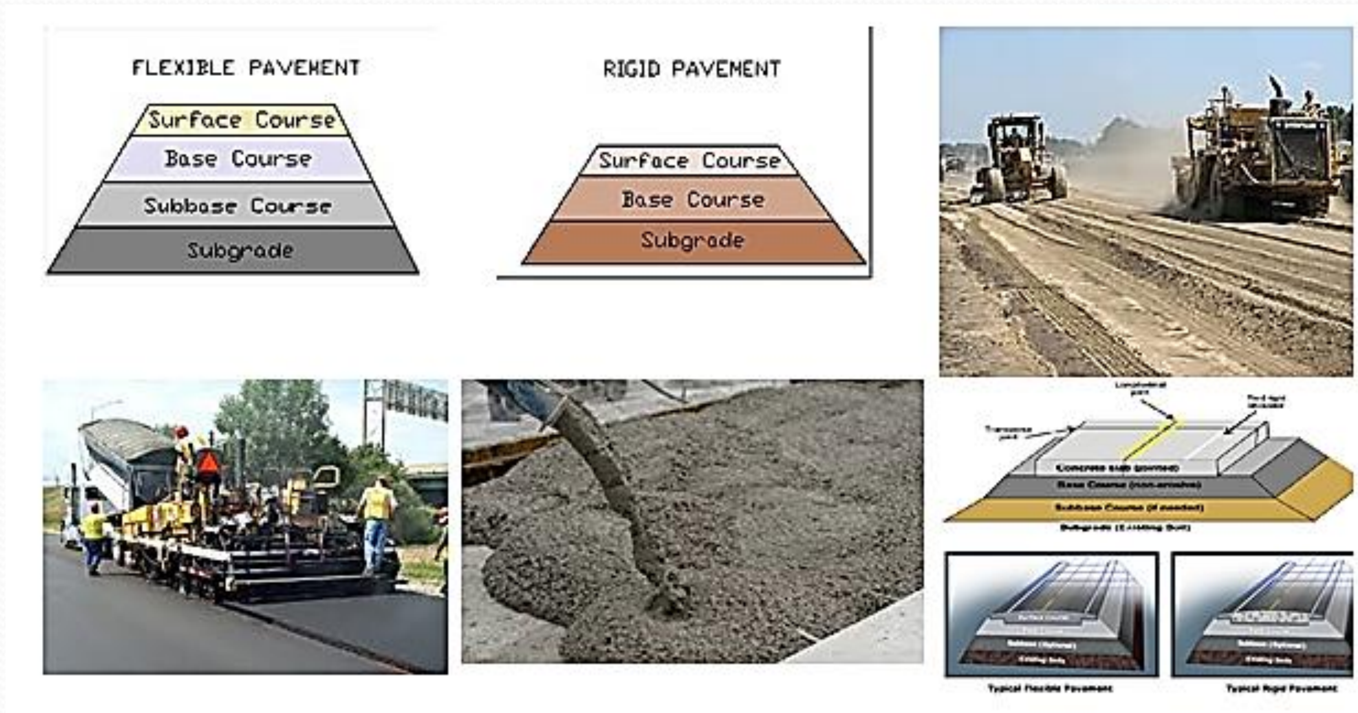
University of Anbar – College of Engineering
Departement of Civil Engineering
Highway Materials
Course No:*CE 4345*



Prepared By:
Dr Talal H. Fadhil
Dr Taher M. Ahmed

C. Bitumen, bituminous binders:

C.1. *General, Natural asphalt, Rock asphalt, Tar, Asphalt cement, Cut-back asphalts, Emulsified asphalt and Modified bitumen*

.

C.2. Rational and Superpave Laboratory tests and properties of bitumen:

General, Penetration test, Softening point test, Penetration index, Ductility test, Viscosity test viscometers, (Superpave Tests) Viscosity tests by rotational viscometers, Dynamic shear rheometer, Rolling thin oven test (RTOT), Thin film oven test (TFOT), Flash and fire point – cleveland open cup, Accelerated ageing by PAV, Bending beam rheometer test for flexural creep stiffness, and Direct tension test for fracture properties.

C. Bitumen, Asphalt binders:

General

Bitumen or asphalt is well known and used since ancient times, it is used as a waterproofing and binder material of great quality. It is combined of a long series of carbon and hydrogen atoms, it known as a hydrocarbon molecules.

Sources

There are two sources of asphalt binders:

1. Those occurring naturally , and
2. Those obtained by the refining of petroleum.

In both cases, the asphalt binder is the product of the fractional distillation of petroleum, whether over short periods as in the refinery process or longer periods as in nature.

1. Natural Asphalt

- A number of naturally occurring deposits of bituminous material can be found in various parts of the world. Natural asphalts can exist either in a relatively:

1. Pure form (lake) such as in Heet city, Trinidad and Gilsonite in USA

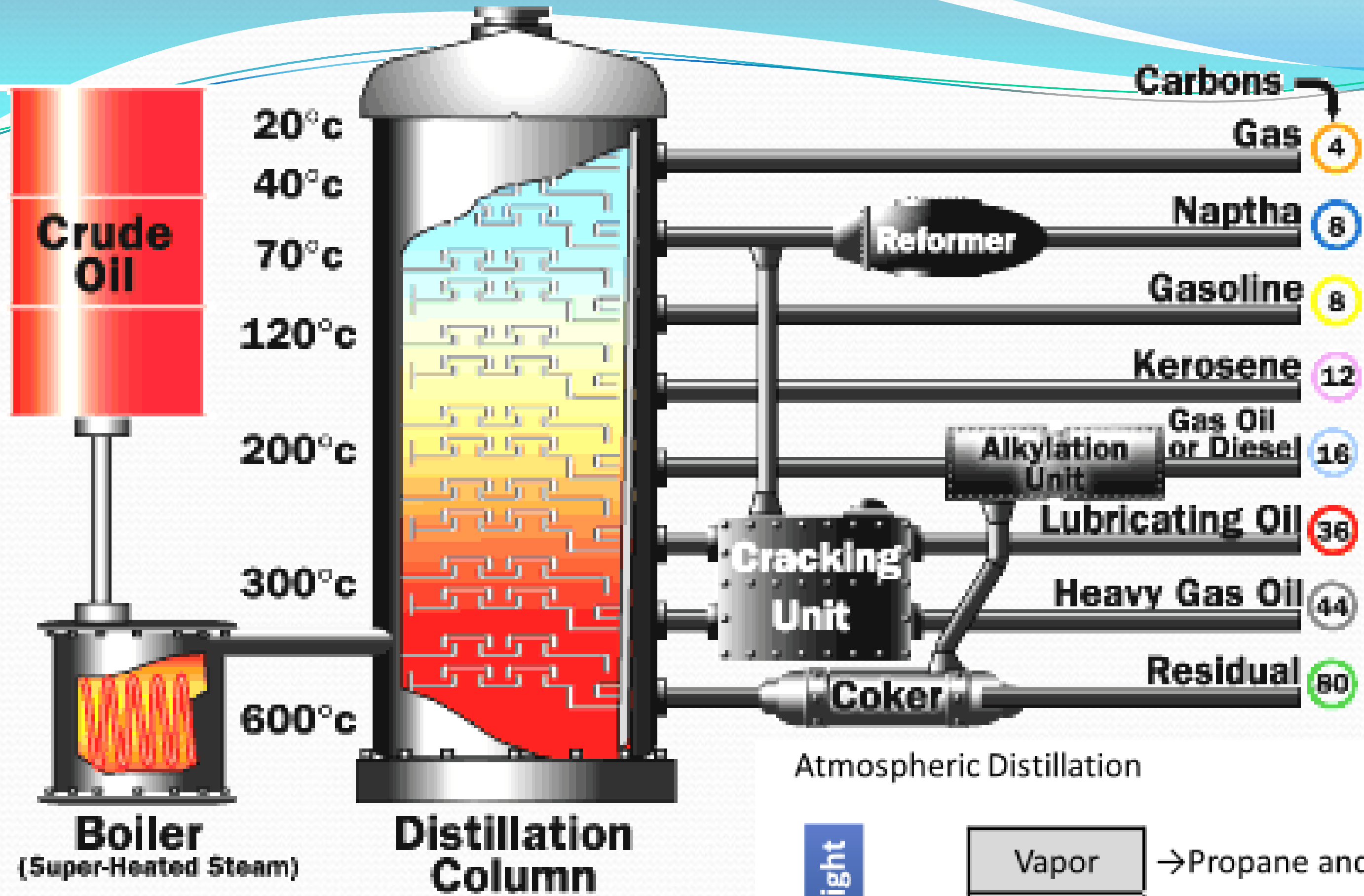
2. Rock asphalt is as a rock partially filled with natural asphalt such as limestone or sandstone. It is found in solid form. It was formed millions of years ago when layers of petroleum harden after heavier components settled while lighter components evaporated. Natural asphalt is defined as ‘a relatively hard bitumen found in natural deposits, often mixed with fine or very fine mineral matter, which is virtually solid at 25°C but which is a viscous fluid at 175°C’.

2. Artificial Asphalt

Artificial asphalt is an asphalt produced by interface of the refining technology using pressure and temperature to produce materials called bitumen. Two methods are used for this purpose named fractional and distractive distillation. The bitumen which is produced from crude oil by fractional distillation is known as asphalt cement while the bitumen produced from coal or wood by distractive distillation is known as tar.

Asphalt Cement

- Asphalt is a sticky, black and highly viscous liquid or semi-solid form of petroleum. Most of the asphalt used today for paving comes from petroleum crude oil. The first step in the processing of all crude petroleum is straight reduction by distillation. The distillation principle is used to separate various crude fractions which have different boiling ranges. Asphalt cement is made up of the highest boiling fractions so it becomes the residuum from the vacuum tower. The crude oil is heated in a large furnace to about 650 °C and partially vaporized. It is then introduced into a distillation tower where the lightest components vaporize, rise to the top, cool, condense, and are drawn off for further processing. At various heights, different fractions reach their boiling point and then condense on trays inside the tower as the temperature is reduced. The lower temperature or upper-tower components result in gasoline, while the mid-tower components are drawn off at those levels and treated to make more expensive fuels (jet fuel, kerosene, and diesel). The bottom fraction from the distillation tower is the material used to produce lubricating oil to asphalt binder. The grade of the asphalt binder is controlled by the amount of heavy gas oil removed.



Atmospheric Distillation

Increasing Molecular Weight ↓

Vapor	→Propane and butane
Naphtha	→Feedstock for gasoline
Kerosene	→Aviation/domestic fuel
Gas Oil	→Feedstock for diesel
Residuum	→Lubrication oils →Feedstock for asphalt binder production

"Bottom of the Barrel"

Increasing Value ($) ↑

- Asphalt cement behaves as viscoelastic materials depending on temperature, time of loading, magnitude of stress and ageing.

- The asphalt can be liquefied by three methods: heating, using solvent (i.e. gasoline and kerosene) to produce cutback asphalt, and using water with emulsifying agent (emulsifier) to produce emulsified asphalt.

Tar

- Tar is produced by destructive distillation for the natural organic matters, such as coal or wood. When the tar is derived from coal, the product is called **pitch tar**. Similarly, when it is derived from wood, it is called **wood tar**. the destructive distillation is performed at high temperature and pressure causes a change in the chemical composition for the original materials (coal and wood).

- The tar was widely used for many years both in highway engineering and for the production of insulators. Over the last years, the usage of tar has been minimised mainly for environmental and health reasons, so it has been prohibited.

- Nowadays, tar is used almost exclusively for the production of specific bituminous mixtures, not affected by petrol or oils, known as fuel-resistant mixtures.

Difference between Asphalt Bitumen and Tar

No.	Bitumen	Tar
1	Bitumen is found in black to brown in colour	Tar is usually found in brown colour
2	Bitumen is obtained from fractional distillation of crude oil	Tar is obtained by destructive distillation of coal or wood
3	Bitumen is soluble in carbon disulphide and carbon tetra chloride	Tar is soluble in toluene
4	It shows more resistance to weathering action	It shows less resistance to weathering action
5	Less temperature susceptibility	More temperature susceptibility

Cutback asphalt

➢Cutback asphalt is asphalt that is liquefied by the addition of diluents (typically petroleum solvents) and is generally designated as liquid asphalt However, it is important to note that the asphalt binder is the base material that has been liquefied by cutting back with a solvent. Cutback asphalt is used in both paving and roofing operations, depending on whether it is used as paving asphalt and as roofing asphalt.

➢ If the solvent used in making the cutback asphalt is highly volatile, it will quickly escape by evaporation. Solvents of lower volatility evaporate more slowly. On the basis of the relative speed of evaporation, cutback asphalts are divided into **three types**: rapid curing (RC), medium curing (MC) and slow curing (SC).

- The type of cutback asphalt depends on:
1. grade of the base asphalt (60-70, 85-100).
2. Type of solvent (gasoline, kerosene, naphtha, …...)
3. Proportion of the solvent to the asphalt cement.

- **Rapid curing (RC**) asphalt cement (85-100 pen) is a combination of light diluents of high volatility, generally in the gasoline or naphtha and asphalt cement. The (RC-70, RC- 250, RC- 800, RC- 3000). Where the numbers are related to approximate kinematic viscosity in centistokes (cSt) at 60 ^{o}C (140 ^{o}F). For example RC-70 (70 is the value of viscosity in centistokes).

For example:

RC – 3000 has 15% solvent (Gasoline) + 85 % asphalt cement (by volume).

RC – 70 has 40% solvent (Gasoline) + 60% asphalt cement (by volume).

Notes:

• RC is used of construction pavement as a tack coat. In ISSRB - R8B the tack coat is provided by cutting-back **(85-100)** Pen asphalt with Gasoline **(1 Gasoline : 2 Asphalt cement)** by volume.

• The application is more than 0.15 l/m^2 and less than 0.5 l/m^2. Tack coat must be spread before paving asphalt by at least **2 h**.

- **Medium curing (MC**) is a combination of intermediate volatility solvent (kerosene) with asphalt cement (85-100), generally the kerosene has intermediate degree of evaporation, for example (MC-30, MC-70, MC-250, MC-800 and MC-3000).

The fluidity of the medium – curing asphalt depends on the amount of solvent in the materials for example:

MC – 3000 has 20% solvent + 80 % asphalt cement (by volume).

MC – 70 has 45% solvent + 55 % asphalt cement (by volume).

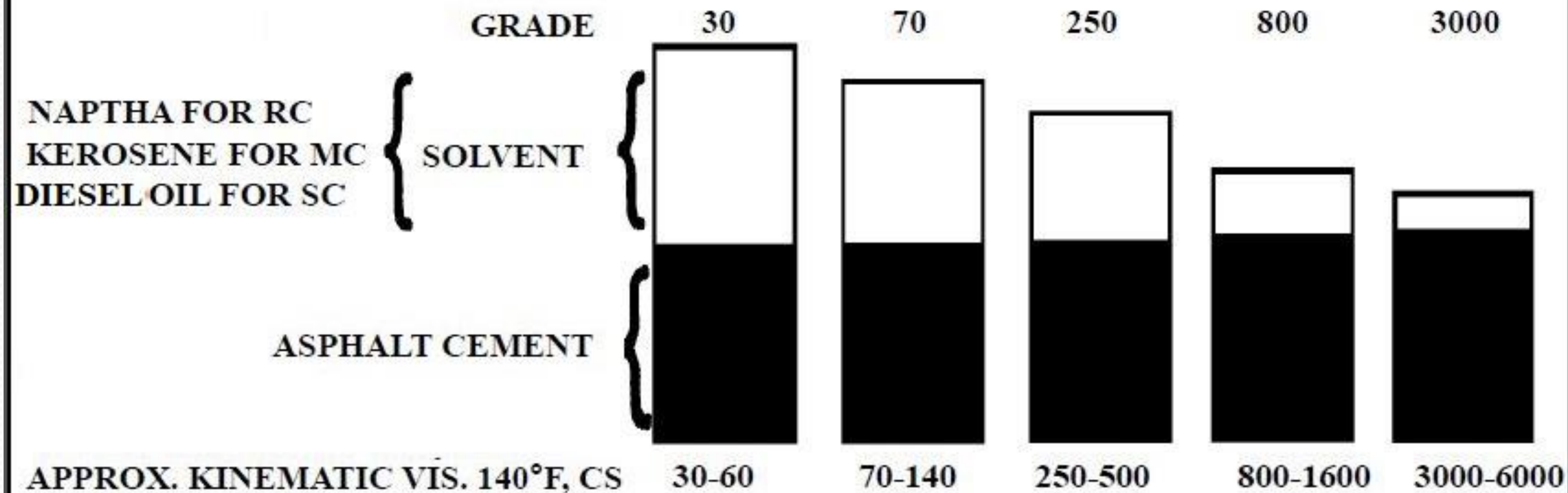
Notes:

- MC is used of construction pavement as a prime coat. In ISSRB - R8A the prime coat is provided by cutting-back **(85-100)** Pen asphalt with kerosene **(1 kerosene : 1.5 Asphalt cement)** by volume.
- The application more than 0.5 l/m^2 and less than 1.2 l/m^2. Prime coat must be spread before paving asphalt by at least **24 h**.

- **Slow curing (SC**) is a combination of low volatility solvent (diesel oil) with asphalt cement (200-300), generally the road oil (diesel oil) has low degree of evaporation, for example (SC-70, SC-250, SC-800 and SC-3000).

It is limited to be used in stabilization of light traffic volume road such as in the villages.

Composition of Cutback Asphalts



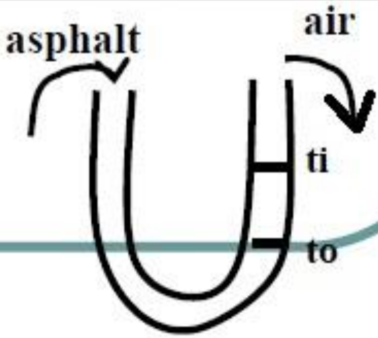
Grades based on min. Kinematic Viscosity @ 60C (cSt)

$\nu = k * t$ (sec)

stoke = St = cm^2/sec

$t = ti - to$

k = constant for viscometer



Emulsified Asphalt

- Emulsified asphalt is simply a suspension of small asphalt cement globules in water, which is assisted by an emulsifying agent (such as soap). The emulsifying agent assists by imparting an electrical charge to the surface of the asphalt cement globules so that they do not coalesce. Emulsions are used because they effectively reduce asphalt viscosity for lower temperature uses (tack coats, bituminous surface treatment and stabilization material). Emulsions are typically **either anionic (asphalt droplets are negatively charged)** or **cationic (asphalt particles are positively charged).**

- **Asphalt emulsions composition consists of three basic ingredients**

Asphalt	**+ Mechanical Mixing**
Water	
Emulsifying Agent	

- Generally, emulsions appear as a thick brown liquid when initially applied. When the asphalt cement starts to adhere to the surrounding material (aggregate, existing surface, sub-grade, etc.) the color changes from brown to black and the emulsion is said to have "broken" . As water begins to evaporate, the emulsion begins to behave more and more like pure asphalt cement. Once all the water has evaporated, the emulsion is said to have "set". The time required to break and set depends upon the **type and amount of emulsifying agents (emulsifier),** the temperature of the surface which depends on the **environmental (climate) conditions**. Under most circumstances, an emulsion will set in about 1 to 2 hours.

Mechanism of Emulsifying agent (Emulsifier)

There are two basic classifications of emulsions: **anionic and cationic**. **Emulsifying agents are the chemicals used to stabilize the emulsion and keep the "billions and billions" of asphalt drops separated from one another. These compounds are large organic molecules that have two distinct parts to them. These parts are called the "head" and "tail." The "head" portion has positive or negative charge area**. These two charged areas give rise to the head being called polar (as in poles of a magnet). Because of this polarity, and the nature of some of the atoms in this polar head, the head is soluble in water. **The tail consists of a long chain organic group that is not soluble in water, but is soluble in other organic materials like asphalt**. Thus, an emulsifying agent is one molecule with both water-soluble and oil soluble portions. This unique characteristic gives the chemical its emulsifying ability.

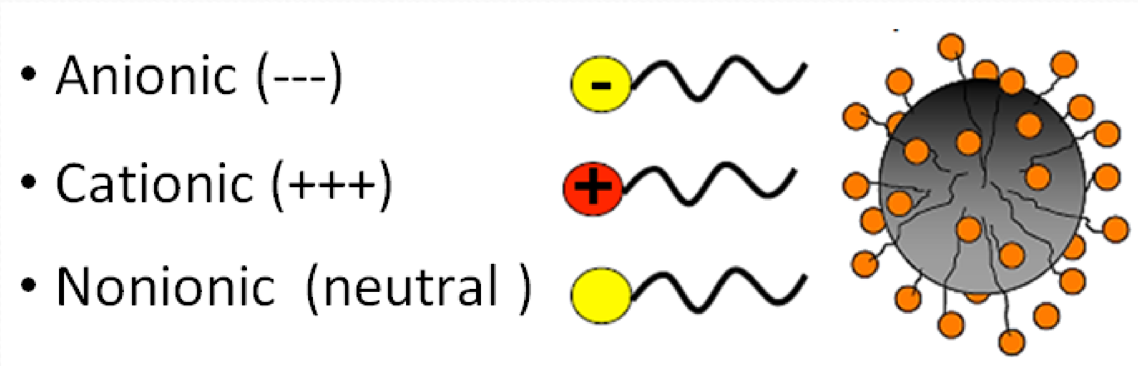
Note: Emulsifying agent can be broken by one or both of the following:

1. Neutralization of the electro-static charges.

2. Water evaporation.

Classification of Emulsified Asphalt

Based on electrical charges surrounding asphalt particles, Asphalt emulsions are classified into three categories:



Anionic Emulsions

In an anionic emulsion, there are “billions and billions” of asphalt droplets with emulsifying agent at the water asphalt interface. The tail portion of the emulsifying agent aligns itself in the asphalt leaving the rest of the head negatively charged and at the surface of the droplet. This imparts a negative charge to all the droplets. Since negatives repel each other, all the droplets repel each other and remain as distinct asphalt drops in suspension.

Cationic Emulsions

In an cationic emulsion, there are "billions and billions" of asphalt droplets with emulsifying agent at the water asphalt interface. The tail portion of the emulsifying agent aligns itself in the asphalt leaving the rest of the head positively charged and at the surface of the droplet. This imparts a positive charge to all the droplets. Since positives repel each other, all the droplets repel each other and remain as distinct asphalt drops in suspension.

Nonionic (Neutral) Emulsions

In this type of emulsion the agent is being active when water is added, so the asphalt droplets have a neutral charges. These emulsions are rarely used in highway engineering.

Types of Emulsions

There are different types of emulsion depending on the time of setting (time required to set).

1. Rapid Setting (RS).
2. Medium Setting (MS)
3. Slow Setting (SS)
4. Quick setting (QS)

} **For Anionic emulsion**

Note: for Cationic emulsion add a letter C before the abbreviation to be: CRS, CMS, CSS, and CQS

Modified Bitumen

❑ Modified bitumen is a bitumen whose rheological properties have been modified during manufacture by the use of one or more chemical agents (modifiers). The modification alters and improves certain bitumen properties, which results in the improvement of the respective bituminous mixture or application and therefore improve construction quality.

❑**Why do the need for modifications of asphalt ?**

- Bitumen origin and production sources (variability in bitumen properties).
- Rapid increase of traffic volume and axial loading.
- The higher demands of users for better and constant ride quality (increase the life of pavement).
- To improve the performance of bitumen to be familiar with the climatic changes.

❑ The modifiers are chemical additives, each one satisfying some or almost all of the above requirements.

Rheological: is a branch of physics which deals with the deformation and flow of materials, both solids and liquids.

The role of modified bitumen

The role of modified bitumen in paving is mainly fourfold:

1. to increase asphalt's resistance to permanent deformation,

The increase of asphalt's permanent deformation resistance solves the problem of premature rutting typically developed in areas with high–medium traffic volume and normal–high ambient temperatures.

2. to improve asphalt's fatigue life,

The improvement of asphalt's fatigue life delays the development of the pavement's fatigue cracking.

3. to increase asphalt's stiffness modulus, and

The increase of asphalt's stiffness modulus improves the load spreading ability of the asphalt layer; hence, lower stresses are transferred to the sub-grade. This could be interpreted as the ability to decrease the asphalt layer's thickness, and hence the pavement's thickness, for a given sub-grade strength and under the given traffic conditions.

4. to improve adhesion between bitumen and aggregate particles.

Improvement of the adhesion between bitumen and aggregate particles positively affects the life of surface dressings and eliminates the development of raveling.

Types of Modifiers and Their Usages

Table of Some bitumen modifiers/additives and supervened improvements

Type of additive		*Example*	*Main improvements*
Polymers	Thermoplastic elastomers	Styrene–butadiene–styrene (SBS), styrene–butadiene–rubber (SBR), styrene–isoprene–styrene (SIS), styrene–ethyl–butadiene–styrene (SEBS), ethyl-propyl-dien tetropolymer (EPDM), isobutene–isoprene copolymer (IIR), polybutadiene (PBD), natural rubber	(1), (2), (3), (4), [8], [9], [10], [11], [13]
		Crumb rubber	(2), [8], [9], [11]
	Thermoplastic polymers (plastics)	Ethylene–vinyl acetate (EVA), ethylene–methyl acrylate (EMA), ethylene–butyl acrylate (EBA), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS)	(2), (3), [8], [9], [10]
	Thermosetting polymers	Resins: epoxy resin, acrylic resin, polyurethane resin, phenolic resin	(2), (3), (4), (6), [8], [9], [10]
Chemical modifiers		Sulfur, lignin and certain organo-metallic compounds	(2), (5), (6), [8], [9], [12]
Natural asphalts		Trinidad lake asphalt, rock asphalt, gilsonite	(2), (4), (6), [8], [9]
Fillers		Hydrated lime, lime, carbon black, fly ash fillers	(4), (6), [8], [9]
Fibres		Cellulose, mineral, plastic, glass, asbestos fibres	[9], [11]
Hydrocarbons		Recycled or rejuvenating oils	(5), (7), [12]

Improvements to bitumen:

(1) Improves elastic behaviour
(2) Improves thermal susceptibility
(3) Improves binding ability
(4) Ageing retardation
(5) Viscosity reduction
(6) Hardens the bitumen
(7) Rejuvenates the bitumen

Improvements to asphalts:

[8] Stiffness increases
[9] Increases resistance to permanent deformation
[10] Cohesion improvement
[11] Better behaviour to fatigue cracking
[12] Workability increases
[13] Better behaviour to thermal cracking

Note: Fibers and fillers (inorganic powders) are not considered to be bitumen modifiers

Basic type of Modifiers	Type of additive	Example	Main Improvements to	
			Bitumen (only asphalt cement)	Asphalt concrete mixture (with aggregates) to increase
Polymers	Thermo-plastic elastomers	Styrene–butadiene–styrene (SBS), styrene–butadiene–rubber (SBR), styrene–isoprene–styrene (SIS), styrene–ethyl–butadiene–styrene (SEBS), ethyl-propyl-dien tetropolymer (EPDM), isobutene–isoprene copolymer (IIR), polybutadiene (PBD), natural rubber	Elastic behavior, Thermal susceptibility , binding ability, Ageing retardation	stiffness, resistance to rutting, Cohesion, resistance to fatigue cracking, workability ,resistance to thermal cracking
	Crumb rubber	Crumb rubber	Thermal susceptibility	stiffness, resistance to rutting, resistance to fatigue cracking,
	Thermo-plastic Polymers (Plastics)	Ethylene–vinyl acetate (EVA), ethylene–methyl acrylate (EMA), ethylene–butyl acrylate (EBA), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS)	Thermal susceptibility , binding ability	stiffness, resistance to rutting, Cohesion,
	Thermo-setting Polymers	Resins: epoxy resin, acrylic resin, polyurethane resin, phenolic resin	Thermal susceptibility, binding ability, Ageing retardation, Hardens	stiffness, resistance to rutting, Cohesion,
Chemical modifiers	Chemical modifiers	Sulfur, lignin and certain organo-metallic compounds	Thermal susceptibility, viscosity reduction ,Hardens	stiffness, resistance to rutting, workability
fillers	fillers	Hydrated lime, lime, carbon black, fly ash fillers	Ageing retardation, Hardens	stiffness, resistance to rutting
fibers	fibers	Cellulose, mineral, plastic, glass, asbestos fibres	---------------	resistance to rutting resistance to fatigue cracking
Hydrocarbons	Hydrocarbons	Recycled or rejuvenating oils	viscosity reduction, rejuvenates	Workability

Rational and Superpave Laboratory tests and properties of bitumen

The purpose of the laboratory tests performed on bitumen is to define its characteristic properties, so as to ascertain its suitability and predict its behaviour during the service life of the pavement

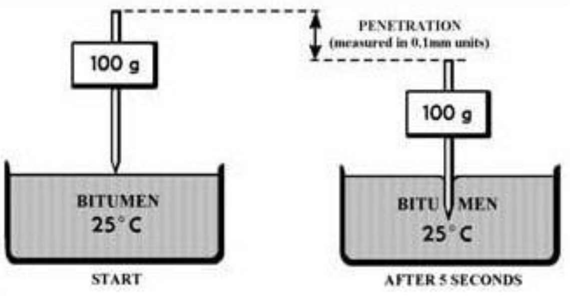
Rational Laboratory Tests

- The general properties of bitumen (asphalt cement) are defined by the following tests, such as penetration, softening point, viscosity, ductility, flash point, solubility, weight loss after heating etc.
- These properties are the key importance for predicting the mechanical behaviour of bitumen and thus of the bituminous mixture (asphalt concrete mixture) .

Penetration Test (ASTM D-5, AASHTO T 49)

- The penetration test is the most widely known test, developed at the end of the 19th century and still in use, for grading the paving bitumen. This test method also determines the consistency of the bitumen and bituminous binders at intermediate service temperature. **Higher values of penetration indicate softer consistency**. The test involves the determination of the penetration depth of a standard penetration needle into the bituminous binder under standard conditions of 1-temperature (25°C), 2-applied load and 3-loading time.

➢ A standardized needle first touches the surface of the bituminous specimen and then is allowed to penetrate into the mass of the specimen under the influence of its own weight and an additional mass so that the **total load is 100 ± 0.1 g**, for a period of **5 s**. After loading, the penetration depth of the needle is measured in 0.1 mm . This unit is also called 'pen' (1 pen = 0.1 mm). Figure shows an automatic penetration test apparatus.

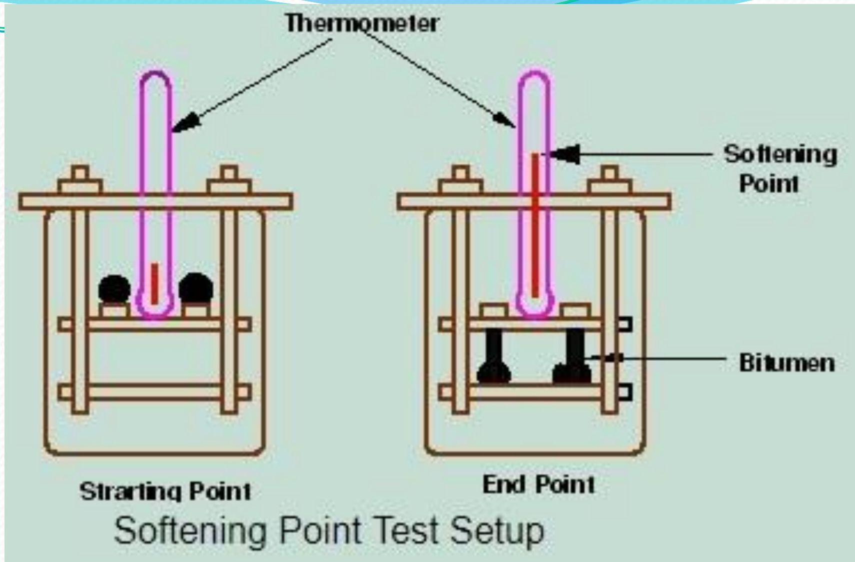


Softening Point Test (ASTM D 36, AASHTO T 53)

➢ The consistency of the bituminous binders at elevated temperature is empirically determined with the softening point test, also known as a **'Ring and Ball' (R&B) test**.

➢ Bitumen, a viscoelastic material, does not have a defined melting point. It gradually becomes softer and less viscous as the temperature rises. Softening point is defined as the temperature at which material under standardised test conditions attains a specific consistency. The test is used to determine the softening point of bitumen (asphalt cement).

➢Two horizontal brass rings (approximately 19.8 mm internal diameters) filled with bituminous binder are placed in a ring holder and heated at a controlled rate in a liquid bath (water) while each supports a steel ball. The softening point is the mean of the temperatures at which the two discs soften enough to allow each ball, enveloped in bituminous binder, to fall a distance of 25.0 mm till touching a base plate at below.



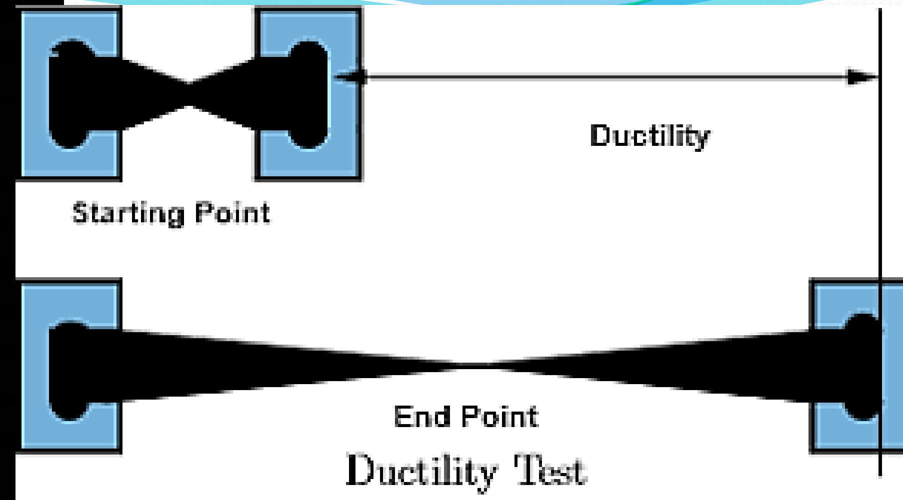
Ductility Test (ASTM D 113, AASHTO T 51)

➢ The ductility test indirectly measures the tensile properties of the bituminous materials. During the ductility test, the bitumen specimen is pulled apart at a specified speed and temperature condition (50 mm/min, 25°C) until it breaks or reaches the length limitations of the machine. The elongation length at breaking, measured in centimeters, is defined as the bitumen's ductility value.

➢ The test is performed on three briquette specimens and the average of the three values is determined.

➢The main purpose of ductility test is that gives an indication to the temperature susceptibility and adhesion of binder with aggregate.

➢According to ISSRB specification ductility must be more than 100 cm.

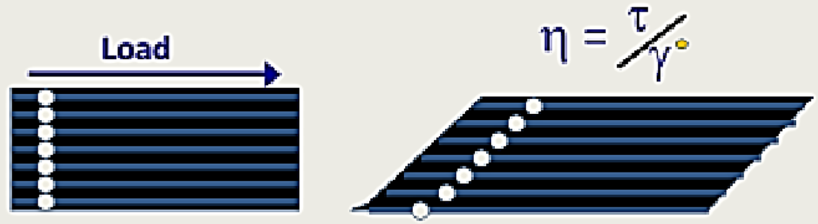


Viscosity

➢ Grading of asphalt on the bases of the penetration test is an old empirical method that is now known to be inadequate for modern technology. A more scientific bases is the viscosity test. The grade of asphalt cement according to their viscosities is adopted now. Generally, two types of viscosities are commonly known: **absolute viscosity** (measured under vacuum pressure at at 60°C (140 °F)) and **kinematic viscosity** (measured due to gravity of the asphalt mass at 135°C (275 °F)). The absolute's unit is Poises (1 Poise = 0.1 Pa.sec) while Kinematics' unit is (mm^2/ sec).

➢ Mechanically, the viscosity in which a stress acting tangentially between two plans separately to produce a difference in velocity due to the deformation of the liquid under stresses.

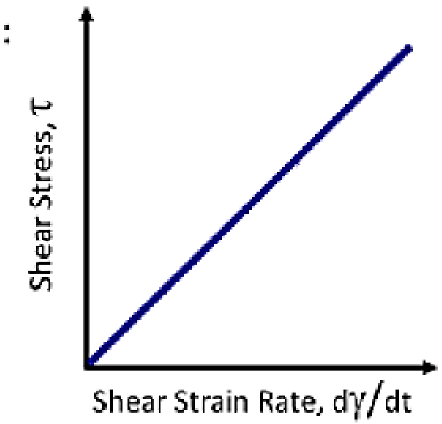
- Viscosity:
  - Ratio between the applied shear stress and the rate of shear strain
  - Fundamental consistency measurement of the resistance to flow



Rate of shear strain is the rate at which the dots separate

Viscous Materials:

$$\tau = \eta\left(\frac{d\gamma}{dt}\right)$$



Where:

τ = shear stress   η = coefficient of viscosity

dγ/dt = rate of application of shear strain

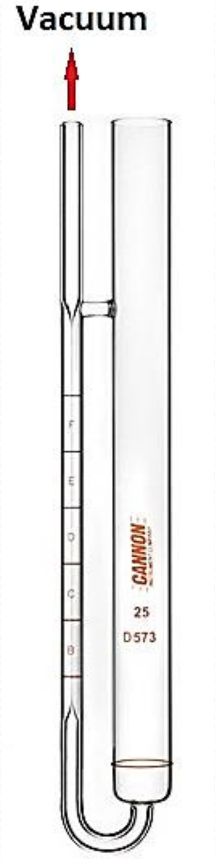
➢ There are two series of viscosity grades by which asphalt cement is available.

1. Consists of grades AC – 2.5, AC -5, AC -10, AC – 20, and AC – 40. the numerical values indicate the viscosity in hundreds of poises at 60°C.
2. Consists of grades AR – 1000, AR – 2000, AR – 4000, AR – 8000 and AR – 16000 with the numerical values indicting the viscosity in Poises but with viscosity being measured after the asphalt has been suffered the Rolling Thin Film Oven Test (RTFO). It means that AR is aged residue.

Note: the lower viscosity graded asphalts correlate with the softer asphalt having higher penetration values.

Absolute Viscosity: (ASTM D 2171, AASTO T 202)

➢Procedure: After the bath, viscometer, and asphalt have stabilized at 60ºC (the maximum temperature of asphalt pavement surface in summer), the vacuum is applied and the time in seconds required for the asphalt cement to flow between two timing marks is mastered by a stopwatch. Multiplying this measured time by the calibration factor for the viscometer gives the value for viscosity in poises. Poise is the standard unit for measurement of absolute viscosity.



Kinematic Viscosity: (ASTM D 2170, AASHTO T 201)

- Paving-grade asphalt cements are sufficiently fluid at 135^{o}C (275^{o}F) to flow through capillary tubes under gravitational forces alone. Therefore, a vacuum is not required but a deferent a type of viscometer is used. The one most commonly used is the Zeitfuchs cross-arm viscometer.
- The kinematic viscosity is carried out:

▪ By using Zeitfuchs cross-arm viscometer at 135^{o}C temperature (135^{o}C is the temperature of mixing and laydown of hot asphalt concrete pavement) of used liquid.

▪ The asphalt is poured into the large opening of the viscometer until it reaches the filling line.

▪ The system (asphalt, viscometer) is then allowed to reach equilibrium test temperature.

▪ A low pressure is applied on the large opening or a low vacuum is applied on the small opening to let the asphalt cement moving to cross the filling line, due to the fluidity of the heated asphalt, it moves by gravitational forces toward the timing marks.

▪ Stopwatch is used to account the time needed between these two timing marks.

▪ The time interval (t) in seconds, multiplied by a calibration factor (C) for the viscometer, gives kinematic viscosity (*η*) in centistokes (mm^2/sec).

$$\eta = C \times t$$

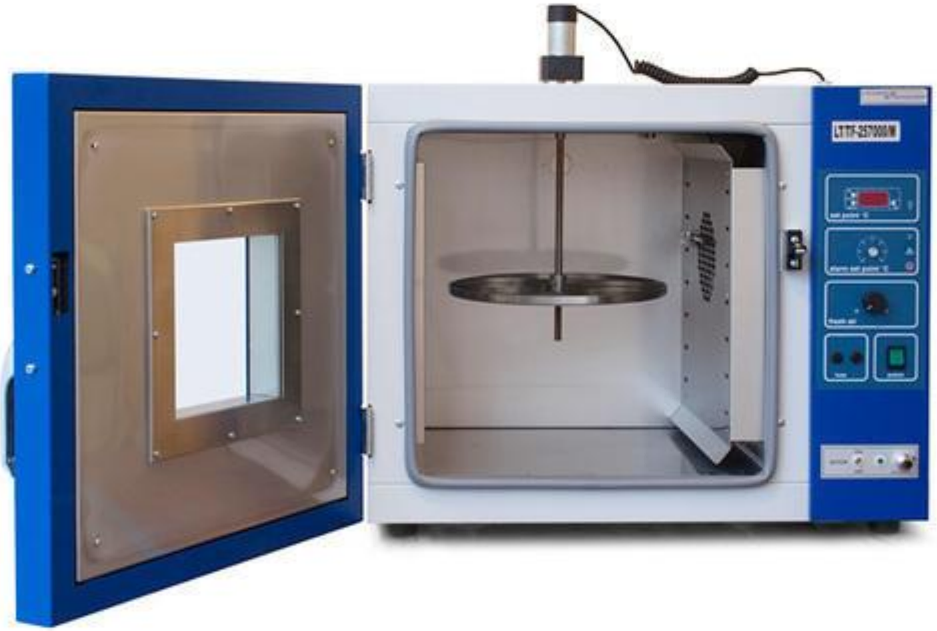
Flash Point (ASTM D 92, AASHTO T 48)

- Flash point indicates the temperature to which the asphalt maybe **safely** heated without an instantaneous flash in the presents of an open flame. It is the lowest temperature at which the material gets ignited and burns under specified condition of test. Object: The flash point of bitumen is measured by the Cleveland Open Cup (COC) in centigrade.
- the asphalt is poured in COC and heated, a small flame is passed over the surface of asphalt at prescribed time intervals. The temperature at which a sufficient volatiles ate released to cause an instantaneous flash is the flash point in (^{o}C).

Thin Film Oven Test (TFO): (ASTM D 1754, AASHTO T 179).

- The thin film oven (TFO) test actually is not a test, but is a procedure intended to subject a sample of asphalt to hardening conditions approximating those that accrue in hot mix plant operations. Penetration test made on the sample before and after the TFO test, are considered to be a measure of the resistance of the material to change under hardening conditions.

- The TFO test is made by placing a 50 CC sample of asphalt cement in a cylindrical flat-bottomed pan 140 mm (5.5 in) in inside diameter and 10 mm (3/8 in) deep. The asphalt layer is about 3 mm (1/8 in) deep. The sample and container placed on a shelf, which rotate approximately 5 to 6 revolutions per minute in a ventilated oven maintained at 163 ^{o}C (325 ^{o}F) for 5 hours. The asphalt cement is than poured into a standard container use for the penetration test.



Solubility Test (ASTM D 2042, AASHTO T 44)

The solubility test is performed to determine the purity and degree of solubility of asphalt cement. A trichloroethylene, carbon tetrachloride or another solvent are used as a solvent in the tests.

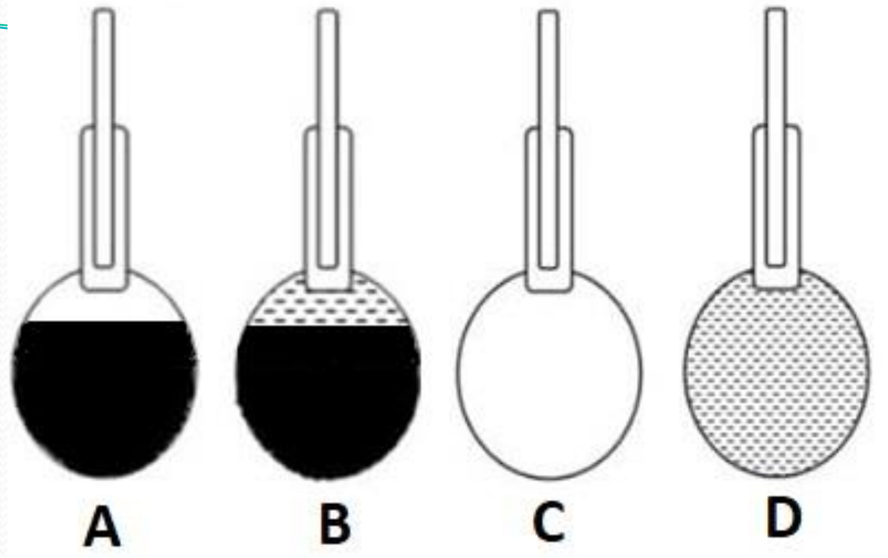
A mass of 2 g of asphalt cement is dissolved in 100 ml of solvent and then the solution is filtered. The amount of substances withheld by the filter is washed, dried, weighed and expressed as a percentage of the initial mass of bitumen. The degree of solubility should be above a certain specified value, normally more than 99%.

Specific gravity of asphalt cement Test (ASTM D 70, AASHTO T 228)

This test method determines the specific gravity and density of bituminous binders at 25°C using capillary-stoppered pycnometer. A quantity of heated binder is poured in the pycnometer, filling approximately 3/4 of its volume and try to remove any air bubbles. After the pycnometer containing the asphalt cement is allowed to cool in ambient temperature for at least 40 min, the test sample is weighed (**weight A**), together with the pycnometer and the stopper. The remaining volume is then fully completed with water; the pycnometer is placed in a water bath for at least 30 min in order to reach the temperature of 25°C and is weighted (with the stopper) (**weight B**). After the pycnometer is emptied and thoroughly cleaned, it is weighed in air **(weight C).** Then, the pycnometer is filled completely with water and is weighed (**weight D)**. All weight measurements include the stopper. The specific gravity and the density of bituminous binder are calculated by the following equations:

Pycnometer

A-C = weight of bitumen in air (gm).
D - C = volume of pycnometer (cm^3).
B-A = volume occupied by water in pycnometer B (cm^3).



$$Sp.gr = \frac{A-C}{(D-C)-(B-A)}$$

Example: Compute the specific gravity of asphalt cement grade 40-50, from the following data: A = 60.85 gm, B = 67.0 gm, C = 42.5 gm and D = 66.5 gm. Note: the density of used water is 1 gm/cm^3 at 25^{o}C?

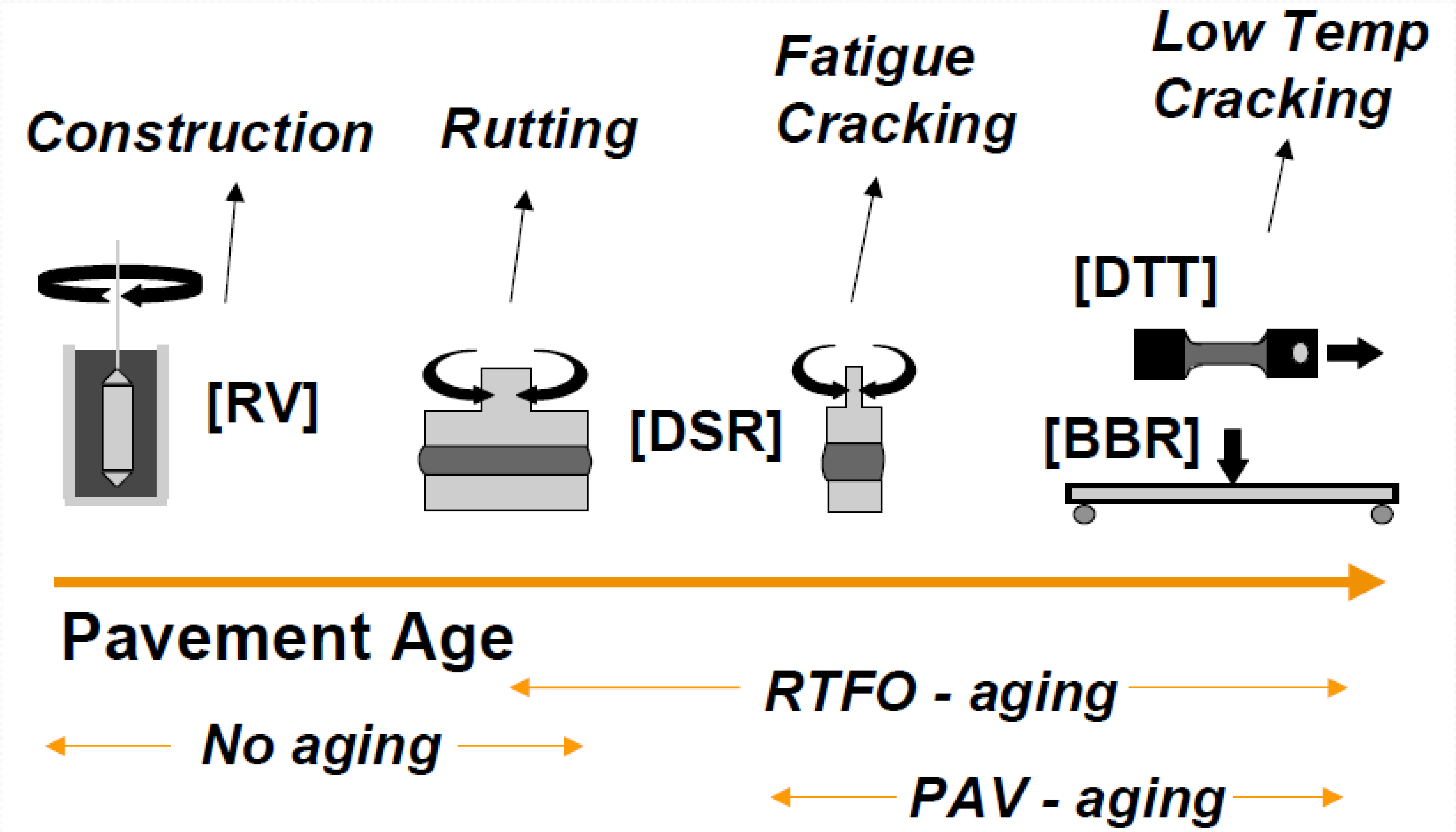
Solution:

(Superpave Tests), Dynamic shear rheometer, Rolling thin oven test (RTOT), Thin film oven test (TFOT), Accelerated ageing by PAV, Bending beam rheometer test for flexural creep stiffness, and Direct tension test for fracture properties.

Superpave Tests

- Superpave is an acronym for **Su**perior **Per**forming Asphalt **Pave**ments. Superpave is a new, comprehensive asphalt mix design and analysis system, a product of the **S**trategic **H**ighway **R**esearch **P**rogram **(SHRP)**. Congress established SHRP in 1987 as a five-year, $150 million research program to improve the performance and durability of United States roads and to make those roads safer for both motorists and highway workers.
- The goal of the SHRP asphalt research was the development of a system that would relate the material characteristics of hot mix asphalt to pavement performance.
- **A unique feature of the Superpave system** is that its tests are performed at **temperatures and aging** conditions that more realistically represent those encountered by in-service pavements.
- The Superpave performance graded (PG) binder specification makes use of these tendencies to test the asphalt under a project’s expected climatic and aging conditions to help reduce pavement distress. SHRP researchers developed new equipment standards as well as incorporated equipment used by other industries to develop the binder tests.

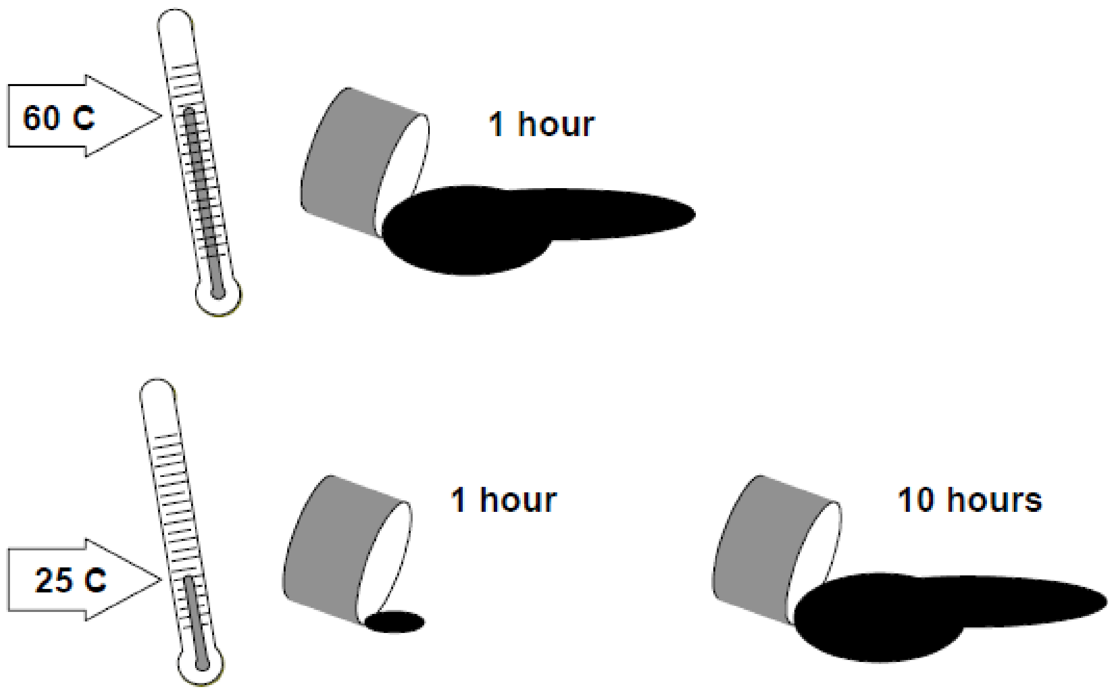
Superpave Main Tests



HOW ASPHALT BEHAVES

Asphalt is a *viscoelastic material. This term* means that asphalt has the properties of both a viscous material, such as motor oil, or more realistically, water, and an elastic material, such as a rubber. However, the property that asphalt exhibits, whether viscous, elastic, or most often, a combination of both, depends on *temperature and time of loading. The flow* behavior of an asphalt could be the same for one hour at 60°C or 10 hours at 25°C.

In other words, the effects of time and temperature are related; the behavior at high temperatures over short time periods is equivalent to what occurs at lower temperatures and longer times.



Aging Behavior

➢ Because asphalt cements are composed of organic molecules, they react with oxygen from the environment. This reaction is called oxidation and it changes the structure and composition of asphalt molecules. Oxidation causes the asphalt cement to become more brittle, generating the term oxidative hardening or age hardening. In practice, a considerable amount of oxidative hardening occurs before the asphalt is placed. **At the hot mix facility, asphalt cement is added to the hot aggregate and the mixture is maintained at elevated temperatures for a period of time. Because the asphalt cement exists in thin films covering the aggregate, the oxidation reaction occurs at a much faster rate.** **"Short term aging"** is used to describe the aging that occurs in this stage of the asphalt's "life".

➢ Oxidative hardening also occurs during the life of the pavement, due to exposure to air and water. **"Long term aging"** happens at a relatively slow rate in a pavement, although it occurs faster in warmer climates and during warmer seasons.

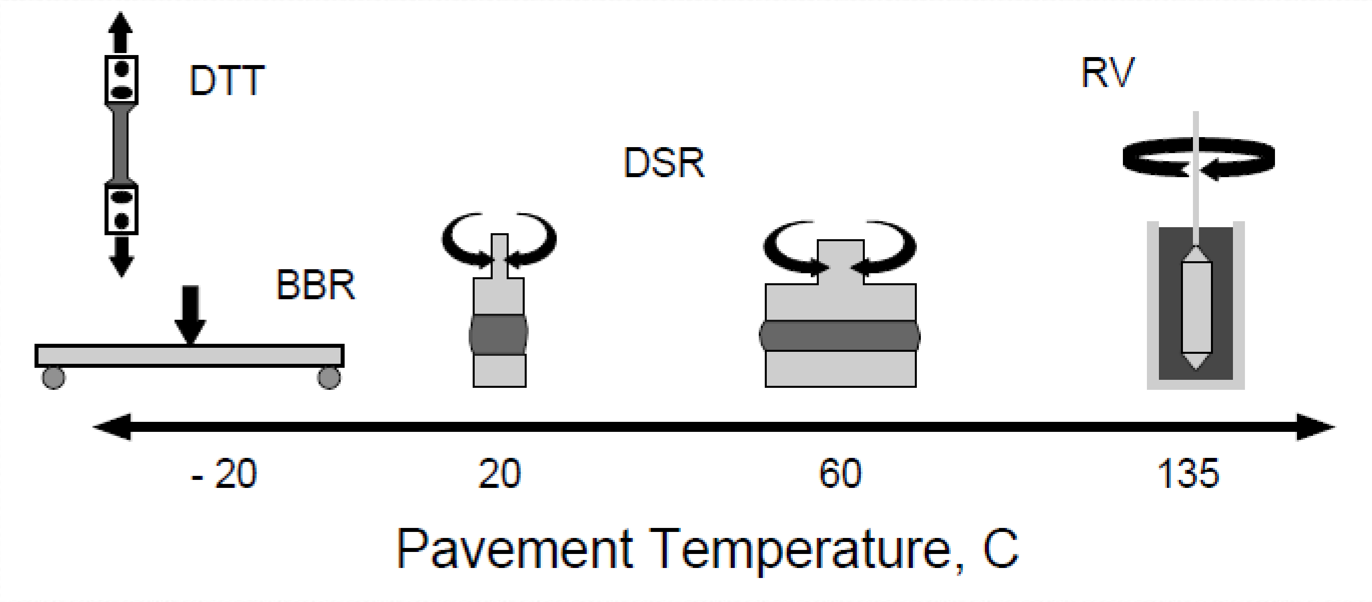
➢ Other forms of hardening **include volatilization and physical hardening**. ***Volatilization occurs during hot mixing and construction, when volatile components tend to evaporate from the asphalt***. **Physical hardening occurs when asphalt cements have been exposed to low temperatures for long periods. When the temperature stabilizes at a constant low value, the asphalt cement continues to shrink and harden**. Physical hardening is more pronounced at temperatures less than 0°C and must be considered when testing asphalt cements at very low temperatures

The three most critical stages of ageing are:

1. During transport, storage, and handling,
2. During mix production and construction, and
3. After long periods in a pavement.

➢The new Superpave binder tests measure physical properties that can be related directly to field performance by engineering principles.

Superpave Binder Test	Purpose
Dynamic Shear Rheometer (DSR)	Measure properties at high and intermediate temperatures
Rotational Viscometer (RV)	Measure properties at high temperatures
Bending Beam Rheometer (BBR) Direct Tension Tester (DTT)	Measure properties at low temperatures
Rolling Thin Film Oven (RTFO) Pressure Aging Vessel (PAV)	Simulate hardening (durability) characteristics



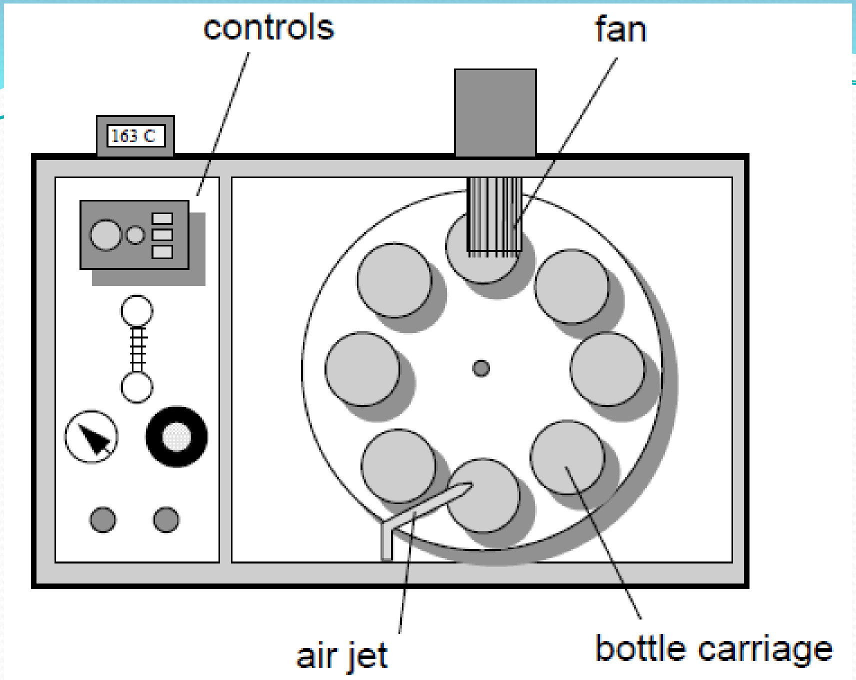
Aging the binder in a **Rolling Thin Film Oven (RTFO) simulates the second stage,** during mix production and construction.

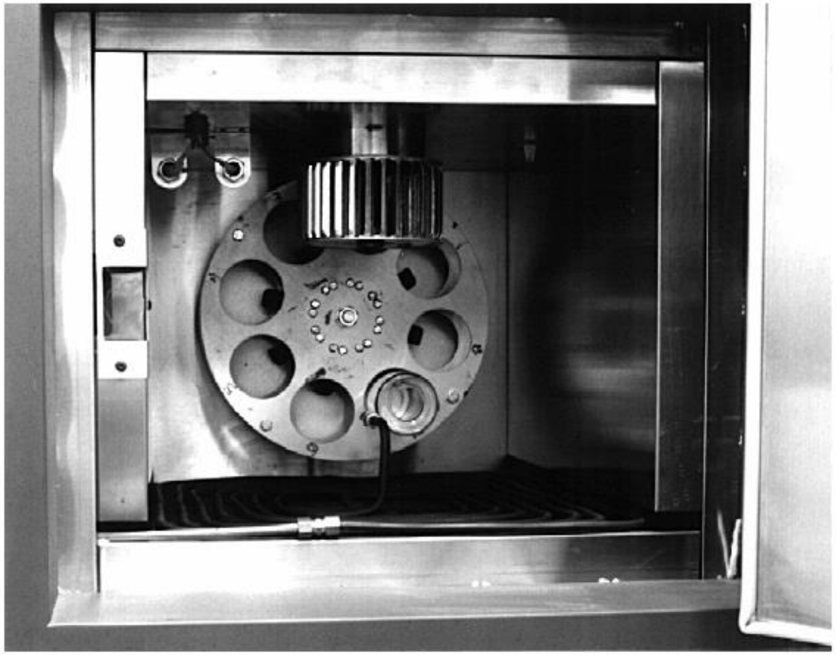
Third stage of binder aging occurs after a long period in a pavement. **Pressure Aging Vessel(PAV) test (simulate third stage) exposes binder samples to heat and pressure in order to simulate, in a matter of hours, years of in-service aging in a pavement.**

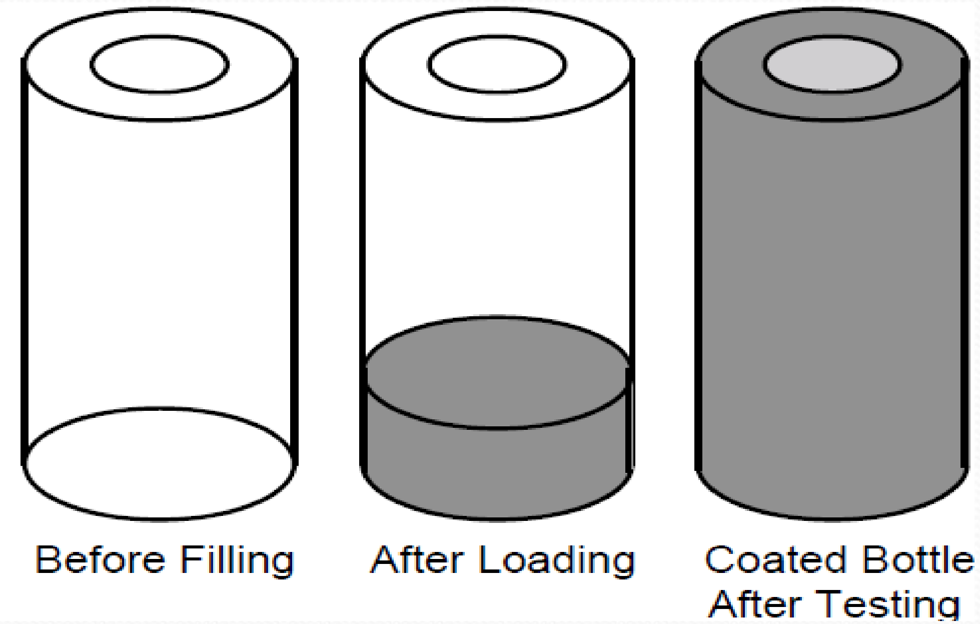
Note: It is important to note that for specification purposes, binder samples **aged in the PAV have already been aged in the RTFO**.

Rolling Thin Film Oven Test (RTFO) Test (ASTM D 2872, AASHTO T 240)

- The RTFO procedure requires an electrically heated convection oven. 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.
- To prepare for RTFO aging, a binder sample is heated until sufficiently fluid to pour. 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. 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.


controls
fan
163 C
air jet
bottle carriage




Before Filling
After Loading
Coated Bottle
After Testing

RTFO Test Procedure

1. Preheated oven at 163° + 0.5° C at least 2 hours.
2. The bottles with samples (35 g ± 0.5 gm / bottle) are set horizontally in their location inside the oven.
3. The rate of air flow inside the oven is 4 L/min.
4. Rate of rotation is 15 ± 0.2 RPM.
5. The samples are maintained under these conditions for 85 minutes.

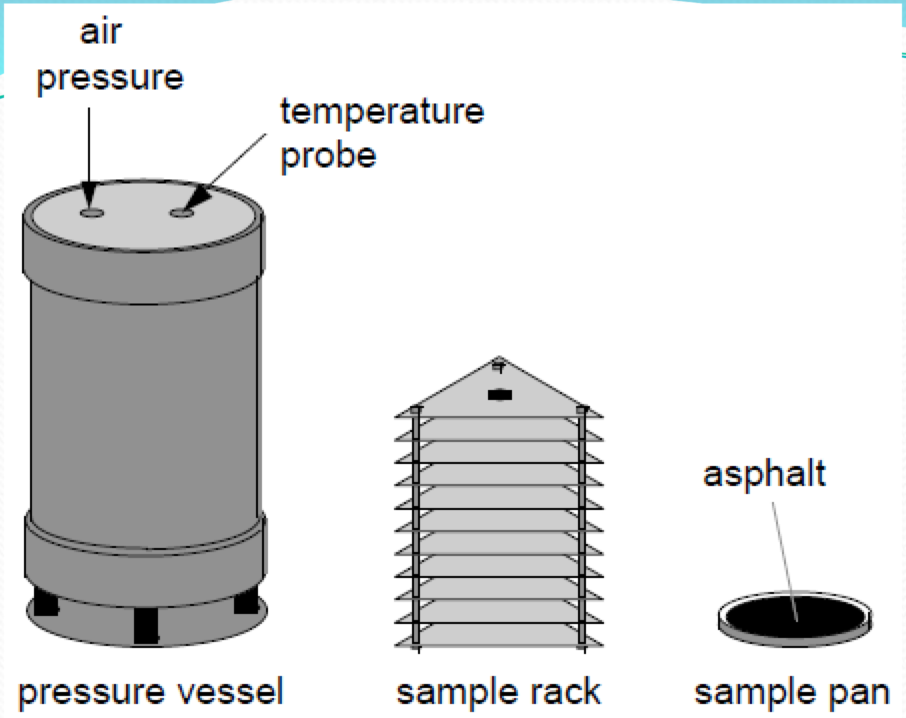
➢ **The primary purposes of RTFO procedure are:**

- 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,

Pressure Aging Vessel (PAV) (ASTM D 6521, AASHTO R 28)

➢ PAV was Designed specifically to prepare specimens for tests developed by the Strategic Highway Research Program (SHRP), to simulate oxidative aging that occurs in asphalt binders during service life. In other words PAV is accelerated aging of asphalt binder test using a pressurized aging vessel (PAV).

➢ 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**).



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

PAV Test 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 (cover of chamber) is installed and the lid is secured. This step should be completed as quickly as possible to avoid excessive loss of vessel heat.
- When the **vessel temperature ((90, 100 or 110°C) ± 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.**
- PAV test **takes 20 hours**, then the pressure is slowly released using the release valve. Usually, 8 to 10 minutes are required to gradually release the pressure.
- 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 *((The sole purpose of the PAV procedure is the preparation of aged binder materials for further testing and evaluation with the Superpave binder tests.))***

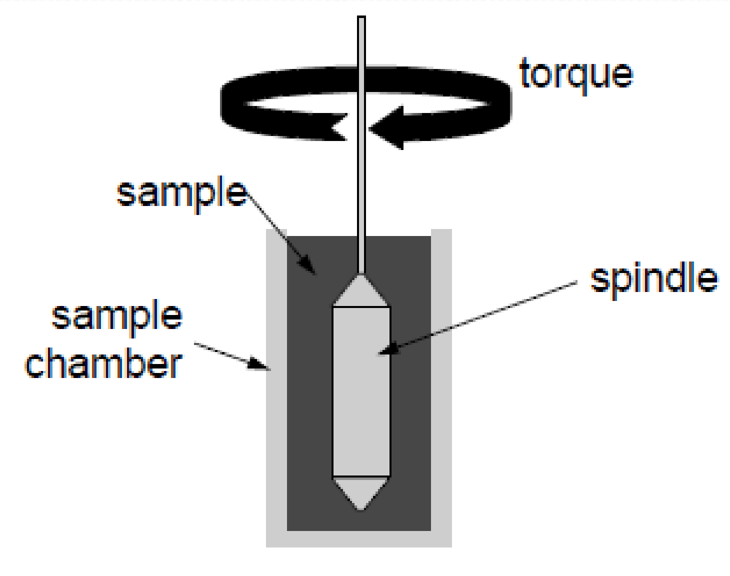
Pressure Vessel Built into Oven

Pressure Aging Vessel Inside of Oven

Rotational Viscometer (AASHTO TP48)

- 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. High temperature binder viscosity is measured **to ensure that the asphalt is fluid enough when pumping and mixing**. Consequently, rotational viscosity is measured on un-aged asphalt at 135° C or higher.

- 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(No.27) at a constant speed(20rpm) 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 **((the sample should not 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 size**. 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 thermosel container and is ready to test when the temperature stabilizes, usually about **15 minutes**.

Test Equipment

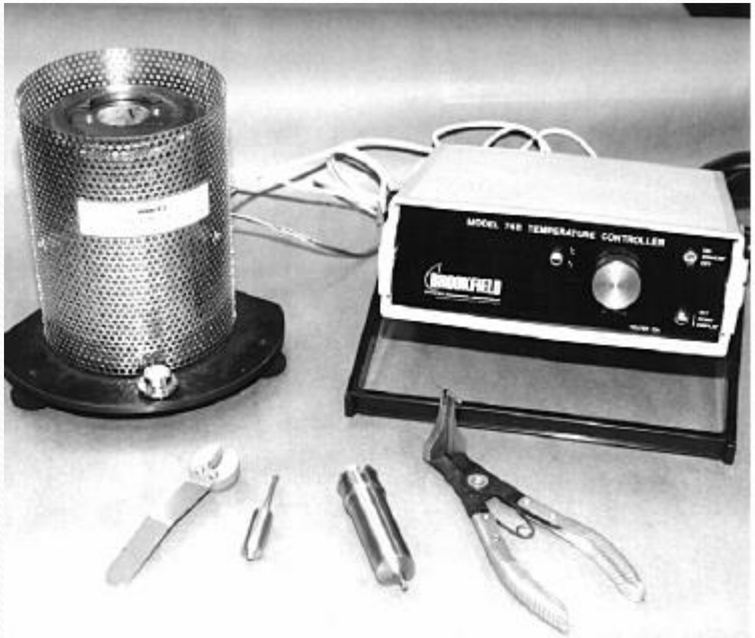
1. Brookfield Viscometer

The Brookfield viscometer consists of a motor, spindle, control keys, and digital readout. The motor powers the spindle through a spring. 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 which is used to conduct asphalt viscosity is spindle No. 27.

- 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.

2. Thermosel system

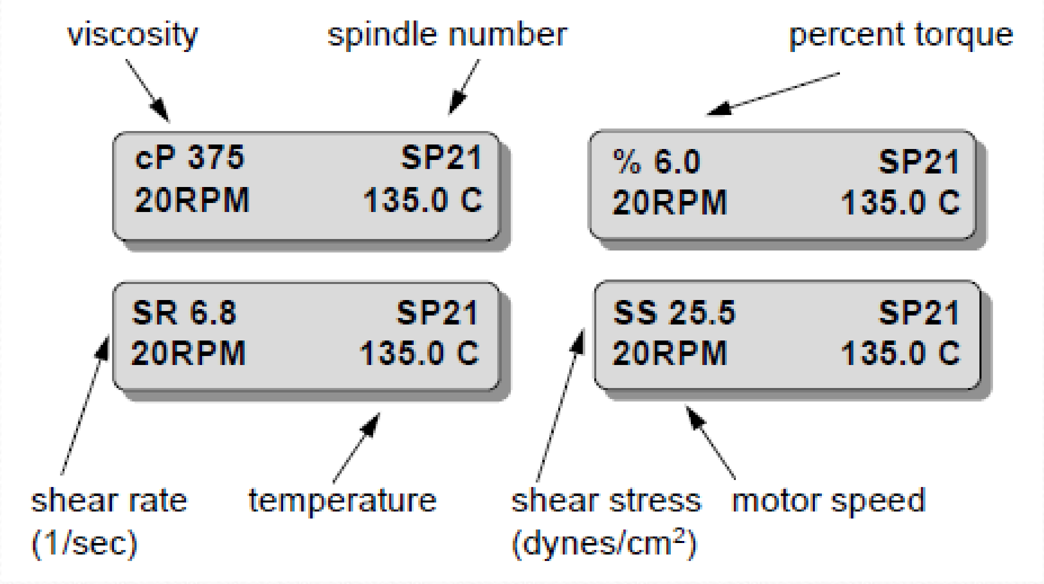
The Thermosel system consists of the **sample chamber, thermo container, and temperature controller.** The sample chamber is a stainless steel cup in the shape of a test tube. An extracting tool is used to handle the sample chamber when hot. The thermo-container holds the sample chamber and consists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



Test 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.**

- 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.



- 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:

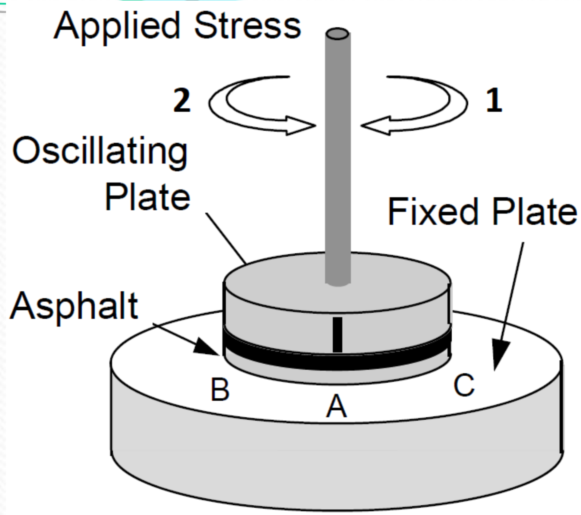
$$1000\ cP = 1\ Pa \cdot s$$

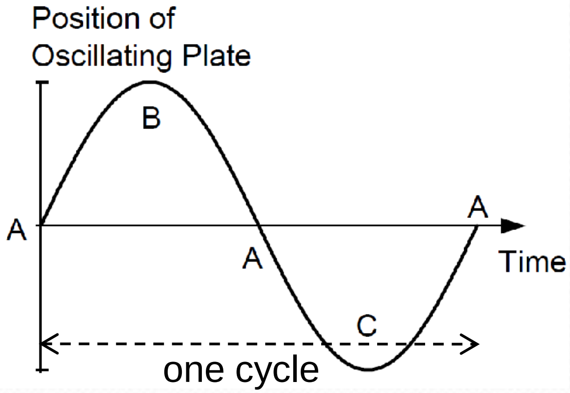
Dynamic Shear Rheometer: AASHTO TP5

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. honey or molasses). The relationship between these two properties is used **to measure the ability of the binder to resist rutting (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.

Mechanism of Test Equipment

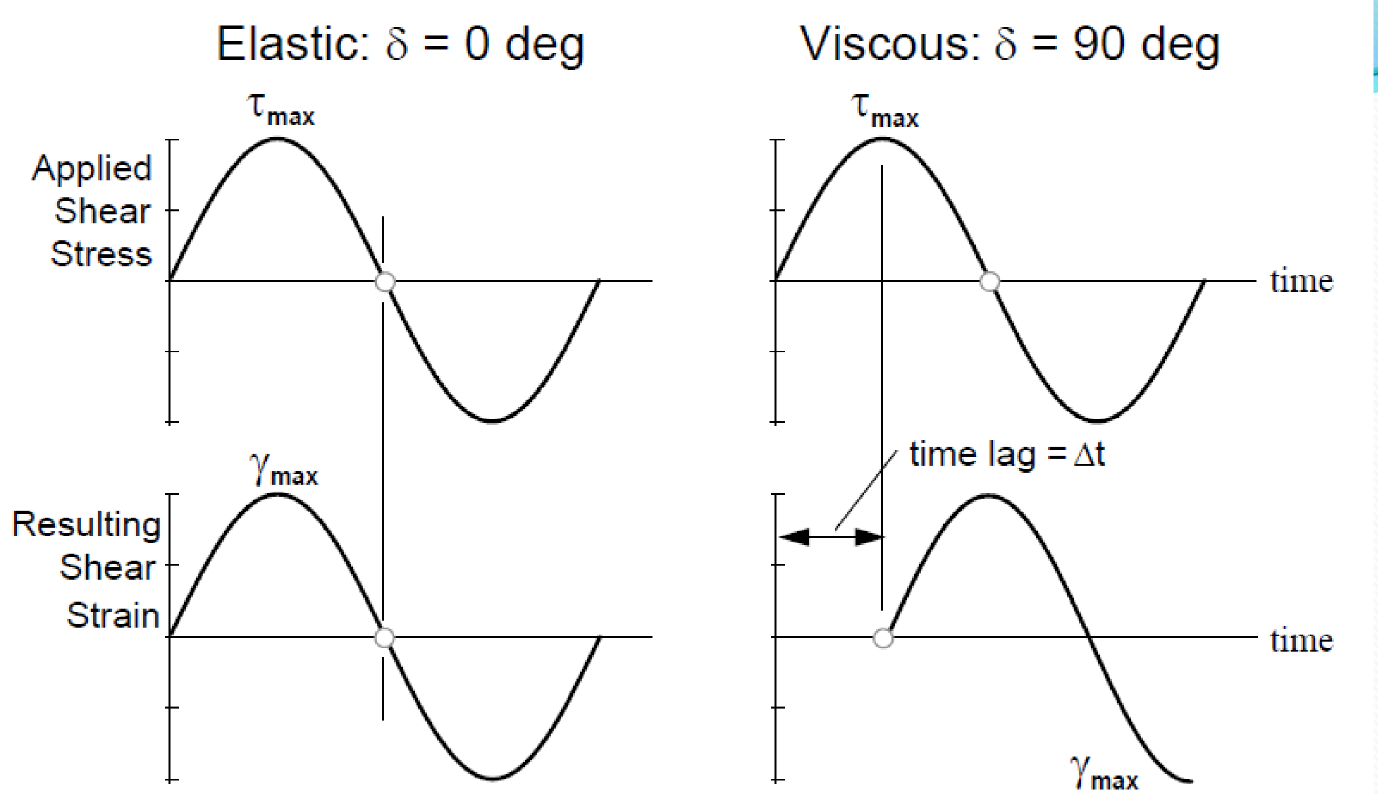
- The principle of operation of the DSR is simple and easy. An asphalt sample is sandwiched between an oscillating spindle and the fixed base. The oscillating plate (often called a "spindle") starts at point A and moves to point B. From point B the oscillating plate moves back, passing point A on the 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.





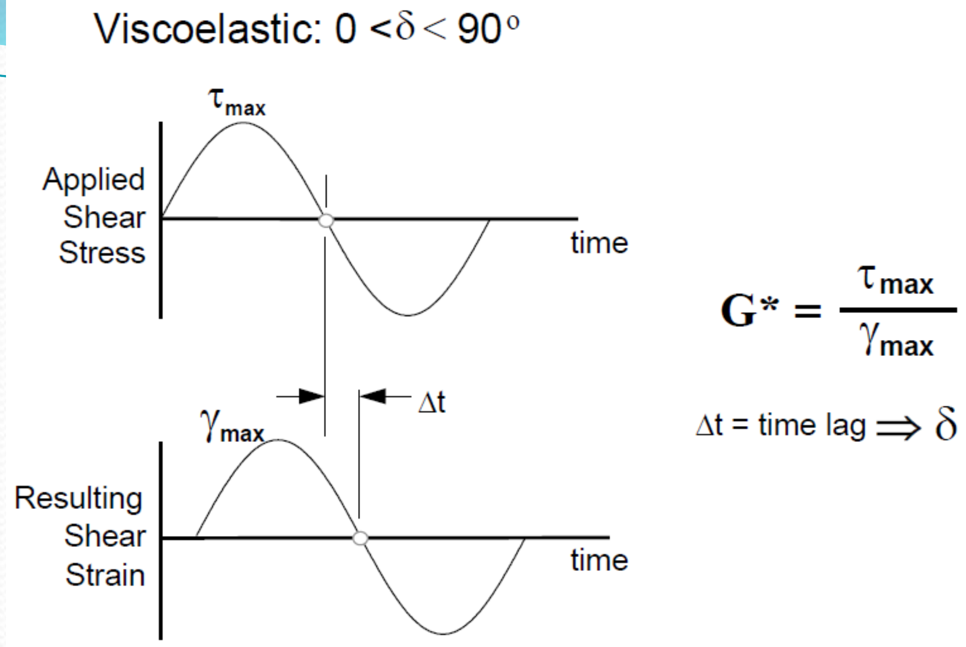
- As the force (or shear stress, τ) is applied to the asphalt by the spindle, the DSR measures the response (or shear strain, γ) of the asphalt to the force. If the asphalt were a perfectly elastic material, the response would coincide immediately with the applied force, and the time lag between the 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.

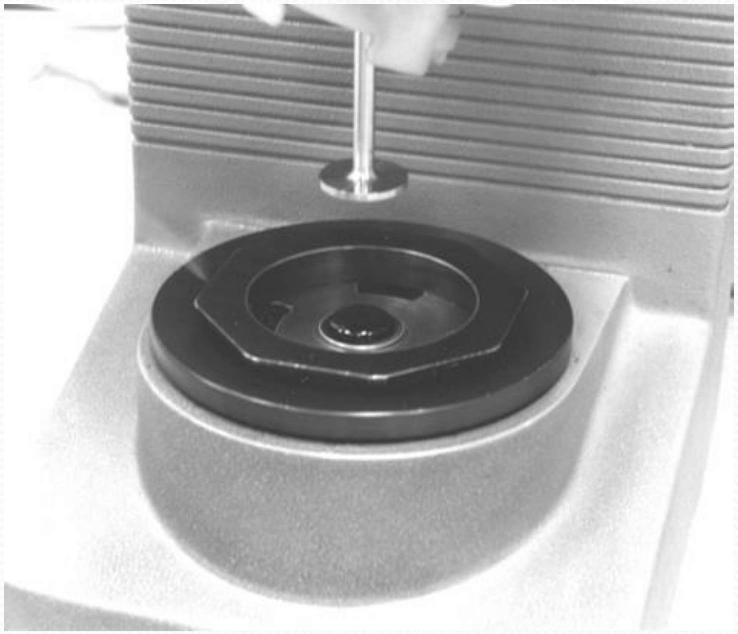


- Along the year, the temperatures of pavement vary from **cold to hot under** traffic loading repetition, so the asphalt pavement behaves both like an **elastic solid and a viscous liquid**. The relationship between the applied stress and the response strain in the DSR quantifies both types of behavior, 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.



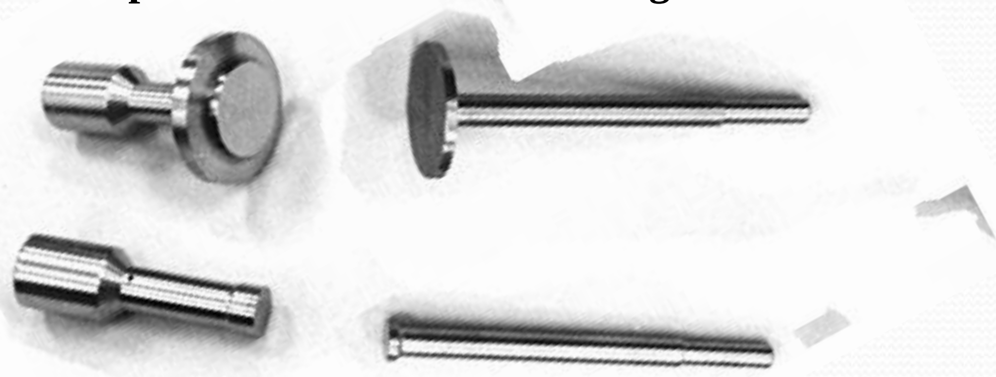
- Because the properties of asphalt binders are so temperature dependent, Rheometer must have a precise means of controlling the temperature of the sample. The accuracy of temperature controller must be ± 0.1 °C



• The thickness of gap used depends on the **test temperature** and **the aged condition** of the asphalt.

1. Un-aged and RTFO aged asphalt, tested at **high temperatures of 46°C or greater,** require a small gap **of 1 mm using a large spindle size (25 mm diameter).**
2. PAV aged asphalts, tested at **intermediate test temperatures**, in the range of **4° to 40°C**, require a larger gap of **2 mm using a small spindle size (8 mm diameter).**

Large spindle (25 mm)



Small spindle (8 mm)

➢ **G* is divided by sin δ (G* ÷ sin δ) to develop a "High temperature stiffness" factor that addressed Rutting. At least 1.0 kPa for original asphalt and minimum of 2.20 kPa after ageing asphalt in the RTFO**

➢ **G* is multiplied by sin δ (G* x sin δ) to develop an "Intermediate temperature stiffness" factor that addresses Fatigue cracking. Maximum value is 5000 kPa**

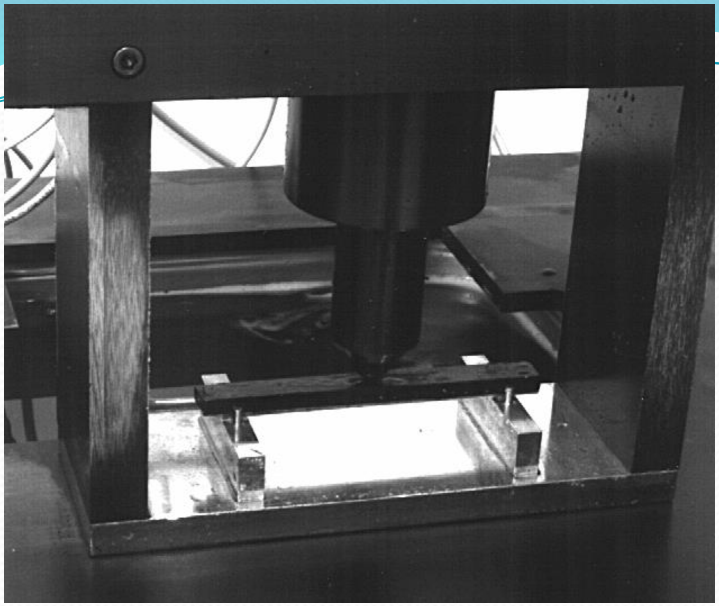
Bending Beam Rheometer (BBR): (AASHTO TP1)

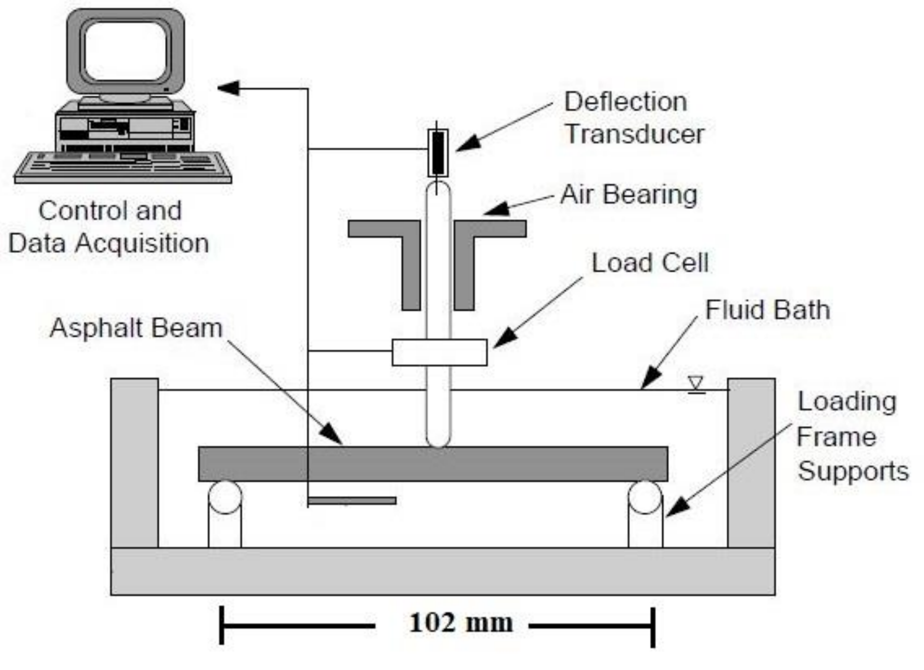
- The Bending Beam Rheometer (BBR) is used to measure the stiffness of asphalts at very low temperatures. The test uses engineering beam theory to measure the stiffness of a small asphalt beam sample under a creep load.

- The BBR is used in combination with the **Direct Tension Tester (**DTT) to determine an asphalt binder's low temperature PG grade. As with other Superpave binder tests, **the actual temperatures anticipated in the area where the asphalt binder will be placed determine the test temperatures used**.

- The basic BBR test uses a small asphalt beam that is simply supported and immersed in a cold liquid bath . A load is applied to the center of the beam and its deflection is measured against time. Stiffness is calculated based on a measured deflection (strain), standard beam properties, and bending stresses. BBR tests are conducted on PAV aged asphalt binder samples.

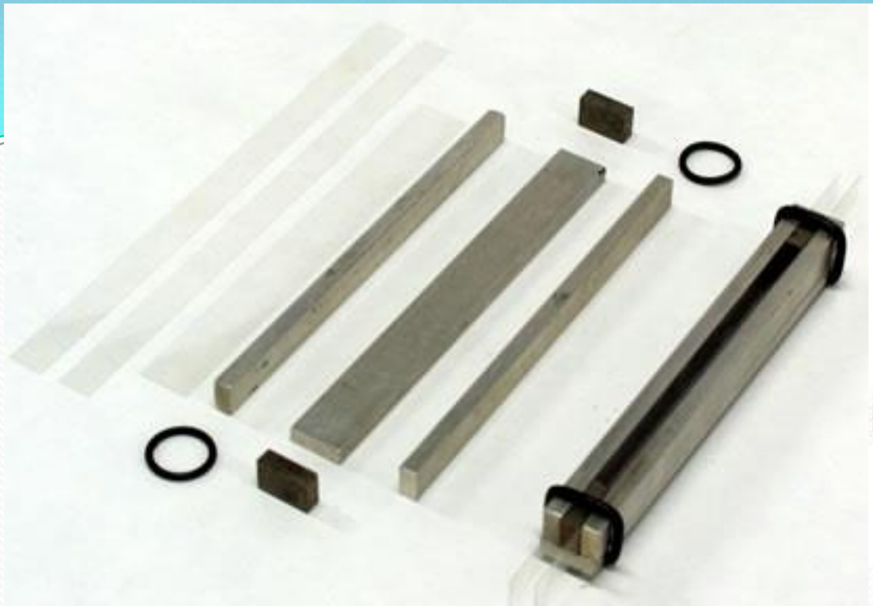
- As surrounding temperatures drop, pavements contract and build up internal stresses. If this contraction occurs fast enough the pavement may crack because it does not have time to relax these stresses. This type of crack, typically called a "thermal crack", or transverse crack.

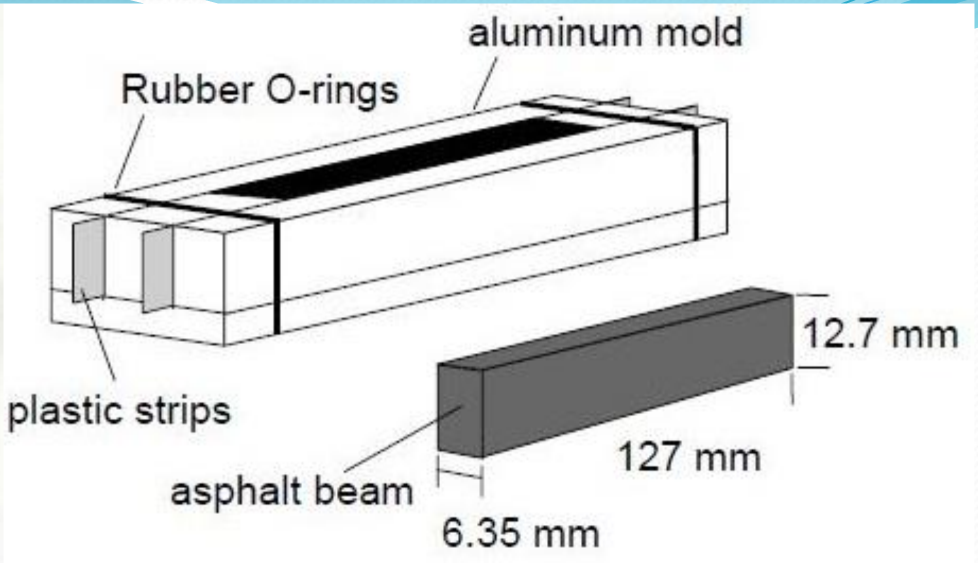




BBR Test Procedure:

1. A sample of asphalt binder is molded into a beam measuring 6.35 x 12.7 x 127 mm.
2. The sample is simply supported at two points 102 mm apart in a controlled temperature fluid bath **(the minimum daily temperature found during the year).**
3. The beam is then loaded at the midpoint by a 100 g (force = 980 mN).
4. The beam deflection is measured at 8, 15, 30, **60**, 120 and 240 seconds.
5. Beam stiffness, often called "creep stiffness", is calculated for these times.
6. A stiffness curve is then fitted to these points.
7. The BBR test is done on two beam samples.





Data Presentation

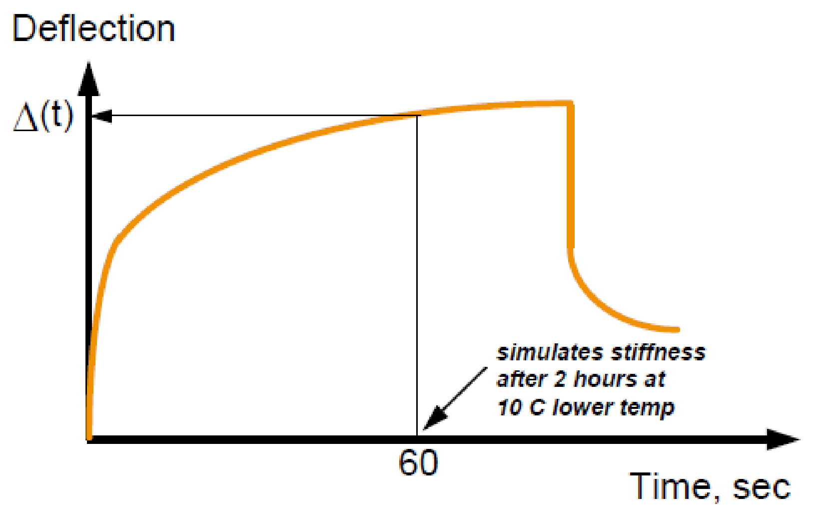
Beam analysis theory is used to obtain creep stiffness of the asphalt in this test. The formula for: calculating creep stiffness, S(t), is:

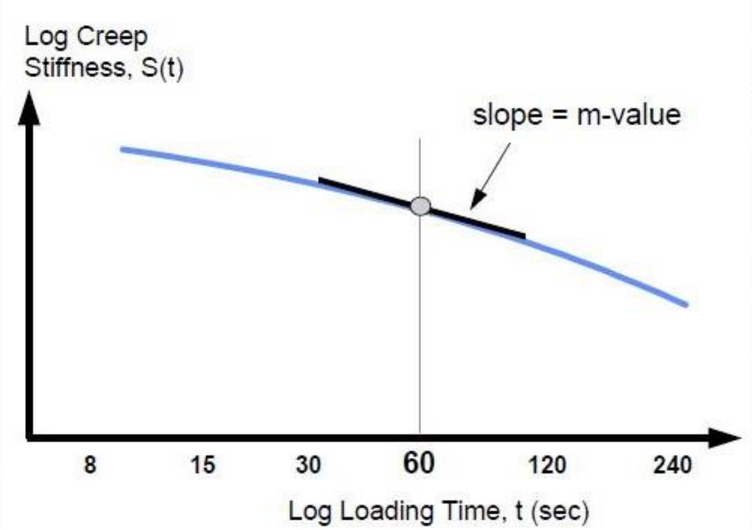
$$S(t) = \frac{PL^3}{4bh^3\Delta(t)}$$

where, S(t) = creep stiffness (MPa (N/mm^2)) 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

Parameters Measured

1. Creep stiffness (S) at 8, 15, 30, 60, 120, and 240 seconds.
2. m-value, at 8, 15, 30, 60, 120, and 240 seconds





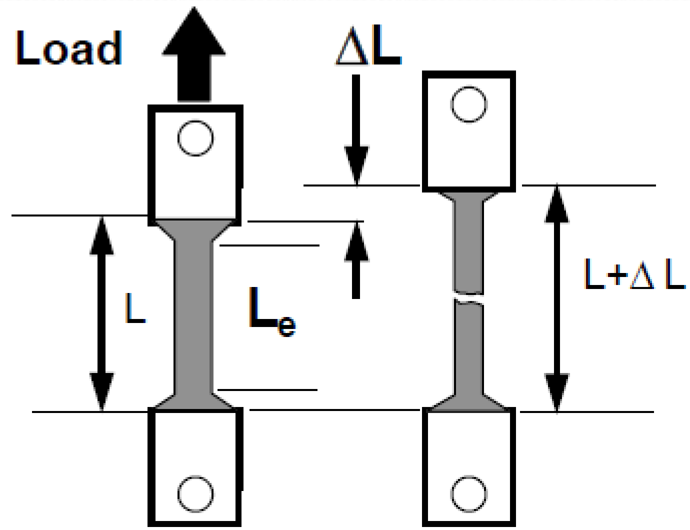
The m-value is the slope of the log stiffness versus log time curve at any time, t.

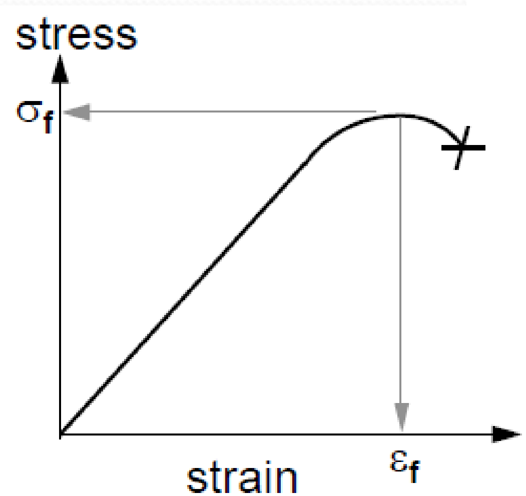
Specification Limits

Material of concern	Value	Specification	HMA Distress
PAV residue	Creep stiffness at 60 s	≤ 300 MPa (43.5 psi)	Low temperature cracking
PAV residue	m-value at 60 s	≥ 0.300	Low temperature cracking

Direct Tension Tester: AASHTO TP3

- The direct tension test (*Determining the Fracture Properties of Asphalt Binder in Direct Tension)* measures the low temperature at which where maximum stress (failure stress σ_f) is occurred and producing **failure strain (ε_f)** of an aged asphalt binder (aged by RTFO and PAV). The test is performed at relatively low temperatures ranging from -36° to +6°C (lowest temperature of the country is adopted), the temperature range within which asphalt exhibits brittle behavior(i.e. the tested asphalt is very cold).
- 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).
- Failure stress (σ_f) is the failure load divided by the original cross section of the specimen (36 mm^2).

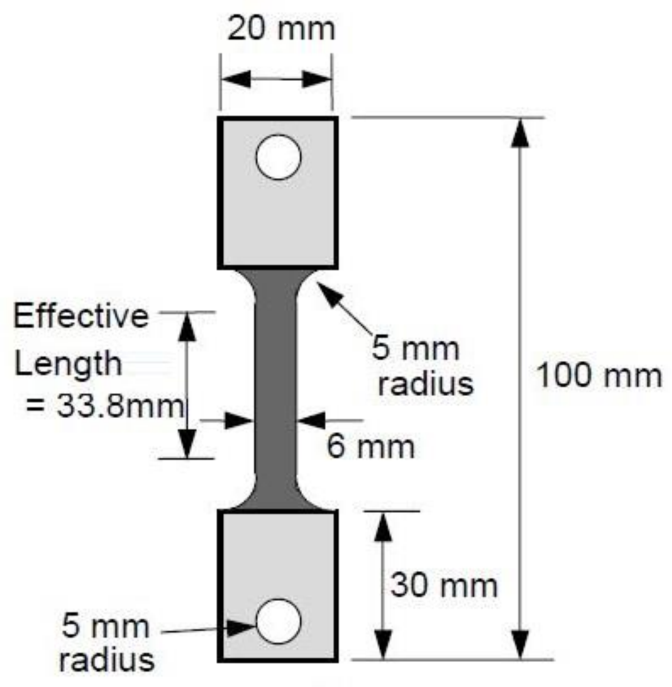




$$\varepsilon_f = \frac{\text{change in length } (\Delta L)}{\text{effective length } (L_e)}$$

Specimens Preparation and Test Procedure

- ➢ The main purpose of DTT test is to determine an asphalt binder's failure stress and strain at low temperatures.
- ➢ 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 sample of asphalt binder is molded and setting in a pulling device machine which can provides at least a **500 N** at a loading rate of **1.0 mm/min**. This sample is then pulled until it fails at which point the strain at failure is recorded. **The DTT test is done on 6 samples**.

Specification Limits

Material of Concern	Value	Specification	HMA Distress
PAV residue	Failure strain	≥ 1.0% at 1.0 mm/min (0.039 inch/min)	Low temperature cracking

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

Equipment	Purpose	Performance Parameter	Testing Procedure
Rolling Thin Film Oven (RTFO)	Simulate binder aging during HMA production and construction	Resistance to aging during construction	AASHTO T240 ASTM D2872
Pressure Aging Vessel (PAV)	Simulate binder aging during HMA service life	Resistance to aging during service life (5- 10 years)	AASHTO PP1
Rotational Viscometer (RV)	Measure binder properties at high construction temperatures	Handling and pumping	ASTM D4402 AASHTO TP48
Dynamic Shear Rheometer (DSR)	Measure binder properties at high and intermediate temperatures	Resistance to permanent deformation (rutting) and fatigue cracking	AASHTO TP5
Bending Beam Rheometer (BBR)	Measure binder properties at low service temperatures	Resistance to thermal cracking	AASHTO TP1
Direct Tension Tester (DTT)	Measure binder properties at low service temperatures	Resistance to thermal cracking	AASHTO TP3

Binder Grade Selection According to PG System

(very important table)

Performance Grades (PG)

Max. Design Temp.	PG 46			PG 52						
Min. Design Temp.	-34	-40	-46	-10	-16	-22	-28	-34	-40	-46
≥ 1.00 kPa — DSR G*/sin δ (Original)	46			52						
≥ 2.20 kPa — DSR G*/sin δ (RTFO)	46			52						
PAV 20 hours, 2.10 MPa	90			90						
≤ 5000 kPa — DSR G*sin δ	10	7	4	25	22	19	16	13	10	7
BBR: Test Temp. = Min. Temp. +10 °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36
DTT: Test Temp. = Min. Temp. +10 °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36

Max. Design Temp.	PG 58					PG 64					
Min. Design Temp.	-16	-22	-28	-34	-40	-10	-16	-22	-28	-34	-40
≥ 1.00 kPa — DSR G*/sin δ (Original)	58					64					
≥ 2.20 kPa — DSR G*/sin δ (RTFO)	58					64					
PAV 20 hours, 2.10 MPa	100					100					
≤ 5000 kPa — DSR G*sin δ	25	22	19	16	13	31	28	25	22	19	16
BBR: Test Temp. = Min. Temp. +10 °C	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
DTT: Test Temp. = Min. Temp. +10 °C	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

Max. Design Temp.	PG 70						PG 76					PG 82				
Min. Design Temp.	-10	-16	-22	-28	-34	-40	-10	-16	-22	-28	-34	-10	-16	-22	-28	-34
≥ 1.00 kPa — DSR G*/sin δ (Original)	70						76					82				
≥ 2.20 kPa — DSR G*/sin δ (RTFO)	70						76					82				
PAV 20 hours, 2.10 MPa	100(110)						100(110)					100(110)				
≤ 5000 kPa — DSR G*sin δ	34	31	28	25	22	19	37	34	31	28	25	40	37	34	31	28
BBR: Test Temp. = Min. Temp. +10 °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24
DTT: Test Temp. = Min. Temp. +10 °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24

Original

- ≥230 °C — **Flash Point**
- ≤ 3 Pa-s @ 135 °C — **Rotational Viscosity**
- ≥ 1.00 kPa — **DSR G*/sin δ** (Dynamic Shear Rheometer) **I. Agianst Rutting**

(Rolling Thin Film Oven) RTFO, Mass Change ≤ 1.00%

- ≥ 2.20 kPa — **DSR G*/sin δ** (Dynamic Shear Rheometer) **II. Agianst Rutting**

(Pressure Aging Vessel) PAV

- 20 hours, 2.10 MPa
- ≤ 5000 kPa — **DSR G*sin δ** (Dynamic Shear Rheometer) **Agianst Fatigue** — Intermediate Temperature = [(Max. Temp. + Min. Temp.)/2] +4
- Ex= [(46-34)/2]+4=10
- S ≤ 300 MPa, m ≥ 0.300 — **BBR S (creep stiffness) & m-value** (Bending Beam Rheometer) (Against Low Temperature Cracking) — Test Temp. = Min. Temp. +10 °C

If BBR m-value ≥ 0.300 and creep stiffness is between 300 and 600, the Direct Tension failure strain requirement can be used in lieu of the creep stiffness requirement.

- ε_f ≥ 1.00% — **DTT** (Direct Tension Tester) (Against Low Temperature Cracking) — Test Temp. = Min. Temp. +10 °C

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