of variables, the equation is written in terms of real time, *t*, as follows:

$$\sigma(t) = \int_0^{t} E[\xi(t) - \xi'(t)] \frac{d\epsilon}{dt'} dt'$$

where t = real time
$\sigma(t)$ = stress at real time t
t' = variable of integration

For the permanent deformation and fatigue cracking prediction model, a two-dimensional finite element code for material linearity as developed by Owen and Hinton (1980) for the plain stress, plain strain and axisymmetric problems was adopted. The formulation of the finite element method was obtained by the use of the principle of virtual work. The primary response model is based on a two-dimensional axisymmetric finite element program. A four node element is used with one gauss point for integration, and incremental loading with iterations for convergence.

Distress Models

Thermal Cracking. The low temperature cracking prediction model consists of three parts: l) the stress intensity factor model, 2) the crack depth (or fracture) model, and 3) the crack amount model. The stress intensity factor model predicts the stress at the tip of a local vertical crack using stresses computed by the pavement response model, layer thicknesses, and material properties. The stress intensity factor is a two-dimensional finite element program that models a single vertical crack in the asphaltic concrete layer via a crack tip element.

Based upon the stress at the tip of the crack, the crack depth model predicts the amount of crack propagation due to the imposed stress. The Paris Law for crack propagation is used to predict the change in depth of a crack subjected to a given cooling cycle:

$$\Delta C = A\ (\Delta K)^n$$

where: ΔC = change in the crack depth due to a cooling cycle
ΔK = change in the stress intensity factor due to a cooling cycle
A, n = fracture parameters

The change in crack depth is computed and accumulated on a daily basis to determine the total crack depth as a function of time. In order to perform these computations, the asphalt concrete layer is subdivided into four sublayers. On any given cooling cycle, the crack is never allowed to propagate any further than through two sublayers.

Finally, the crack amount model predicts the number (or frequency) of thermal cracks per unit length of pavement from the depth of the local vertical crack and the assumed crack depth distribution. The model was developed between the amount of cracking for the pavement section and the proportion of the maximum number of vertical cracks that have actually broken through the surface layer. Essentially, the amount of cracking is a function of the probability that the crack depth is equal to or greater than the thickness of the surface layer. This probability is determined by assuming that the log of the depth of cracks in the pavement is normally distributed with a mean equal to $\log C_o$ (the crack depth predicted by the model), and variance, σ^2.

Fatigue Cracking. The total number of load applications to fatigue failure is defined in a two-part process of crack initiation and crack growth. In the crack initiation phase, it is assumed that microcracks are developed and they increase in size to form a visible crack with a damage zone in front of the visible crack. The number of load repetitions to crack initiation was defined using the dissipated energy concept, results from laboratory beam fatigue tests, and regression analyses.

Crack propagation is defined using a fracture mechanics law and the Paris-Erdogan equation shown below (which is similar to the non-load related models).

$$N_p = \frac{1}{A}\int_{C_0}^{h}\frac{dc}{(\Delta K_{II})^n}$$

where N_p = number of load applications to propagate the crack from the bottom to the top of the asphalt concrete surface layer
C_0 = initial crack length, which is assumed to be 8 mm for all conditions
h = layer thickness (mm)
K_{II} = stress intensity factor in shear
c = expected crack area

The predicted damage caused to the pavement is determined in accordance with Minor's law, which is simply the ratio of the actual wheel load applications to the allowable number of load applications for a specific stress state. The allowable number of load applications for a specific season is the sum of the number of load cycles to crack initiation and crack propagation. The value of the damage index is assumed to be a normally distributed variable with a mean and variance. The probability that the damage index reaches the value of 1 is computed and used to evaluate the cracked area by the expression: $c = 1000\ [1 - F(1)]$. Here c is the expected cracked area ($m^2/1{,}000m^2$) and $F(1)$ is the probability that the damage index reaches a value of 1. Figure B.2 shows an example of fatigue cracking predictions with traffic.

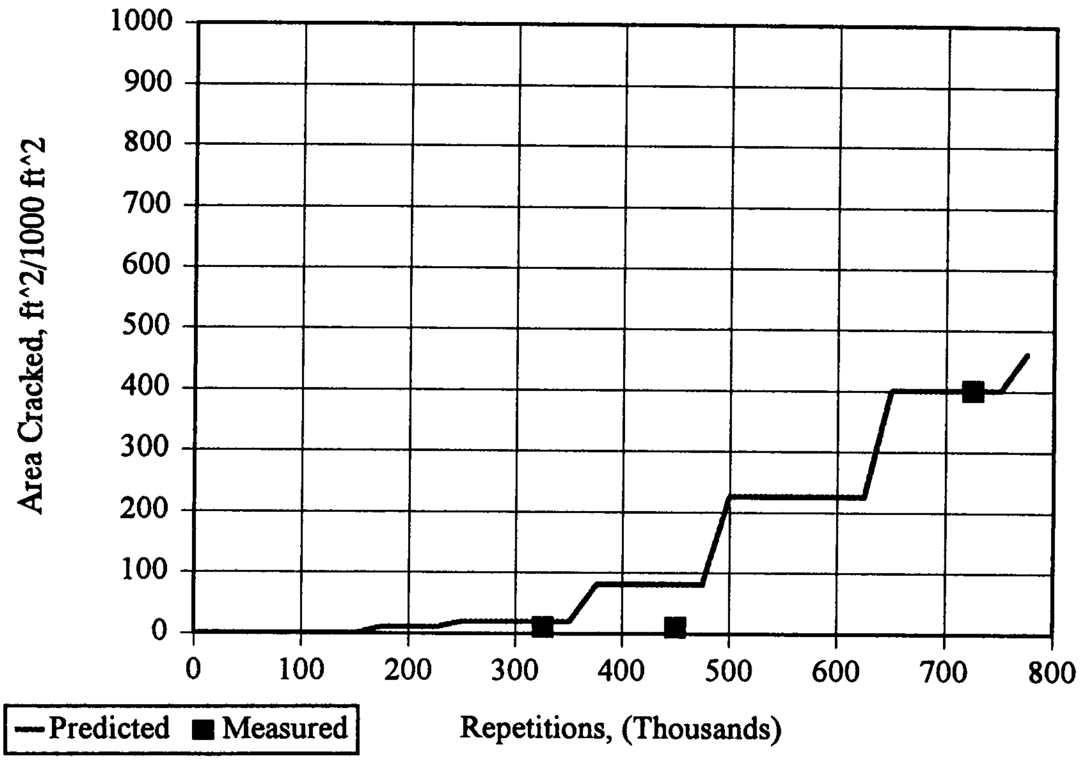


Figure B.2 Fatigue Cracking Model Predictions with Traffic

Permanent Deformation

The model used to calculate rutting is the linear relation between the plastic strain and the number of repetitions on a log-log scale. The permanent deformation from an applied load is characterized into two parts: the permanent deformation at the end of the first loading cycle, and the slope of the permanent deformation accumulation, as measured in the laboratory. The resilient properties are obtained from a repeated load test with 0.1 sec loading and 0.9 sec unloading, and the total permanent deformation is:

$$\log \epsilon^{P}(N) = \log \epsilon^{P}(N = 1) + S \log N$$

where N = number of load repetitions
$\varepsilon^{P}(N)$ = accumulated strain at N load repetitions. The Vermeer model is used as a framework to represent $\varepsilon^{P}(N = 1)$ as function of the state of stress in proportional loading.
S = slope of the log $\varepsilon^{P}(N)$ versus log N curve. The slope is related to the slope of the creep curve m, and may be stress dependent.

The model uses stresses computed under one wheel along a vertical line at the center of the elements; the Vermeer model to compute the permanent strain in the first load application, $\varepsilon^{P}(N = 1)$; and the parameter S to compute the permanent strain at any number of load repetitions. The rut depth in the pavement is accumulated by summing the products of the plastic strain and the corresponding sublayer thickness during the analysis period for all seasons in the sequence. Figure B.3 shows an example of the rutting predictions with traffic.

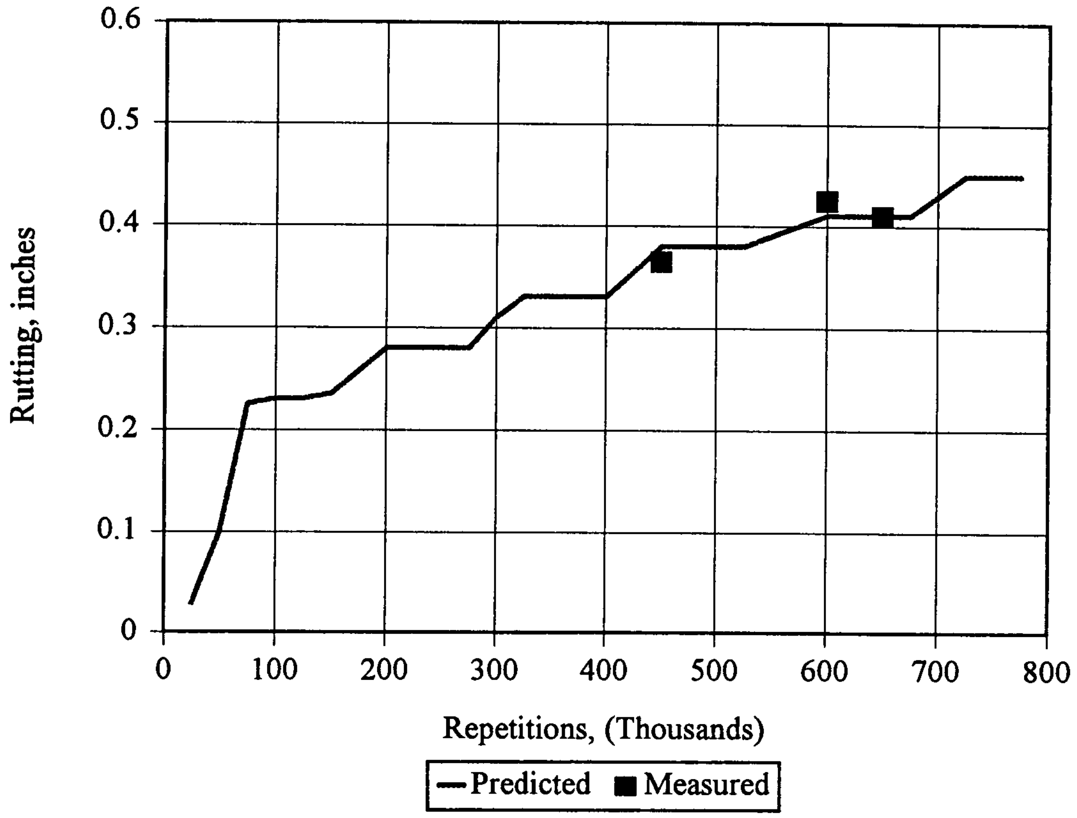


Figure B.3 Rutting Model Predictions with Traffic

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