Bituminous binders for roads

A course on their properties, use and applications

SARF better roads

ASPHALT ACADEMY Excellence in Asphalt Training

Intro & background

Work experience

- Contracting
  - S&L, Power (Blitz)
- Consulting
  - TvE, JGI, C2C, SABITA, private work
- Lecturing
  - Cape Tech, Pen Tech, CPUT, NMMU
- Training & accreditation
  - AsAc, SARF, NLA
- Laboratory technical audits
  - TA for SANAS

Sport & recreation

- Travelling
- Cycling
  - Road & MTB
  - 28 Argus cycle tours
- Surfing & body boarding

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Intro & background cont'd

Currently

- Contracted by **AsAc**
  - present MTC courses around SA & SADC regions
  - NQF 1 – 4 training in HMA
- **SARF**
  - Present various courses in Southern Africa with AsAc
- Contract to **SABITA**
  - Asphalt SANS revisions
  - LIC methods
  - Bituminous PT protocols
- Private consulting work
- **MatCivils chair - NLA**
  - PTS : Sampling prep, Analysis & reporting
  - QCTO & AQP (NLA), Materials testers qual / ISO 17024 certification
- **SANAS TA**

Important web addresses

- www.asphaltacademy.co.za
  - Training & development
- www.sabita.co.za
  - Corporate
- www.sarf.co.za
  - Roads industry training body

Purpose of the course

To inform the young professional on the constituents and engineering properties of bituminous binders in general use and their significance in practice.

To create an awareness of the importance of the safe and responsible handling of these products to mitigate risk of injury or loss

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

House rules & stuff ...

What you have ...

- SARF / AsAc marketing brochure / folder
- Course notes
  - SABITA manuals / CD's 2 & 8
  - AsAc TG1
  - PPT handout sheets
  - Course evaluation
    - Handed out @ end of course
- Business card

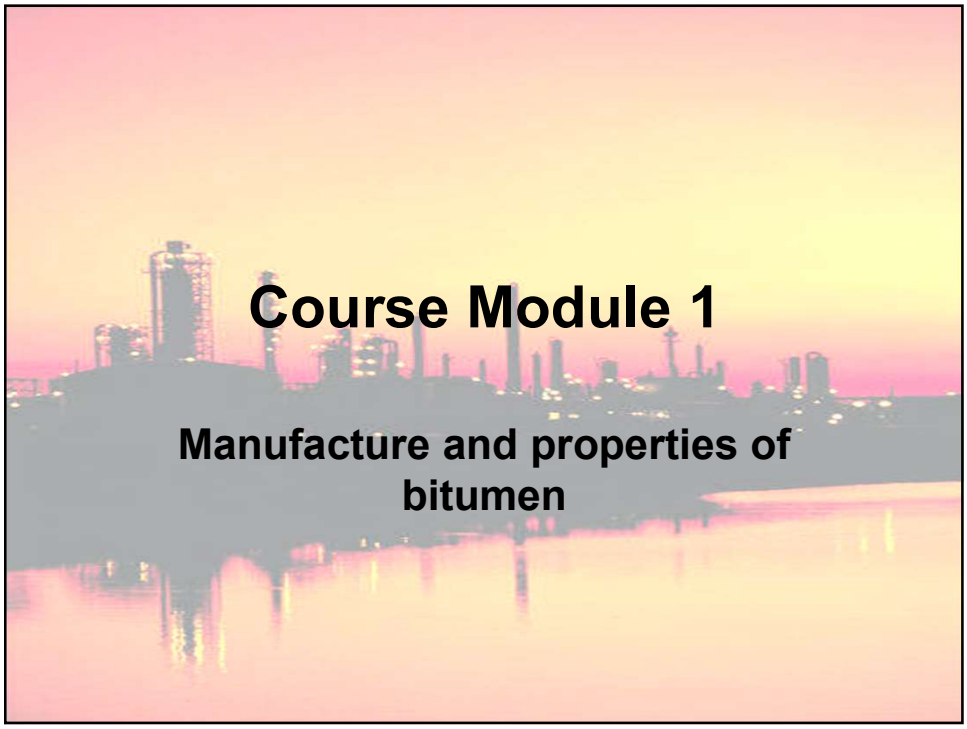
House rules

- Approx 1 hr / session between breaks
  - Smokers
  - Toilets
- Lunch & teas
- Assessments
  - Multiple choice based on previous days lectures
- Ask questions – anything!!
  - There are NO dumb questions

Ice breaker

Assists delegates to get familiar with other participants & feel comfortable interacting with others during the course duration

- Employer ...
- Work experience ...
- Qualification/s ...
- Position you hold in your organisation ...
- Experience in bituminous products used in roads ...



Manufacture and properties of bitumen

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

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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
- Although solid or semi-solid at normal temperatures bitumen may be liquefied by:
  - Applying heat
  - Dissolving in petroleum solvents
  - Emulsifying in water

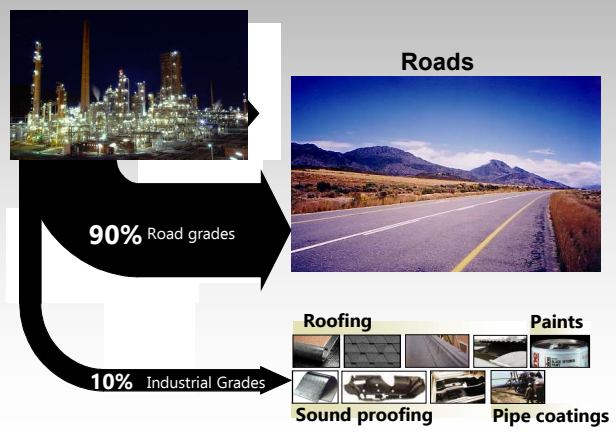
Petroleum Crude oils

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
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Glossary of general terms

- **Bitumen, Penetration Grade** – That fraction of the crude petroleum remaining after refining processes. It is solid or near solid at normal air temperature and which has been blended or further processed to products of varying hardness or viscosity. The binder is graded in terms of its penetration – a measurement of viscosity
- **Bitumen, Performance Grade (PG)**. The same fraction referred to above, but graded in terms of the environment (climate & traffic) and performance parameters to be addressed – resistance to viscous flow, fracture and thermal cracking.

Glossary/cont…

- **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.
- **Binder, Modified** - bitumen modified by the addition of compounds to enhance performance. Examples of modifiers are polymers, such as natural or synthetic rubbers.
- **Bitumen-Rubber** – A blend of bitumen and approximately 20% by weight of crumb rubber, containing where necessary extender oil and/or dilutent and additives

Glossary/cont…

- **Bituminous Surfacing** – A layer consisting of a bituminous binder and aggregate with which traffic makes direct contact. Also termed a **wearing course**.
- **Bituminous Curing Membrane** – A coat of bituminous material applied to a newly constructed cemented pavement layer to promote the curing of the layer
- **Fog Spray** – A light application of diluted bitumen emulsion to the final layer of stone of a spray seal or to an existing bituminous surfacing as a maintenance treatment.

Glossary/cont…

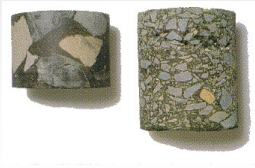
- **Prime** – A coat of suitable bituminous binder applied to a non-bituminous granular pavement layer as a preliminary treatment before the application of a bituminous base or surfacing. of the
- **Bond Coat** – A coat of bituminous binder applied to a primed layer or to an existing bituminous surface as a preliminary treatment to promote adhesion between the existing surface and a subsequently applied bituminous layer, especially asphalt. Bond coats are also used to enhance adhesion along transverse and longitudinal joints in asphalt layers.

Glossary/cont…

- **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.
- **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)
- **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

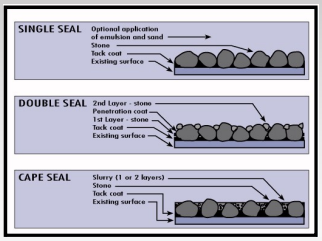
Glossary/cont…

- **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
- **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,.
- **Asphalt–** A mixture of aggregate, mineral filler and bituminous binder in pre-determined proportions to function as a wearing course of base



Glossary/cont…

- **Chip Seal** - Spray seals consist of ordered applications of one or more bituminous products and aggregates in controlled proportions. Chip 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



Manufacture and properties of bitumen

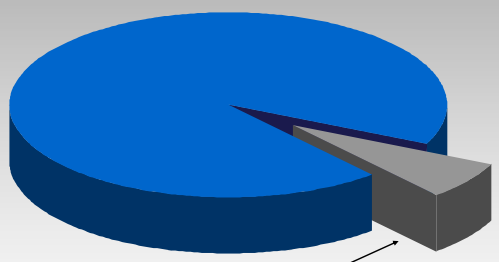
- Description
- Glossary of terms
- **Manufacturing/distillation of crude petroleum oil**
- Composition
- Structure
- Rheology
- Behaviour
  - Visco-elasticity
  - Durability
  - Hardening

Source of bitumen

- Bitumen is manufactured at 4 refineries by the distillation of crude petroleum oil
- Full range of penetration 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

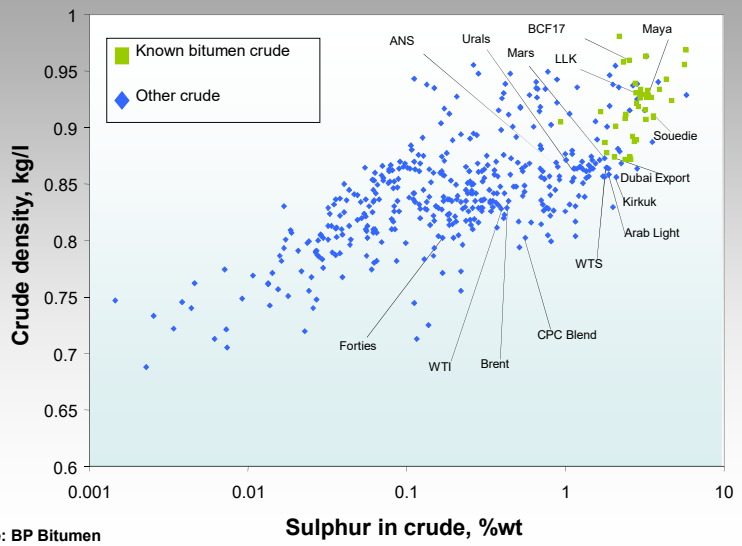
Deployment of refineries

Limited crudes suitable for bitumen



1500 known crudes
100 suitable for bitumen

Heavy crudes – best for bitumen production

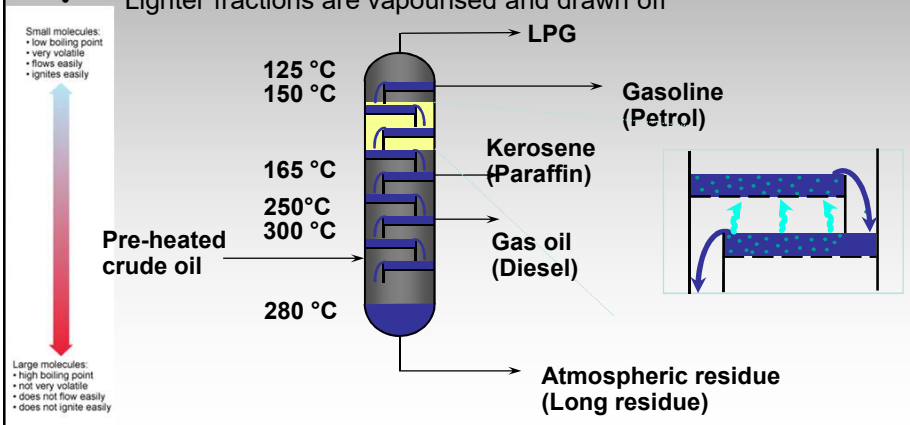


Source: BP Bitumen

Distillation process

1. Atmospheric distillation

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



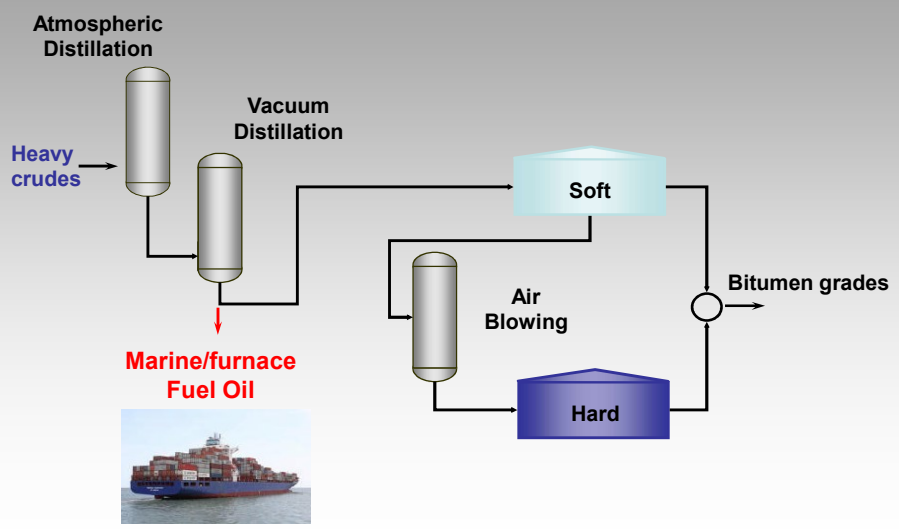
Distillation process

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

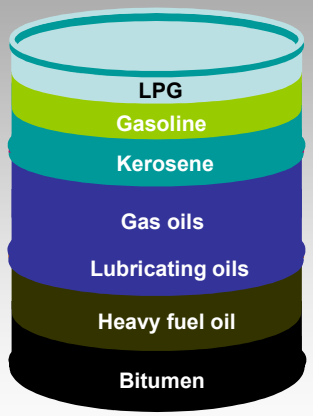
Simplified refinery layout

(indicating bitumen production line)



Range of refinery products

Carbon number		Boiling point (°C)
3 - 4	LPG	-10 - 15
5 - 10	Gasoline	15 - 150
12 - 18	Kerosene	150 - 260
18 - 24	Gas oils	230 - 370
24 - 40	Lubricating oils	370 - 525
24 - ~300	Heavy fuel oil	370 -
~40 - ~300	Bitumen	525 -



Bitumen constitutes about 2 – 2.5% of total refined product

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Chemical composition

- Complex combination of hydrocarbons
- Small quantities of
  - Sulphur
  - Nitrogen
  - Traces of metals
  - Polycyclic aromatic hydrocarbons (PAH's)

Polycyclic aromatic hydrocarbons

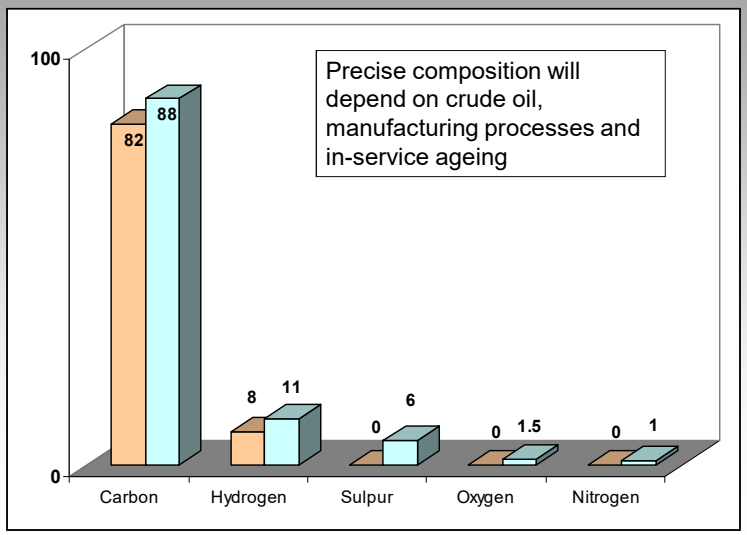
- Some PAH's suspected of causing cancer in human beings
- Concentrations are extremely low
- Global research - no causal link to cancer in human beings has been established

IARC classification of bitumen 2011 research – up from 3 -2B

- Group 1
  - carcinogenic to humans
- Group 2A
  - probably
- **Group 2B**
  - **possibly**
- Group 3
  - not classifiable
- Group 4
  - probably not

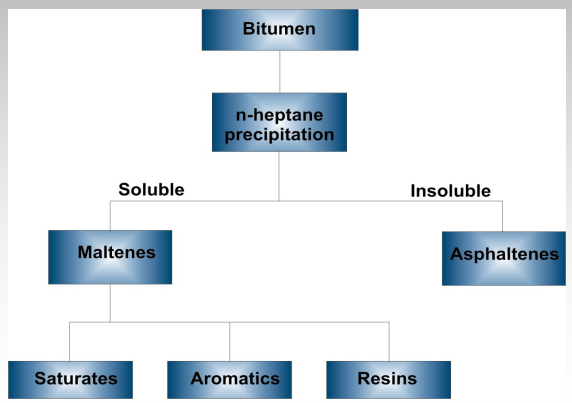
- Same classification as
  - cell phones & coffee
- No increased risk for cancer
- Warm asphalt
  - < 135 °C further assists to reduce exposure
  - reduced fume emissions

Bitumen from crude oil



Chemistry of bitumen

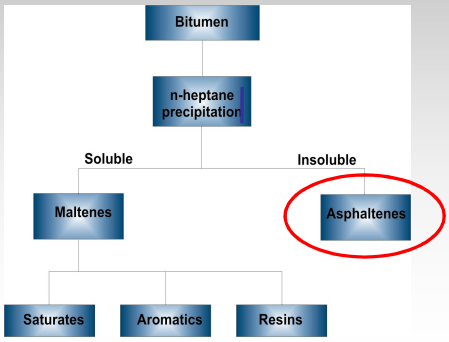
- Complex
- For descriptive purpose divided from chemical separation techniques:



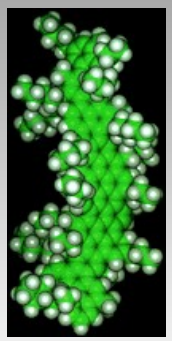
Bitumen constituents

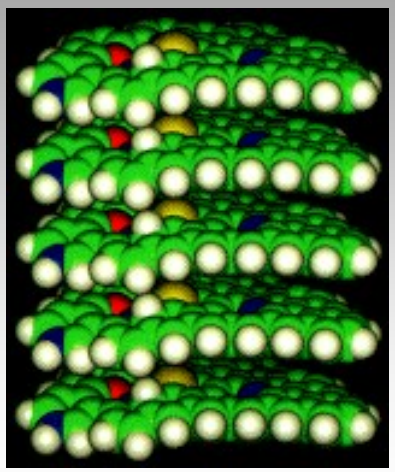
Asphaltene properties

- n-heptane insoluble
- High molecular weight, polar
- Black and glassy
- Make up 5 – 25% of bitumen
- Contain
  - Carbon
  - Hydrogen
  - Some nitrogen
  - Sulphur
  - Oxygen



Asphaltene structure



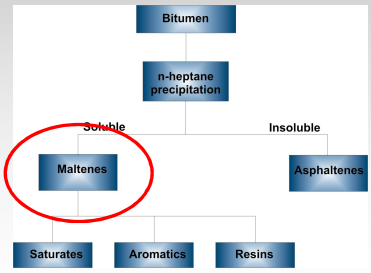


Complex, flat structure
High molecular weight
Insoluble in n-heptane

Source: BP Bitumen

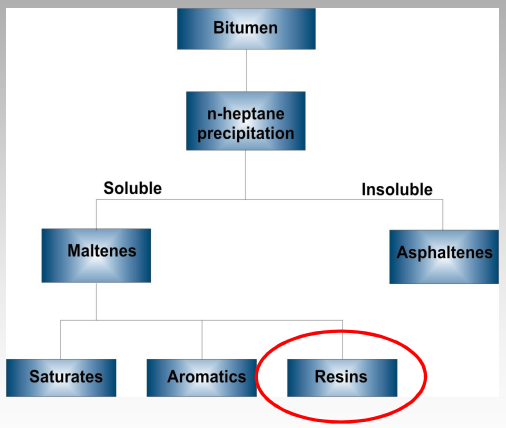
Maltenes

- N-heptane soluble
- Further subdivided (depending on molecular mass and polarity):
  - *Resins*
  - *Aromatics*
  - *Saturates*



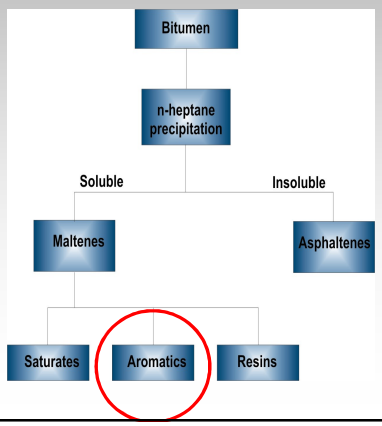
Resins

- Dark brown solids/semisolids
- Largely composed of hydrogen and carbon
- Small amounts of oxygen, sulphur and nitrogen
- Makes up 30 – 50% of total bitumen
- Polar – strongly adhesive



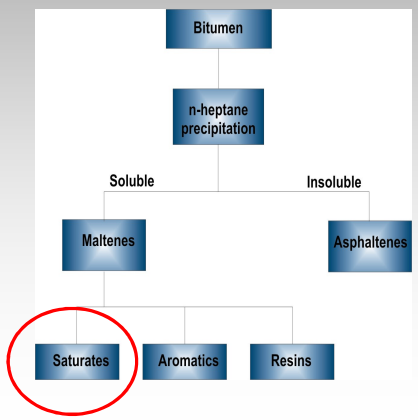
Aromatics

- Dark brown viscous fluid
- Low molecular mass
- Makes up 40 – 65% of total bitumen
- High dissolving ability for other high molecular mass hydrocarbons
- Determines to a significant extent compatibility with polymers (modification)



Saturates

- Straw coloured or white viscous oils
- Molecular mass – similar to *aromatics*
- Both waxy and non-waxy
- Make up 5 – 20% of total bitumen



Manufacture and properties of bitumen

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

Bitumen structure

- Physical arrangement of bitumen particles
- Effects of ageing

Physical arrangement

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 maltenes (saturates and aromatics)

Molecular categories

- Molecules fall into two categories
  - Polar molecules – ***asphaltenes*** and ***resins*** form a network and provide elastic properties
  - Non-polar molecules – ***saturates*** and ***aromatics*** form the body (carrier of the polar molecules) and provide viscous properties
- Two categories coexist in a homogeneous mixture
- Chemical bonds are relatively weak – readily destroyed by heat or shear stress which gives bitumen its viscous and elastic properties

Molecular properties/cont…

- Constitution has major effect on viscosity and influence of temperature
- Too little or too much of a particular molecule group – brittleness and poor behaviour at low temperature
- There is no ideal proportion of SARA – the interaction between these fractions will characterise the behaviour of the bitumen

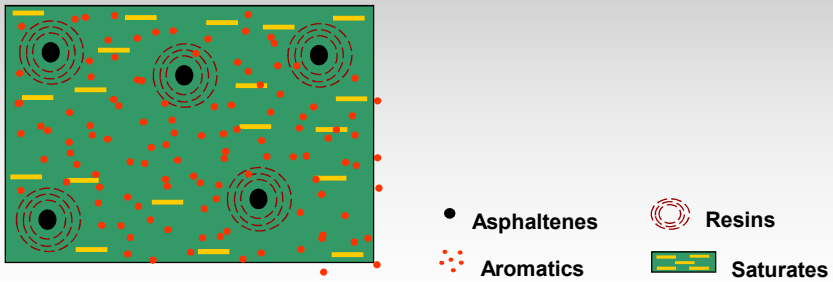
Types of bitumen

- 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

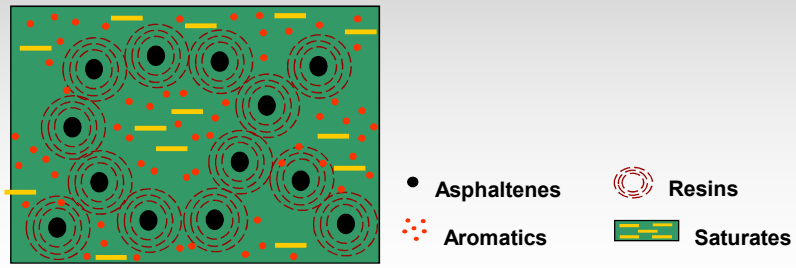
Sol type bitumen



GEL type bitumen

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

Gel type bitumen



Heating/air-blowing

- Air-blowing of bitumen from a vacuum residue:
  - significant ***increase in asphaltene*** content
  - ***decrease in aromatics***
  - saturate and resin content substantially unchanged
- Exposure to heat (asphalt manufacture and construction) effects major changes in viscosity and relative proportions of chemical components

Bitumen structure

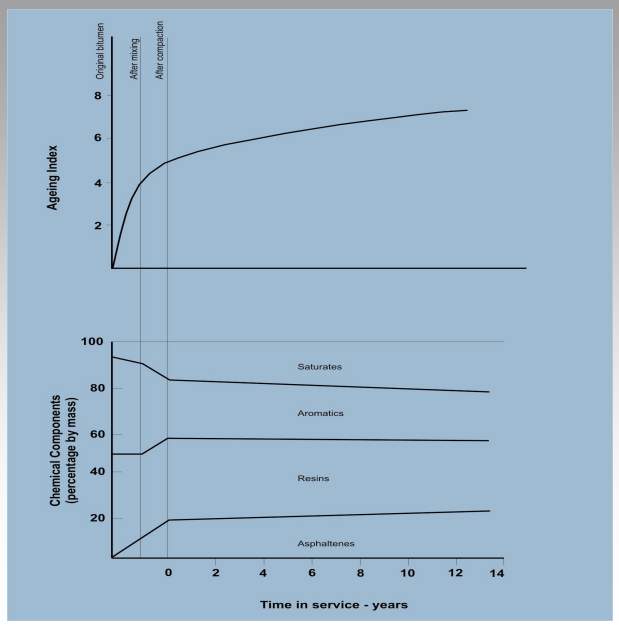
- Physical arrangement of bitumen particles
- Effects of ageing

Effects of ageing

- Ageing index measures changes due to exposure of heat
- Ageing index:

$$\frac{\text{Viscosity of aged binder}}{\text{Viscosity of original binder}}$$

Ageing of bitumen in asphalt



Note

- Chemical composition will determine physical properties and performance characteristics of a bitumen
- Complex and variable molecular structure makes it extremely difficult to measure and define chemical composition for required performance
- Bitumen from different crude sources (different chemical composition) can have similar physical properties
- Little sense to ensure performance by specifying chemical component concentrations nor define individual components (e.g. required proportion of asphaltenes)
- Instead - use ***performance related*** physical properties for specifying and selecting bituminous binders

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- **Rheology**
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  - Visco-elasticity
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Rheology

- Science of the flow and deformation of matter including soft solids
- An ***fundamental engineering property***
- Influenced by
  - Temperature
  - chemical composition
  - structure (physical arrangement) of the binder molecules

Factors affecting rheological properties

1. Temperature

Bitumen is a ***thermoplastic*** hydrocarbon material which softens when heated and turns into a glassy state when cooled:

- At low road temperatures
  - Brittle solid ***(?)***
- At room temperature
  - Sticky semi-solid
- At high service temperatures
  - Visco-elastic substance ***(?)***
- Elevated temperatures ***(?)***
  - Viscous liquid

Factors affecting rheological properties/cont…

2. Composition

- Increase in asphaltenes – increase of viscosity
- Increase in aromatics at constant ratio of saturates: resins has little effect on rheology
- Increase in saturates at constant ratio of resins: aromatics softens the bitumen
- Addition of resins hardens the bitumen

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Visco-elasticity

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***
- Flow takes place as adjacent molecules flow past each other
- The force resisting this flow is related to the relative velocity of sliding

Viscous behaviour/cont…

- Penetration grade bitumen above 60 – 100º C shows a linear relationship:

$$\frac{\text{resistive force}}{\text{relative velocity (of sliding)}}$$

- Viscosity is therefore constant irrespective of the magnitude of applied shear
- Such materials known as ***Newtonian fluids***

Viscosity measurement defined

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

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

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

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 penetration grade bitumen:

0.970 – 1.040 kg/l

A dynamic viscosity of 1 Pa.s equates to:

kinematic viscosity of 962 – 1 031 cSt

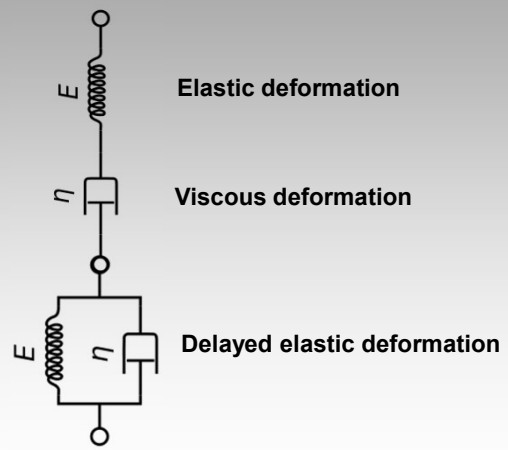
Visco-elastic behaviour

- During manufacture and application of bituminous layers bitumen at elevated temperatures – behaviour mainly viscous
- Service conditions – behaviour is visco-elastic, except in extremely low temperatures when it tends to be elastic
- Bitumen specifications are formulated in terms of these requirements

Bitumen response to imposed stress

- 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

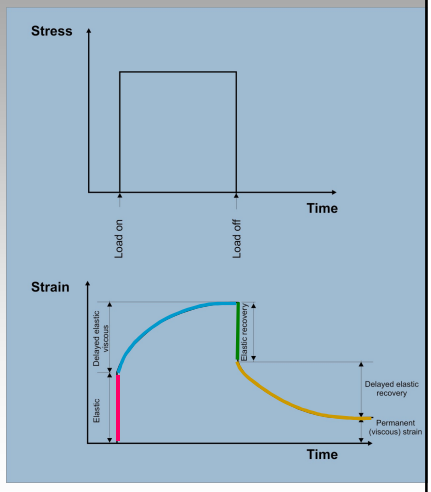
Response model – Burger's



- Kelvin
- Voight
- Kelvin - Voight
- Maxwell

Bitumen response to simple creep test

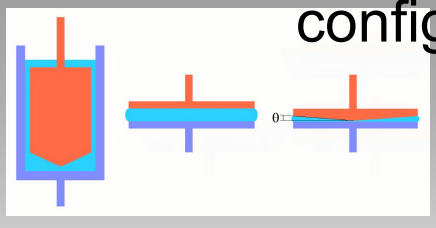
- Load applied
  - Instantaneous elastic response
  - Gradual increase in strain – viscous and delayed elastic behaviour
- Load removed
  - Instantaneous elastic recovery
  - Additional recovery with time – delayed elastic
  - Permanent residual strain



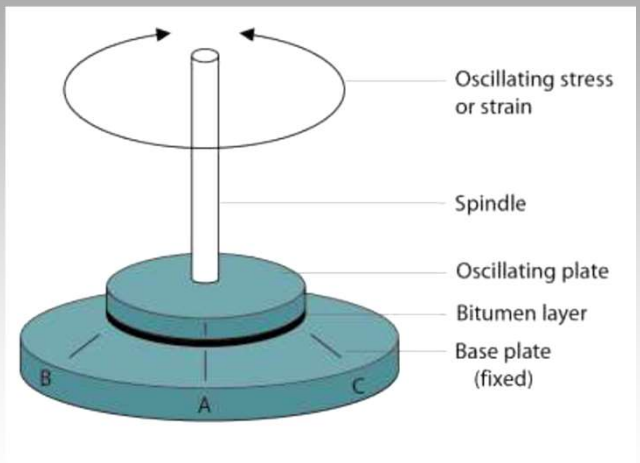
Dynamic Shear Rheometer

- Used to determine the rheological properties of bitumen according to AASHTO T 315
- Test uses a thin bituminous binder film between two plates
  - Lower plate fixed
  - Upper plate oscillates at selected frequency
- DSR measures both ***elastic*** and ***viscous*** properties of binders in the in-service temperature range (10°- 70° C)

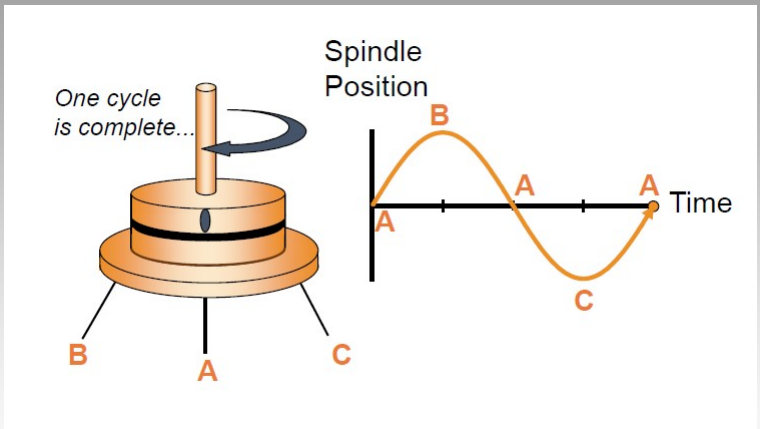
DSR cup & bob configuration



Apparatus



Basic operation



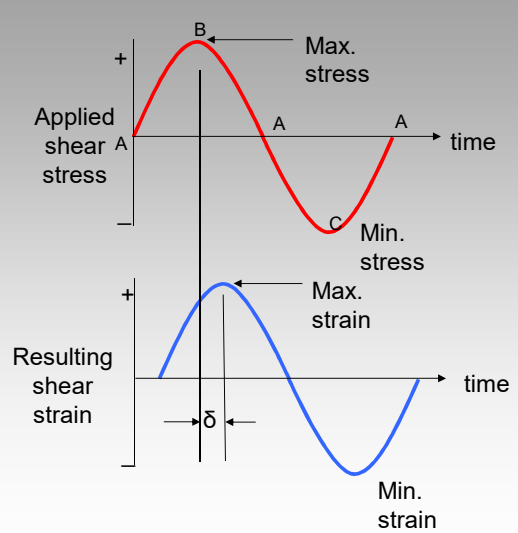
Properties measured by DSR

1. Fundamental rheological properties
   - Complex shear modulus
   - Phase angle
2. Creep behaviour of a bituminous binder
   - Extent pf recovery after relaxation of applied torque at elevated temperature

1. Fundamental rheological properties

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

Stress/strain outputs



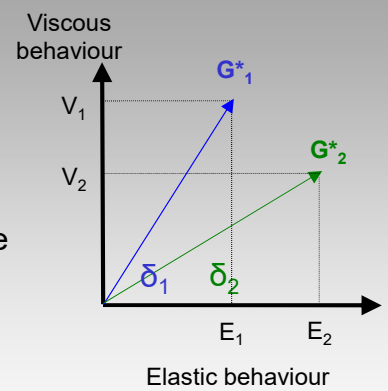
Complex Shear Modulus = G*

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

Phase angle = δ

Visco-elastic behaviour

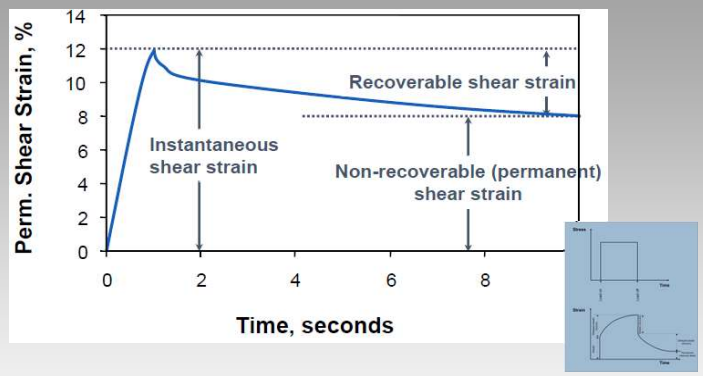
- Although G^*_1 and G^*_2 are of similar magnitude, they represent binders that are significantly different in visco-elastic behaviour
- Thus G* alone cannot describe asphalt behaviour, δ is also required
- Bitumen 2 has a larger elastic component ($E_2 > E_1$) and will recover better from applied loading.



2. Creep behaviour

- Multiple Stress Creep Recovery (MSCR) test measures recovery and non-recoverable creep
- A 1-second constant stress interval followed by 9-second unloaded recovery period. - repeated 30 times as follows:
  - 1st 10 cycles are performed at 0.1 kPa stress;
  - 10 more cycles at 0.1 kPa stress level and
  - 10 cycles at 3.2 kPa stress level.

Creep / recovery per cycle



the *Non-recoverable Creep Compliance* (J_{NR}) for a particular cycle is determined as follows:

$$J_{NR} = \frac{non - recoverable\ shear\ strain}{applied\ shear\ stress}$$

Resistance to viscous deformation

- Assessed by means of creep / recovery properties
- Conducted at elevated temperature
  - extent to which a bituminous binder will recover after the relaxation of an applied torque load
  - significant when considering
    - permanent deformation (rutting potential) of asphalt
    - the flushing / bleeding of spray seals.

Manufacture and properties of bitumen

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

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

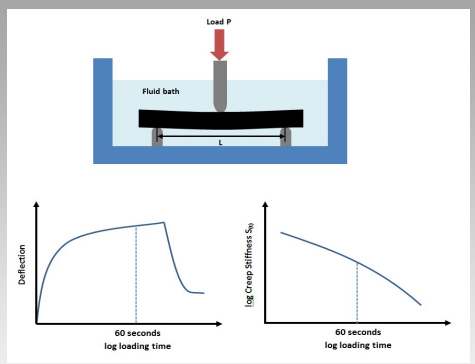
Ensuring durability / fatigue resistance

- The bituminous binder should be elastic (able to dissipate energy by rebounding and not cracking)
- It should not be too stiff - excessively stiff substances will crack rather than deform-then-rebound
- It should have stress relaxation properties to counter the formation of cracks

Low temperature behaviour

- To measure the ability to resist low temperature (fatigue) cracking
  - low temperature stiffness
  - stress relaxation properties of binders
- Bending Beam Rheometer (BBR) measures permanent deformation (or creep) under a sustained load at a given temperature

BBR



- Carried out on aged binders to simulate hardening during manufacture, handling and in service

BBR criteria

- A maximum creep stiffness (S) after 60 seconds to limit tensile stresses
- A minimum m-value, being the rate of change of S with time, indication of stress relaxing properties
- Elastic beam theory and the elastic-viscoelastic correspondence

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

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

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  - **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
  - Increase in stiffness
  - 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
- Penetration grade bitumens are 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

Exudative hardening

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

Hardening during use

The most important conditions bitumen is exposed to in use under which hardening can occur are:

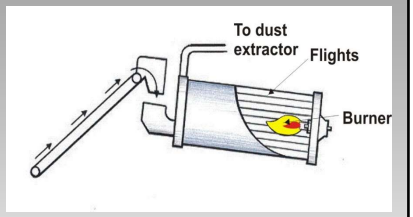
- Hot bulk storage
- Hot mix asphalt manufacture
- Handling of asphalt
- In-service

Hot bulk storage

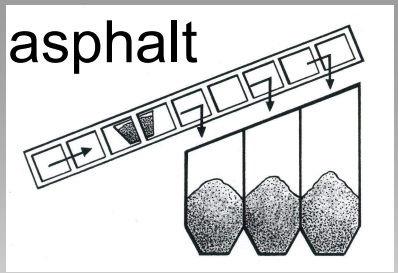
- Bitumen is kept at elevated temperatures for periods ranging from days to weeks
- Surface area exposed to oxygen is small relative to the volume
- Very little hardening occurs during this phase

Hot mix asphalt manufacture

- Thin films of bitumen (5 - 15μm) exposed to high temperature of superheated aggregates in presence of oxygen in pugmill
- Ideal conditions for oxidation and loss of volatiles
- Process is well known and should be taken into account when selecting grade of bitumen
- Guide: Penetration of bitumen falls by about 30% during mixing
  - Approx 1 pen grade



Handling of asphalt



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

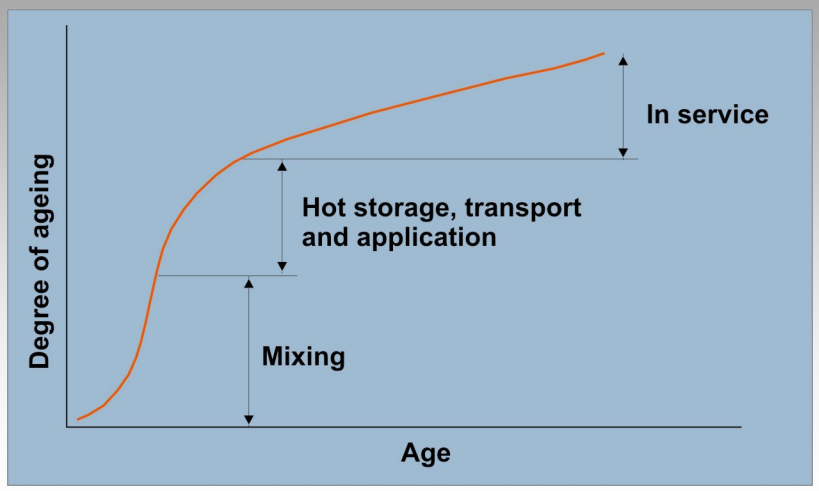
In-service hardening

- Hardening will continue until a limiting value is reached
- Exposure of binder films to the atmosphere will influence hardening
- Air void content is a major determining factor
- Studies have shown that:
  - 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
- Recommended minimum film thickness should be 6 – 8μm
- For porous mixes a minimum thickness of 12 μm is recommended

Ageing of bitumen



Ageing characteristics

- Short term ageing – rolling thin film oven test
- Long term ageing – Pressure ageing vessel

Note on 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
- Age hardening of bitumen can be minimised by proper handling