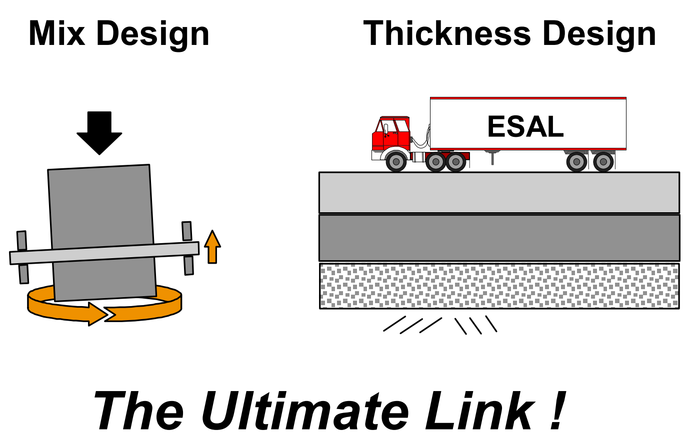
IX. Superpave Mix Analysis and Testing

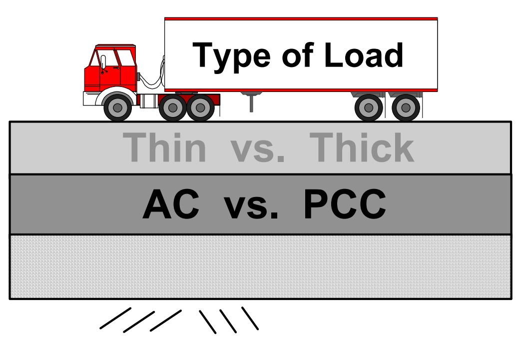
Superpave volumetric mix design is the key step in developing a well-performing HMA mixture. Under SHRP, additional laboratory analysis tests and material performance models were developed to further determine the capabilities of Superpave mixtures to perform well for the specific project design traffic and climatic condition. This chapter describes the benefits that can be derived from conducting Superpave Mix Analysis and discusses the system of models and test procedures currently being evaluated/refined.

THE GOAL OF SUPERPAVE MIX ANALYSIS

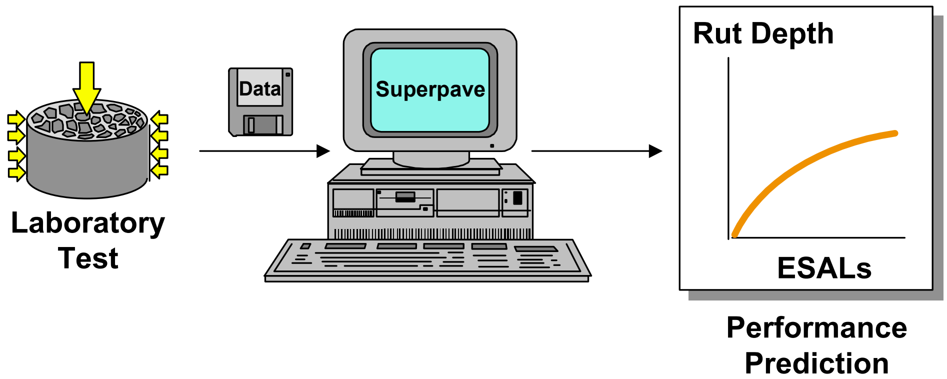


Superpave Mix Analysis would ideally allow us to truly link the design of the asphalt mixture with the design of the pavement cross-section. Currently, most highway agencies perform these functions in completely different departments that rarely interact. In reality, these two tasks are so well connected, that it may be much more effective to integrate the design process.

Mix behavior and performance are greatly affected by the conditions that exist at the specific project. "Standard" mix designs should not be used for all circumstances because the best mix for one location may be the worst mix for another. Conditions such as the predominant type of wheel loads, the climate, the thickness of the new layer, and the type of structural support (soft or hard, asphalt or concrete) affect mix selection. A truly integrated mix analysis system would provide us with the capability to understand, evaluate, and optimize these factors.



SHRP MIX ANALYSIS DEVELOPMENTS



The framework of the Superpave asphalt mix analysis system that was developed under SHRP includes a system of analytical pavement performance models that take results from laboratory tests and determine if the design mixture would perform under the design conditions. Several test procedures were developed to impose various stress and temperature conditions to asphalt mixture specimens to characterize the many properties necessary to model pavement behavior. SHRP developed two performance test devices: the Superpave Shear Tester (SST) and the Indirect Tensile Tester (IDT).

The University of Maryland critically evaluated the original SHRP analytical models under an FHWA contract. Some concerns and suggestions for improvement were documented in a Models Evaluation Report. As a result of the models evaluation, changes will be made in the system that was developed under SHRP. What the extent of these changes will be and what the final Superpave Mix Analysis System will look like can only be conjectured at this point. However, the basic performance analysis framework and the test equipment that were developed under SHRP are still valid, and are discussed further in this section.

Performance Models

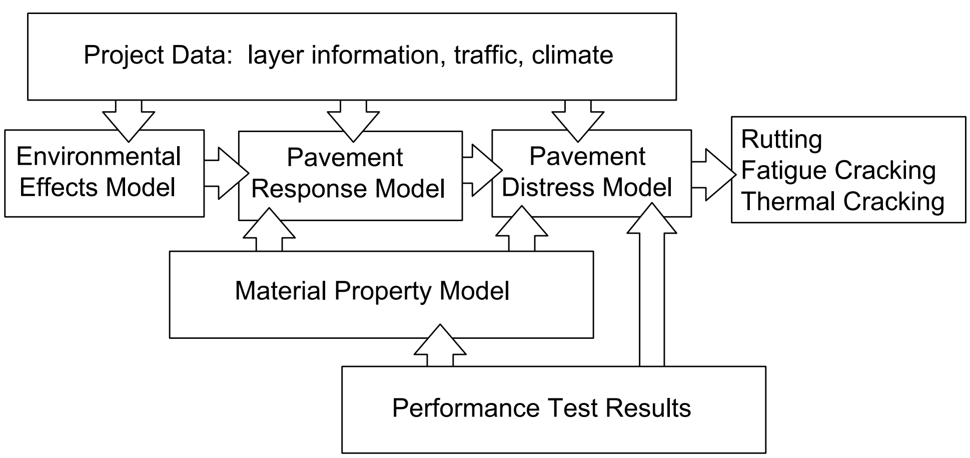
While much attention in SHRP was focused on the new test equipment and testing protocols, a key ingredient for using the test results were the performance models. These models are the mathematical theory and equations that process the laboratory measurements and provide output in the form of predicted pavement performance. The models are needed to determine the properties of the new asphalt mixture being designed and to incorporate the conditions of the existing climate and support of the in-place pavement in the analysis. The use of mix analysis testing and performance prediction models represents an important new capability for engineers in designing and optimizing pavements.

The modeling framework established by SHRP uses four basic components:

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

Laboratory test results (loads and deflections recorded over time) can be used as input to the material property model to determine various properties, such as non-linear elastic, viscoelastic, plastic, and fracture. The environmental effects model calculates the pavement temperature as a function of air temperatures available in a database, depth, and thermal properties assumed for the pavement layers in the cross-section. These temperatures are used to adjust the material properties for the various seasons of the year.

The pavement response model uses the properties from the material property and environmental effects models to predict stresses and strains caused by traffic (fatigue cracking and rutting) or climatic changes (low temperature cracking) at critical locations within the layered pavement system. These calculated responses and adjusted material properties may then be used by the pavement distress model to predict rutting, fatigue, and low temperature cracking as it occurs with time or number of traffic repetitions. This framework is illustrated graphically below; although some of the modeling will be revised in the future, the overall approach is still valid and appropriate.

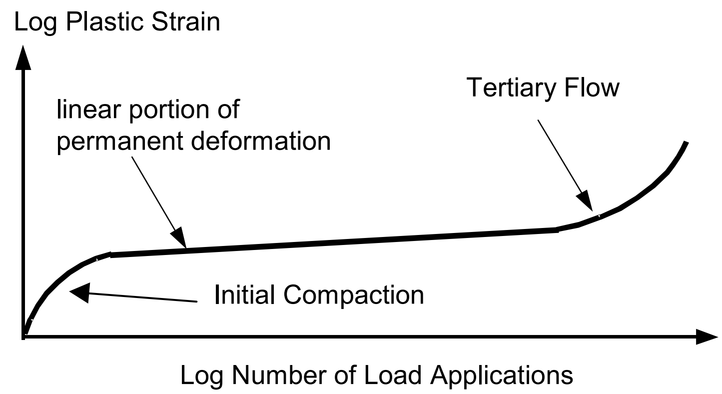


The models evaluation determined that the low temperature cracking model was basically sound, while the modeling for the load-related fatigue cracking and permanent deformation portions of the system will probably change. Even so, the overall mechanistic principles documented in the SHRP reports for how these different distresses form in the pavement still apply. For this reason, the concepts of distress predictions will only be highlighted in this course text.

PERMANENT DEFORMATION

The development of permanent deformation or rutting can be separated into three distinctive phases, when plotted on log-log scale. Initially, the mix in the pavement typically compacts an initial, small amount immediately after construction. Then, the pavement usually compacts gradually for many load repetitions. Because this portion plots as a straight line on log-log scale, it is also referred to as linear deformation. If the mixture is stable, this linear range will continue indefinitely.

However, if the mixture densifies to a point of low air voids during secondary compaction, about two to three percent, the mix may become unstable and deform "plastically". This condition is known as *tertiary flow* and it occurs when there is too much binder for the aggregate structure of the mix. In tertiary flow, an asphalt mixture exhibits extreme plastic flow with very few load applications as shown in the figure. The modeling of permanent deformation is difficult because of the many types of behavior and material properties that are involved. This will be a challenge for a future research contract.

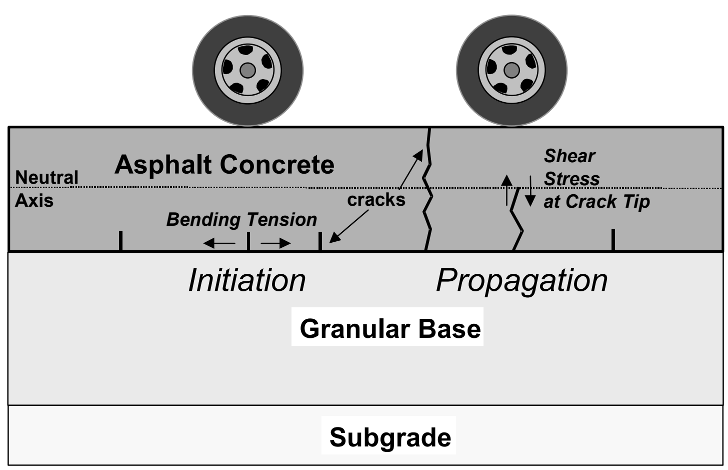


FATIGUE CRACKING

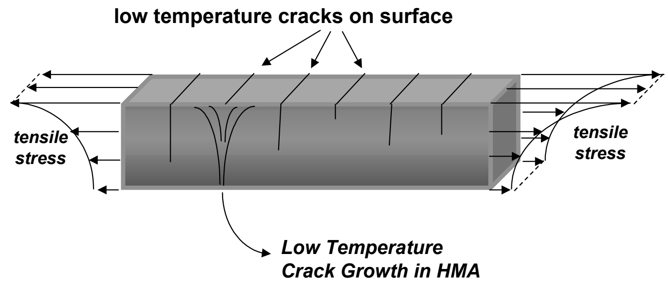
The approach to modeling fatigue cracking is divided into two stages:

- crack initiation caused by repeated bending under load
- crack propagation through the entire layer by fracture due to repeated loads causing high stress at the crack tip

The classical theory for fatigue cracking is that the layer begins to crack at the bottom and the crack propagates upward with increasing numbers of load repetitions. However, more recent observations appear to indicate that some fatigue cracking may also initiate at the top of the layer, near the edge of the tire or wheel path, and then propagate downward. A future research contract will be developing the models to consider both types of fatigue distress.



LOW TEMPERATURE CRACKING



At very cold temperatures, the asphalt mixture tries to contract. Because the layer is somewhat "bonded" to the underlying layers, the asphalt layer shrinkage is restrained. This resistance causes tensile stresses to build up in the asphalt layer. If these stresses continue to increase and do not diminish through "relaxation", the tensile strength of the mixture may be exceeded, causing a *low temperature crack* to occur. This crack usually begins at the top of the layer, where the tensile stress is the greatest, and propagates downward until the layer is completely "fractured". Normally, these cracks are spaced far apart initially; however, in a severe condition, these cracks may occur at regular intervals of 6 to 30 m.

For this modeling, Superpave uses a property called the relaxation modulus and an m-value, similar to the binder specification, to predict:

- stress in the layer due to cold weather contraction
- growth of the crack and ultimate fracture in the layer

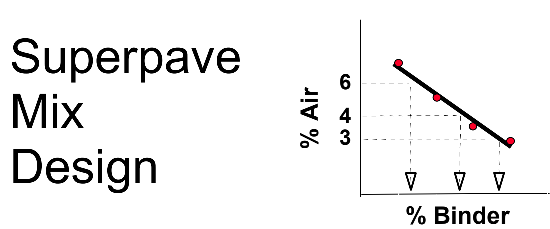
Superpave Test Procedures

Two mechanical test devices were developed under SHRP: the Superpave Shear Tester (SST) and the Indirect Tensile Tester (IDT). The original Superpave mix analysis procedures used the results from tests in these equipment to determine the extent of permanent deformation, fatigue cracking, and low temperature cracking that would develop under the project conditions. Depending on the traffic level, either an intermediate or complete analysis of the design mixture would be performed. An intermediate analysis could be used for traffic levels up to ten million ESALs. A complete analysis would be used for heavily trafficked pavements, those exceeding ten million ESALs.

This table describes the original Superpave mix analysis test procedures. All of these tests would be performed for the evaluation of a mix used in a new pavement. If an overlay were being designed, only the permanent deformation tests would be conducted. The difficulty in differentiating reflective cracking from fatigue and low temperature cracking precluded their evaluation for overlays.

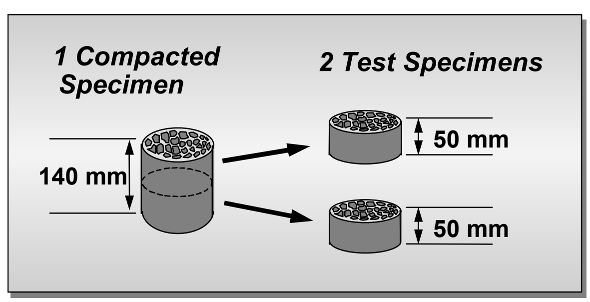
Superpave Mix Analysis Testing

Type of Analysis	Type of Distress		
	Permanent Deformation	Fatigue Cracking	Low Temperature Cracking
Inter-mediate	Simple shear test at constant height. Frequency sweep test at constant height. Repeated shear test at constant stress ratio	Simple shear test at constant height. Frequency sweep test at constant height. Indirect tensile strength.	Indirect tensile creep compliance. Indirect tensile strength. Binder creep stiffness (S) and creep rate (m).
Complete		Indirect tensile strength.	Indirect tensile creep compliance. Indirect tensile strength. Binder creep stiffness (S) and creep rate (m).
	Frequency sweep test at constant height. Uniaxial strain test. Volumetric test. Simple shear test at constant height. Repeated shear test at constant stress ratio		



Superpave mix analysis testing is usually performed on specimens compacted at multiple asphalt binder contents. Typically, the binder contents are selected based on the results of the Superpave Mix Design. For tests concerned with permanent deformation, fatigue cracking, and low temperature cracking, binder contents that result in three, four, and six percent air voids at N_{des} are selected to cover the possible range.

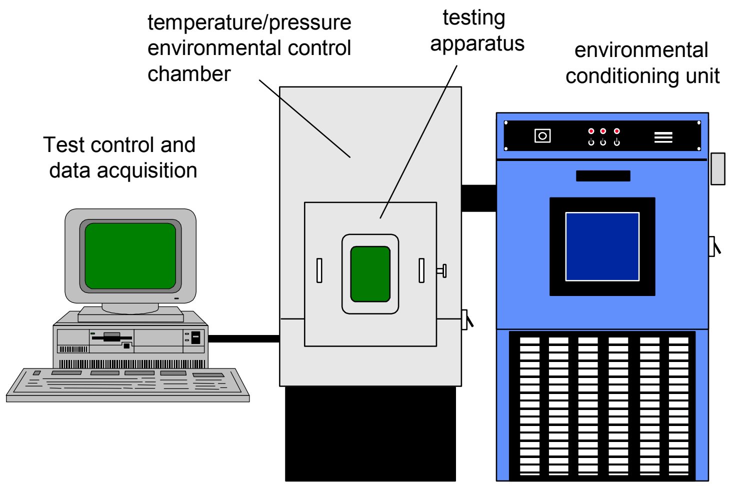
Superpave Mix Analysis test specimens are cut from taller compacted specimens that are fabricated in the SGC to a specific height using fewer gyrations to achieve test specimens containing approximately seven percent air voids. In the testing used for permanent deformation and fatigue cracking, two replicate specimens are prepared. In the testing conducted for low temperature cracking, three replicate specimens



are required by the modeling software.

SUPERPAVE SHEAR TESTER

The SST is a closed-loop feedback, servo-hydraulic system that consists of four major components: the testing apparatus, the test control unit and data acquisition system, the environmental control chamber, and the hydraulic system.



The testing apparatus includes a reaction frame and shear table. It also serves to house the various components that are driven by other system components such as temperature/pressure control, hydraulic actuators, and input and output transducers. The reaction frame is extremely rigid so that precise specimen displacement measurements can be achieved without worrying about displacements from frame compliance. The shear table holds specimens during testing and can be actuated to impart shear loads.

The test control unit consists of the system hardware and software. The hardware interfaces with the testing apparatus through input and output transducers, and 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 also operate in a closed loop feedback mode, which means that LVDT signals are used to control applied testing loads.

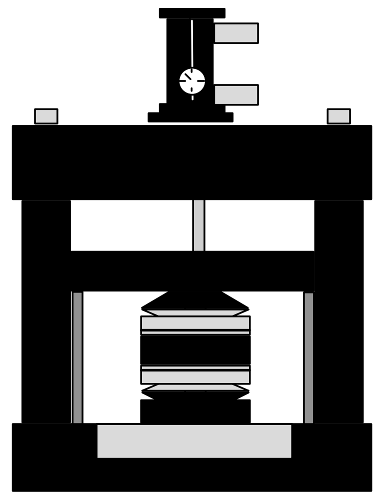
The environmental control unit is required to control the temperature and air pressure inside the testing chamber at a constant level. The unit is capable of maintaining temperatures within a wide range from 1° to 80° C. Air pressure and the rate of pressure change within the chamber is precisely controlled. 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 six tests.

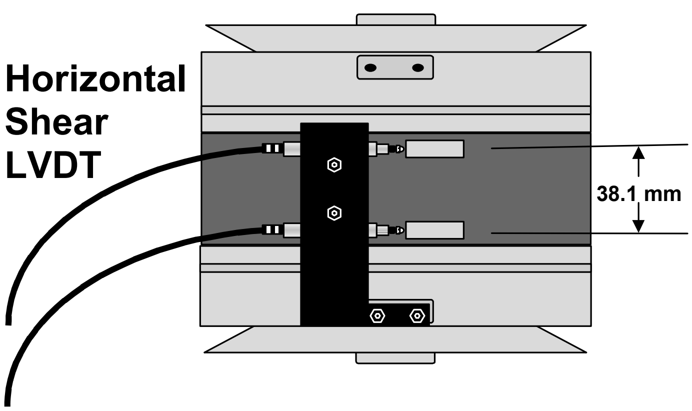
The hydraulic system provides the force required to load specimens in different testing conditions. A hydraulic motor powers two actuators, each with a capacity of approximately 32 kN. The vertical actuator applies an axial force to test specimens. The horizontal actuator drives the shear table, which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

Specimen Preparation and Instrumentation

The first step in specimen preparation is to trim test specimens to a thickness of 50 mm. For the three tests that require no confining pressure, the specimen is glued between two platens.

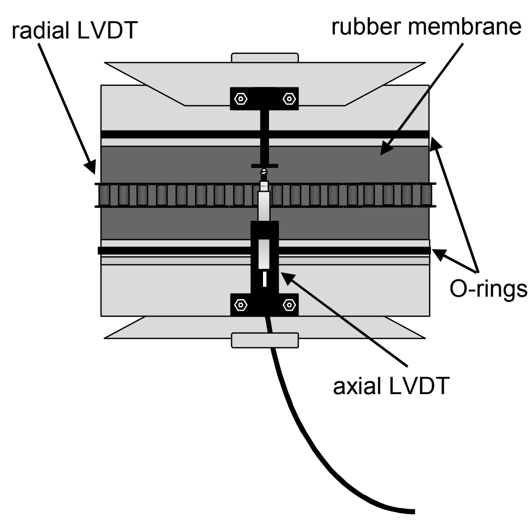
A gluing device is used to squeeze the specimen between the platens while the glue cures. Epoxy glue such as Devcon Plastic Steel is used. The gluing device rigidly holds the platens and specimen to ensure that the platen faces are parallel.





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. 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 collar that surrounds the perimeter of the specimen affixes the radial LVDT. Axial LVDTs are affixed to the platens.



Test Procedures

Six tests are performed using the SST:

- volumetric test,
- uniaxial strain test,
- repeated shear test at constant stress ratio,
- repeated shear test at constant height (not required by Superpave),
- simple shear test at constant height, and
- frequency sweep test at constant height.

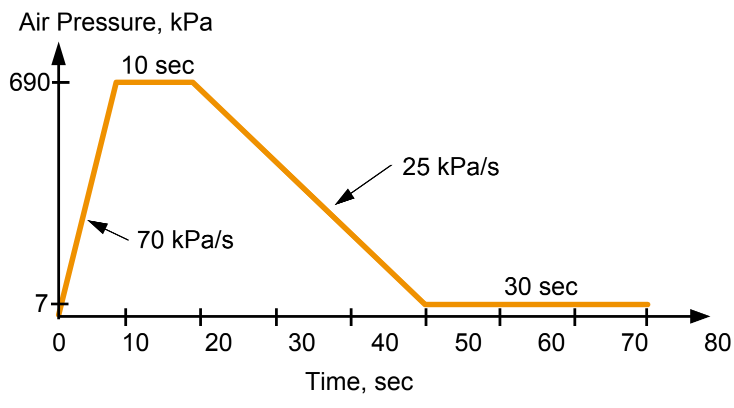
The volumetric and uniaxial strain tests use confining pressure. These two tests are performed to provide additional stress states for a complete analysis. Repeated shear at constant stress ratio, simple shear at constant height, and frequency sweep at constant height tests are used in both intermediate and complete analysis. The repeated shear test at constant height is a stand-alone test that can be used for rut depth estimation and it is not a part of the Superpave mixture design and analysis system. A brief description of each test follows. A full description of the test procedures can be found in AASHTO TP7 *"Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device"*

Volumetric Test

The volumetric test is one of two tests that use confining pressure. The volumetric test results are used for permanent deformation and fatigue cracking analysis in a complete analysis. It is performed at three temperatures and pressures:

Volumetric Test Parameters	
Temperature, °C	Pressure, kPa
4	830
20	690
40	550

The test is performed by increasing the confining stress at a rate of 70 kPa per second up to the values shown and measuring the circumferential or radial strain using the radial LVDT. This figure shows the change in confining pressure versus time during the volumetric test at 20° C.

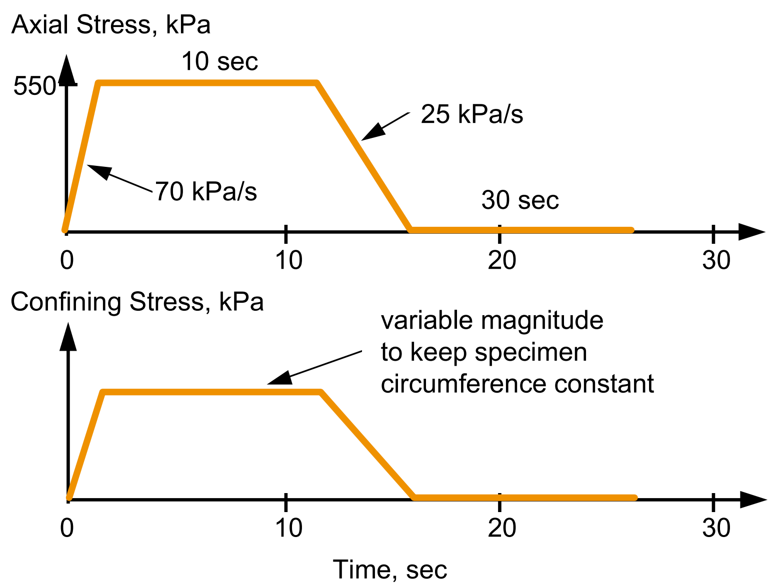


Uniaxial Strain Test

The uniaxial strain test also uses confining pressure. The uniaxial test is used for permanent deformation and fatigue cracking analysis in a complete analysis. In this test, axial stress is applied to the test specimen and the specimen tries to increase its circumference. A radial LVDT senses this change in circumference and air pressure is applied so that the circumference remains constant. As such, the signal from the radial LVDT is used as feedback for the purpose of applying confining pressure to prevent radial deformation. Three axial stress levels are used depending on the test temperature:

Uniaxial Strain Test Parameters	
Temperature, °C	Axial Stress, kPa
4	655
20	550
40	345

Confining pressure is measured throughout the test. Axial deformation is measured on both sides of the specimen by the vertical LVDTs. Axial load is also measured. Radial deformation is also measured although it should be relatively small. This figure shows the application of axial stress during the test.



Repeated Shear Test at Constant Stress Ratio

The repeated shear test at constant stress ratio is performed for either an intermediate and complete analysis as a screening test to identify an asphalt mixture that is subject to tertiary rutting. This form of rutting occurs at low air void contents and is the result of bulk mixture instability.

In this test, repeated synchronized haversine shear and axial load pulses are applied to the specimen. The 0.7-second load cycle consists of a 0.1-second load followed by 0.6-second rest period. Test specimens are subjected to a varying number of load cycles in the range from 5000 to 120,000, depending on the traffic level and climate conditions or until accumulated permanent strain reaches five percent. The ratio of axial to shear stress is maintained constant in the range from 1.2 to 1.5. The magnitude of stresses is selected to simulate actual in-place stresses that will be encountered by the mixture.

The test temperature used is called the control temperature (T_c) for permanent deformation. It is computed by Superpave as a function of the project traffic conditions and climate. The test is typically performed at high asphalt contents corresponding to three percent air voids, which is the extreme condition for tertiary rutting. During the test axial and shear loads and deformations are measured and recorded.

Repeated Shear Test at Constant Height

This test is performed as an option to intermediate or complete analysis to estimate rut depth and is not a required by Superpave. A haversine shear load is applied to achieve a controlled shear stress level of 68 kPa. When the repeated shear load is applied, the test specimen seeks to dilate. The signal from the axial LVDT is used as feedback by the vertical actuator to apply sufficient axial load to keep the specimen from dilating.

A load cycle consists of 0.7-second, which is comprised of 0.1-second shear load application followed by 0.6-second rest period. Test specimens are subjected to 5000 load cycles or until the permanent shear strain reaches five percent. The test temperature used is T_{max}, which is the seven-day maximum pavement temperature at 50 mm depth. During the test, axial and shear loads and deformations are measured and recorded.

Simple Shear Test at Constant Height

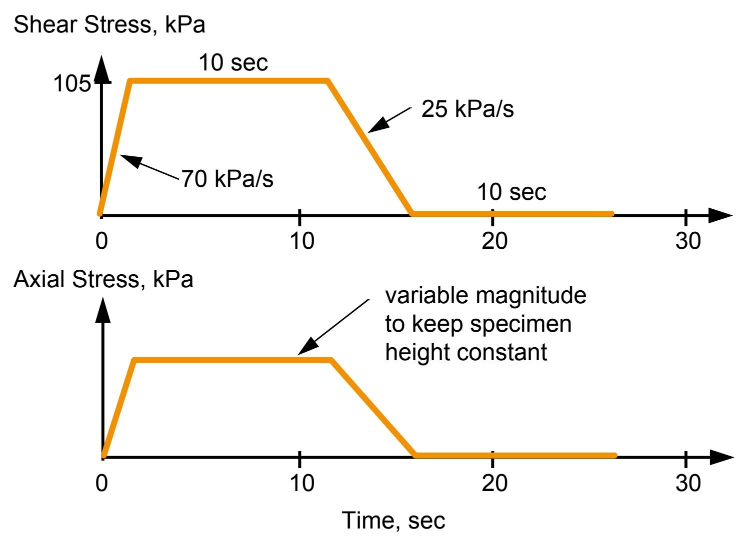
This test is used for permanent deformation and fatigue cracking analysis in intermediate or complete analysis. A controlled shearing stress is applied to a test specimen, causing the specimen to dilate and increase in height. The vertical actuator uses the signal from the axial LVDT to apply sufficient axial stress to keep the specimen height constant. The test is performed at different stress levels and temperatures depending on whether an intermediate or complete analysis is being performed:

Simple Shear Test Parameters

Analysis Level	Temperature, °C	Shear Stress, kPa
Intermediate	T_{eff}(PD) T_{eff}(FC)	35 105
Complete	4 20 40	345 105 35

In this table, T_{eff}(FC) is the effective pavement temperature for fatigue cracking. It is computed by Superpave as a function of climate, depth of mixture in pavement, and designer selected reliability level in the same manner as T_{eff}(PD).

This figure shows the application of stresses during the test. During the test axial and shear loads and deformations are measured and recorded.



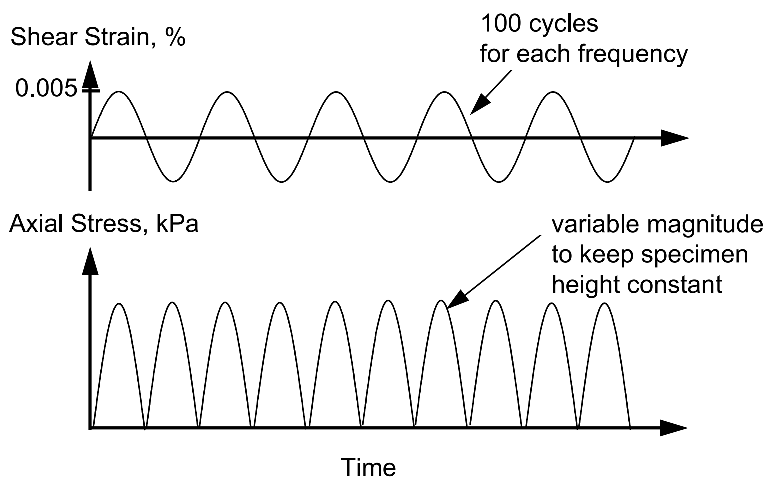
Frequency Sweep Test at Constant Height

This test is used for permanent deformation and fatigue cracking analysis in intermediate or complete analysis. A repeated sinusoidal shearing load is applied to the specimen to achieve a controlled shearing strain of 0.005 percent. One hundred cycles are used for the test at various loading frequencies.

As the test specimen is sheared, it wants to dilate and increase in height. The vertical actuator uses the signal from the axial LVDT to apply enough axial stress to keep the specimen height constant. The test is performed at different temperatures depending on whether an intermediate or complete analysis is being performed:

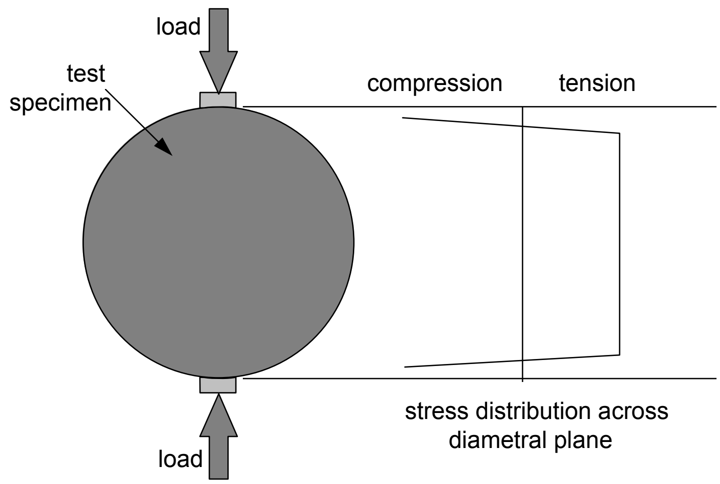
Frequency Sweep Test Parameters	
Analysis Level	Temperature, °C
Intermediate	T_{eff}(PD) T_{eff}(FC)
Complete	4 20 40

During the test axial and shear loads and deformations are measured and recorded. This figure illustrates the application of shearing strains and axial stresses during the test.

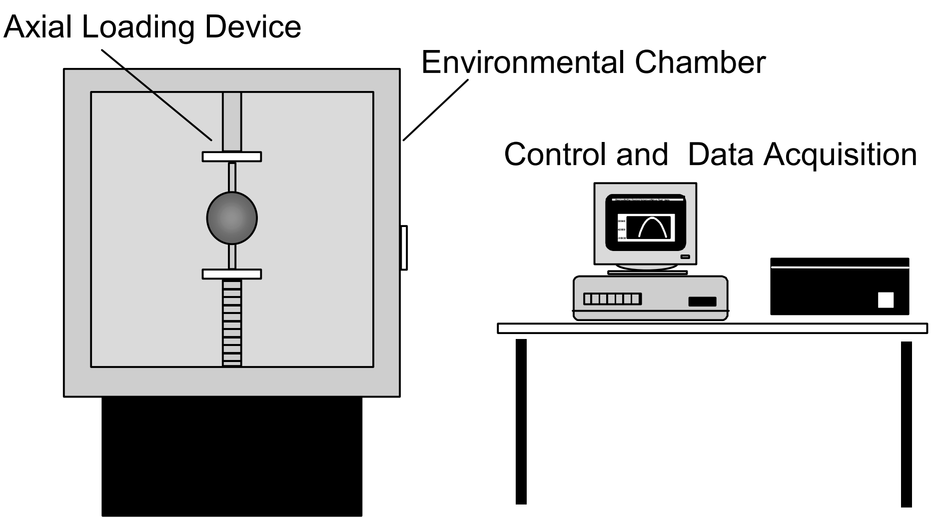


INDIRECT TENSILE TESTER

The IDT measures the creep compliance and strength of asphalt mixtures using indirect tensile loading techniques at intermediate to low temperatures (< 20°C). Indirect tensile testing involves applying a compressive load across the diametrical axis of a cylindrical specimen. The mechanics of the test place a nearly uniform state of tensile stress across the diametrical plane.



The IDT device has four components: the testing apparatus, the test control unit and data acquisition system, load measuring device, and the environmental control chamber.



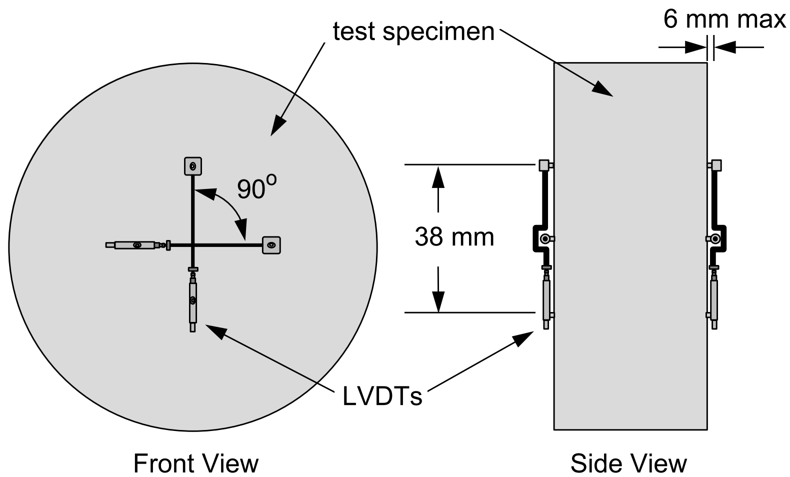
The testing apparatus consists of a closed-loop servo-hydraulic, or mechanical screw system capable of resolving static loads as low as 5 N. A rigid loading frame is also necessary so that precise displacement measurements can be made without frame movement.

The reaction of specimens to load can be measured using a strip chart recorder or a data acquisition device. Applied loads are measured and controlled using an electronic load cell. The environmental chamber controls test temperatures in the range from -20° to 20°C and accommodates at least three test specimens and the loading frame.

Specimen Preparation and Instrumentation

The first step in specimen preparation is to trim test specimens to a thickness-to-diameter ratio greater than 0.33. For a 150-mm diameter specimen, the minimum specimen thickness is 50 mm. The trimmed specimens must have smooth, parallel surfaces for mounting measurement gauges.

The load response of test specimens is measured by LVDTs mounted to the face of the specimen. Two sets of two LVDTs are mounted at right angles on each side of the specimen.



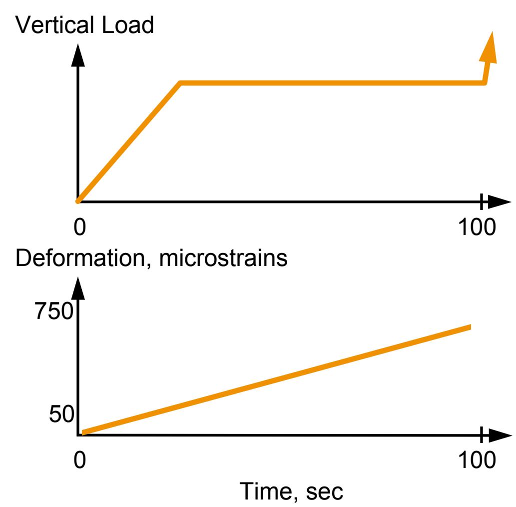
Test Procedures

Two tests are performed using the IDT: Creep Compliance and Strength at Low Temperatures and IDT Strength at Intermediate Temperatures. A full description of the procedures can be found in AASHTO TP9 *"Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device".*

IDT Creep Compliance and Strength (Low Temperature Cracking Analysis)

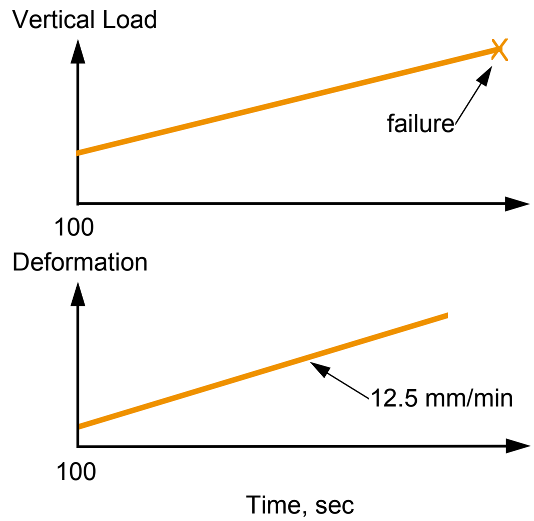
This test is used to analyze mixtures for low temperature cracking. It is performed at three temperatures (0°, -10°, and -20°C) for both intermediate and complete analysis.

Initially, a static creep load of fixed magnitude is placed on the specimen. The load applied should be that which produces between 50 and 750 horizontal microstrain in the test specimen during the 100-second creep phase of the test. Vertical and horizontal deformations are measured on both sides of the specimen throughout the test.



After the 100-second creep loading, the specimen is loaded until failure (peak load) by applying additional load at a rate of 12.5 mm per minute. 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.

For intermediate analysis, test specimens are tested for creep compliance at 0°, -10°, and -20°C with tensile strength measured only at -10°C. Complete analysis requires that creep compliance and tensile strength be measured at all three temperatures.

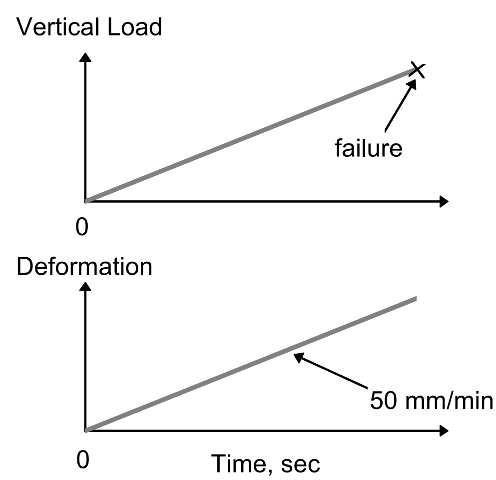


IDT Strength (Fatigue Cracking Analysis)

This test is used to analyze mixtures for fatigue cracking resistance. Intermediate and complete analysis use various temperatures ranging from -10°C to 20°C::

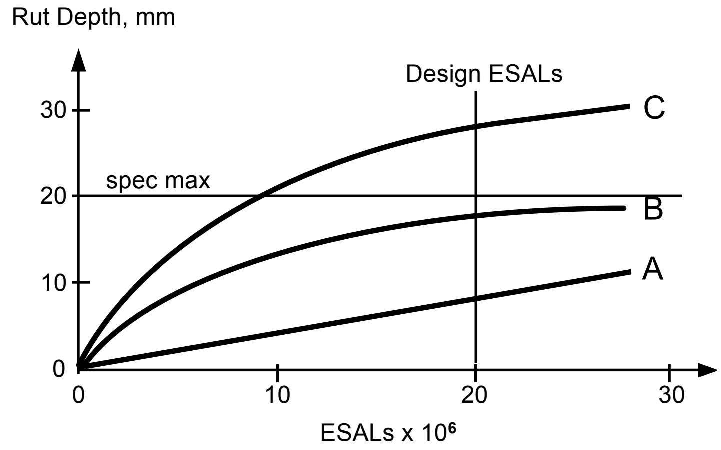
Indirect Tensile Strength Test Parameters	
Analysis Level	Temperature, °C
Intermediate	T_{eff}(FC)
Complete	-10, 4, 20

In this test, the specimen is loaded at a constant deformation rate of 50 mm per minute of vertical ram movement. The specimen is loaded until failure -- peak load. Load and deformation are measured throughout the test.



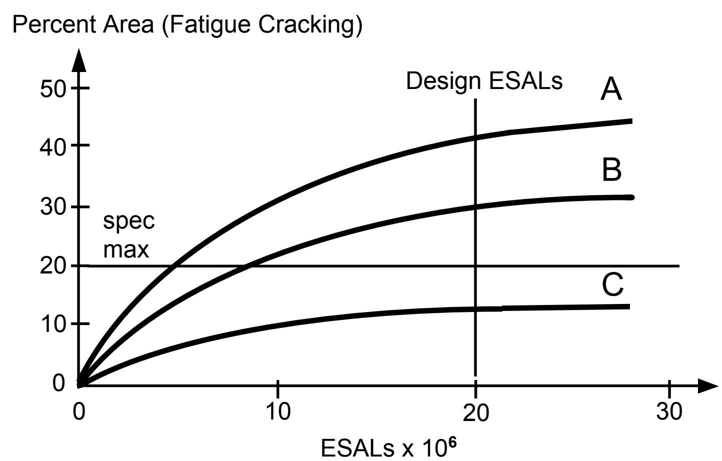
DATA ANALYSIS AND INTERPRETATION

The data collected from mix analysis testing can be analyzed separately by looking at individual properties or eventually, these files will be used in the performance prediction models in Superpave to predict pavement performance for various combinations of asphalt binder and mineral aggregate. Performance plots such as those shown are used to select a mixture that offers the desired level of performance. In these figures, Materials A, B, and C might be three entirely different materials. If so, the performance prediction would be considered part of an *analysis* procedure. This methodology is suited to evaluating the performance effects of aggregate types and proportions, asphalt and mixture modifiers, or any other potentially innovative HMA ingredient.



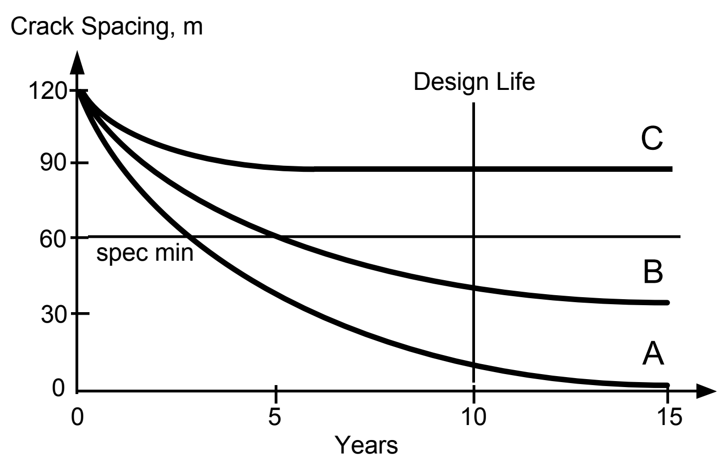
Permanent Deformation

For the materials represented in the figures, no material meets all the distress criteria at the design number of ESALs. However, if cracking distress, such as fatigue or low temperature, were the primary concern, Material C would be a clear choice since it meets the specified performance values. Unfortunately, Material C would exhibit significant rutting after relatively few load applications. Both Materials A and B meet the rutting criterion but they fail the cracking criteria. Because fatigue life is greatly affected by pavement thickness, it may be possible to slightly increase the layer thickness so that Material B would meet the fatigue cracking criterion.

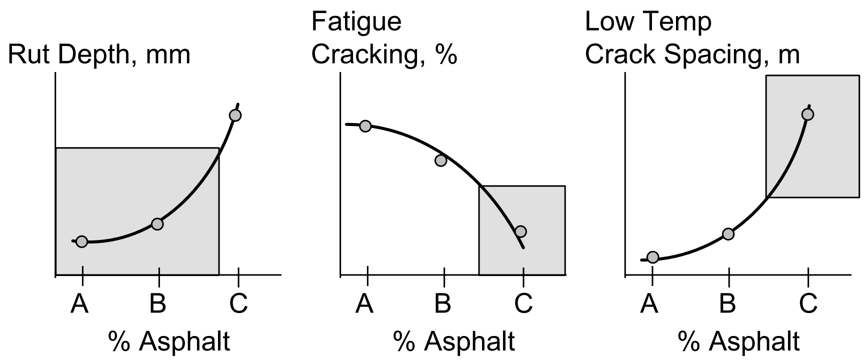


Fatigue Cracking

Alternatively, Materials A, B, and C might be the same aggregate blend with varying binder content. Material A has the lowest binder content while Material C has the highest binder content. Material B has a median value of binder content. In that case, the performance prediction would be considered a *design* procedure and three additional design plots would be useful. These design plots would define the range of binder contents meeting performance standards. In this example, a binder content that lies approximately two-thirds of the way between B and C would optimize pavement performance. This type of information would also be useful in establishing job control tolerances.



Low Temperature Cracking



Design Chart

In summary, the interpretation of data in a mix analysis is usually a balancing act between opposing factors. With alternative mixtures, many times a compromise is necessary between cost and performance; mixes with special additives typically require more money than one with more conventional materials. When selecting the optimum binder content, lower values are more favorable for rutting while higher values are more favorable to cracking. Sometimes, a compromise may not be possible; it may be decided by which kind of distress is more critical.

Finally, the ultimate utilization of a fully-functional Superpave Mix Analysis System would be to compare not only mix alternatives, but structural alternatives as well. Because the mix performance is greatly dependent on the structure in which it is placed, there may exist some optimizations and tradeoffs between the properties and components of a mixture and the layer design thickness.