III. Superpave Binders

Superpave uses a completely new system for testing, specifying, and selecting asphalt binders. The objectives of this section will be to:

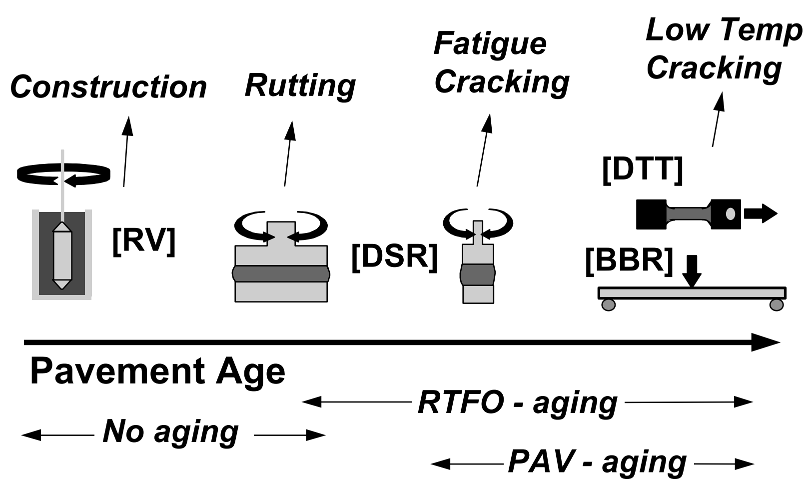
- describe the Superpave binder test equipment
- discuss where the tests fit into the range of material conditions (temperature and aging conditions) experienced by asphalt pavements
- explain the Superpave specification requirements and how they are used in preventing permanent deformation, fatigue cracking and low temperature cracking
- discuss how to select the performance grade (PG) binder for a project's climatic and traffic conditions

SUPERPAVE BINDER TESTS

Binder Aging Methods

A central theme of the Superpave binder specification is its reliance on testing asphalt binders in conditions that simulate critical stages during the binder's life. The three most critical stages are:

- during transport, storage, and handling,
- during mix production and construction, and
- after long periods in a pavement



Tests performed on unaged asphalt represent the first stage of transport, storage, and handling.

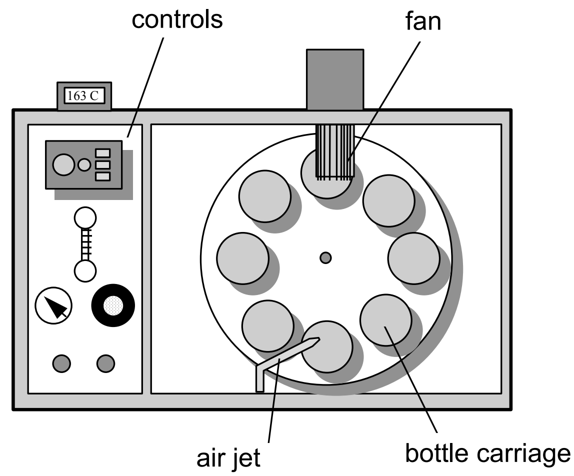
Aging the binder in a rolling thin film oven (RTFO) simulates the second stage, during mix production and construction. The RTFO aging technique was developed by the California Highway Department and is detailed in AASHTO T-240 (ASTM D 2872). This test exposes films of binder to heat and air and approximates the exposure of asphalt to these elements during hot mixing and handling.

The third stage of binder aging occurs after a long period in a pavement. This stage is simulated by use of a pressure aging vessel (PAV). This test exposes binder samples to heat and pressure in order to simulate, in a matter of hours, years of in-service aging in a pavement.

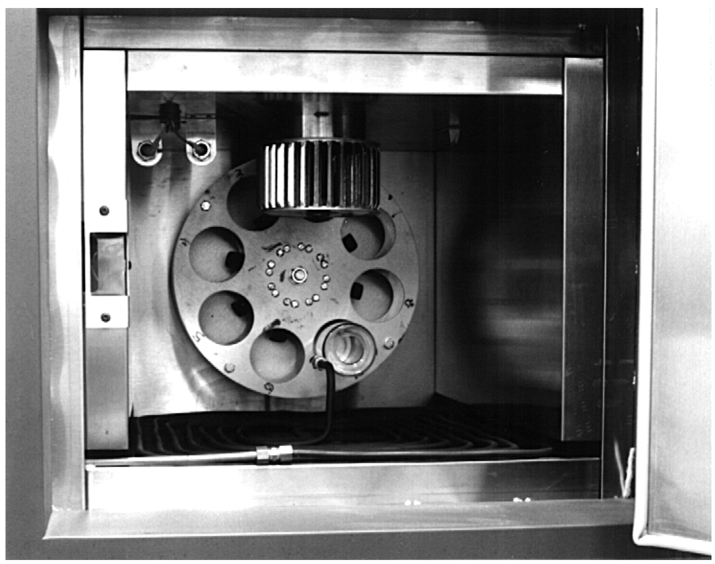
It is important to note that for specification purposes, binder samples aged in the PAV have already been aged in the RTFO. Consequently, PAV residue represents binder that has been exposed to all the conditions to which binders are subjected during production and in-service.

ROLLING THIN FILM OVEN (RTFO)

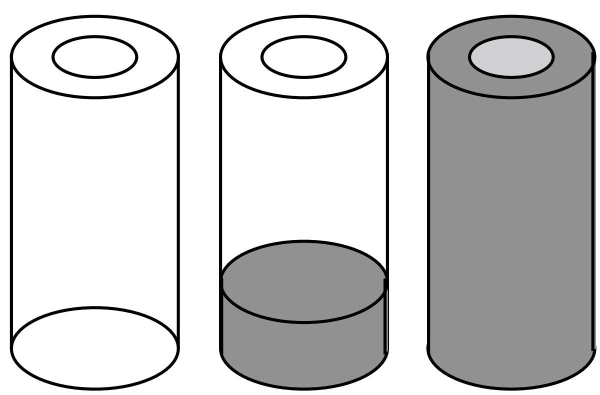
Test Equipment



The RTFO procedure requires an electrically heated convection oven. Specific oven requirements are detailed in AASHTO T 240, "*Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin Film Oven Test*)." The oven contains a vertical circular carriage that contains holes to accommodate sample bottles. The carriage is mechanically driven and rotates about its center. The oven also contains an air jet that is positioned to blow air into each sample bottle at its lowest travel position while being circulated in the carriage.



Specimen Preparation



Before Filling　After Loading　Coated Bottle After Testing

To prepare for RTFO aging, a binder sample is heated until sufficiently fluid to pour. In no case should the sample be heated to 150° C. RTFO bottles are loaded with 35 ± 0.5 g of binder. The RTFO has an eight bottle capacity; however, the contents of two bottles must be used to determine mass loss. If mass loss is being determined, the two bottles containing samples should be cooled and weighed to the nearest 0.001 g. Otherwise, the RTFO residues from the eight bottles are poured into a single container and stirred to ensure homogeneity. RTFO residue should be poured from the coated bottle and as much of the remaining residue as practical should be scraped out. This material may be used for DSR testing or transferred into PAV pans for additional aging or equally proportioned into small containers and stored for future use.

Overview of Procedure

The RTFO oven must be preheated at the aging temperature, 163° ± 0.5° C, for a minimum of 16 hours prior to use. The thermostat should be set so that the oven will return to this temperature within 10 minutes after the sample bottles are loaded.

Bottles are loaded into the carriage with any unused slots filled with empty bottles. The carriage should be started and rotated at a rate of 15 ± 0.2 rev/min. The air flow should be set at a rate of 4000 ± 200 ml/min. The samples are maintained under these conditions for 85 minutes.

If mass loss is being determined, the mass loss sample and bottles are allowed to cool to room temperature and weighed to the nearest 0.001 g.

Data Presentation

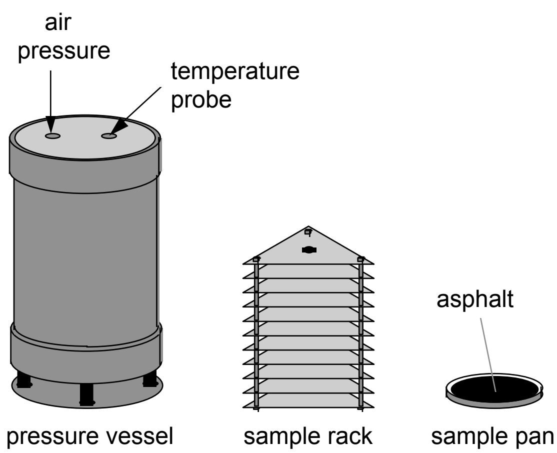
The primary purpose of RTFO procedure is the preparation of aged binder materials for further testing and evaluation with the Superpave binder tests. The RTFO procedure is also used to determine the mass loss, a measure of the material vaporized by the RTFO procedure. A high mass loss value would identify a material with excessive volatiles, and one that could age excessively. Mass loss is reported as the average of the two samples after RTFO aging, and is calculated by this formula:

Mass Loss, % = [(Original mass - Aged mass)/Original Mass] x 100 %

PRESSURE AGING VESSEL

Test Equipment

Two types of pressure aging devices have been developed. The first type consisted of the stand-alone pressure aging vessel that was placed inside a temperature chamber. The second type consists of the pressure vessel built as part of the temperature chamber. The operating principles of the equipment are the same. Specific equipment details can be found in AASHTO PP1, *"Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)"*. For illustrative purposes, the separate vessel type is shown and described here.



The pressure vessel is fabricated from stainless steel and is designed to operate under the pressure and temperature conditions of the test (2070 kPa and either 90°, 100°, or 110° C). The vessel must accommodate at least 10 sample pans and does so by means of a sample rack, which is a frame that fits conveniently into the vessel. The vessel lid is secured to prevent pressure loss.

Air pressure is provided by a cylinder of dry, clean compressed air with a pressure regulator, release valve, and a slow release bleed valve. The vessel lid is fitted with a pressure coupling and temperature transducer. The temperature transducer connects to a digital indicator that allows visual monitoring of internal vessel temperature throughout the aging period. Continuous monitoring of temperature is required during the test.

A forced draft oven is used as a temperature chamber. The oven should be able to control the test temperature to within ± 0.5° C for the duration of the test. A digital proportional control and readout of internal vessel temperature is required.

Specimen Preparation

To prepare for the PAV, RTFO residue is transferred to individual PAV pans. The sample should be heated only to the extent that it can be readily poured and stirred to ensure homogeneity. Each PAV sample should weigh 50 g. Residue from approximately two RTFO bottles is normally needed for one 50-g sample.

Overview of Procedure

The temperature chamber (oven) is turned on and the vessel is placed in the chamber, unpressurized, and allowed to reach the desired test temperature.

The PAV pans are placed in the sample rack.   When the test temperature has been achieved the vessel is removed from the oven and the samples in the sample rack are placed in the hot vessel. The lid is installed and the lid is secured. This step should be completed as quickly as possible to avoid excessive loss of vessel heat.

The temperature chamber and the pressure hose and temperature transducer are coupled to their respective mates. When the vessel temperature is within 2° C of the test temperature, air pressure is applied using the valve on the air cylinder regulator. When air pressure has been applied, the timing for the test begins.

After 20 hours, the pressure is slowly released using the bleed valve. Usually, 8 to 10 minutes are required to gradually release the pressure. If pressure is released more quickly, excessive air bubbles will be present in the sample and it may foam.

The pans are removed from the sample holder and placed in an oven at 163° C for 15 minutes. Remove the entrapped air from the samples. The samples are then transferred to a container that stores the material for further testing.

Data Presentation

The sole purpose of the PAV procedure is the preparation of aged binder materials for further testing and evaluation with the Superpave binder tests. A report for the PAV procedure contains:

- sample identification,
- aging test temperature to the nearest 0.1° C,
- maximum and minimum aging temperature recorded to the nearest 0.1° C,
- total time during aging that temperature was outside the specified range to the nearest 0.1 min., and
- total aging time in hours and minutes.

Pressure Vessel Built into Oven

Pressure Aging Vessel Inside of Oven

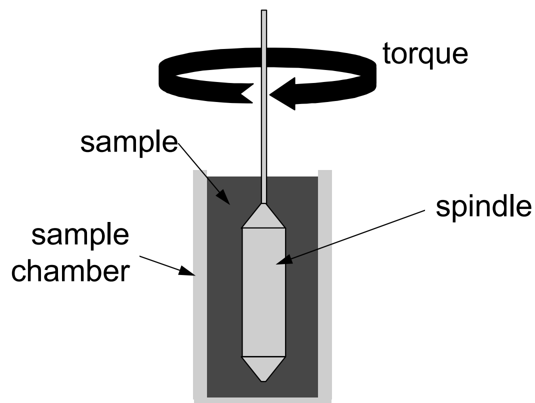
Rotational Viscometer

Rotational viscosity is used to evaluate high temperature workability of binders. A rotational coaxial cylinder viscometer, such as the Brookfield apparatus is used rather than a capillary viscometer. Some asphalt technologists refer to this measure as "Brookfield viscosity." This method of measuring viscosity is detailed in AASHTO TP48, *"Viscosity Determination of Asphalt Binders Using Rotational Viscometer."*

High temperature binder viscosity is measured to ensure that the asphalt is fluid enough when pumping and mixing. Consequently, rotational viscosity is measured on unaged or "tank" asphalt and must not, according to the Superpave binder specification, exceed 3 Pa-s when measured at 135° C.

Rotational viscosity is determined by measuring the torque required to maintain a constant rotational speed of a cylindrical spindle while submerged in a sample at a constant temperature.

The torque required to rotate the spindle at a constant speed is directly related to the viscosity of the binder sample, which is determined automatically by the viscometer.



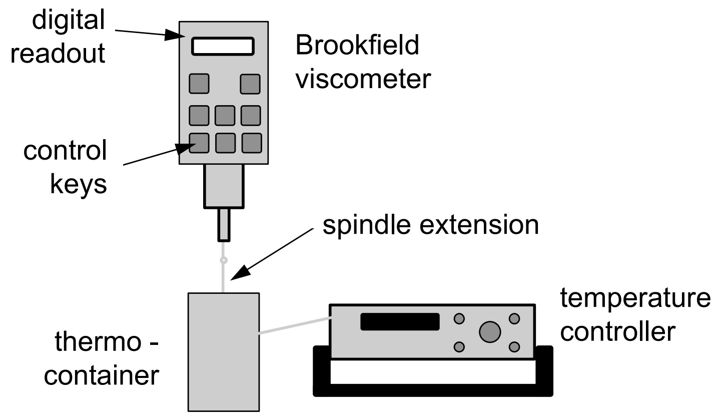
Specimen Preparation

Approximately 30 g of binder is heated in an oven so that it is sufficiently fluid to pour. In no case should the sample be heated above 150° C. During heating, the sample occasionally should be stirred to remove entrapped air. Asphalt is weighed into the sample chamber. The amount of asphalt used varies depending on the spindle. A larger spindle means that less asphalt can be placed in the chamber. Typically, less than 11 grams are used. The sample chamber containing the binder sample is placed in the thermo container and is ready to test when the temperature stabilizes, usually about 15 minutes.

Test Equipment

The apparatus used to measure rotational viscosity consists of two items:

- Brookfield viscometer
- Thermosel™ system



The Brookfield viscometer consists of a motor, spindle, control keys, and digital readout. The motor powers the spindle through a spring. The spring is wound as the torque increases. A rotary transducer measures torque in the spring. For most rotational viscometers and specification testing, the motor should be set at 20 rpm.

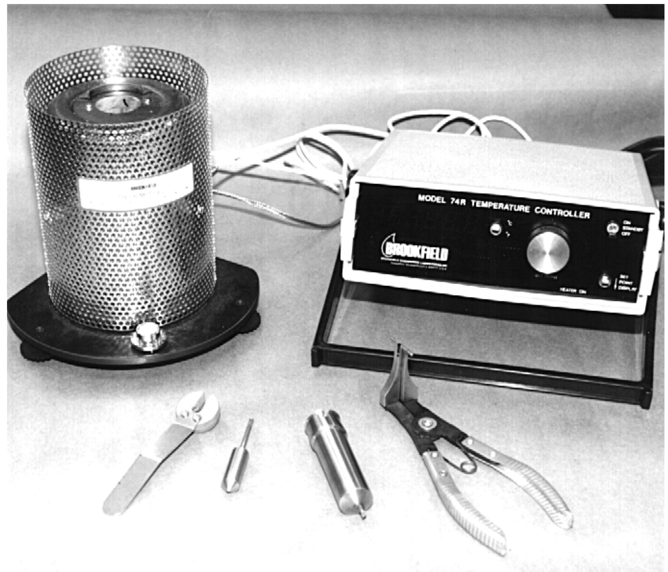
The spindle is cylindrical in shape and resembles a plumb bob. It resists rotation due to the viscosity of the binder in which it is submerged. Many spindles are available for the Brookfield apparatus. The proper spindle is selected based on the viscosity of the binder being tested. Many binders can be tested with only two spindles: Nos. 21 and 27. Of these, spindle No. 27 is used most frequently.

Applied torque and rotational speed are indicated on the digital readout. The control keys are used to input test parameters such as spindle number, which tells the viscometer which spindle is being used. The keys also are used to set rotational speed and turn the motor on and off.

The viscometer must be leveled to function properly. A bubble-type level indicator is located on top of the viscometer and is adjusted by means of leveling screws on the base.

The Thermosel system consists of the sample chamber, thermo container, and temperature controller. The sample chamber is a stainless steel cup in the shape of a test tube. An extracting tool is used to handle the sample chamber when hot.

The thermo-container holds the sample chamber and consists of electric heating elements that maintain or change test temperature. The temperature controller allows the operator to set the test temperature at the required 135° C. A bubble-type level mounted on the base of the thermo-container stand ensures that the thermo-container is level.

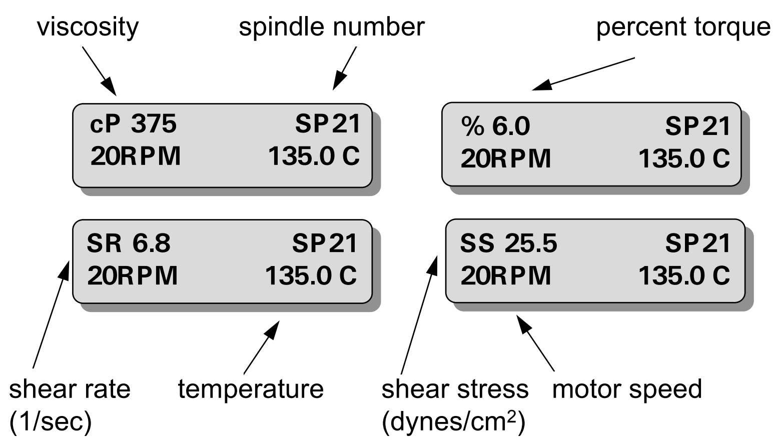


Overview of Procedure

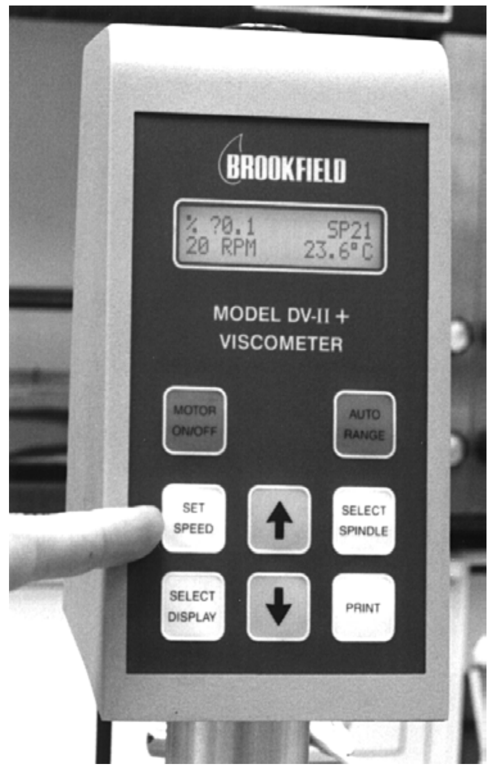
When the digital indicator on the temperature controller shows that the sample temperature has equalized, the sample can be tested. The spindle is lowered into the chamber containing the hot sample and the spindle is coupled with the viscometer using a threaded connector.

A waiting period (normally about 15 minutes) is required to allow the sample temperature to return to 135°C. During this period, the viscometer motor is turned-on and the operator can observe the viscosity reading. As the temperature equalizes, the viscosity reading will stabilize and the operator can begin to obtain test results.

The operator can set the digital display to show viscosity information that is needed for the report. This information is: viscosity, test temperature, spindle number, and speed. Three viscosity readings should be recorded at 1-minute intervals. Note that in selection the display information, only the upper-left item in the display changes.



In some cases, it may be desirable to determine binder viscosity at temperatures other than 135°C. For example, most agencies use equiviscous temperatures for mixing and compaction during mix design. To accomplish this, the Thermosel™ controller is reset to the desired temperature, such as 165°C, until the thermo-container brings the sample to this temperature. This step takes about 30 minutes, after which, the test is again performed as described above.



Data Presentation

The viscosity at 135°C is reported as the average of three readings. The digital output of the rotational viscosity test is viscosity in units of centipoise (cP) while the Superpave binder specification uses Pa-s. To convert, this equation is used:

$$1000 \text{ cP} = 1 \text{ Pa}\cdot\text{s}$$

Therefore, multiply the Brookfield viscosity output in cP by 0.001 to obtain the viscosity in Pa·s. As mentioned previously, in addition to viscosity, the test temperature, spindle number, and speed are required items to be reported.

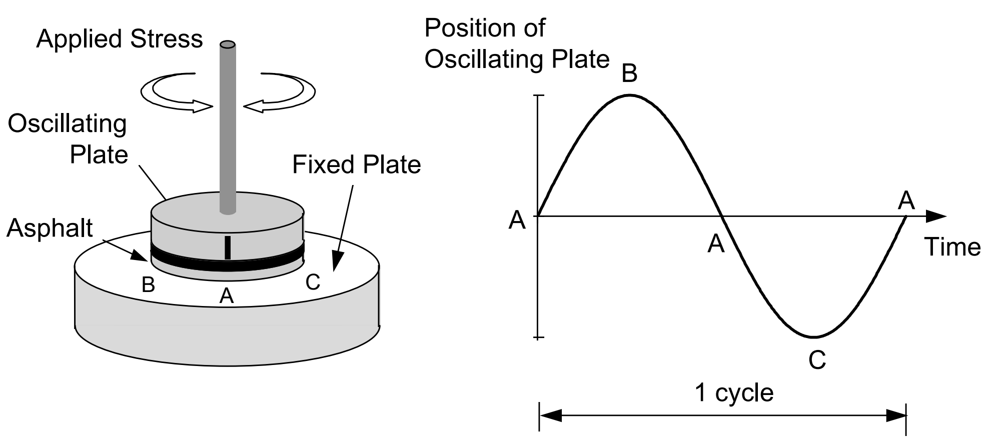
Dynamic Shear Rheometer

As discussed earlier, asphalt is a viscoelastic material, meaning that it simultaneously shows the behavior of an elastic material (e.g. rubber band) and a viscous material (e.g. molasses). The relationship between these two properties is used to measure the ability of the binder to resist permanent deformation and fatigue cracking. To resist rutting, a binder needs to be stiff and elastic; to resist fatigue cracking, the binder needs to be flexible and elastic. The balance between these two needs is a critical one.

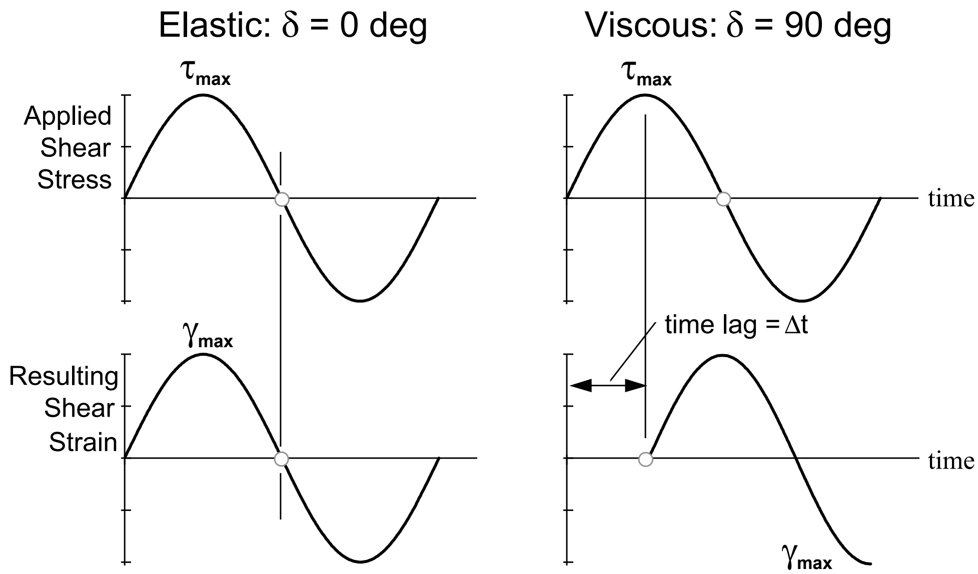
The Dynamic Shear Rheometer (DSR) is used to characterize the viscous and elastic behavior of asphalt binders. It does this by measuring the viscous and elastic properties of a thin asphalt binder sample sandwiched between an oscillating and a fixed plate. Operational details of the DSR can be found in AASHTO TP5 *"Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer."*

Test Equipment

The principle of operation of the DSR is straightforward. An asphalt sample is sandwiched between an oscillating spindle and the fixed base. The oscillating plate (often called a "spindle") starts at point A and moves to point B. From point B the oscillating plate moves back, passing point A on the way to point C. From point C the plate moves back to point A. This movement, from A to B to C and back to A comprises one cycle.

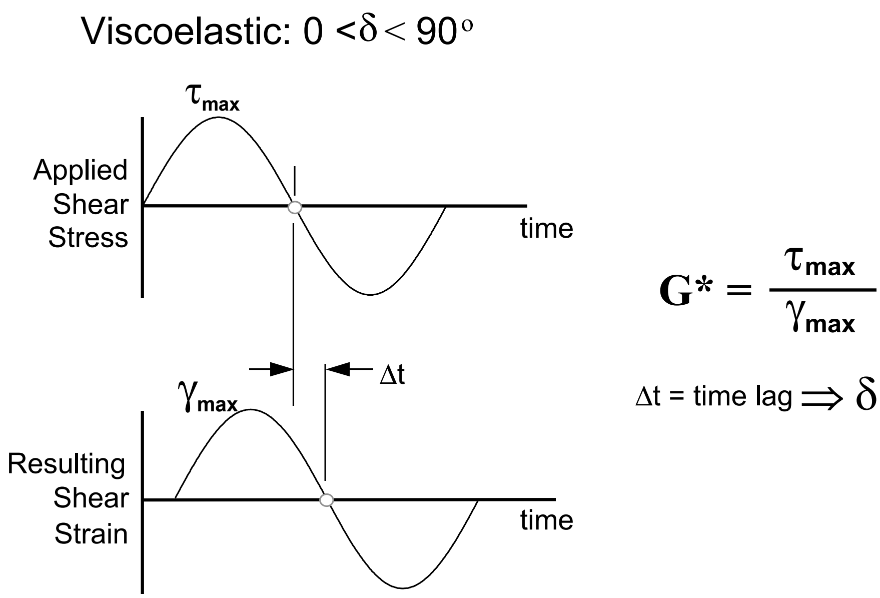


As the force (or shear stress, τ) is applied to the asphalt by the spindle, the DSR measures the response (or shear strain, γ) of the asphalt to the force. If the asphalt were a perfectly elastic material, the response would coincide immediately with the applied force, and the time lag between the two would be zero. A perfectly viscous material would have a large time lag between load and response. Very cold asphalt performs like an elastic material. Very hot asphalt performs like a viscous material.

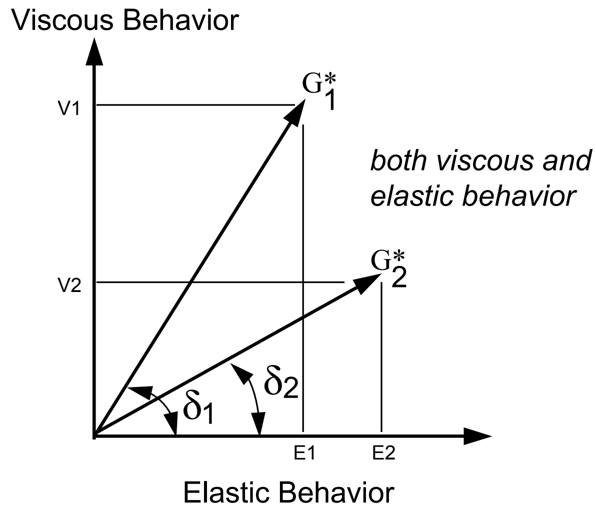


At temperatures where most pavements carry traffic, asphalt behaves both like an elastic solid and a viscous liquid. The relationship between the applied stress and the resulting strain in the DSR quantifies both types of behavior, and provides information necessary to calculate two important asphalt binder properties: the complex shear modulus (G* -"G star") and phase angle (δ - "delta").

G* is the ratio of maximum shear stress (τ_{max}) to maximum shear strain (γ_{max}). The time lag between the applied stress and the resulting strain is the phase angle δ. For a perfectly elastic material, the phase angle, δ, is zero, and all of the deformation is temporary. For a viscous material (such as hot asphalt), the phase angle approaches 90 degrees, and all of the deformation is permanent. In the DSR, a viscoelastic material such as asphalt at normal service temperatures displays a stress-strain response between the two extremes, as shown below.



Describing this viscoelastic behavior in a different manner, G* is a measure of the total resistance of a material to deforming when repeatedly sheared. It consists of two parts: a part that is elastic (temporary deformation) as shown by the horizontal arrow, and a part that is viscous (permanent deformation) as indicated by the vertical arrow. δ, the angle made with the horizontal axis, indicates the relative amounts of temporary and permanent deformation. In this example, even though both asphalts are viscoelastic, asphalt 2 is more elastic than asphalt 1 because of its smaller δ. By determining both G* and δ, the DSR provides a more complete picture of the behavior of asphalt at pavement service temperatures.



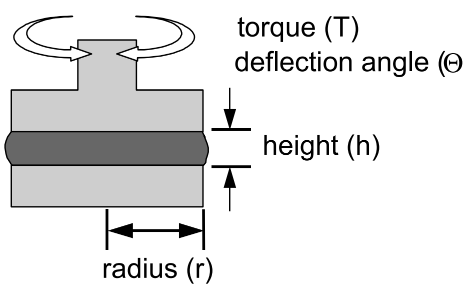
For asphalt, the values of G* and δ are highly dependent on the temperature and frequency of loading. Therefore, it is important to know the climate of the project where the pavement is being constructed, as well as the relative speed of the traffic to be using the facility. These concepts will be furthered discussed later in this section.

The formulas used by the rheometer software to calculate τ_{max} and γ_{max} are:

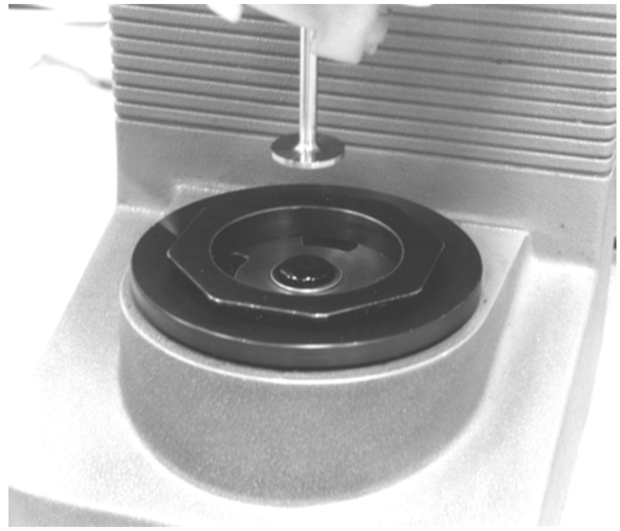
$\tau_{max} = 2T/\pi r^3$ and

$\gamma_{max} = \Theta r/h$

where T = maximum applied torque,
r = radius of specimen/plate (either 12.5 or 4 mm),
Θ = deflection (rotation) angle,
h = specimen height (either 1 or 2 mm).



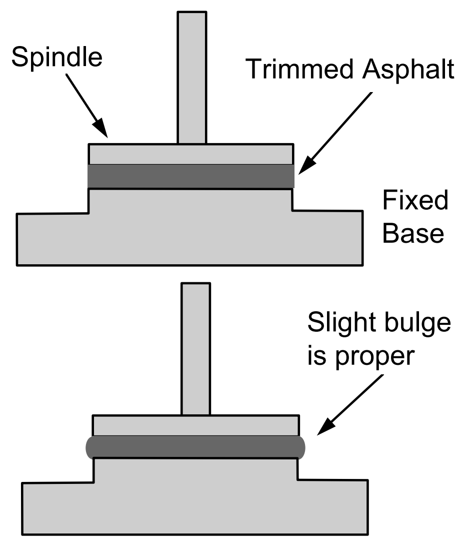
Because the properties of asphalt binders are so temperature dependent, rheometers must have a precise means of controlling the temperature of the sample. This is normally accomplished by means of a circulating fluid bath or forced air bath. Fluid baths normally use water to surround the sample. The water is circulated through a temperature controller that precisely adjusts and maintains the sample temperature uniformly at the desired value. Air baths operate in the same manner as water baths except that they surround the sample with heated air during testing. In either case, the temperature of the air or water must be controlled so that the temperature of the sample across the gap is uniform and varies by no more than 0.1° C.



Again, the operator need not worry about performing these calculations since they are performed automatically by the rheometer software. However, the radius of the specimen is a crucial factor since its value is raised to the fourth power in the G* calculations, so careful specimen trimming is very important. Specimen height (i.e. the gap between the plates) is also an important factor that is mostly affected by the control and skill of the operator.

Specimen Preparation

The thickness of the asphalt disk sandwiched between the spindle and the fixed plate must be carefully controlled. The proper specimen thickness is achieved by adjusting the gap between the spindle and fixed plate. This gap must be set before mounting the asphalt sample but while the spindle and base plate are mounted in the rheometer and at the test temperature. The gap is adjusted by means of a micrometer wheel. The micrometer wheel is graduated, usually in units of microns. Turning the wheel allows precise positioning of the spindle and base plate relative to each other. On some rheometers the micrometer wheel moves the spindle down. On other rheometers, it moves the base plate up. The thickness of gap used depends on the test temperature and the aged condition of the asphalt. Unaged and RTFO aged asphalt, tested at high temperatures of 46°C or greater, require a small gap of 1000 microns (1 mm). PAV aged asphalts, tested at intermediate test temperatures, in the range of 4° to 40°C, require a larger gap of 2000 microns (2 mm). Likewise, two spindle diameters are used. High temperature tests require a large spindle (25 mm), and intermediate test temperatures require a small spindle (8 mm).



The operator normally sets the gap before mounting the specimen, at the desired value (1000 or 2000 microns) plus an extra 50 microns. This 50 microns is dialed out using the micrometer wheel after final specimen trimming.

A disk of asphalt with diameter equal to the oscillating plate of the DSR is needed for testing. There are two ways to prepare the sample:

(1) asphalt can be poured directly onto the spindle in the proper quantity to provide the appropriate thickness of material

(2) a mold can be used to form the asphalt disk, then the asphalt can be placed between the spindle and fixed plate of the DSR.

Pouring asphalt onto spindle

In the first method, experience is necessary to apply the proper amount of asphalt. There must not be too much or too little material. If there is too little, the test will be inaccurate. If there is too much, excess sample trimming will be required.

In the second method, asphalt is heated until fluid enough to pour. The heated asphalt is poured into a silicone mold and allowed to cool until solid enough to remove the asphalt from the mold. After removal from the mold, the asphalt disk is placed between the fixed plate and the oscillating spindle of the DSR. As before, excess asphalt beyond the edge of the spindle should be trimmed.

Pouring asphalt into molds

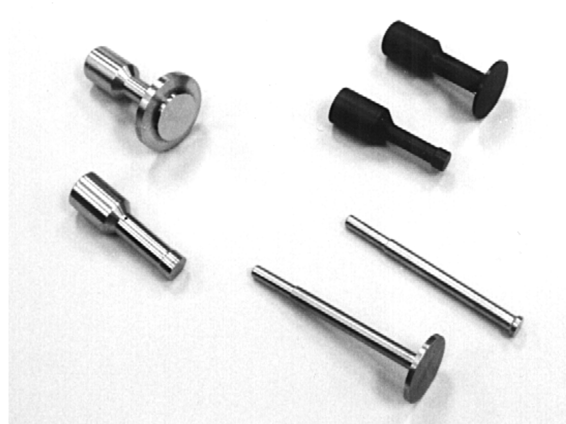
After specimen trimming, the final step in preparing the specimen is to close the gap between the spindle and lower plate by 50 mm, so that a slight bulge is evident near the edge of the spindle. This step normally occurs immediately prior to testing.

Overview of Procedure

After the asphalt sample is correctly in place and the test temperature appears stable, the operator must allow about ten minutes for the temperature of the specimen to equilibrate to the test temperature. The actual temperature equilibration time is equipment and asphalt dependent and should be checked using a dummy specimen equipped with very accurate temperature sensing capabilities.

A computer is used with the DSR to control test parameters and record test results. Testing consists of using the rheometer software to apply a constant oscillating stress, and then recording the resulting strain and time lag. The Superpave specifications require the oscillation speed to be 10 radians/second, which is approximately 1.59 Hz.

The operator enters the value of applied stress that will cause an approximate amount of shear strain (sometimes called "strain amplitude") in the asphalt. Shear strain values vary from one to 12 percent and depend on the stiffness of the binder being tested. Relatively soft materials tested at high temperatures, (e.g., unaged binders and RTFO aged binders) are tested at strain values of approximately ten to twelve percent. Hard materials (e.g., PAV residues tested at intermediate temperatures) are tested at strain values of about one percent.



The stiffness of the material tested also relates to the spindle size used for testing. Unaged binders and RTFO aged binders are tested using the 25 mm spindle. PAV aged binders are tested using the 8 mm spindle.

In the initial stages of the procedure, the rheometer is used to measure the stress required to achieve the specified shear strain and then maintains this stress level very precisely during the test. The shear strain can vary in small amounts from the set value during the test. The rheometer software controls variation in shear stress.

To begin the test, the sample is first conditioned by loading the specimen for 10 cycles. Ten additional cycles are then applied to obtain test data. The rheometer software automatically computes and reports G* and δ, which can be compared with specification requirements.

Data Presentation

The DSR is capable of measuring asphalt response over a range of temperature, frequency, and strain levels. However, G* and δ are required for Superpave specification testing at specific conditions. The DSR software calculates G* and δ. Therefore, it is a simple matter of comparing results with requirements of the Superpave specification to determine compliance. A complete report includes:

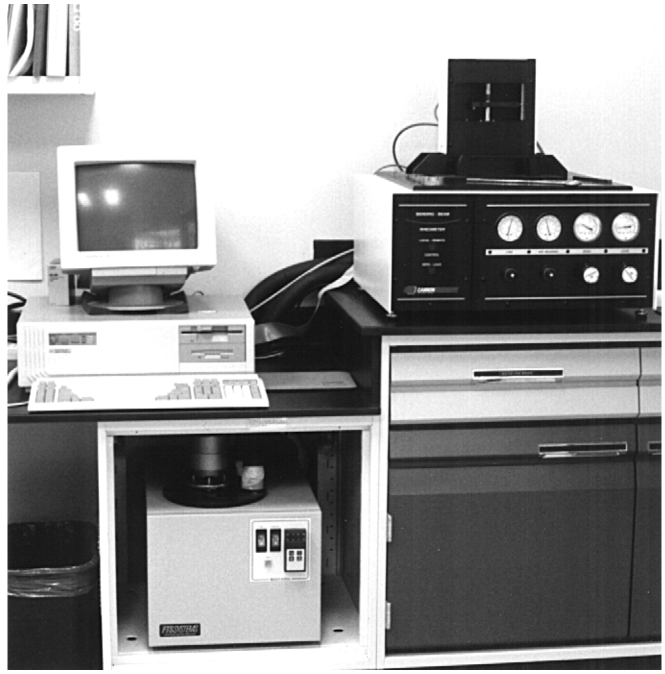
- G* to the nearest three significant figures,
- δ to the nearest 0.1 degrees,
- test plate size to the nearest 0.1 mm and gap to nearest 1µm,
- test temperature to the nearest 0.1° C,
- test frequency to the nearest 0.1 rad/sec, and
- strain amplitude to the nearest 0.01 percent.

G* is divided by sin δ to develop a “high temperature stiffness” factor that addressed rutting; G* is multiplied by sin δ to develop an “intermediate temperature stiffness” factor that addresses fatigue cracking. The use of these parameters in discussed later in this section.

Bending Beam Rheometer

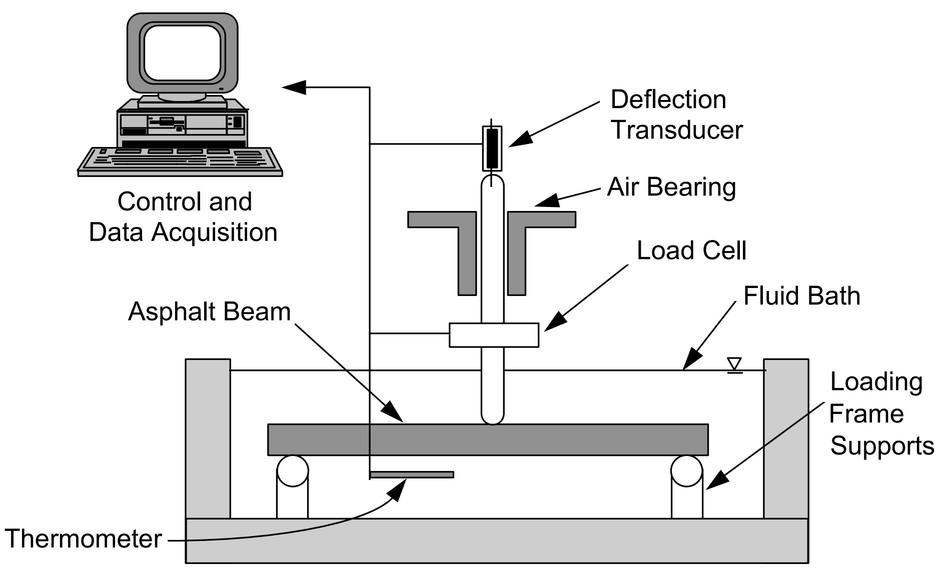
The Bending Beam Rheometer (BBR) is used to measure the stiffness of asphalts at very low temperatures. The test uses engineering beam theory to measure the stiffness of a small asphalt beam sample under a creep load. A creep load is used to simulate the stresses that gradually build up in a pavement when temperature drops. Two parameters are evaluated with the BBR. *Creep stiffness* is a measure of how the asphalt resists constant loading and the *m-value* is a measure of how the asphalt stiffness changes as loads are applied.

Details of the BBR test procedure can be found in AASHTO TP1 *"Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)."*

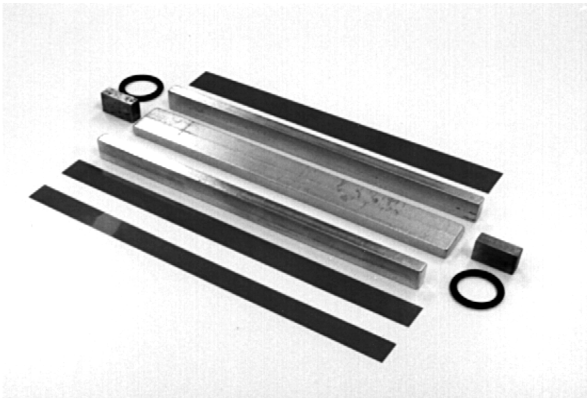


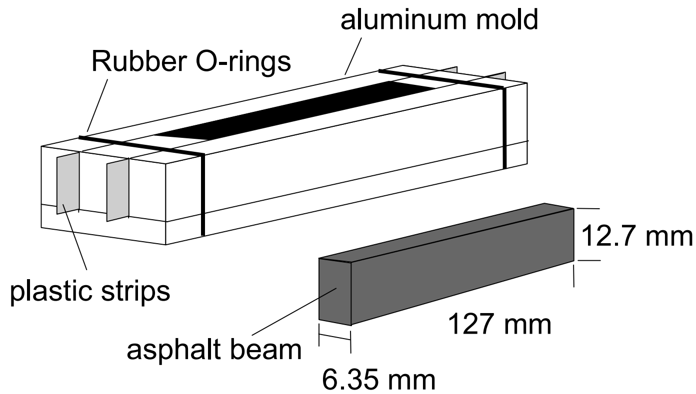
Test Equipment

The BBR gets its name from the test specimen geometry and loading method used during testing. The key elements of the BBR are a loading frame, controlled temperature fluid bath, computer control and data acquisition system, and test specimen. The BBR uses a blunt-nosed shaft to apply a midpoint load to the asphalt beam , which is supported at two locations. A load cell is mounted on the loading shaft, which is enclosed in an air bearing to eliminate any frictional resistance when applying load. A deflection measuring transducer is affixed to the shaft to monitor deflections. Loads are applied by pneumatic pressure and regulators are provided to adjust the load applied through the loading shaft.



The temperature bath contains a fluid consisting of ethylene glycol, methanol, and water. This fluid is circulated between the test bath and a circulating bath that controls the fluid temperature to within 0.1°C. Circulation or other bath agitation must not disturb the test specimen in a manner that would influence the testing process. The data acquisition system consists of a computer (with software) connected to the BBR for controlling test parameters and acquiring load and deflection test results.



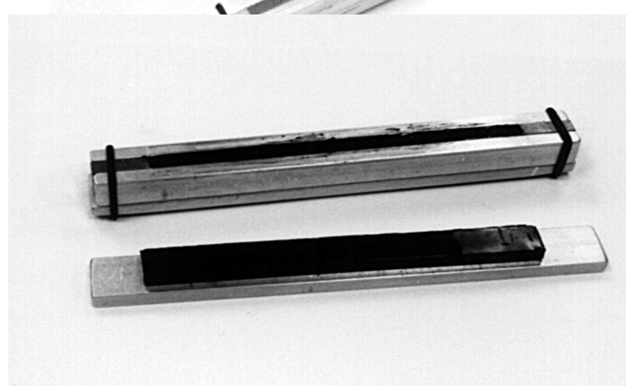


Specimen Preparation

Pouring heated asphalt into a rectangular mold forms the asphalt beam. The aluminum mold pieces are greased with petroleum jelly. Plastic strips are placed against the greased faces. The end pieces are treated with a release agent composed of glycerin and talc that have been mixed to achieve a paste-like consistency.

After a cooling period of about 45 to 60 minutes, excess asphalt is trimmed from the upper surface using a hot spatula. Store the test specimens in their molds at room temperature prior to testing. Schedule testing so that it is completed within 4 hours after specimens are poured.

To demold the specimen, cool the assembly in a freezer or ice bath at –5°C for five to ten minutes. In addition, do not use the rheometer testing bath since this may cause excessive fluctuations in the bath temperature.

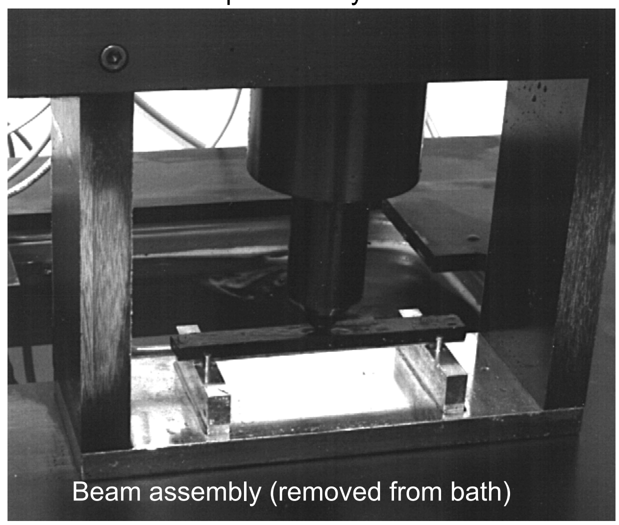


After removal of the aluminum and plastic strips, the resulting asphalt beams are ready for temperature conditioning. This requires that they be placed in the test bath for 60 ± 5 minutes. At the end of this period, the beams may be tested. Because the test procedure requires this tight tolerance on testing, the operator must carefully coordinate equipment preparation and specimen preparation.

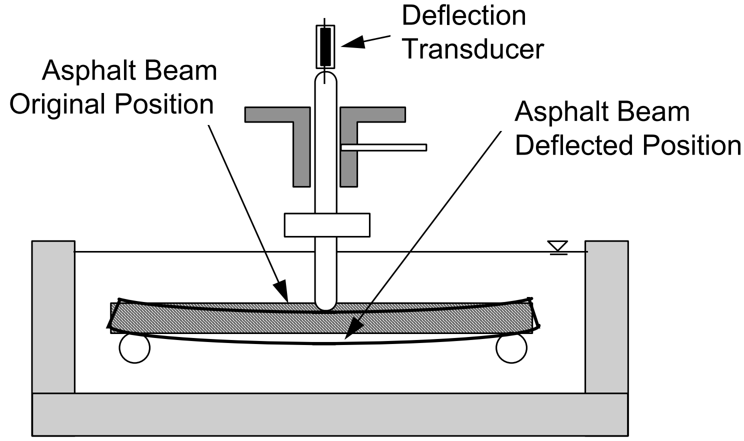
Overview of Procedure

The operator initiates the control software before the test begins. While the test specimens are brought to test temperature in the testing bath, systems calibration and compliance are accomplished. These include calibration of the displacement transducer and load cell. Compliance of the test device is checked with a rigid stainless steel reference beam. The temperature transducer is also checked by using a calibrated mercury-in-glass thermometer. A thinner reference beam is also supplied that can be periodically used to check the performance of the overall system. This beam functions as a dummy test specimen allowing quick checks on rheometer performance. The rheometer software controls most of the system calibration and the operator need only follow the instructions provided by the software.

At the end of the 60-minute thermal conditioning period, the asphalt beam is placed on the supports by gently grasping it with forceps. A 30 ± 5 mN preload is manually applied by the operator to ensure that the beam is firmly in contact with the supports. A 100-gram (980 mN) seating load is automatically applied for one second by the rheometer software. After this seating step, the load is automatically reduced to the preload for a 20-second recovery period. At the end of the recovery period, apply a test load ranging from 980 ± 50 mN, and maintain the load constant to ± 50 mN for the first five seconds and ± 10 mN for the remainder of the test. The deflection of the beam is recorded during this period.


Beam assembly (removed from bath)

As the 100-gram (980 mN) load bends the beam, the deflection transducer monitors the movement. This deflection is plotted against time to determine creep stiffness and m-value. During the test, load and deflection versus time plots are continuously generated on the computer screen for the operator to observe. At the end of 240 seconds, the test load is automatically removed and the rheometer software calculates creep stiffness and m-value.



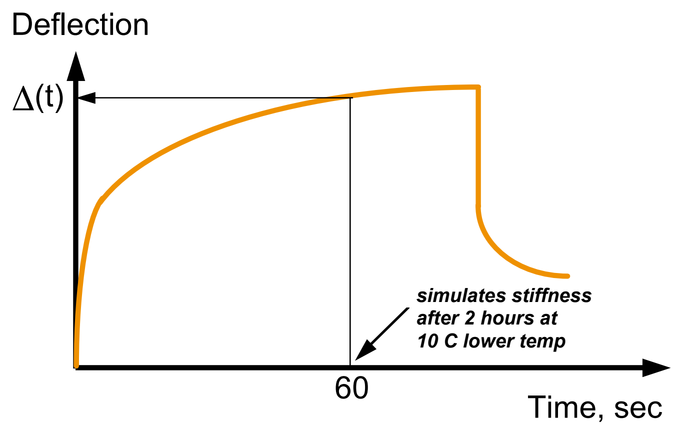
Data Presentation

Beam analysis theory is used to obtain creep stiffness of the asphalt in this test. The formula for calculating creep stiffness, S(t), is:

$$S(t) = \frac{PL^3}{4bh^3\Delta(t)}$$

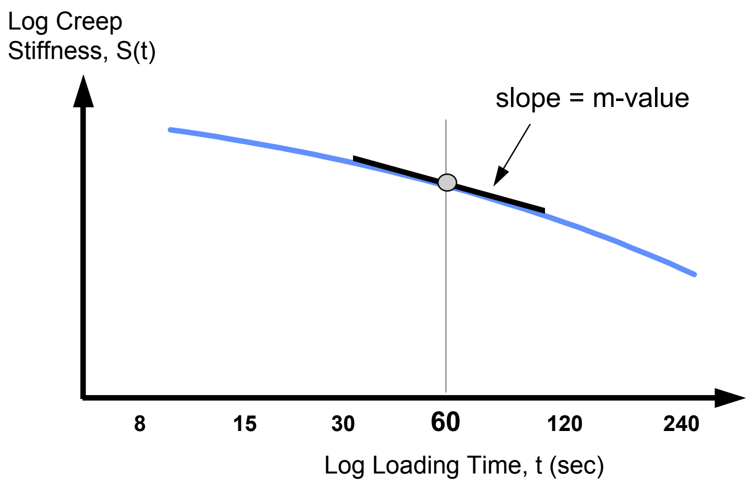
where,
S(t) = creep stiffness at time, t = 60 seconds
P = applied constant load, 980 mN
L = distance between beam supports, 102 mm
b = beam width, 12.5 mm
h = beam thickness, 6.25 mm
Δ(t) = deflection at time, t = 60 seconds

Although the BBR uses a computer to make this calculation, it can be determined manually by reading deflection data from the graph of deflection versus time from the printer connected to the computer.



By using the equation for S(t) and the deflection from the graph, the stiffness at time, t=60 seconds can be obtained. Creep stiffness is desired at the minimum pavement design temperature after two hours of load. However, SHRP researchers discovered that by raising the test temperature 10° C, an equal stiffness is obtained after a 60 second loading. The obvious benefit is that a test result can be measured in a much shorter period of time.

The second parameter needed from the bending beam test is the m-value. The m-value represents the rate of change of the stiffness, S(t), versus time. This value also is calculated automatically by the bending beam computer. However, to check the results from the computer, the value for m is easily obtained. To obtain m-value, the stiffness is calculated at several loading times. These values are then plotted against time. The m-value is the slope of the log stiffness versus log time curve at any time, t.

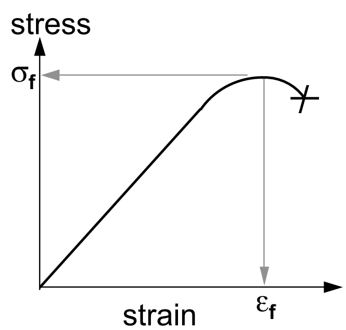


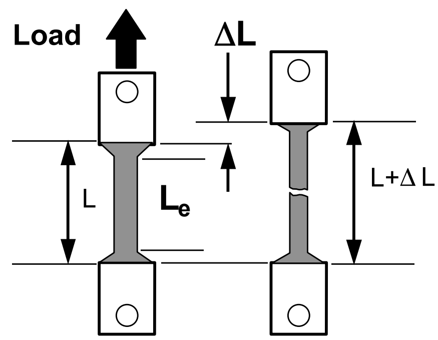
Computer-generated output for the bending beam test automatically reports all required reporting items. It includes plots of deflection and load versus time, actual load and deflection values at various times, test parameters, and operator information.

Direct Tension Tester

The direct tension test measures the low temperature ultimate tensile strain of an asphalt binder. The test is performed at relatively low temperatures ranging from +6° to -36° C, the temperature range within which asphalt exhibits brittle behavior. Furthermore, the test is performed on binders that have been aged in a rolling thin film oven and pressure aging vessel. Consequently, the test measures the performance characteristics of binders as if they had been exposed to hot mixing in a mixing facility and some in-service aging.

A small dog-bone shaped specimen is loaded in tension at a constant rate. The strain in the specimen at failure (ε_f) is the change in length (ΔL) divided by the effective gauge length (L).

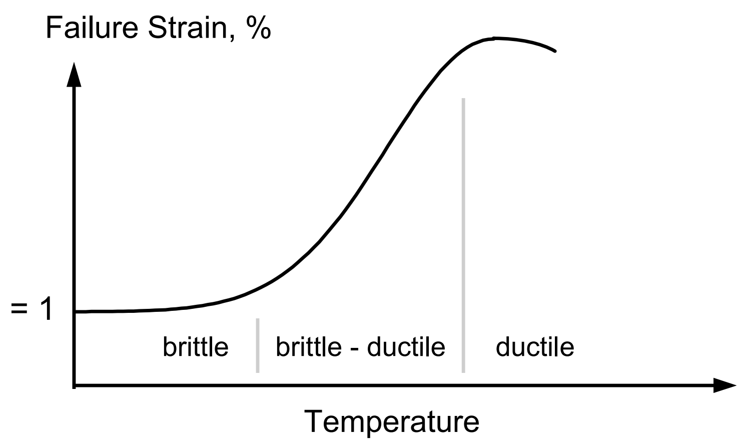




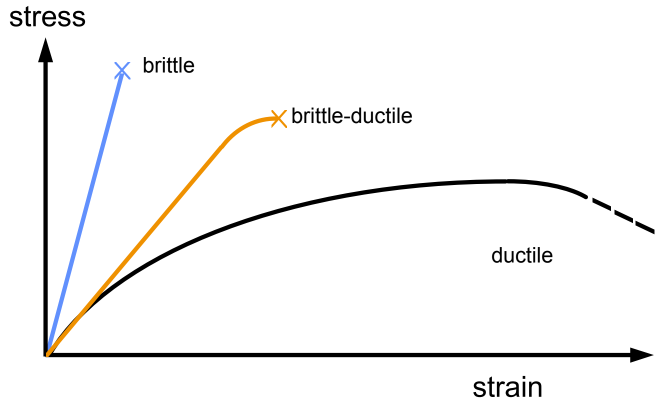
$$\textbf{failure strain } (\varepsilon_f) = \frac{\textbf{change in length } (\Delta L)}{\textbf{effective length } (L_e)}$$

In the direct tension test, failure is defined by the stress where the load on the specimen reaches its maximum value, and not necessarily the load when the specimen breaks. Failure stress (σ_f) is the failure load divided by the original cross section of the specimen (36 mm^2).

The stress-strain behavior of asphalt binders depends greatly on their temperature. If an asphalt were tested in the direct tension tester at many temperatures, it would exhibit the three types of tensile failure behavior: brittle, brittle-ductile, and ductile.



In illustrating the characteristic stress-strain relationships in this figure, the three different lines could represent the same asphalt tested at multiple temperatures or different asphalts tested at the same temperature. Brittle behavior means that the asphalt very quickly picks up load and elongates only a small amount before it cracks. An asphalt that is ductile may not even crack in the direct tension test but rather "string-out" until its elongation exceeds the stroke of the loading frame. That is why the point at which the specimen stops picking up load, which is the strain at peak stress, defines tensile failure strain.



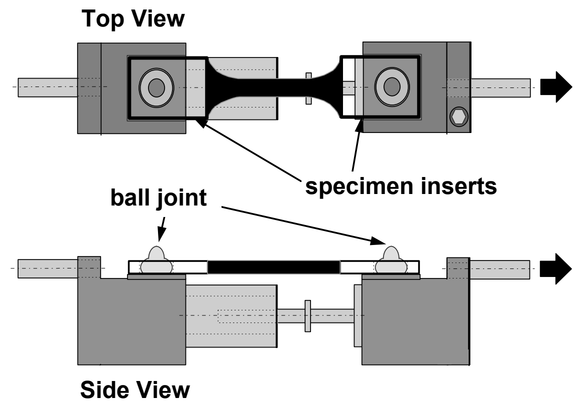
Test Equipment

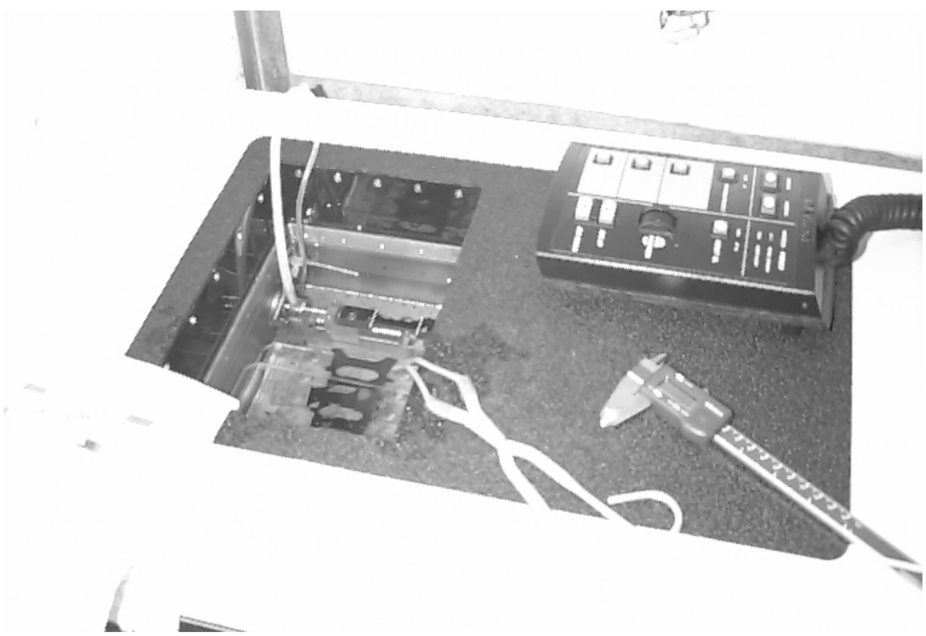
The apparatus used to perform the direct tension test consists of three components:

- a testing machine to apply tensile load,
- an elongation measuring system, and
- an environmental system

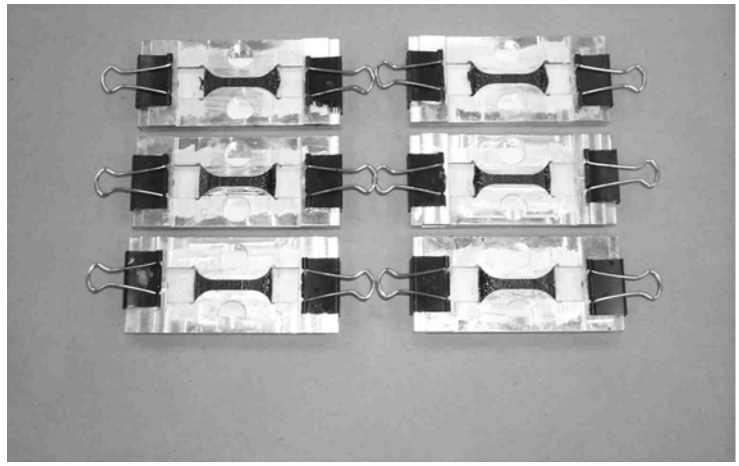
The universal testing machine is a loading device capable of producing at least a 500 N load at a loading rate of 1.0 mm/min. The machine must be equipped with an electronic load cell capable of resolutions of ± 0.1 N. A computer is used to acquire data. The test equipment and procedure are detailed in AASHTO TP3 *"Determining the Fracture Properties of Asphalt Binder in Direct Tension (DT)."*

A key feature to the testing machine is the gripping system used to attach specimens to the alignment rods that apply tensile load. The grips have a ball joint connection that ensures no bending is induced in the specimen.



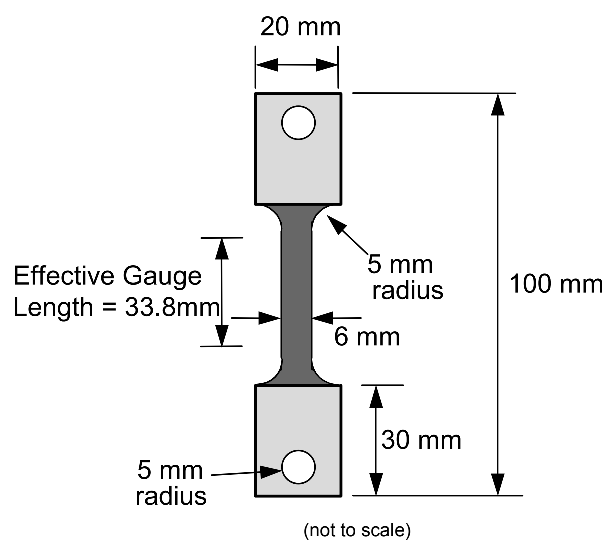


Specimen Preparation



Direct tension specimens are formed in an aluminum mold. Test specimens are prepared by pouring hot asphalt into a suitable mold. Two plastic end tabs are used to bond the asphalt binder during the test and to transfer the tensile load from the test machine to the asphalt binder.

Test specimens weigh approximately 2 g and are 100 mm long, including the end inserts. The inserts are each 30 mm long and the formed binder test specimen is 40 mm long. The nominal cross section is 6 mm by 6 mm. A 12 mm radius is used to gradually widen the specimen to 20 mm, the end insert width. The end inserts are made from a specified type of plastic material with a linear coefficient of thermal expansion similar to asphalt (0.00006 mm/mm/° C). Asphalt readily adheres to these materials and no bonding agent is necessary.



After the specimens are poured, trimmed, and demolded, they must be tested within 60 $\pm$ 10 minutes. Because the test procedure requires this tolerance on testing, the operator must carefully coordinate equipment preparation with specimen preparation.

Overview of Procedure

A sample consists of six replicate test samples. A specimen is mounted on the ball joint, and the operator initializes the load and strain indicators. A tensile load is applied until the specimen fails. A normal test requires less than a minute from application of load until specimen failure. A test is considered acceptable when fracture occurs within the narrow, center portion of the specimen. After testing is completed, the results for the two samples with the lowest strain at failure are discarded.

Data Presentation

A single test result consists of the average strain to failure of the four specimens. The table below demonstrates typical test output. In this example, samples #3 and #6 were not included in the average.

Batch Number - Acme Refining 759AC1196-16						
Operator - Smith						
Date - 3/15/00						
Time 14:16:26						
Sample	Max Strain (%)	Max Stress (MPa)	Max Load (N)	Max Ext (mm)	Test Time (sec)	Test Temp (°C)
1	1.854	5.56	229.35	0.77	41.11	-24.00
2	1.380	5.00	179.97	0.53	27.61	-24.00
3	1.287	4.92	177.24	0.48	25.76	-24.00
4	1.550	5.29	193.75	0.59	30.95	-24.00
5	1.789	5.43	244.45	0.87	46.53	-24.00
6	0.951	3.94	141.69	0.37	19.05	-24.00
Mean	1.643	5.32	211.88	0.69	36.55	-24.00
S.D.	0.22	0.24	30.07	0.16	8.79	0.00
C.V.	13.32	4.51	14.19	22.82	24.04	0.00

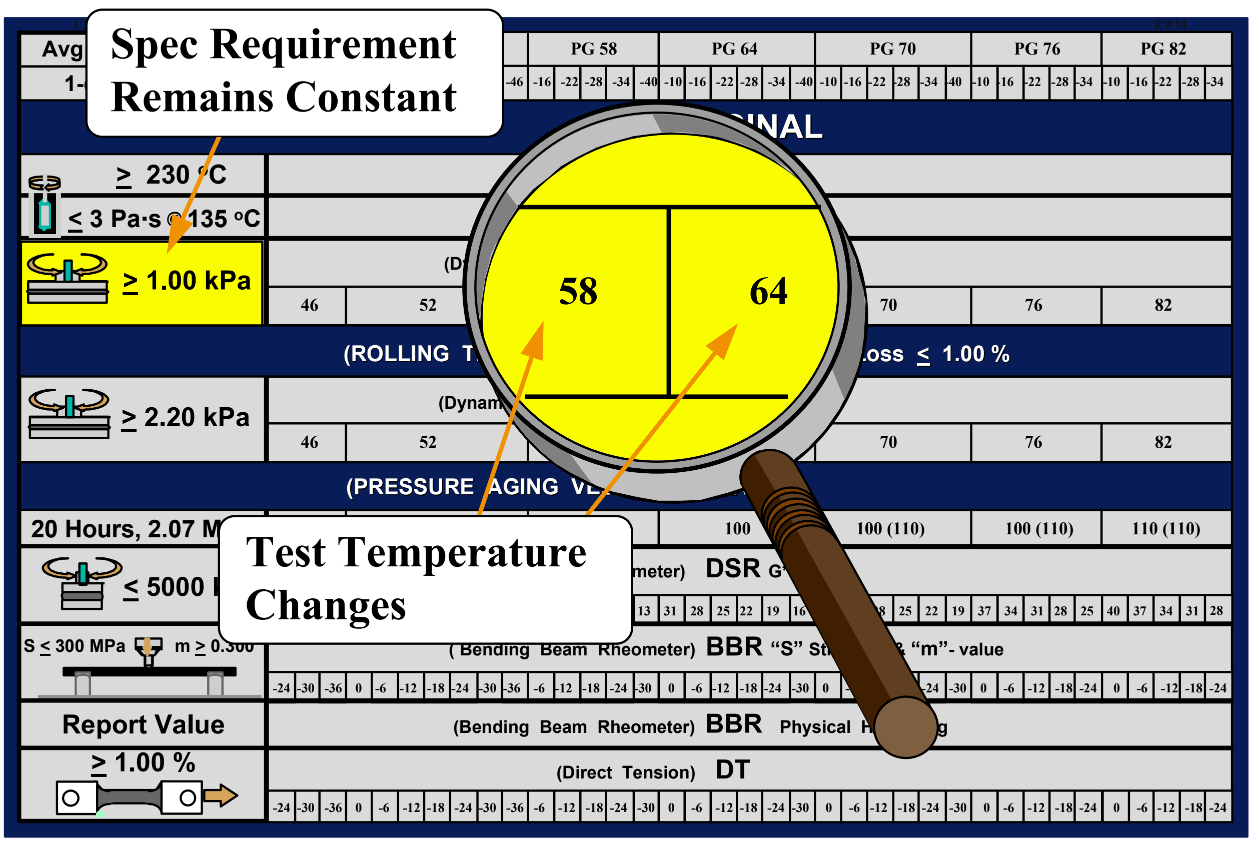
In this case, the test result of interest is the maximum percentage of strain (1.643%). This value would meet the specification requirement of one percent minimum strain. Although they are not used to determine specification compliance the following are also required reporting items:

- test temperature to the nearest 0.1° C,
- rate of elongation to the nearest 0.01 mm/min,
- failure stress to the nearest 0.01 MPa,
- peak load to the nearest N, and
- type of break observed (brittle, brittle-ductile, or no break).

SUPERPAVE ASPHALT BINDER SPECIFICATION

The Superpave asphalt binder specification (the complete provisional specification is shown in Appendix A) is intended to improve performance by limiting the potential for the asphalt binder to contribute to permanent deformation, low temperature cracking and fatigue cracking in asphalt pavements. The specification provides for this improvement by designating various physical properties that are measured with the equipment described previously. This section will explain how each of the new test parameters relates to pavement performance, and how to select the asphalt binder for a specific project.

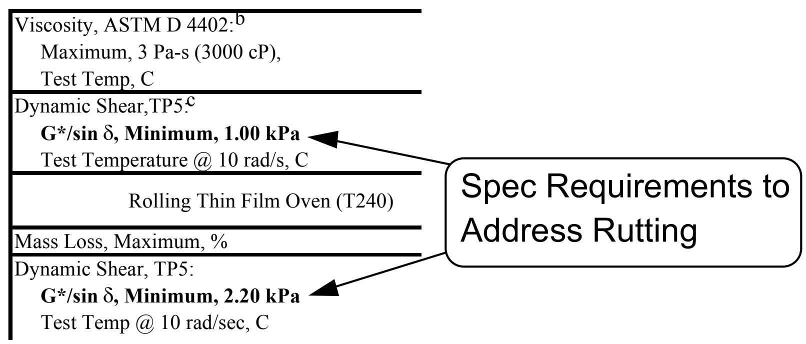
One important difference between the currently used asphalt specifications and the Superpave specification is the overall format of the requirements. The physical properties remain constant for all of the performance grades(PG). However, the temperatures at which these properties must be achieved vary depending on the climate in which the binder is expected to serve. As an example, this partial view of the specification shows that a PG 58-22 grade is designed to sustain the conditions of an environment where the average seven day maximum pavement temperature of 58°C and a minimum pavement design temperature is -22°C.



Permanent Deformation (Rutting)

As discussed earlier in the section describing the DSR, the total response of asphalt binders to load consists of two components: elastic (recoverable) and viscous (non-recoverable). Pavement rutting or permanent deformation is the accumulation of the non-recoverable component of the responses to load repetitions at high service temperatures. If permanent deformation occurs, it generally does so early on in the life of a pavement, so Superpave addresses rutting using unaged binder and binder aged in the RTFO.

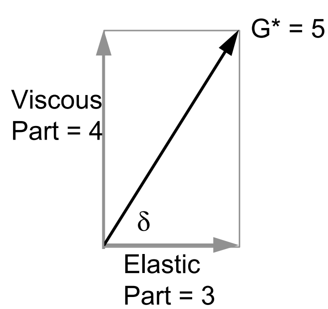
The Superpave specification defines and places requirements on a rutting factor, G*/sin δ, , that represents the high temperature viscous component of overall binder stiffness. This factor is called "G star over sine delta," or the high temperature stiffness. It is determined by dividing the complex modulus (G*) by the sine of the phase angle (δ), both measured by the DSR. G*/sin δ must be at least 1.00 kPa for the original asphalt binder and a minimum of 2.20 kPa after aging in the rolling thin film oven test. Binders with values below these may be too soft to resist permanent deformation.



Viscosity, ASTM D 4402:[b] Maximum, 3 Pa-s (3000 cP), Test Temp, C
Dynamic Shear,TP5:[c] **G*/sin δ, Minimum, 1.00 kPa** Test Temperature @ 10 rad/s, C
Rolling Thin Film Oven (T240)
Mass Loss, Maximum, %
Dynamic Shear, TP5: **G*/sin δ, Minimum, 2.20 kPa** Test Temp @ 10 rad/sec, C

Higher values of G* and lower values of δ are considered desirable attributes from the standpoint of rutting resistance. For the two materials A and B shown there is a significant difference between the values for sin δ. Sin δ for Material A (4/5) is larger than sin δ for Material B (3/5). This means that when divided into G* (equal for both A and B), the value for G*/sin δ will be smaller for Material A (6.25) than Material B (8.33). Therefore, Material B should provide better rutting performance than Material A. This is sensible because Material B has a much smaller viscous part than Material A.

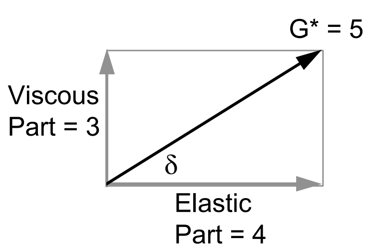
Material A



$$\sin\delta = \frac{\text{Viscous Part}}{G^*} = \frac{4}{5}$$

$$\frac{G^*}{\sin\delta} = \frac{5}{4/5} = 6.25$$

Material B



$$\sin\delta = \frac{\text{Viscous Part}}{G^*} = \frac{3}{5}$$

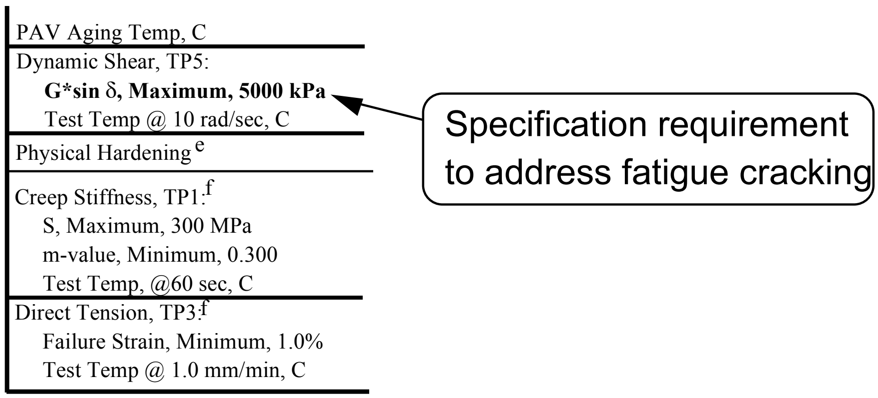
$$\frac{G^*}{\sin\delta} = \frac{5}{3/5} = 8.33$$

Larger value means behaves more like elastic solid

Fatigue Cracking

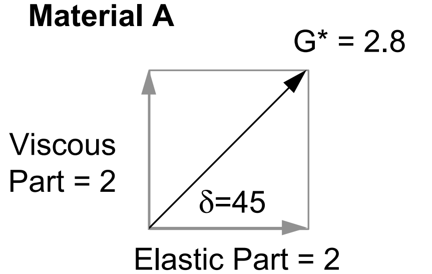
G* and δ are also used in the Superpave asphalt specification to help control fatigue in asphalt pavements. Since fatigue generally occurs at low to moderate pavement temperatures after the pavement has been in service for a period of time, the specification addresses these properties using binder aged in both the RTFO and PAV.

The DSR is again used to generate G* and sin δ. However, instead of dividing the two parameters, the two are multiplied to produce a factor related to fatigue. The fatigue cracking factor is G*sin δ, which is called "G star sine delta," or the intermediate temperature stiffness. It is the product of the complex modulus, G*, and the sine of the phase angle, δ. The Superpave binder specification places a maximum value of 5000 kPa on G* sin δ.



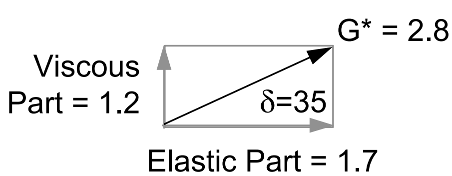
The ability to function as a soft elastic material and recover from many loadings is a desirable binder trait in resisting fatigue cracking. As shown below, for two materials with the same stiffness, the material with a smaller value of δ would be more elastic, and that would improve its fatigue properties. It is possible that a combination of G* and δ could result in a value for G*sin δ so large that the viscous and elastic parts would become too high and the binder would no longer be able to effectively resist fatigue cracking. This is why the specification places a maximum limit of 5000 kPa for G*sin δ.

Material A



Viscous Part = G* sin δ
= 2.8 sin 45
= 2.8 x 0.71
= 2.0

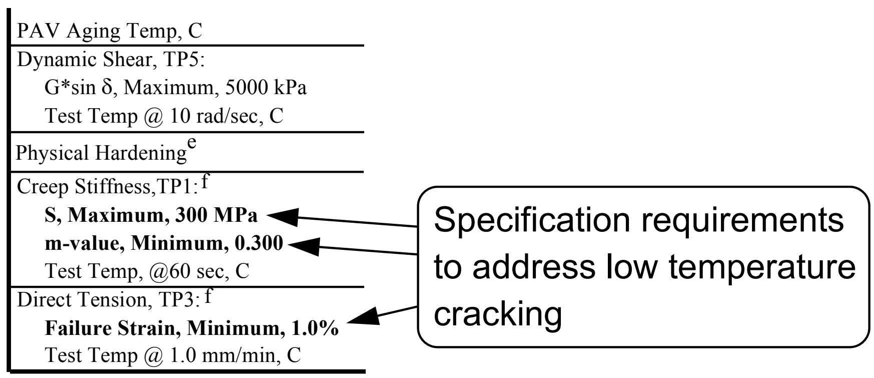
Material B



Viscous Part = G* sin δ
= 2.8 sin 35
= 2.8 x 0.57
= 1.6 ← Smaller value means softer elastic material

Low Temperature Cracking

When the pavement temperature decreases HMA shrinks. Since friction against the lower pavement layers prevents movement, tensile stresses build-up in the pavement. When these stresses exceed the tensile strength of the asphalt mix, a low temperature crack occurs -- a difficult distress to alleviate. The bending beam rheometer is used to apply a small creep load to the beam specimen and measure the creep stiffness -- the binder’s resistance to load. If creep stiffness is too high, the asphalt will behave in a brittle manner, and cracking is more likely to occur. To prevent this cracking, creep stiffness has a maximum limit of 300 MPa.



The rate at which the binder stiffness changes with time at low temperatures is controlled using the m-value. A high m-value is desirable because as the temperature decreases and thermal stresses accumulate, the stiffness will change relatively fast. A relatively fast change in stiffness means that the binder will tend to shed stresses that would otherwise build up to a level where low temperature cracking would occur. A minimum m-value of 0.300 is required by the Superpave binder specification.

As the temperature of a pavement decreases, it shrinks. This shrinkage causes stresses to build in the pavement. When these stresses exceed the strength of the binder, a crack occurs. Studies have shown that if the binder can stretch to more than 1% of its original length during this shrinkage, cracks are less likely to occur. Therefore, the direct tension test is included in the Superpave specification. It is only applied to binders that have a creep stiffness between 300 and 600 MPa. If the creep stiffness is below 300 MPa, the direct tension test need not be performed, and the direct tension requirement does not apply. The test pulls an asphalt sample in tension at a very slow rate, that which simulates the condition in the pavement as shrinkage occurs. The amount of strain that occurs before the sample breaks is recorded and compared to the 1.0 percent minimum value allowed in the specification.

Miscellaneous Specification Criteria

Other binder requirements are contained in the specification. They are included to control handling and safety characteristics of asphalt binders.

The flash point test (AASHTO T 48) is used to address safety concerns. The minimum value for all grades is 230°C. This test is performed on unaged binders.

To ensure that binders can be pumped and handled at the hot mixing facility, the specification contains a maximum viscosity requirement on unaged binder. This value is 3 Pa•s (3000 cP on rotational viscometer) for all grades. Purchasing agencies may waive this requirement if the binder supplier warrants that the binder can be pumped and mixed at safe temperatures.

A mass loss requirement is specified to guard against a binder that would age excessively from volatilization during hot mixing and construction. The mass loss is calculated using the RTFO procedure and must not exceed 1.00 percent.

During storage or other stationary periods, particularly at low temperatures, physical hardening occurs in asphalt binders. Chemical association of asphalt molecules causes physical hardening. Because of this physical hardening phenomenon, the Superpave specification requires that physical hardening be quantified. To measure this hardening, the bending beam test is performed on pressure aged binder after it has been conditioned for 24 hours at the required test temperature. Therefore, two sets of beams are fabricated for creep stiffness and m-value measurements. One set is tested after one hour of conditioning, while the other set is tested after 24 hours of conditioning. The creep stiffness and m-value are reported for information purposes. Currently, no specified values must be achieved.

SELECTING ASPHALT BINDERS

Performance graded asphalt binders are selected based on the climate in which the pavement will serve. The distinction among the various binder grades is the specified minimum and maximum pavement temperatures at which the requirements must be met.

Appendix A provides a listing of the more common binder grades in the Superpave specification. However, the PG grades are not limited to those given classifications. In actuality, the specification temperatures are unlimited, extending unbounded in both directions. The high and low temperatures extend as far as necessary in the standard six-degree increments. For example, even though a PG 58-10 is not shown, it exists as a legitimate grade in the system.

A module in the Superpave software assists users in selecting binder grades. Superpave contains three methods by which the user can select an asphalt binder grade:

- By Geographic Area: An Agency would develop a map showing binder grade to be used by the designer based on weather and/or policy decisions.
- By Pavement Temperature: The designer would need to know design pavement temperature.
- By Air Temperature: The designer determines design air temperatures, which are converted to design pavement temperatures.

The Superpave software contains a database of weather information for 6092 reporting weather stations in the US and Canada that allows users to select binder grades for the climate at the project location. For each year that these weather stations have been in operation, the hottest seven-day period was determined and the average maximum air temperature for this seven-day period was calculated. SHRP researchers selected this seven-day average value as the optimum method to characterize the high temperature design condition. For all the years recorded, the mean and standard deviation of the **seven-day average maximum air temperature** have been computed. Similarly, the **one-day minimum air temperature** of each year was identified and the mean and standard deviation of all the years of record was calculated. Weather stations with less than 20 years of records were not used.

However, the design temperatures to be used for selecting asphalt binder grade are the pavement temperatures, not the air temperatures. Superpave defines the high pavement design temperature at a depth 20 mm below the pavement surface, and the low pavement design temperature at the pavement surface.

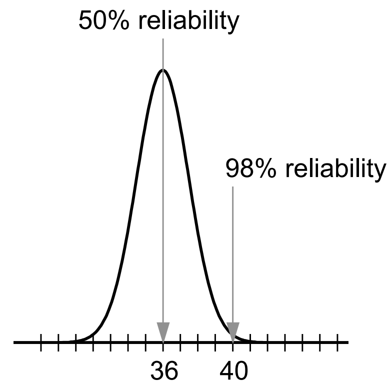
Using theoretical analyses of actual conditions performed with models for net heat flow and energy balance, and assuming typical values for solar absorption (0.90), radiation transmission through air (0.81), atmospheric radiation (0.70), and wind speed (4.5 m/sec), this equation was developed for the:

$$T_{20mm} = (T_{air} - 0.00618\ Lat^2 + 0.2289\ Lat + 42.2) (0.9545) - 17.78$$

where T_{20mm} = high pavement design temperature at a depth of 20 mm
T_{air} = seven-day average high air temperature
Lat = the geographical latitude of the project in degrees.

The low pavement design temperature at the pavement surface is defined as the low air temperature.

The Superpave system allows the designers to use reliability measurements to assign a degree of design risk to the high and low pavement temperatures used in selecting the binder grade. As defined in Superpave, reliability is the percent probability in a single year that the actual temperature (one-day low or seven-day average high) will not exceed the design temperatures.

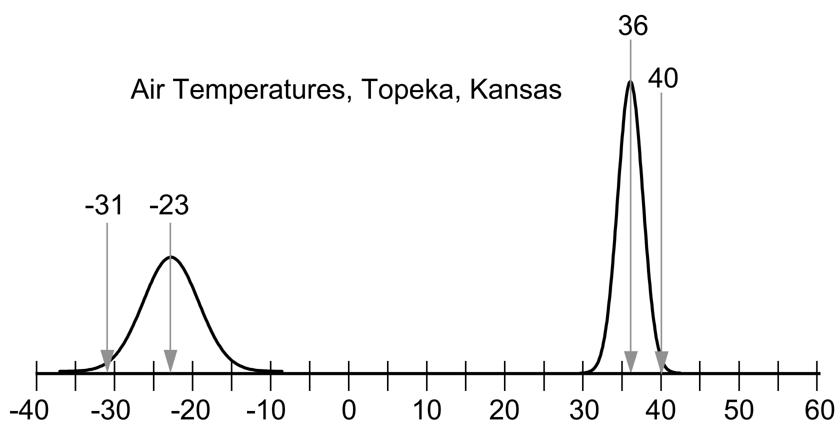


7-Day Maximum Air Temperature
Topeka, Kansas

Superpave binder selection is very flexible in that a different level of reliability can be assigned to high and low temperature grades. Consider summer air temperatures in Topeka, Kansas, which has a mean seven-day maximum of 36°C and a standard deviation of 2°C. In an average year there is a 50 percent chance the seven-day maximum air temperature will exceed 36°C. However, only a two percent chance exists that the temperature will exceed 40°C; hence, a design air temperature of 40°C will provide 98 percent reliability.

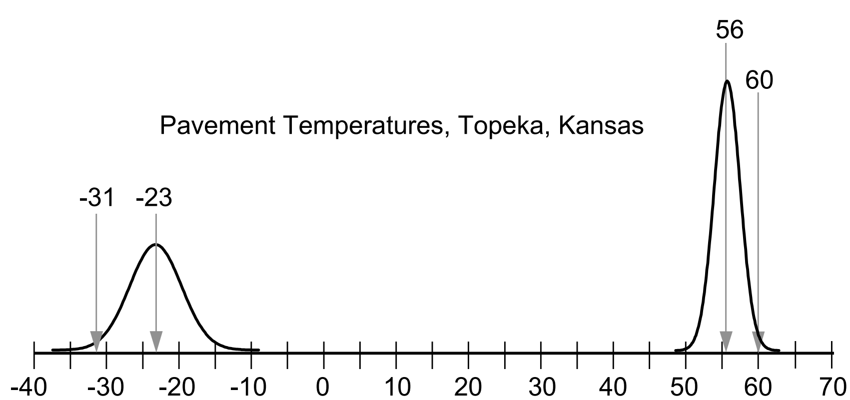
Start with Air Temperature

To see how the binder selection works assume that an asphalt mixture is designed for Topeka. In a normal summer, the average seven-day maximum air temperature is 36°C with a standard deviation of 2°C. In a normal winter, the average coldest temperature is -23°C. For a very cold winter the temperature is -31°C, with a standard deviation of 4°C.

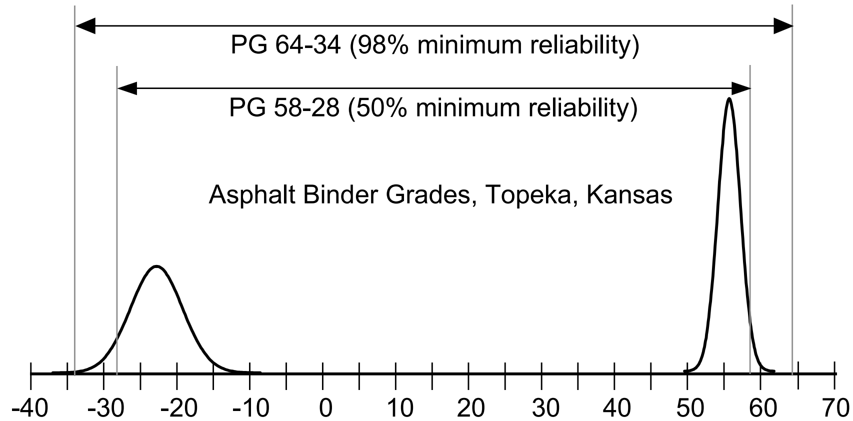


Convert to Pavement Temperature

Superpave software calculates high pavement temperature 20 mm below the pavement surface and low temperature at the pavement surface. For a wearing course at the top of a pavement section, the pavement temperatures in Topeka are 56°C and -23°C for 50 percent reliability and 60°C (56°C + 2 standard deviations) and -31°C for 98 percent reliability.



Select the Binder Grade



For a reliability of at least 50 percent, the high temperature grade for Topeka must be PG 58. Selecting a PG 58 would actually result in a higher level of reliability, about 85 percent, because of the "rounding up" to the next standard grade. The next lower grade only protects to 52°C, less than 50 percent reliability. The low temperature grade must be a PG -28. Likewise, rounding to this standard low temperature grade results in almost 90 percent reliability. For 98 percent reliability, the needed high temperature grade is PG 64; the low temperature grade is PG -34. Also, the reliabilities of the high and low temperature grades could be selected at different levels depending upon the needs of the design project. For instance, if low temperature cracking was more of a concern, the binder could be selected as a PG 58-34.

Manipulating temperature frequency distributions is not a task that the designer needs to worry about. Superpave software handles the calculations. For any site, the user can enter a minimum reliability and Superpave will calculate the required asphalt binder grade. Alternately the user can specify a desired asphalt binder grade and Superpave will calculate the reliability obtained.

Effect of Traffic Speed and Volume on Binder Selection

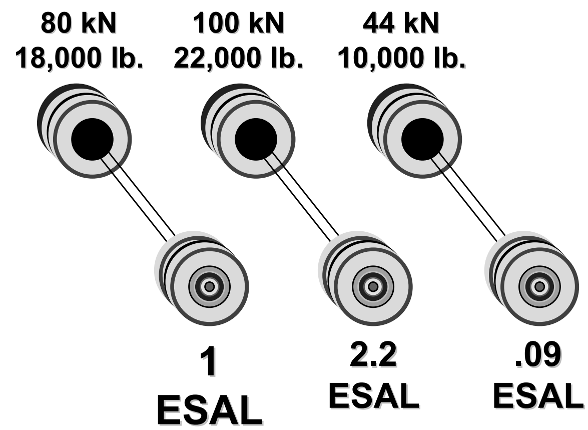
The Superpave binder selection procedure described is the basic procedure for typical highway traffic conditions. Under these conditions, it is assumed that the pavement is subjected to a design number of fast, transient loads. For the high temperature design situation, controlled by specified properties relating to permanent deformation, the traffic speed has an additional effect on performance. The AASHTO MP1 specification includes an additional shift in the selected high temperature binder grade for slow and standing traffic situations. Also, a shift is included for extraordinarily high numbers of heavy traffic loads. Similar to the time-temperature shift described with the test temperature for the BBR (testing at 10°C higher temperature reduced the test duration from 2 hours to 60 seconds), higher maximum temperature grades are used to offset the effect of the slower traffic speed and extreme traffic loads. The table shows the adjusted grades recommended by AASHTO MP-2.

Design ESALS (million)	Adjustment to Binder PG Grade		
	Traffic Load Rate		
	Standing	Slow	Standard
< 0.3	-	-	-
0.3 to < 3	2	1	-
3 to < 10	2	1	-
10 to < 30	2	1	-
≥ 30	2	1	1

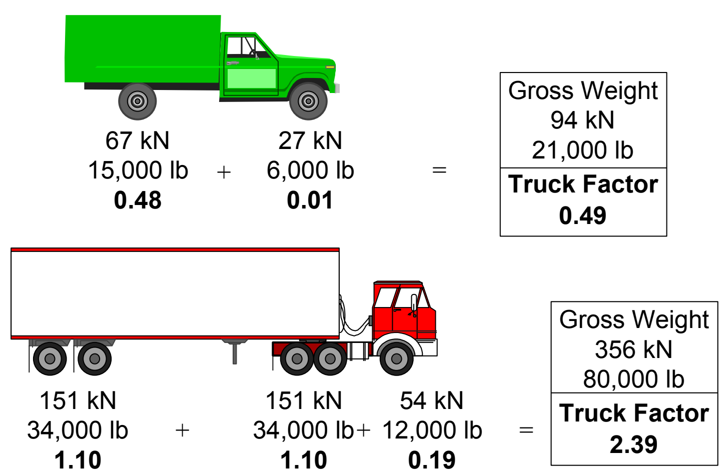
Traffic Analysis

Superpave material selection criteria are based on the traffic volume of the design project, expressed in equivalent single axle loads (ESAL). This brief synopsis describes the calculation of ESALs. For further information, see the Asphalt Institute's *Thickness Design -- Asphalt Pavements for Highways and Streets,* Manual Series No. 1.

An ESAL is defined as one 18,000-pound (80-kN) four-tired dual axle and is the unit used by most pavement thickness design procedures to quantify the various types of axle loadings into a single design traffic number. If an axle contains more or less weight, it is related to the ESAL using a *load equivalency factor.* The relationship between axle load and ESAL is not a one to one equivalency, but a fourth power relationship. If you double an 18,000 lb load, the ESAL is not 2, but almost the fourth power of two, (2^4) or about 14. As well, if axles are grouped together, such as in tandem or tridem axle arrangements, the total weight carried by the axle configuration determines its load equivalency factor.



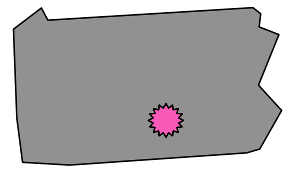
For a given vehicle the load equivalency factors are totaled to provide the *truck factor* for that vehicle. Truck factors can be calculated for any type of trucks or combination of truck types. Traffic count and classification data is then used in combination of the truck factor for each vehicle classification to determine the design traffic in ESAL.



The Superpave binder specification and tests are intended for both unmodified and modified binders. However, there are certain occasions, such as RTFO aging, binder selection and budgeting, when it would be helpful to know if the binder is modified. The difference between the high and low temperature grades can provide some indication whether the binder may be modified. A very general rule of thumb in the industry says if the difference is greater than 92, the binder may be modified, and the likelihood and quantity of modification increases as the difference increases. For instance, the difference between the high and low temperature grades of a PG 64-34 is 98. This grade will probably include a modifier in the binder. However, many factors affect the value (92) of this "rule", such as the viscosity of the binder and the crude oil source.

Class Example Binder Selection

- **Southcentral Pennsylvania**
  - **rural 4-lane access road**
  - **11 million ESAL**
  - **many traffic lights**



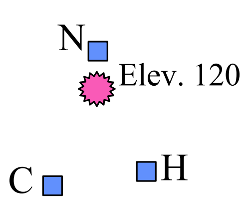
- **Budget for project : $29/ton mix**
- **Governor's mother's street needs repairs**
  - **milling & leveling equivalent of $6/ton**
  - **patching costs equivalent of $2/ton**

Which PG would you select ?

PG 52-16, 52-22, 58-22 : $23/ton
PG 64-22, 58-28 : $27/ton
PG 70-22, 64-28 : $29/ton
PG 70-28 : $43/ton
PG 76-28 : $52/ton

Class Example Binder Selection
Southcentral Pennsylvania Project

							Air Temp			
							Low Temp		High Temp	
ST	County	Dist	Station	Long	Lat	Elev	Avg	Std	Avg	Std
PA	Perry	8	Newport	77.13	40.48	116	-20	4	33	2
PA	York	30	Harrisburg	76.85	40.22	104	-17	3	33	2
PA	Cumb.	31	Carlisle	77.22	40.20	143	-19	4	34	2



50% Reliability						
TEMPERATURES				Binder Grade		
MaxAir	MaxPvt	MinAir	MinPvt	PG	HT	LT
33	53	-20	-20			
33	53	-17	-17	PG	?-?	
34	54	-19	-19			

98% Reliability						
TEMPERATURES				Binder Grade		
MaxAir	MaxPvt	MinAir	MinPvt	PG	HT	LT
35	57	-28	-28			
37	57	-23	-23	PG	?-?	
38	58	-27	-27			