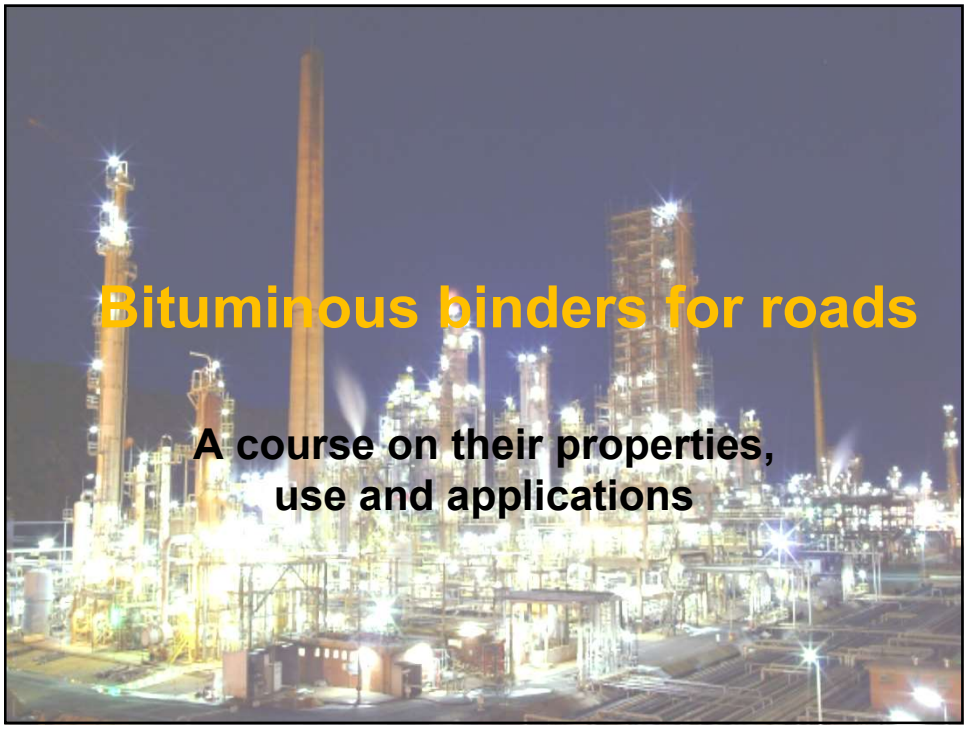


Bituminous binders for roads

A course on their properties, use and applications

Purpose of the course

1. To inform the young professional on the constituents and engineering properties of bituminous binders in general use and their significance in practice.
2. To create an awareness of the importance of the safe and responsible handling of these products to mitigate risk of injury or loss
3. Content ***covers*** and ***focuses*** on bitumen ***properties as identified, tested & specified*** in a performance graded ***(PG) specification***
4. Course reference book is Sabita Manual 2 (PG)

Scope of the course

- Manufacture and properties
- Types and grades of binders
- Specifications and test methods
- Handling of bituminous binders
- Selection and application of binders

Structure of the course

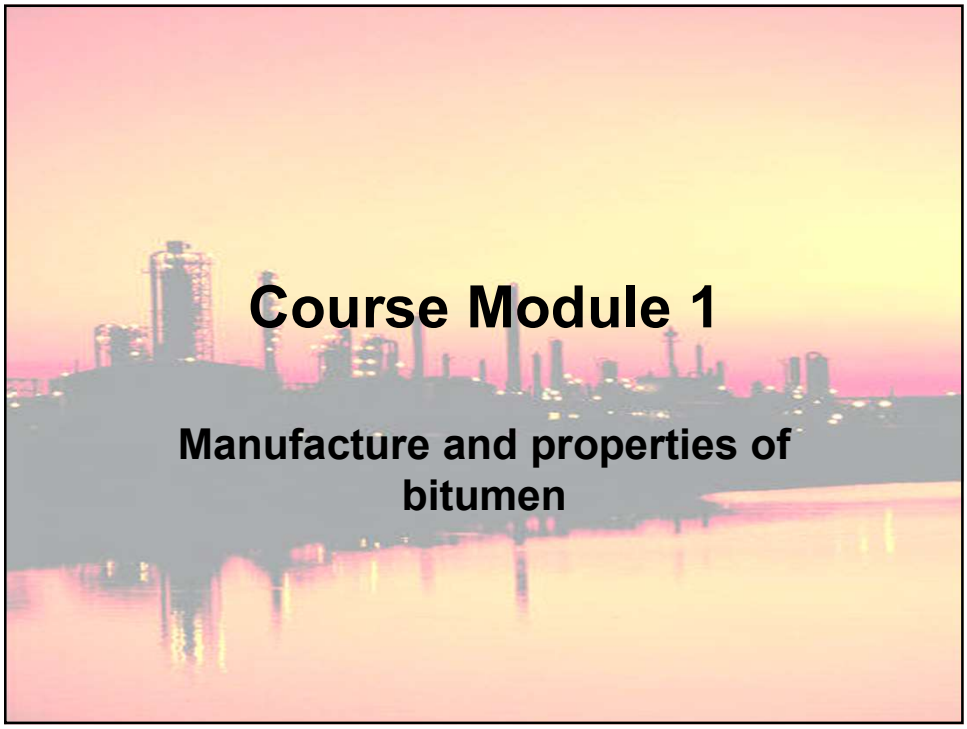
Module 1: Manufacture and properties of bitumen

Module 2: Types and grades of bituminous binders

Module 3: Specification and test methods

Module 4: Handling of bituminous binders

Module 5: Selection and application



Manufacture and properties of bitumen

- Description
- Glossary of terms
- Manufacturing
- Properties of bitumen

Manufacture and properties of bitumen

- **Description**
- Glossary of terms
- Manufacturing
- Properties of bitumen

Description of bitumen

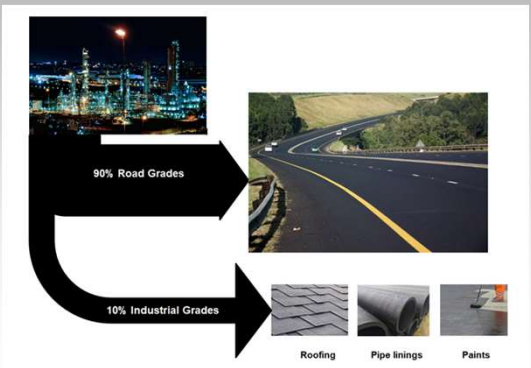
- In SA obtained by refining petroleum crude oil (also found as naturally occurring deposit elsewhere)
- Bitumen is a dark brown to black viscous liquid or solid
- Consists essentially of hydrocarbons and their derivatives
- Soluble in trichloroethylene and non-volatile
- Although solid or semi-solid at normal temperatures bituminous binders may be rendered fluid by:
  - Applying heat
  - Dissolving in petroleum solvents
  - Emulsifying in water

Description/cont.…

- Bitumen is valuable in engineering applications:
  - Strong
  - Readily adhesive
  - Waterproof
  - Durable
  - Imparts flexibility when used in conjunction with aggregates in asphalt mixes and spray seals
  - Highly resistant to the action of most acids, alkalis and salts

Description/cont.…

- Bitumen used in many industrial applications
- 90% of bitumen refined from crude oil used in road/airfield pavement layers



Description/cont.…

- Both physical and chemical properties - dependent on crude from which it is derived
- Refineries generally use consistent crude oil sources – consistent bitumen properties
- Laboratory tests focus on physical tests that attempt to measure performance related properties

Manufacture and properties of bitumen

- Description
- **Glossary of terms**
- Manufacturing
- Properties of bitumen

Glossary of general terms

- **Bitumen, conventional** – An end product of the crude petroleum refining process. It may be blended or further processed to obtain products of varying hardness or viscosity. It is solid or near solid at normal air temperature
- **Bitumen Emulsion** - An emulsion of bitumen and water with the addition of an emulsifying agent to ensure stability. Conventional bitumen emulsion most commonly used in road works has the bitumen dispersed in the water.

Glossary/cont.…

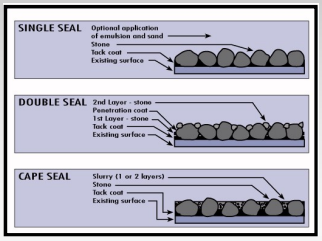
- **Bitumen, Cutback** – a liquid bitumen product obtained by blending penetration grade bitumen with a volatile solvent. After evaporation of the solvent, the properties of the original penetration grade bitumen become operative.
- **Bitumen, modified** – a bitumen with rheological properties modified to enhance performance. Examples of modifiers are:
  - polymers, such as natural or synthetic rubbers.
  - crumb rubber, containing where necessary extender oil and/or diluent.

Glossary/cont.…

- **Bituminous Surfacing** – A layer consisting of a bituminous binder and aggregate with which traffic makes direct contact. Also termed a **wearing course**
- **Asphalt** – A mixture of inert mineral matter, such as aggregate, mineral filler and bituminous binder in predetermined proportions
- **Surface Treatment** – A general term typically incorporating chip seals, micro surfacing or fog sprays. It is applied to improve the texture and integrity of an existing surface

Glossary/cont.…

- **Spray Seal** - Spray seals consist of ordered applications of one or more bituminous products and aggregates in controlled proportions. Spray seals are applied on either newly constructed roads or as a reseal maintenance measure on existing roads
- **Reseal** – A surface treatment applied to an existing bituminous surface



Glossary/cont.…

- **Slurry** – A mix of suitably graded fine aggregate, cement or hydrated lime, bitumen emulsion and water, used for filling the voids in the final layer of stone of a new surface treatment or as a maintenance treatment (also referred to as a slurry seal)
- **Micro-surfacing –** is similar to a slurry seal but generally incorporating modified emulsions to render the product suitable for cold mix overlays, texture improvements and rut-filling

Glossary/cont.…

- **Bitumen stabilised material -** Pavement materials that are treated with relatively low concentrations of bitumen through the introduction of either bitumen emulsion or foamed bitumen to improve material strength and stiffness

Glossary/cont.…

- **Prime** – A coat of suitable bituminous binder applied to a non-bituminous granular pavement layer as a preliminary treatment before the application of a bituminous base or surfacing
- **Bond Coat** – A coat of bituminous binder applied to a primed or an existing bituminous surface as a preliminary treatment to promote adhesion between the existing surface and a subsequently applied bituminous layer, especially asphalt. Tack coats are also used to enhance adhesion along transverse and longitudinal joints in asphalt layers.
- **Precoating fluid -** Low viscosity bitumen-based products containing petroleum cutters and a chemical adhesion agent applied to stone chippings to improve their adhesion to the bituminous binder.

Manufacture and properties of bitumen

- Description
- Glossary of terms
- **Manufacturing**
- Properties of bitumen

Manufacturing

- Source / origins of bitumen
- Distillation process

Manufacturing

- **Source / origins of bitumen**
- Distillation process

Source of bitumen

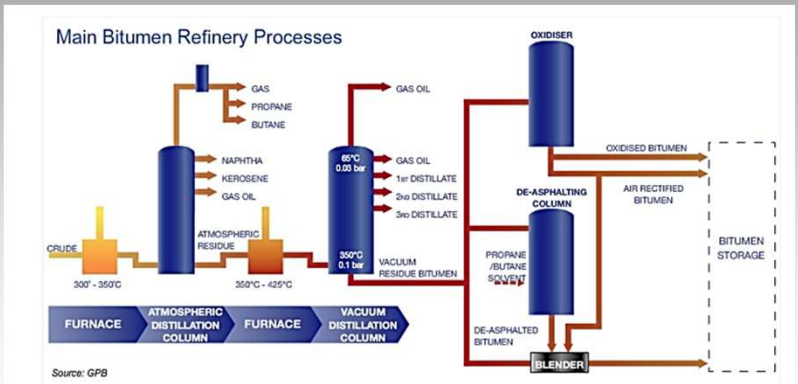
- Bitumen is manufactured at 4 refineries by the distillation of crude petroleum oil
- Range of conventional and cutback bitumen for road making purposes
- Availability of crude oil sources – as well as local demand – may result in this not always being feasible

Deployment of refineries

Manufacturing

- Source / origins of bitumen
- **Distillation process**

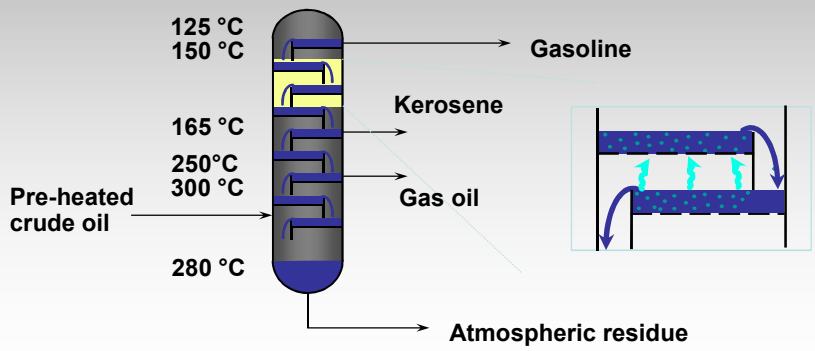
Petroleum refinery



Distillation process #1

1. Atmospheric distillation

- Crude oil is heated & introduced to an atmospheric distillation column
- Lighter fractions are vaporised and drawn off



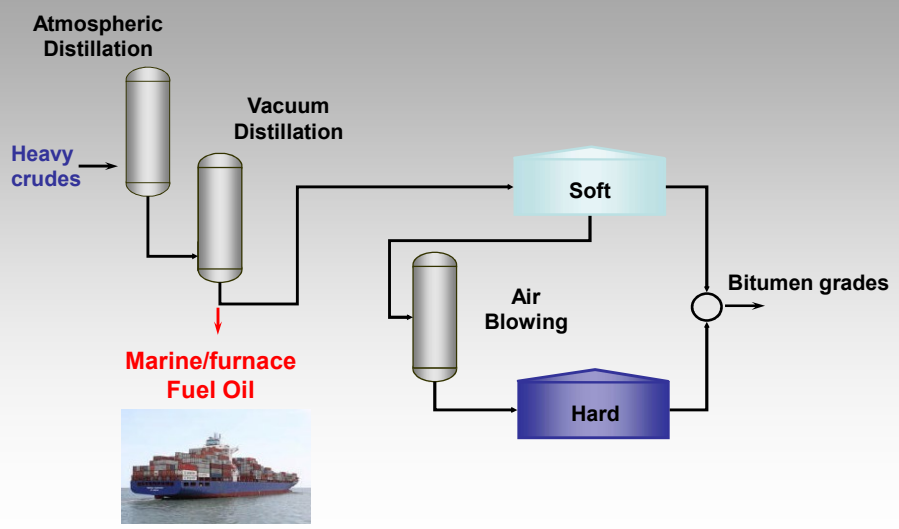
Distillation process #2

2. Vacuum distillation

- Residue from atmospheric distillation further distilled under vacuum
- Oil fractions are drawn off in vapour at relatively low temperatures
- Residue ("vacuum bottoms") used to produce *straight run* bitumen
- Sometimes these are further processed by air blowing to produce harder grades of bitumen
- Vacuum bottoms not used in bitumen manufacture - further processed to produce marine and furnace fuel oil

Simplified refinery layout

(indicating bitumen production line)



Range of refinery products

Bitumen constitutes about 2 – 3 % of total refined product

Safety note

- Bituminous binders are often heated to make them sufficiently fluid for handling and application
- Contact with bitumen or the equipment can cause severe skin burns at handling temperatures.
- It is essential that anyone working with bitumen is familiar with the necessary health, safety and environmental considerations
- Users should always refer to product Material Safety Data Sheets (MSDS) for a full description of hazards associated with the use of bitumen products

Manufacture and properties of bitumen

- Description
- Glossary of terms
- Manufacturing
- **Properties of bitumen**

Properties of bitumen

- Composition of bitumen
- Behaviour
- Rheometry
- Durability

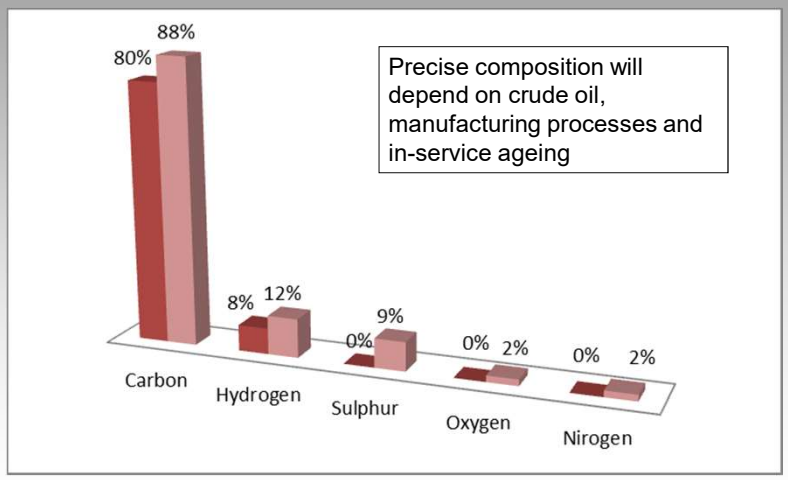
Composition

- Chemical composition
- Bitumen structure
- Factors influencing bitumen characteristics

Chemical composition

- Complex combination of hydrocarbons
- Small quantities of heteroatoms:
  - Sulphur
  - Nitrogen
  - Traces of metals
- Polycyclic aromatic hydrocarbons (PAH's)
  - Suspected human carcinogen
  - Extremely low concentrations
  - Global research: no causal link to cancer in humans established

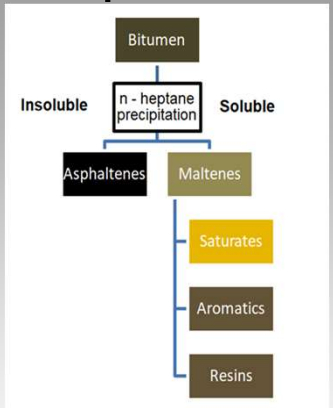
Bitumen from crude oil



Chemistry of bitumen

- Complex: 300 - 2 000 constituents in unaged bitumen
- Number of constituents increase with ageing
- For descriptive purpose divided from chemical separation techniques
- Two main categories, based on solubility in h-heptane:
  - Asphaltenes (non-soluble)
  - Maltenes (soluble)
    - Saturates
    - Aromatics
    - Resins

Broad chemical components



Components given in terms of

Saturates, **A**romatics **R**esins & **A**sphaltenes
Values can vary according to method of determination
No ideal proportions of SARA

Asphaltene properties

- n-heptane insoluble
- Heavy molecular weight, polar
- Black and glassy
- Make up 5 – 40 % of bitumen
- Significant influence on rheological properties

- Asphalt content ⇧ hardness, viscosity ⇧

Maltenes

- N-heptane soluble
- Further subdivided based on chemical separation techniques:
  - *Resins*
  - *Aromatics*
  - *Saturates*

Resins

- Dark brown solids/semi-solids
- Makes up 30 – 50% of total bitumen
- Act as stabiliser for asphaltenes
- Polar – strongly adhesive
- Determine bitumen structure

Aromatics

- Brown, yellow red fluids
- Low molecular mass
- Makes up 15 – 65% of total bitumen
- Determines to a significant extent compatibility with polymers (modification)

Saturates

- Straw coloured or white viscous oils
- Make up 1 – 15 % of total bitumen
- Both waxy and non-waxy

Composition

- Chemical composition
- **Bitumen structure**
- Factors influencing bitumen characteristics

Bitumen structure

- Physical arrangement of bitumen particles
- Effects of ageing

Physical arrangement

Traditionally regarded as colloidal system

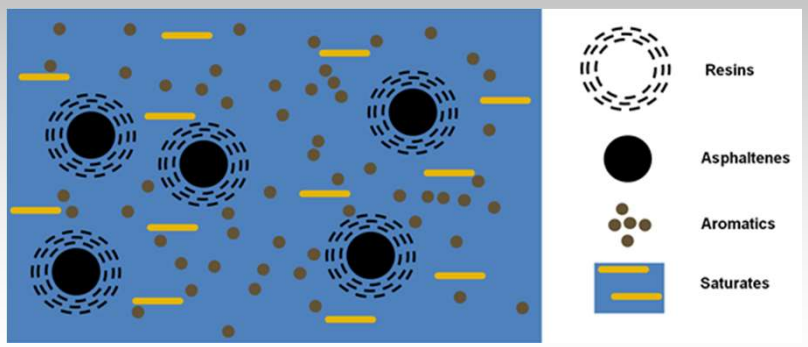
- High molecular mass asphaltene micelles
- Absorbed sheath of high molecular mass resins
- Dispersed or dissolved in lower molecular mass of oily medium of saturates & aromatics

Types of bitumen

- Ratio of resins/asphaltenes determines to a degree the type of bitumen:
  - "Solution" type – SOL
  - "Gelatinous" type – GEL
- Most bitumens are of intermediary character
- Examples of GEL types are oxidised grades (roofing)

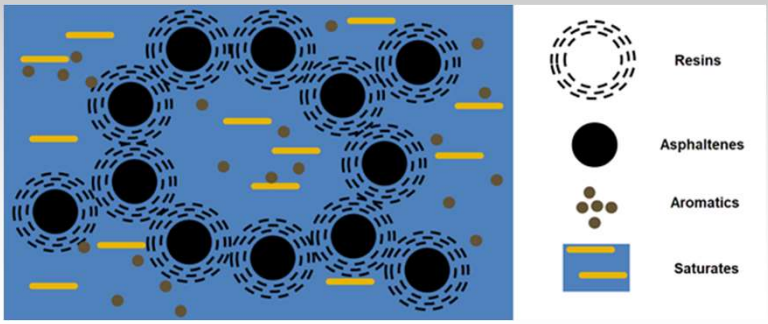
SOL type bitumen

- Asphaltenes are fully dispersed (peptised) in sufficient quantities of resins and aromatics
- Micelles have good mobility



GEL type bitumen

- Micelles of asphaltenes and resins associated together when insufficient quantities of aromatic or resin fractions exist
- Structures of linked micelles



Factors influencing properties

- Increase in the concentration of asphaltenes – increase in viscosity.
- Air-blowing of bitumen –
  - increase in asphaltenes content
  - significant decrease in aromatics
  - saturates and resins largely unchanged.
- During construction and in service
  - changes in viscosity
- No formula for the ideal proportions of SARA – interaction between them will characterise the rheology

- Chemical composition determines physical properties & performance characteristics
- Complex and variable molecular structure – extremely difficult to measure and define ideal chemical composition
- Bitumen from different crude sources (different chemical composition) can have similar physical properties
- Specification of bitumen in terms of its chemical component concentrations has been limited
- Instead - general practice to use performance related physical properties for specifying and selecting bituminous binders

Properties of bitumen

- Composition of bitumen
- **Behaviour**
- Rheometry
- Durability

Visco-elasticity behaviour

Bitumen displays both *elastic* and *viscous* behaviour, depending largely on temperature and load duration

Elastic behaviour

At low temperature and short duration loads:

- Bitumen tends to act as an elastic solid, returning to its original position after removal of the load
- Excessively low temperature in conjunction with rapid loading may cause brittle failure and cracking
- Prolonged low temperature can cause a build-up of internal stress resulting in cracking

Viscous behaviour

At elevated temperature and long duration loads:

- Bitumen acts as a viscous fluid – undergoes plastic deformation that is not recovered
- Pavement layers tend to deform under repeated loads and elevated temperatures
- Plastic behaviour can be offset by aggregate interlock in layer

Viscosity measurement defined

Dynamic viscosity – (or coefficient of viscosity or simply viscosity) measure of the resistance to flow of a fluid, symbol η

Ratio: $\frac{\text{Applied shear stress}}{\text{Rate of shear}}$

SI unit of dynamic viscosity is Pascal second (Pa.s)

Dynamic viscosity / cont.

- Fluids like water and conventional bitumen above 60 - 100°C show a linear relationship $\frac{Resistive\ force}{relative\ velocity\ of\ sliding}$
- This value of viscosity is therefore constant, irrespective of the applied shear stress
- Termed Newtonian behaviour (Newtonian fluid)

Viscosity measurement defined/cont.…

Kinematic viscosity

Ratio: $\frac{\text{Dynamic viscosity}}{\text{Density of fluid}}$

The SI unit of kinematic viscosity is mm^2/s or centiStoke (cSt)

Densities of SA conventional bitumen:

0.970 – 1.040 kg/l

A dynamic viscosity of 1 Pa.s equates to:

kinematic viscosity of 962 – 1 031 cSt

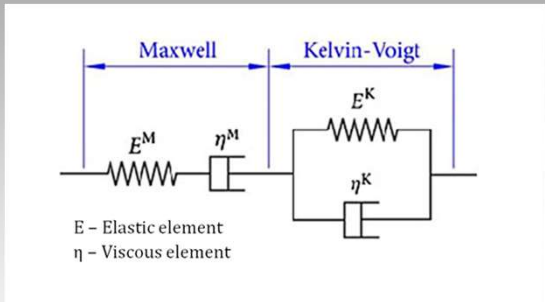
Visco-elastic behaviour

- During manufacture and application of bituminous layers bitumen at elevated temperatures – behaviour mainly viscous
- In-service conditions – visco-elastic (except in extremely low temperatures - elastic
- Bitumen specifications are formulated in terms of these requirements

Visco-elastic response

- Can be represented by a system of dashpots and springs
- Spring
  - Elastic deformation
  - Not time dependent
  - No permanent deformation
- Dashpot
  - Viscous deformation
  - Time dependent
  - Some permanent deformation
- Spring-dashpot in parallel
  - Delayed elastic deformation
  - Time dependent
  - No permanent deformation

Response model – Burger's

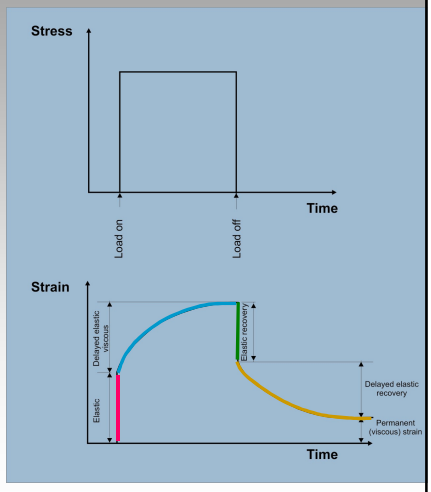


Model components

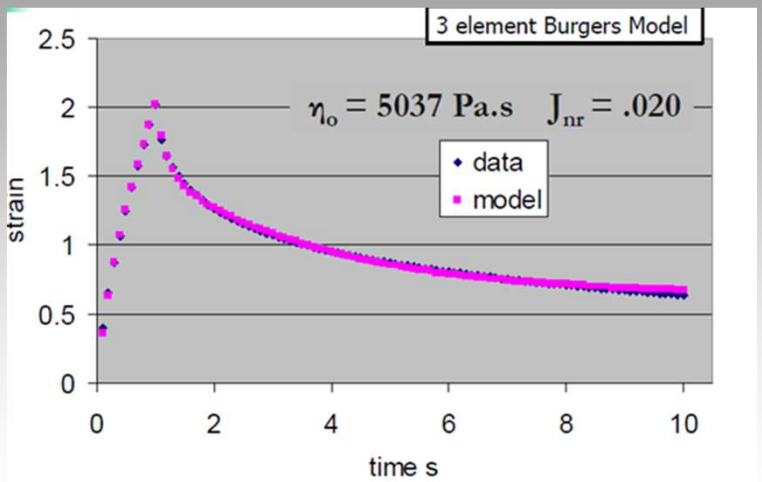
Model component		Type of deformation under constant load
Spring	Maxwell	Elastic deformation – not time dependent, no permanent deformation
Dashpot		Viscous deformation – time dependent, permanent deformation
Spring-dashpot in parallel	Kelvin-Voigt	Delayed elastic deformation – time dependent, no permanent deformation

Bitumen response to simple creep test

- Load applied
  - Instantaneous elastic response
  - Gradual increase in strain – viscous and delayed elastic behaviour
- Load removed
  - Instantaneous elastic recovery
  - Additional recovery with time – delayed elastic
  - Permanent residual strain



Lab results vs Burgers Model



Properties of bitumen

- Composition of bitumen
- Behaviour
- **Rheometry**
- Durability

Rheometry

- ***Rheology***
  - study of flow and deformation of matter (soft solids under conditions in which they flow rather than deform and recover fully)
  - fundamental engineering properties of bituminous binders well described by rheological principles.
- ***Rheometry***
  - laboratory measurement of rheological properties of materials.

Rheometry of bituminous binders

- Measurement of
  - elastic &
  - viscous behaviour
- under varied conditions
  - type of loading
  - frequency of loading
  - temperature

Rheometry instruments

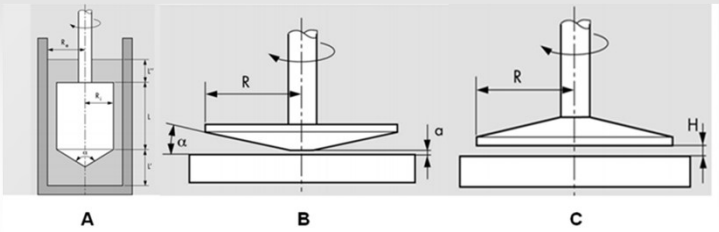
- Two types of instruments in general use globally will be covered in this document:
  - Dynamic shear rheometer
  - Bending beam rheometer

Dynamic shear rheometer (DSR)

- Cornerstone of performance grade (PG) specification
- Incorporated into SATS 3208: 2019 – *Performance Grade (PG) specifications for bitumen in South Africa*

DSR specimen configuration

- sample shape is well defined
- subject to shear between a fixed and moving surface
  - ***concentric cylinder (A)***
  - ***cone & plate (B)***
  - ***parallel plate (C)***.



Two measurement categories

- Fundamental rheological properties
- Creep behaviour of a bituminous binder

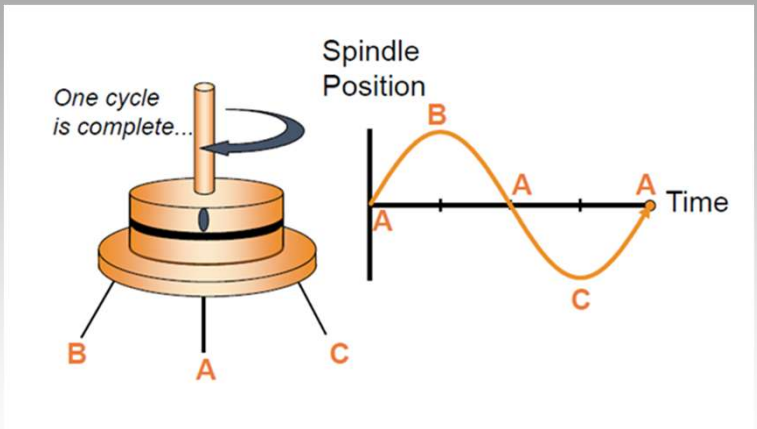
Fundamental rheological properties

- Testing regimen – ASTM D7175,
- Quantifies both elastic and viscous properties at selected temperature
- Thin asphalt binder sample sandwiched between two circular plates
- The lower plate is fixed, upper plate oscillates at a selected frequency to simulate the shearing action at selected traffic speed.

Dynamic Shear Rheometer

- AASHTO T 315: Determining the Rheological Properties of Bitumen using a Dynamic Shear Rheometer (DSR)
- DSR capable of quantifying both elastic and viscous properties of bituminous binders in the in-service pavement temperatures (46°- 82° C)

DSR operation

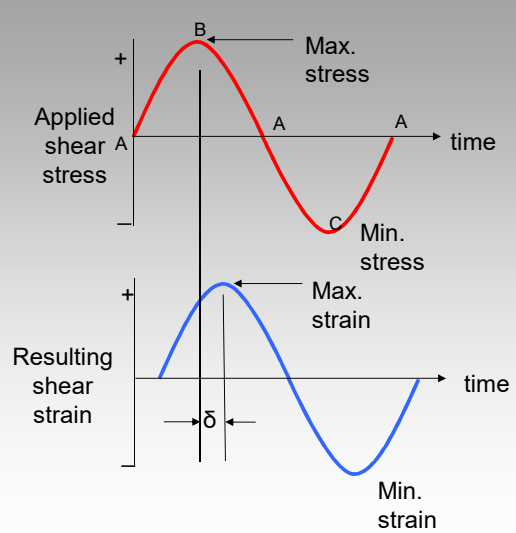


Outputs of the DSR

The DSR measures a specimen's complex shear modulus (G*) and phase angle (δ)

- Complex shear modulus (G*): ***total*** resistance to deformation when repeatedly sheared
- Phase angle (): lag between the applied shear stress and resulting shear strain. Phase angle (δ) limiting values are
  - Purely elastic material: δ = 0 degrees
  - Purely viscous material: δ = 90
- δ for:
  - conventional bitumen is typically about 88 – 89°
  - modified binders as low as 60°

DSR measurements



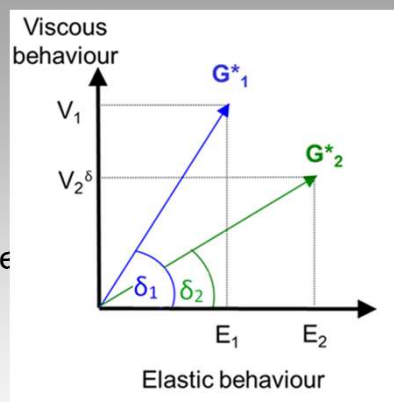
Complex Shear Modulus = G*

$$G^* = \frac{Max\ stress\ - Min.\ stress}{Max\ strain\ - Min.\ strain}$$

Phase angle = δ

Visco-elastic behaviour

- Although G^*_1 and G^*_2 are of similar magnitude, they represent binders that are significantly different in visco-elastic behaviour
- Thus G* alone cannot describe asphalt behaviour, δ is also required
- Bitumen 2 has a larger elastic component and will recover better from applied loading.



DSR cyclical tests

Time sweep

- either strain or stress repetitions over a number of cycles until:
  - predetermined number of cycles have been carried out
  - predetermined degree of damage (e.g. a reduction in G*) is observed. This type is referred to as a *time sweep test*. (See Figure 16 A).

Cyclical tests cont.

Stress or strain sweep

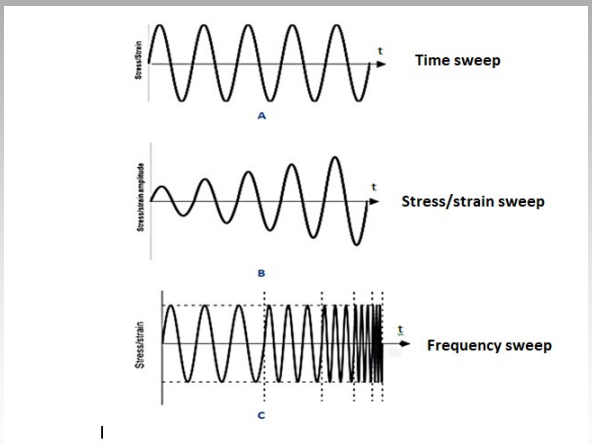
- stress or strain is progressively increased, either continuously or in steps The temperature and frequency is kept constant.

Cyclical tests cont.

Frequency sweep

- Measure the time-dependent behaviour of a sample in non-destructive range
- High frequencies simulate fast motion on short timescales
- Low frequencies simulate slow motion on long timescales or at rest.
- Carried out at a constant temperature and strain.

Sweeps

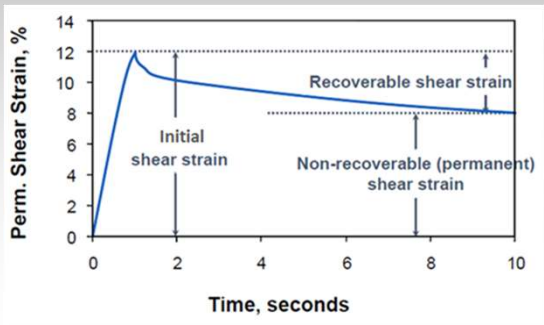


DSR Dynamic tests

- Creep tests at elevated temperatures
  - assess the extent to which a binder will recover after the relaxation of an applied torque load
  - significant when considering the permanent deformation (rutting potential) of asphalt layers and the flushing / bleeding of spray seals.

Dynamic tests / cont.

- The Multiple Stress Creep Recovery (MSCR) test - recovery and non-recoverable creep of binders
  (Dealt with in more detail in Module 3)

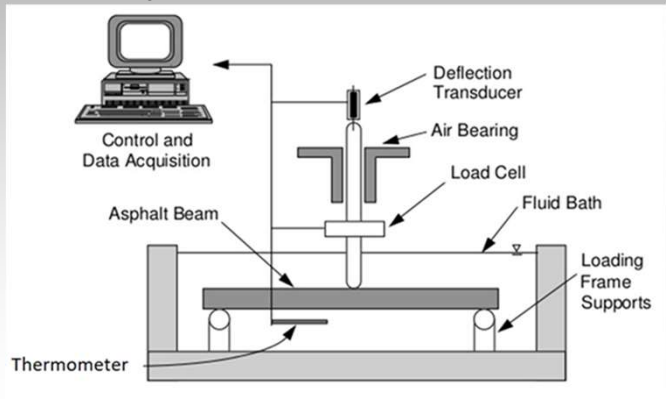


Bending Beam Rheometer (BBR)

- Assess the binder's ability to resist fracture due to:
  - fatigue
  - (non-load associated) low temperatures
- Measures low temperature stiffness and stress relaxation properties of binders
- Carried out on lab aged binders to simulate the hardening that takes place during manufacture paving & in-service

BBR apparatus

- Blunt-nosed shaft applies a load midpoint of a simply-supported binder beam.

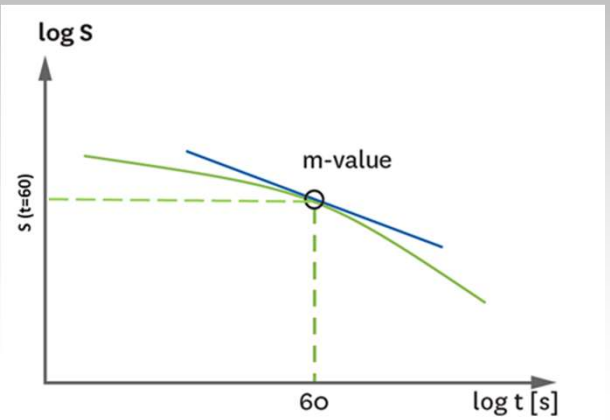


BBR outputs

- Stiffness of binder under a constant (creep) load – based on measurement of the central deflection of the beam during the test.
- BBR software performs the calculation of the stiffness (S) and creep rate (m) with respect to time during the test
  - S is measure of the resistance of the binder to creep loading
  - m is the change in binder stiffness with time during loading – ***stress-relaxation factor***.

Computed values of BBR test

- The computed stiffness at 60 seconds S(60s)
- Slope of the curve, m(60s



Manufacture and properties of bitumen

- Description
- Glossary of terms
- Manufacturing/distillation
- Composition
- Structure
- **Rheology**
- **Behaviour**
  - **Visco-elasticity**
  - **Durability**
  - **Hardening**

Properties of bitumen

- Composition of bitumen
- Behaviour
- Rheometry
- **Durability**

Durability

The ability of bitumen to perform as expected over an extended period of time and enabling the bituminous layer to achieve its design life

Ensuring durability

- Prevent ***excessive hardening*** during
  - Bulk storage
  - Processing (asphalt manufacture and paving)
  - Service life
- ***Avoid thin bitumen films***
  - Detrimental effect – increased brittleness leading to early fracture, fretting and stone loss

Manufacture and properties of bitumen

- Description
- Glossary of terms
- Manufacturing/distillation
- Composition
- Structure
- **Rheology**
- **Behaviour**
  - **Visco-elasticity**
  - **Durability**
  - **Hardening**

Mechanisms of hardening

- Oxidation
- Loss of volatiles
- Physical (steric)
- Exudation

Oxidation

- Main cause of hardening
- Bitumen (an organic compound) is slowly oxidised when in contact with oxygen in the atmosphere
- Influenced by temperature, thickness of binder films and time
- Leads to
  - Increase in viscosity
  - Hardening
  - Loss of flexibility
- Prevented by
  - Adequately thick binder films
  - Proper compaction of e.g. asphalt layers

Loss of volatiles

- Depends on
  - exposure to sunlight
  - prevailing temperatures
- Conventional bitumens
  - relatively involatile
  - not prone to significant loss of volatiles

Physical (steric) hardening

- Occurs at ambient temperatures
- Re-orientation of bitumen molecules
- Formation of waxy crystals
- Reversible on reheating & agitation

Exudative hardening

- Caused by absorption of oily components (i.e. maltenes) into porous aggregates
- Subject is not well researched

Hardening during use

Most important conditions bitumen under which hardening of bitumen can occur are:

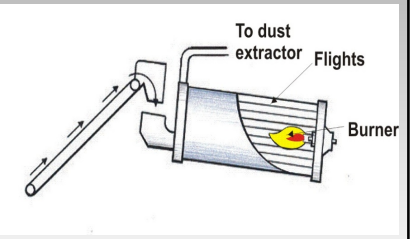
- Hot bulk storage
- Hot mix asphalt manufacture
- Handling of asphalt
- In-service

Hot bulk storage

- Bitumen is kept at elevated temperatures for periods ranging from days to weeks
- Surface area exposed to oxygen is small relative to the volume
- Very little hardening occurs during this phase

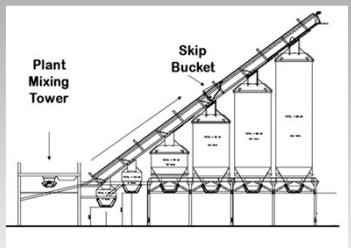
Hot mix asphalt manufacture

- Thin bitumen films (5 - 15μm) exposed to high temperature of superheated aggregates in presence of oxygen during mixing
- Ideal conditions for *oxidation* and *loss of volatiles*
- Process is well known and should be taken into account when selecting grade of bitumen



Handling of asphalt

- Some hardening in hot storage silos and truck bodies while being transported
- Due to exposure of hot binder films to entrained air
- Little or no hardening occurs during laying and compaction



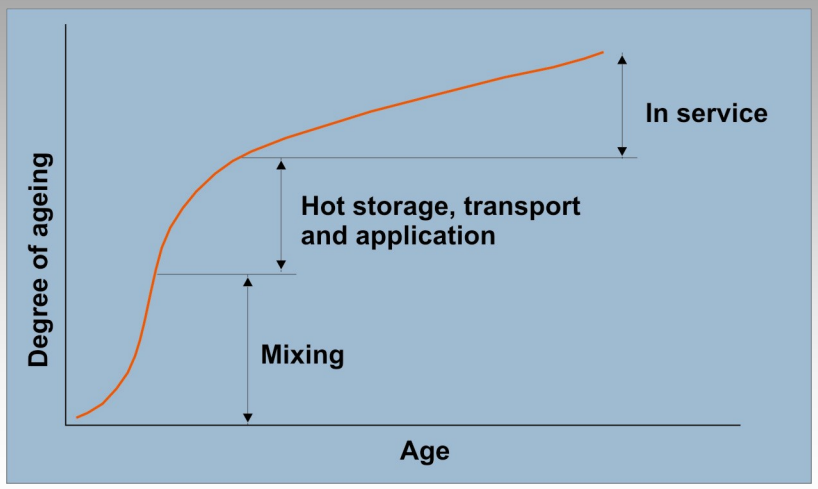
In-service hardening

- Hardening will continue until a limiting value is reached
- Exposure of binder films to the atmosphere will influence hardening
- Air void content in asphalt layers is a major determining factor
- Studies have shown that in asphalt:
  - Little hardening when void content <5%
  - Significant hardening when void content >9%

In-service hardening/cont.

- Bitumen content of asphalt (bitumen film thickness) important factor
- Asphalt design methods specify minimum binder film thickness

Ageing of bitumen



Heating in laboratories

- Small quantities of bituminous materials are (re-)heated for testing
- Care should be taken not to expose bitumen to hardening in excess of what will occur in practice
- Thereby avoid test results that are not realistic

Module 1 - Summary

- Bitumen produced at 4 refineries in SA as an ***end product*** of distillation of crude oil to meet energy needs
- Bitumen has a complex chemical structure – specification of physical properties is preferred worldwide
- Displays visco-elastic properties that characterises its behaviour
- A PG specification defines rheological properties that will support adequate performance
- Age hardening of bitumen can be minimised by proper handling