A practical guide for the application of procedures for designing asphalt mixes as per Sabita Manual 35/TRH8

3. Mix design process -

Design objectives

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Module 3

Introduction

2 Evaluate Design Situation

3 Design Objectives

4 Mix Type Selection

5 Constituent Materials

6 Laboratory Design Procedures

7 Special Mixes

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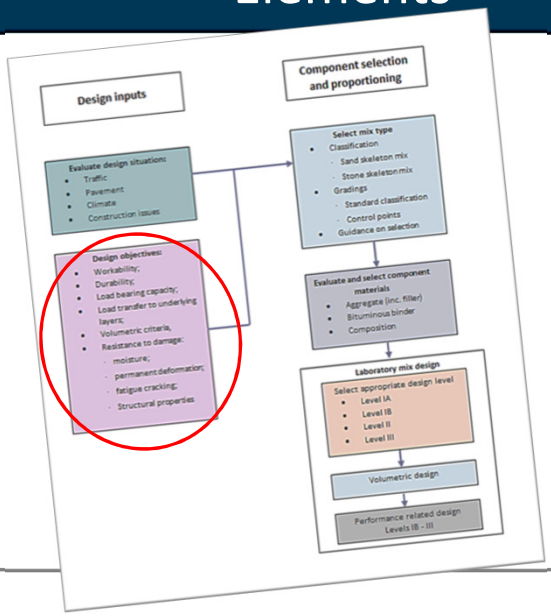
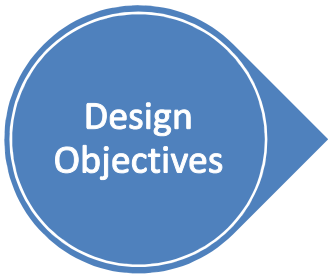
Elements

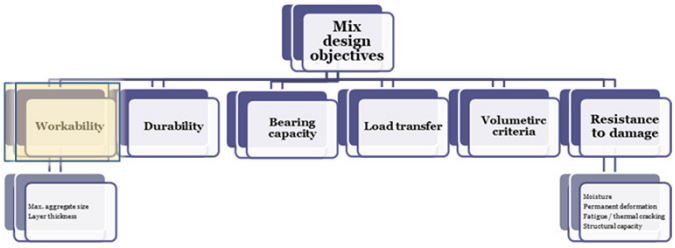


Mix Design Inputs



- Workability
- Durability
- Load Bearing
- Load Transfer
- Volumetric criteria
- Damage Resistance

Workability



- Workability - ***important performance characteristic***
- Ease of
  - Handling
  - placing
  - compaction
- Meeting performance criteria may be severely compromised by poor workability

Design Objectives

Important performance characteristic – ease of handling, placing and compaction

Aggregate size

Layer thickness

- **Not** restriction on min. layer thickness, rather
- Nominal Maximum Particle Size (NMPS) permitted for required layer thickness

Layer thickness determined by pavement design

Factors influencing workability

- High percentage of coarse aggregates - tendency to segregate and present difficulties to attain a uniformly well compacted layer;
- Too high or too low filler in the mix;
- Too low or too high temperature will make the mix unworkable or tender, respectively;
- Excessive proportion of ***large sized aggregate*** in relation to the ***layer thickness***

Layer thickness / aggregate size

- Not always given due consideration
- ***NOT*** a restriction of ***minimum layer thickness*** for a selected maximum aggregate size
- Correct approached as a ***maximum aggregate size*** permitted for a ***predetermined layer thickness*** (as per pavement design)

Nominal Maximum Particle Size

Nominal Maximum Particle Size (NMPS) defined as:

One sieve size larger than the largest sieve to retain a minimum of 15 percent of the aggregate particles

Blend #1: NMPS – 20 mm

Blend #2: NMPS – 14 mm

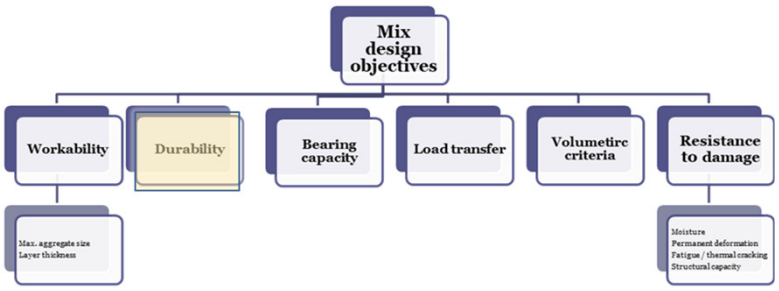
BLEND #1	
Sieve size mm	% Passing
37.5	100
28.0	100
20.0	94
14.0	78
10.0	66
7.1	57
5.00	50
2.00	31
1.00	21.3
0.600	15.7
0.300	11.0
0.150	8.2
0.075	5.6

BLEND #2	
Sieve size mm	% Passing
37.5	100
28.0	100
20.0	100
14.0	99
10.0	83
7.1	73
5.00	64
2.00	40
1.00	27.1
0.600	19.8
0.300	13.9
0.150	10.0
0.075	5.9

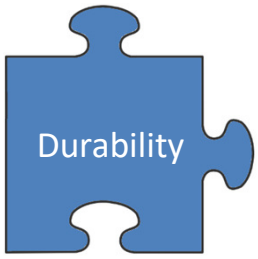
Max aggregate sizes for layer thicknesss

Layer thickness range (mm)	Nominal Maximum Particle Size (mm)
20 - 25	7.1
30 - 35	10
40 - 50	14
60 - 80	20
90 - 120	28

Design objectives



Design Objectives



Permeability

- High binder contents, adequate film thickness
- Dense aggregate packing
- Dispersed rather than inter-connected voids
- Well compacted layer

Penetration of mix by air, water and water vapour

Durability

Ability to ***resist (fatigue and low temperature) fracture*** due to e.g.:

- Hardening of the binder
- Disintegration of the aggregate;
- Stripping of the bituminous binder from the aggregate;
- Action of traffic and influence of temperature

Measures to ensure durability

- ***Appropriate binder*** in adequately ***thick films***;
- Dense aggregate packing, i.e. ***low air voids***;
- Sound, durable and strip resistant aggregates;
- Use of adhesion-promoting or anti-stripping additives or hydrated lime.
- Limiting the ***permeability*** of the mix

Permeability

Manual 35 - ***special attention*** be paid ***to permeability*** of the mix during the design stage.

Low permeability (dense) asphalt:

- promotes long term durability
- protects underlying layers from the ingress of water which may cause distress due to increased flexibility of the substrate

Asphalt wearing course layers in SA - ***relatively thin (40 mm)***, hence:

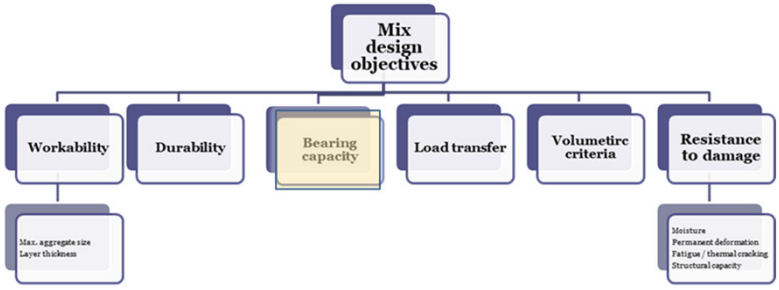
- Permeability is a critical factor particularly where continuously graded wearing courses overlie granular bases
- Potential for binder hardening and stripping

Measures to reduce permeability

- ***High binder contents*** with adequate film thickness;
- ***Dense*** aggregate packing;
- ***Dispersed*** rather than inter-connected air ***voids*** within the mix;
- Well ***compacted*** asphalt layers

Gap- or semi-gap graded (***sand skeleton***) mixes are bound to have ***dispersed voids*** that do not readily offer flow paths for air or water.

Bearing capacity



Design Objectives

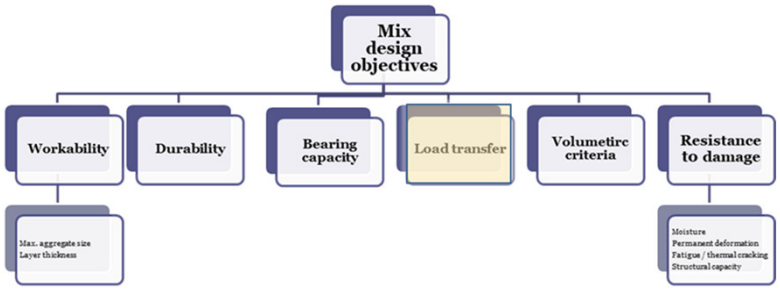
Bearing Capacity

- Aggregate
  - primary load bearer
  - bulk of the mix volume
  - **physical properties and packing of aggregate significant influence on mix performance**

Influence of component materials

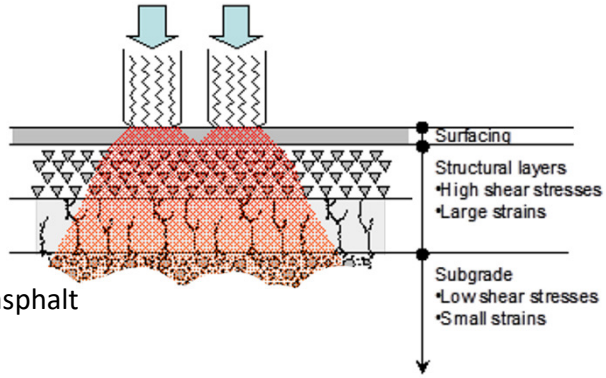
- ***Aggregates*** make up the ***bulk*** of the volume of asphalt mixes
- Provide ***load bearing capacity*** of the asphalt layer
- Structural and functional performance of an asphalt mix - greatly influenced by:
  - the physical properties of aggregate
  - packing characteristics of the aggregate blend
  - the quality of the binder used (to some extent).

Load transfer



Design Objectives

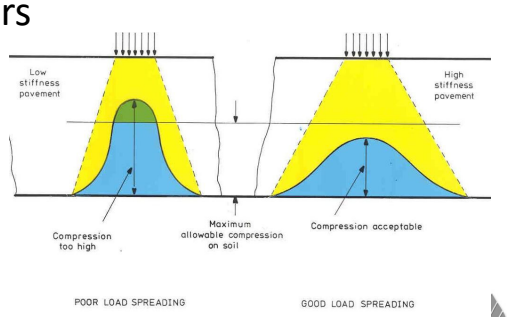
Load Transfer



- Flexural **stiffness** of asphalt
  - Loading time
  - Temperature
  - Binder content & rheology
  - Aggregate packing
  - Compaction

Load transfer

- Important function of asphalt layers
- ***Flexural stiffness*** of asphalt determines the extent to which traffic loading is spread to underlying layers



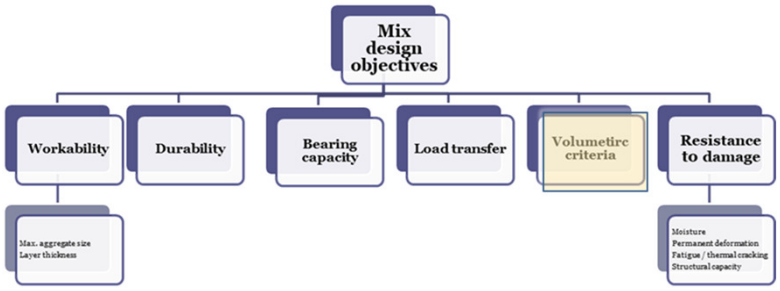
Asphalt stiffness

- Relatively stiff asphalt generally required for asphalt bases
- Asphalt wearing courses on bases with higher transient deflections better served by a lower stiffness, more pliant asphalt, to avoid traffic induced brittle cracking.

Factors affecting stiffness requirements

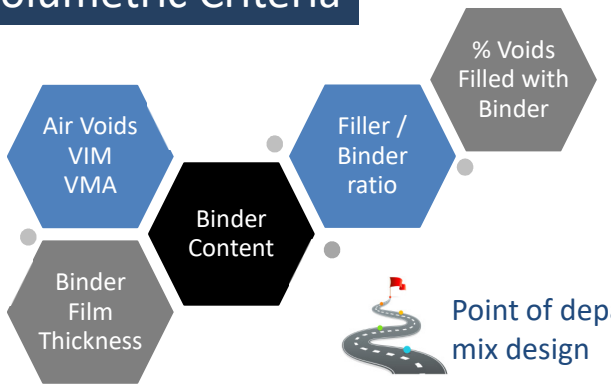
- Traffic loading time;
- Temperature;
- Binder content and binder rheology;
- Aggregate packing; and
- Degree of compaction achieved during construction.

Volumetrics



Design Objectives

Volumetric Criteria



Point of departure for mix design

Volumetric terminology

- Air voids
- Percent Voids in the Mix (VIM)
- Voids in the Mineral Aggregate (VMA)
- Percent Voids Filled with Bitumen (VFB)
- Filler/Binder (F/B) Ratio
- Binder film thickness
- Bitumen Content

Criteria

Volumetric analysis is the ***starting point*** of mix design

Preliminary assessment of mix properties and behaviour prior to additional mechanical tests on the asphalt materials.

Design Objectives

Air Voids

- Percent Voids in the Mix (VIM)
  - Airspaces between coated particles in final compacted mix
  - Allow for in-service densification
  - Link between VIM and **durability**, **flushing**, ability to **compact**

Air voids

- Small ***pockets of air*** between the coated aggregate
- Some air voids - necessary in all dense-graded mixes to allow for:
  - ***additional pavement*** compaction under traffic
  - to prevent ***bleeding and flushing***.
- Allowable % air voids (in laboratory compacted specimens) ≈ 4.0% for most dense mixes.
- The durability of a dense asphalt layer can, in general, be linked to the air-void content - the lower the air-voids, the less permeable and more durable the mixture becomes

Permeability and flushing

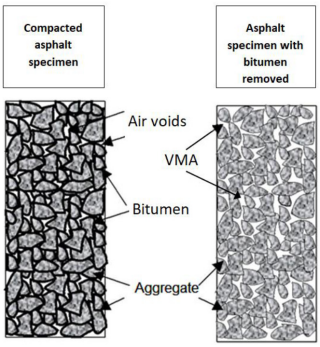
Voids too low – flushing and bleeding

Voids too high – mix is permeable

Design Objectives

VMA

- Voids in Mineral Aggregate
  - Space available for binder and air voids



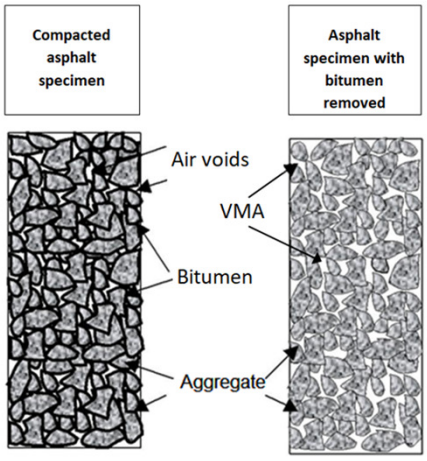
Minimum VMA → thicker film thickness → mix durability

Counter-productive to economise Bc by lowering VMA

VIM & VMA

- VIM is that ***part of the mixture not occupied by aggregate or bitumen*** expressed as a percentage of the total volume
- VMA represents:
  - ***air spaces between the aggregate particles including spaces filled with bitumen***
  - ***space available to accommodate the bitumen AND air*** necessary

VIM / VMA



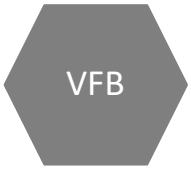
Factors influencing VMA

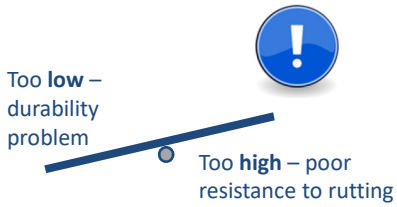
- ***Gradation*** – dominant aggregate packing factor.
- ***Lab Compaction method*** – Marshall compaction orients the aggregate structure differently than gyratory compaction
- ***Aggregate shape*** – cubical particles - pack more densely than flat and elongated particles.
- ***Aggregate texture*** – smooth particles pack more easily than those with rough surface texture
- ***Strength*** – influences degradation or break down during compaction

VMA

- To achieve ***sufficiently thick bitumen film*** on the aggregate particles for durability ***minimum VMA is specified***
- Increased density of gradation where minimum VMA values are not met, leads to:
  - thin films of binder
  - lean, low durability mix
- ***Economizing in binder content by lowering VMA is actually counter-productive*** and detrimental to layer quality.

Design Objectives





- % Voids Filled with Binder
  - Indication of cost effectiveness
  - Avoid over filling voids in coarse aggregate with fine aggregate or mastic
  - Useful information whether VMA will be saturated at especially, refusal density

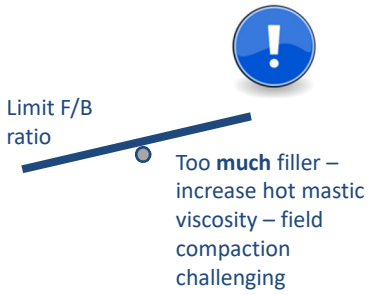
Voids filled with bitumen (VFB)

- The VFB is the percentage of voids filled with bituminous binder.
- The VFB property is important for two reasons:
  - indication of the ***cost effectiveness*** of the use of bituminous binder
    - High % VFB indicates high voids in the mineral aggregate, requiring unnecessarily high volume of costly binder
  - overfilling of voids:
    - in the coarse aggregate with fine aggregates
    - in the fine aggregate with mastic

  should be avoided as ***high VFB*** is known to have a strong relationship with ***poor rutting*** performance.

Design Objectives

F / B ratio



- Filler / Binder (F/B) ratio
  - Adequate filler to provide:
    - Mix cohesion
    - Internal strength and mix toughness
    - Resistance to shearing forces

Filler / binder ratio

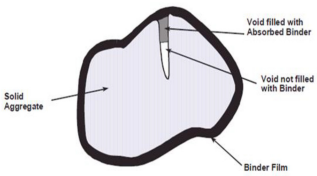
- Adequate amounts of filler:
  - to ensure that the mix has ***adequate cohesion***
  - sufficient ***internal tensile strength***
  - mix ***toughness*** to resist shearing forces
- Important for ***sand-skeleton mixes***, where cohesion is a major factor of resistance to permanent deformation
- Adequate mastic viscosity to prevent ***binder run-off*** during the manufacturing, transport and placement of such mixes.

Limitations on filler

- Presence of too much or too "active" a filler - increase in viscosity of the hot mastic making it ***difficult to achieve adequate compaction***
- For these reasons limitations on the filler-binder ratio is used in the design process.

Design Objectives

Binder Content



- Binder Content
  - Larger **surface area** of aggregate = more binder needed to coat aggregate
  - Effective binder content is ability of aggregate to absorb binder

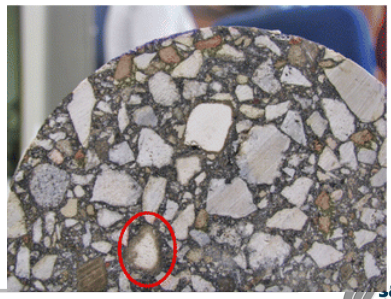
Small increases in filler amount can absorb much binder and give dry, unstable mix

Binder content (b/c)

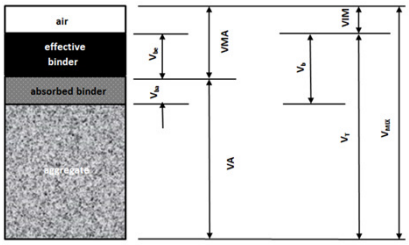
- ***Key volumetric parameter***
  - accurately determined in the laboratory
  - precisely controlled on the job
- Optimum b/c - highly dependent on aggregate characteristics such as gradation and absorptiveness
- The ***finer*** the mix aggregates
  - ***larger*** total aggregate ***surface area***
  - ***greater demand*** for ***bitumen*** to coat the particles adequately
  - Conversely, coarser mixes have less surface area - demand less binder.
- Small increases filler in a mix - absorb much of the binder, resulting in a dry, unstable mix

Effective binder content

- The ability of the aggregate to absorb bitumen is critical in determining optimum bitumen content
- the ***effective*** binder *i.e.* ***the total binder content less the quantity absorbed*** into the aggregate that provides the coating of aggregate and their bonding



Mix volumetrics



VIM = Volume of voids, represents the volume of the pores in the mix and interstices.

VMA = Volume of voids in mineral aggregate.

V_b = Total volume of binder within the asphalt mix.

V_{babs} = Volume of absorbed binder that penetrates into the aggregate pores.

V_{bef} = Effective volume of binder i.e. that which does not penetrate into aggregate pores.

V_A = Bulk volume of aggregate, including all permeable surface pores.

V_T = Total volume of binder and aggregate in the mix.

V_{MIX} = Total (apparent) volume of compacted asphalt specimen

Design Objectives

Binder Film Thickness

More Surface Area

More binder needed for uniform / sufficient coating

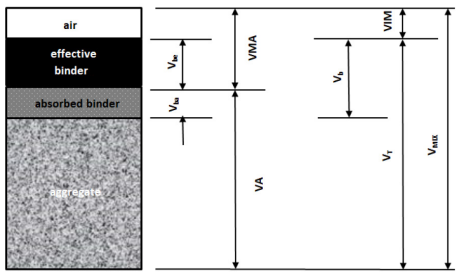
More Finer Mix

Computed average thickness of effective binder coating aggregate in the mix
(volume eff. binder / estimated surface area)

Binder film thickness

- ***Computed average thickness*** of the effective binder coating the aggregate particles in the mix
- Method - divide the ***volume of effective binder*** by the estimated ***surface area*** of aggregates
- Purely empirical, it is the best available at present
- Determines ***minimum binder content***

Design Objectives



- Volumetric design is based on: bulk density, VIM, VMA & VFB
- Check for consistency & reasonableness

Small errors in BRD (fines) vs. BRD (mix) & absorption = significant errors in calculations (voids & Bc)

Volumetric parameters

Volumetric design procedure in Manual 35 requires determination ***specimen properties*** :

- bulk density;
- voids in mix (VIM);
- voids in the mineral aggregate (VMA); and
- voids filled with binder (VFB) at a pre-defined level of compaction.

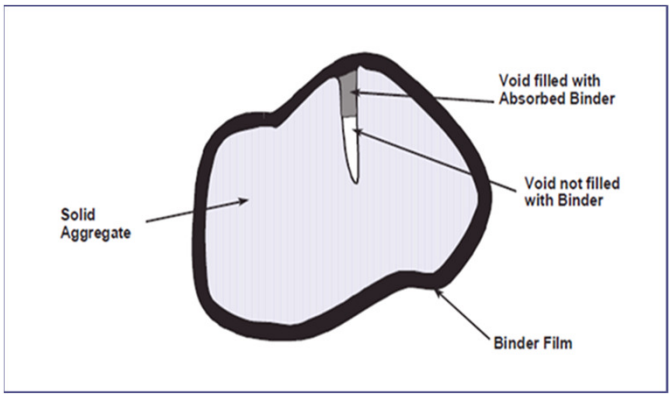
Further volumetrics

Determination of parameters in previous slide requires understanding of:

- ***Bulk density*** of (individual/combined) ***aggregate*** fractions
- ***Maximum voidless density*** - compacted asphalt
- Bulk density of the ***compacted mix***
- ***Effective density*** of the combined aggregate
- Relative density of the ***binder***
- ***Absorption*** of binder by the aggregate
- ***Effective binder content***

Different densities

- General case



Bulk density

- Assumes no absorption
- Measured voids include
  - voids filled with absorbed binder
  - voids not filled with binder
- Use of bulk density may overestimate actual voids in mix

Bulk density assumes aggregate looks like this:

$$Bulk\ density = \frac{mass\ oven\ dry\ aggregate}{(Vol\ agg) + (vol\ voids\ filled\ with\ binder) + (vol\ voids\ not\ filled\ with\ binder)}$$

Effective density

- Takes absorption into account
- Falls between Bulk and Apparent Density

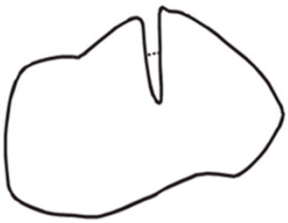
Effective relative density assumes aggregate looks like this:

$$Effective\ Density = \frac{Mass\ of\ oven\ dry\ aggregate}{(Vol.\ of\ aggregate) + (Vol\ voids\ not\ filled\ with\ binder)}$$

Apparent density

- Voids in aggregate not filled with binder are included in the design calculations
- Use of apparent density in design may cause underestimate of actual voids in the mix

Apparent relative density assumes aggregate looks like this:



$$Apparent\ density = \frac{Mass\ of\ oven\ dry\ aggregate}{Vol\ solid\ aggregate}$$

- Volumetric properties should be ***checked for consistency and reasonableness*** when evaluating the various parameters.
- Small errors in:
  - the BD of the fines
  - total BD of the mix
  - absorption properties of the aggregates

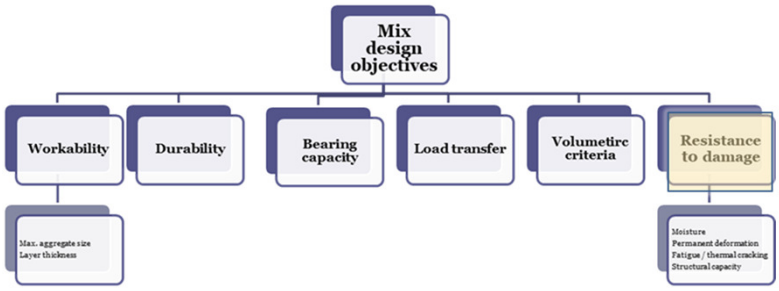
  can result in significant errors in the calculation of
  - voids in the mix and
  - design binder content.
- Accurate ***density measurements are critical*** to the correct calculation of volumetric parameters.

Design Objectives

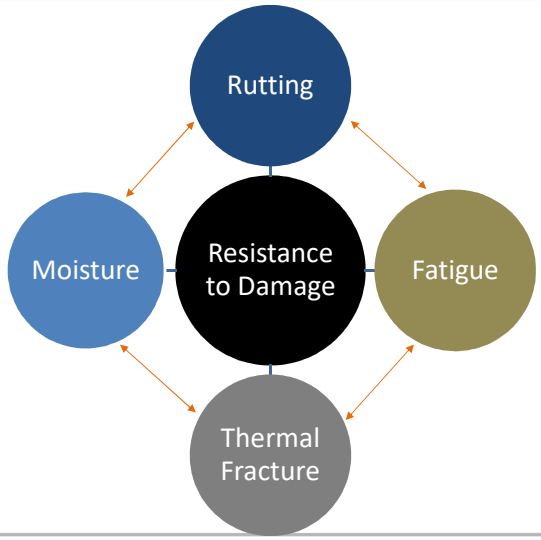
Compacted Asphalt Properties

- Bulk density of:
  - Individual and combined aggregate fractions
  - Compacted mix
- Maximum voidless density of the compacted asphalt
- Effective density of the combined aggregate
- Relative density of the binder
- Absorption of binder by the aggregate
- Effective binder content

Resistance to damage



Resistance to Damage



Resistance to Damage

Moisture Damage

- Durability promoted by **low permeability**

- Modified Lottman test
  - ITS (dry) : ITS (condition)
  - Tensile Strength Ratio

Thermal Fracture

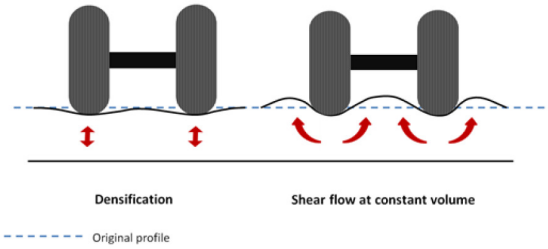
- Contraction & Expansion
  - Environment, structure, mix properties, **binder**
- PG Binder spec
  - Binder stiffness, avoid brittleness, stress relaxation

Moisture damage

- Long term ***durability is promoted by low permeability*** of asphalt - resistance to penetration of the mix by air, water and water vapour
- Assessed by means of the ***modified Lottman test*** (ASTM D4867M–09):
  - Carried out on specimens ***compacte***d to a void content corresponding to ***void levels expected in the field***
  - Two subsets of at least three specimens each and of approximately equal void content
  - ***One subset*** is maintained ***dry***
  - Other is ***partially saturated with*** water, subjected to ***freeze-thaw*** and ***moisture conditioned***
  - The indirect tensile strength of each subset is then determined. The potential for moisture damage is indicated by the ***tensile strength ratio (TSR)*** of the wet subset to that of the dry subset.

Resistance to Damage

Rutting



Densification

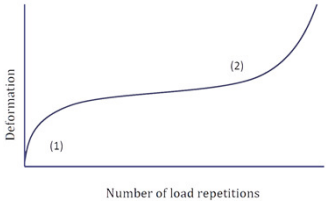
Shear Deformation

- Densification, with **decrease** in **volume**
- Shear deformation at **constant volume**

Resistance to Damage

Rutting

Densification (1)

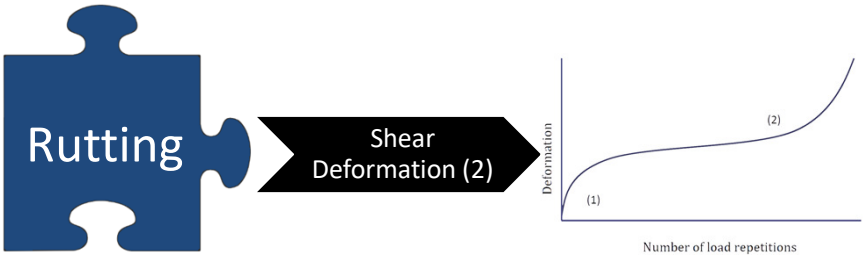


- Initial volume decrease under traffic
  - Typically from 7% to 4%, aggregates re-orientate
- Further densification can
  - Reduce voids to refusal density ≈ 3%, can be countered by
  - Increased mix stability and binder ageing

Densification stage

- Initially a ***volume decrease*** takes place under action of traffic
  - Aggregates are pushed into a preferred orientation
  - decrease in voids - typically from 7% to 4%
  - densification mix - stability improves.
- Further ***densification***
  - reduce voids to refusal density – typically to ≈ 3%
  - increased density and binder ageing may counter this
- Mixes with voids decreasing to <3% are more prone to rutting than mixes with voids of 4%
- Voids after primary densification are a measure of rut susceptibility of mix.

Resistance to Damage



- Imposed stress > layer resistance
- ∑ (repetitive small flow displacements - traffic) • • • rut
- Breakdown of particle-to-particle interface
  - Cohesion (mastic), aggregate skeleton interlock,
  - Durability & frictional aspects

Shear deformation

- Deformation resistance is overcome by the imposed stress
  - ***Summation of small flow displacements*** associated with repetitive traffic loads
  - ***lateral movements causing a depression***, or rut, to be formed.

Rutting distress

- Rutting is a ***frequent and serious type of distress*** in asphalt layers.
- Can lead to a significant ***reduction in road serviceability*** due to:
  - Ponding of water in wheel tracks – a hazard in wet weather;
  - Poor riding quality resulting in increased vehicle operating costs

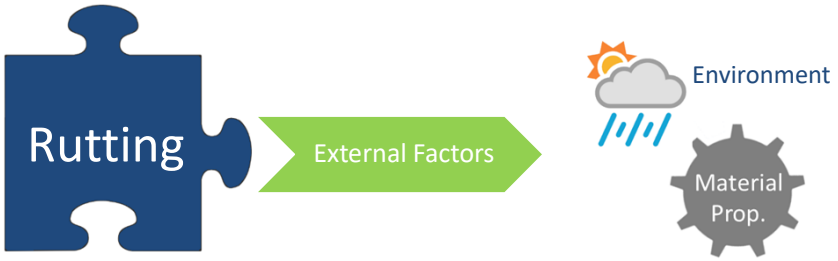
Resistance to rutting

Internal factors

The ability of an asphalt mix to resist permanent or plastic deformation depends primarily on:

- Internal ***frictional resistance of the aggregates*** in the mix;
- Cohesion (tensile strength) resulting from the bonding ability of the binder;
- ***Resistance to viscous flow*** of the binder at elevated temperatures.

Resistance to Damage



- Lower binder **resistance** to viscous **flow**, lower shear resistance
- Aggregate **packing**
- **VFB**: avoid overfilling voids with mastic or fine aggregates

45 °C +

Resistance to rutting

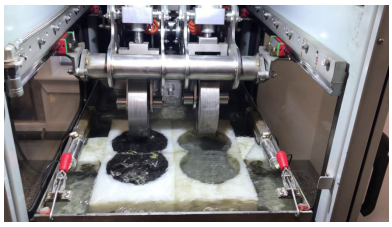
External factors

Extent and rate of rutting influenced by:

- Environmental conditions
- Properties of available material
  - shape, i.e. flaky, elongated, cubical, round
  - surface texture, smooth or rough
  - hardness and durability

Evaluation of rutting performance

- Best correlated to ***wheel tracking tests***:
- Hamburg Wheel Tracking Test (for design)
- Model Mobile Load Simulator (MMLS) (for field validation)
- At level I design
  - Dynamic Creep Modulus



Resistance to Damage

Ability of mix not to crack under repeated tensile strains

- Major aspect of asphalt design, interaction of
  - Layer properties
  - Pavement structure
  - Environment – traffic, temperature & moisture

Worsened by thermal fluctuations, loss of durability (e.g. binder ageing), high voids, low binder content

Fatigue

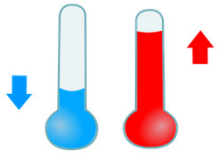
- Resistance to fatigue - ability to ***withstand repeated tensile strains without fracture***
- Occurs when number of load repetitions exceeds the capacity of the asphalt to withstand the associated tensile strains.
- A ***major consideration*** in in the design of asphalt and depends on the interaction of a number of elements:
  - asphalt properties
  - pavement structure
  - the environment e.g. traffic temperature and moisture

Influence of temperature

Capacity of an asphalt layer to resist fatigue ***reduced by:***

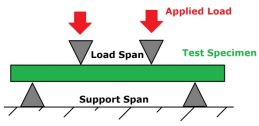
- ***stresses induced by thermal fluctuations***
- ***loss of durability*** due to, for instance, ***binder ageing***
- ***high voids*** - accelerate binder ageing
- ***low binder content*** – thin binder films

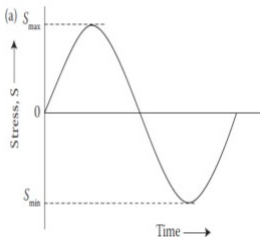
Thin asphalt layers are more prone to fatigue as a result of high flexural deflections



Evaluation of fatigue resistance

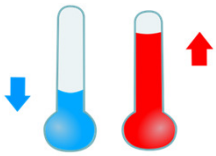
- Subjecting asphalt mixture specimens to ***repeated loading***
- Flexural bending in ***four-point*** beam bending test is a standard test method
- Specimen - subjected to a ***repeated, sinusoidal load*** applied uniformly over the centre third of the beam
- Fatigue life determined when the energy dissipated indicates that ***micro tracks are transformed to macro cracks***.





Thermal fracture

- Due to ***contraction and expansion*** of the asphalt layer under extreme temperature changes
- Interplay of
  - the environment
  - the road structure
  - importantly, the ***properties of the asphalt mixture***
- The PG binder specification, will provide criteria which will safeguard against the use of binders that are not unduly susceptible to thermal cracking



MODULE 3 - DONE