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

6. Laboratory Design Procedures

SARF Manual 24 – 25 Nov. 2020

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Elements

- Mix Type Selection
- Constituents and Proportioning
- Lab Design Procedures Overview
- Special Mixes

You are here

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Balanced design

- Design of asphalt - ***BALANCING conflicting requirements*** for satisfactory performance
- For instance
  - Measures to ***counter rutting***
  - adequate ***fatigue resistance*** and ***durability***
- Strike a ***balance to*** optimise with judicious selection of component materials

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Conflicting design measures

Design objective	
Rut resistance	Fatigue strength / durability
Design considerations	
Reduced binder content	Increased binder content
Highly viscous / non-compliant binder	Binder with stress relaxation properties
Increase void content	Reduced void content
Stone skeleton mixes (Be Careful)	Sand skeleton mixes
High filler / binder ratio	Reduced filler / binder ratio

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Design procedure – design situation

Design procedure that is appropriate for the ***design situation***

- For ***light traffic***, parking lots the design procedure should be fairly ***straightforward and simple***
  - ***Consequence*** of a design inexactness is ***not severe***
- ***Major, heavily trafficked roads*** - design deficiency has ***major disruptive*** and ***safety*** consequences
  - ***Advanced*** and ***precise*** design procedure is ***justified*** to mitigate exposure to the risk of premature structural damage.

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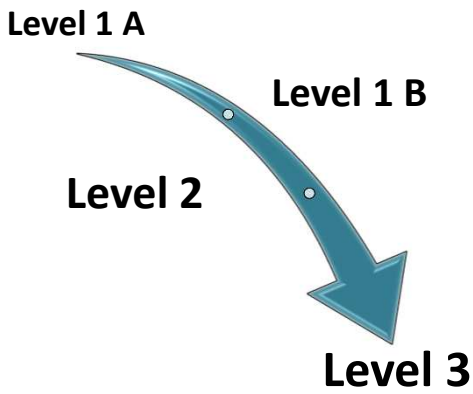
Design levels

- Manual 35 provides for ***4 levels*** of complexity:



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Design levels

- Design level is determined by traffic expressed as:

80 kN axles over the ***design period (service life)*** of the asphalt **pavement**

NOT

the traffic over the expected ***life of the asphalt layer***

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Mix design levels

Design traffic [E80]	Mix design level
< 0.3 million	Level IA
0.3 to 3 million	Level IB
> 3 to 30 million	Level II
> 30 - 100million	Level III
> 100 million	

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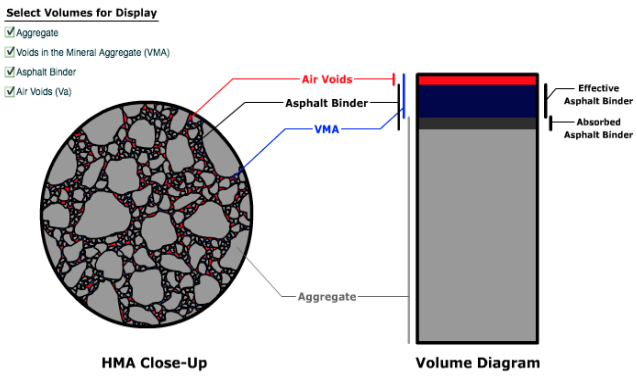
Volumetric design

- ***Starting point*** for ***ALL levels*** of design
- Provides:
  - ***balanced composition***
  - foundation for further testing
  - capacity of the mix to ***meet performance requirements***.



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Volumetric Design Framework

Select constituent materials & proportions

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Produce laboratory design trial mixes

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Select optimum design for mix property testing trials

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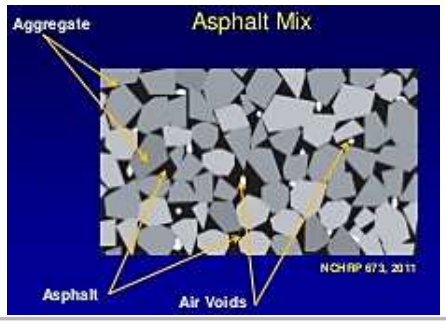
Binder content

- Mix type ✓
- Constituent materials ✓
- Minimum binder content



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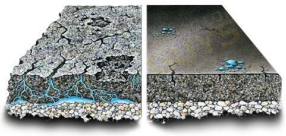
Minimum binder content

- ***Sufficient*** volume of binder - ***critically important*** volumetric aspect
- Ensure that aggregate has a ***adequately thick*** film of ***bitumen coating*** to:
  - bind components;
  - allow suitable compaction;
  - provide cohesive strength;
  - render the asphalt flexible, resilient and durable.



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Mass / volume considerations

- Binder content - ***mass based*** proportion
- Does ***not reflect*** the aspect of ***sufficient volume***
- ***Bulk density*** of aggregates types may ***differ significantly***
- ***Substantially different binder volume concentrations*** for a given mass proportion

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Mass / volume considerations

- Example
  - bulk density of ***quartzite*** and ***dolomite*** is in the region of ***2650***
  - bulk density ***dolerite***, ***basalt*** and ***andesite*** in the region of ***2800 - 2950***
  - binder content ***(m/m)*** of ***5.8%*** for a ***quarzitic sandstone*** - equivalent to a ***5.5% (m/m)*** binder content for ***dolerite***
  - ***same*** binder ***volume for coating aggregates***.

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Binder film thickness

Ensure that:

- A ***binder content*** that will provide ***sufficient coating*** of aggregates is adopted; and
- That the ***bulk density*** of the ***actual aggregate*** blend is ***taken into account*** to adjust the binder concentration accordingly.

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Determination of min binder content

- ***Min value of the binder film thickness F*** is adopted - ***5.5 µm (micron)*** for all cases
- ***No upper limit*** (excess of binder will reflect in various other parameters)
- The ***specific surface area of the aggregate*** blend is calculated in m^2/kg
- Film thickness $= \frac{Volume\ of\ effective\ binder}{Surface\ area\ of\ aggregate}$

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Steps for calculating film thickness

1. Calculate ***effective density*** of blend
2. Calculate percentage ***absorbed binder***
3. Calculate ***effective binder*** content
4. Calculate specific area of aggregate blend
5. Calculate ***binder film thickness***

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Step 1 - Effective density of blend

$$BD_{AEF} = \frac{100 - B}{\frac{100}{MVD} - \frac{B}{BD_B}}$$

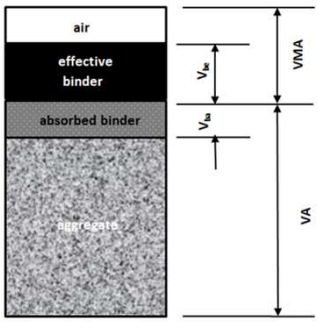
Where:

BD_{AEF} - Effective density of the aggregate blend

MVD - Maximum voidless density of the mix

B - Total binder content expressed as a percentage of the total mass of the mix.

BD_B - Density of the binder (at 25°C)



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Step 2 – Absorbed binder

$$B_{ABS} = \frac{BD_{AEF} - BD_A}{BD_{AEF}.BD_A}.B.100$$

Where:

$B_{ABS} = binder\ absorbed\ (\%\ of\ the\ tot.aggregate\ mass)$

$BD_{AEF} = effective\ density\ of\ the\ aggregate\ blend$

$BD_A = Bulk\ density\ of\ the\ aggregate\ blend$

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Step 3 – Effective binder content

$$B_{EF} = B - \frac{B_{ABS}}{100}.(100 - B)$$

Where:

B_{EF} = *Effective binder content (% of the tot mix mass)*

$B_{ABS} = binder\ absorbed(\%\ of\ the\ tot\ agg\ mass)$

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Step 4 – Specific surface area of aggregate

$$SA = (2 + 0.02a + 0.04b + 0.08c + 0.14d + 0.30e + 0.6f + 1.6g) \times 0.20482$$

Where

- a = percentage passing 5 mm sieve;
- b = percentage passing 2 mm sieve;
- c = percentage passing 1 mm sieve;
- d = percentage passing 0.60 mm sieve;
- e = percentage passing 0.30 mm sieve;
- f = percentage passing 0.15 mm sieve,
- g = percentage passing 0.075 mm sieve

(Based on -5 mm fraction having BD of 2650)

Considering volume aspects, calculate normalised specific area

$$SA_N = SA \times \frac{2650}{BD_{A(-5)}}$$

Where

SA_N = Normalised specific area

$BD_{A(-5)}$ = Bulk density of -5 mm fraction

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Determine film thickness F in µm

$$F = \frac{B_{EF}}{(100 - B)} \cdot \frac{1}{SA_N} \cdot \frac{1000}{BD_B}$$

Where

B_{EF} = Effective binder content (%m/m)

B = Total binder content (% of the total mix mass)

BD_B = Density of the binder (at 25°C)

SA_N = Normalised surface area

The total binder content of the mix shall be such that the binder film thickness, F, based on the effective binder content, shall be ≥ 5.5 µm

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- ***SA*** is essentially
  - ***theoretical value*** and,
  - ***not*** a ***precise computation*** of the actual area
  - value lies in being a ***consistent comparative parameter.***
- ***Filler / binder ratio*** requirements should be given due consideration
- Binder film thickness, *F*, recommended for ***general practice*** (sand and stone skeleton mix types)
  - Special cases
    - ***EME*** - minimum binder content to satisfy a ***Richness Modulus***
    - Binder content of ***SMA*** - ***Appendix B*** of ***Manual 35***

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Preparation of design specimens

- Determination of the ***minimum binder content*** - basis for preparation of specimens for testing
- For ***level IA*** the ***Marshall*** compaction is used
- for ***all other levels - gyratory compaction*** of test specimens is required.

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Specimen binder content

Prepared at four binder contents:

- Min binder – (min ***binder film thickness***)
- Min binder content ***+0.5%***
- Min binder content ***+ 1.0%***
- Min binder content ***+1.5%***
- ***Check filler / binder ratio*** for compliance

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Mixing and compaction temperatures

Mixing and *compaction* of samples - at the ***correct temperature***, based on ***binder (or mix) viscosity (see WMA, etc.)***.

The (rotational) viscosity requirements in general are:

- ***Mixing***: – ***0.17 ± 0.02 Pa.s***
- ***Compaction*** – ***0.28 ± 0.03 Pa.s***

Designer must ***ensure*** use of the ***correct temp***:

- cases of mixes with ***high RA proportions*** (comingling of reclaimed and new binder)
- for ***modified binders -*** information should be obtained from the ***manufacturer***

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Specimen compaction

- ***Level IA*** – Marshall
  - ***75*** blows + ***45*** blows on reverse side
- ***Level IB +***
  - Gyratory compaction (AASHTO T321)
  - Number of gyrations N_{design} depends on ***traffic***

Design Level	Design traffic range (E80)	N_{design}
IB	0.3 – 3 million	75
II	3 – 30 million	100
III	> 30 million	125

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Fine tuning

Strive to achieve ***4% voids*** at N_{design}

May require ***adjustments*** to ***mix proportions***:

- aggregate composition
- binder content; or
- both

In making these adjustments – take care:

- ***permeability*** not affected adversely
- minimum ***binder film thickness*** is maintained
- ***filler / binder*** ratio compliance

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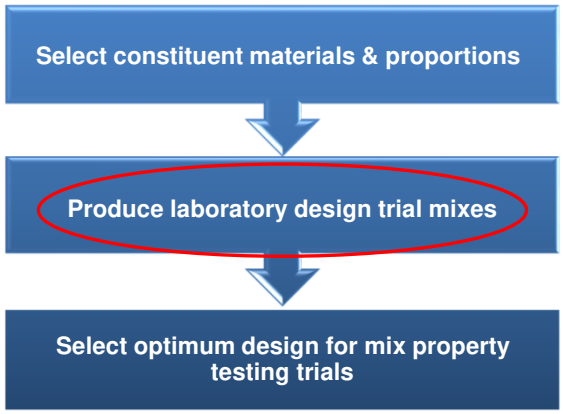
Volumetric Design Framework



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Trial mix evaluation

Level IA

Following ***compaction*** and ***volumetric analysis*** determine optimum binder content as follows:

1. Draw ***graphs*** of the ***following*** six ***relationships vs binder content***:
   - Bulk density
   - Marshall Stability
   - Marshall Flow
   - Air voids
   - VMA
   - VFB

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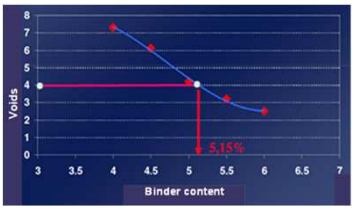
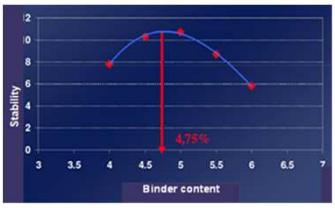
Binder contents determined

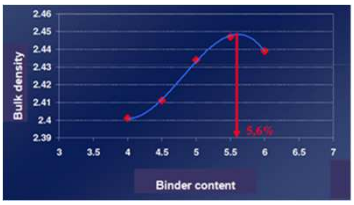
- For voids at 4% - BC ***5.15%***



For peak Marshall stability – BC ***4.75%***



- At peak bulk density – BC ***5.6%***



$$Mean\ BC = \frac{bc_v + bc_d + bc_s}{3}$$

Where:

bc_v *is binder content at 4% voids*
bc_d *is binder content at peak density*
bc_s *is binder content at peak stability*

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Volumetrics check at mean BC

At ***mean binder content***, check volumetrics :

- ***VIM***
- ***VMA***
- ***VFB***

Table 22: Voids requirements

Property	< 0.3 million E80s	
	Minimum	Maximum
VIM (%)	3	5

Table 23: Minimum percent VMA

NMPS (mm)	Minimum VMA* for design voids		
	3%	4%	5%
25	11	12	13
20	12	13	14
14	13	14	15
10	14	15	16

*Only values for continuously graded mixes are available and presented in this table.

Table 24: Percent VFB

Minimum	Maximum
70	80

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Mix acceptance Level IA

Volumetric measurements:

- Voids in the mix
- VMA
- VFB

Note:
Changes to SANS 3001 AS 10 and AS 11 are in progress!!!

Where appropriate, durability check:

- Tensile stress ratio ***(TSR)*** using the modified Lottman similar to Level IB.

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Summary of design procedures

Min binder content for film thickness $\geq 5.5\ \mu m$

Prepare specimens at min, min + 0.5, +1.0, +1.5% BC

Compact laboratory specimens

Level IA	Levels IB, II, III
Marshall compaction (75 + 45 blows)	***Gyratory*** compaction @ $_{Ndesign}$

Loose samples

Determine MVD, BD_{mix}

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Summary of design procedures

Compacted specimens

Calculate
VIM, VMA, VFB

↓

Design (Optimum binder content

Level IA	Levels IB, II, III
Mean of BC at 4% voids, peak density, peak stability	***Binder content at 4% voids***

↓

Check volumetrics at adopted binder content

VIM, VMA, VFB

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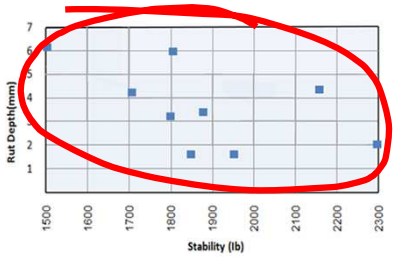
Note on Marshall Stability

- ***Marshall Stability*** in the Level IA design procedure - ***NOT*** a ***COMPLIANCE REQUIREMENT***
- Used purely as an ***INPUT*** to determine ***optimum BC*** (to avoid "over-asphalted" mixes)
- No longer used as a performance related property
- Little evidence in the literature of a consistent correlation between stability and resistance to rutting.



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Mix acceptance Level IB

- Volumetric measurements as per Level IA
- Performance related properties

Property	Test	Method	Criteria
Durability/TSR	Modified Lottman	ASTM D 4867 M	See Table 27 (Manual 35
Stiffness	Indirect tensile strength	ASTM D 6931-07	900 kPa - 1 650 kPa @ 25°C
Creep modulus	Dynamic creep	CSIR RMT 004	10 MPa min. @ 40°C
Permeability	Air permeability	TRH8 (CSRA 1987) Appendix C	$\leq 1 \times 10^{-8}$ cm^2

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Mix acceptance levels II & III

- ***Advanced*** procedures
- Carried out by ***experienced*** practitioners
- Involves ***direct measurements*** to assess the ***damage*** and ***response*** parameters of mixes
- What follows is a <u>brief</u> ***overview***

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Tests performed

- Workability
- Durability
- Dynamic modulus
- Rutting resistance (permanent deformation)
- Resistance to fatigue

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Workability Level IB, II, III

During ***gyratory compaction evaluate workability***

After ***45 gyrations, voids ≤ design voids + 3%***

Case:

- Traffic: ***3 – 30 million E80s***
- Design voids ***4%***

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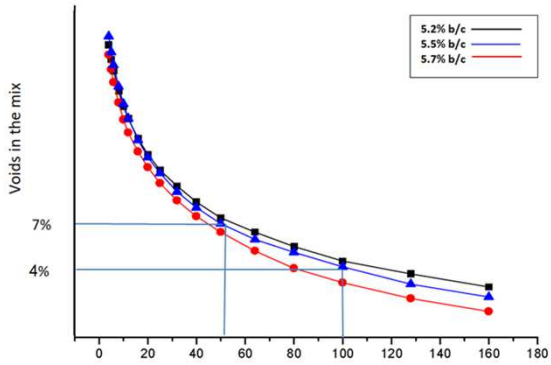
Gyratory cyles vs voids

N_{design} for traffic - ***100*** gyratory cycles
Upper limit of voids at 45 gyratory cycles = $4 + 3 = 7\%$
Mix with 5.5% binder complies



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Durability

- Durability of asphalt mix is its ability to resist:
  - ***Hardening*** of the ***binder*** due to:
    - Oxidation;
    - Loss of volatiles;
    - Physical (steric) hardening;
    - Loss of oily substances from absorption into aggregates (exudative hardening)
  - ***Disintegration*** of the aggregate
  - ***Stripping*** of the bituminous binder from the aggregate.

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Durability

- Durability of mixes can be ***improved*** by using:
  - Suitable binder in relatively ***thick binder 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.

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Durability test

Modified Lottman ASTM D4867

- Min. six samples at expected in-place voids (e.g. 6 – 8%)
- Partially saturated with water
- Three samples conditioned
  - frozen for at least 15 hours
  - immersed for 24 hours in a hot bath set at 60°C
- The durability of mixes assessed by indirect tensile strength (ITS) before and after conditioning by freeze-thaw cycles
- The ratio of the ITS values of the conditioned and unconditioned samples tensile strength ratio TSR.

Layer type	
Base	Wearing course
0.70	0.80

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Permeability

- ***Permeability*** - ***key factor*** to ensure ***durability***
- Where ***thin wearing courses*** (< 40 mm), ***overlay granular bases*** permeability is a critical factor
- Air permeability described in TRH8 (CSRA 1987) (Appendix B of Manual 24) *NOTE: Under Review*

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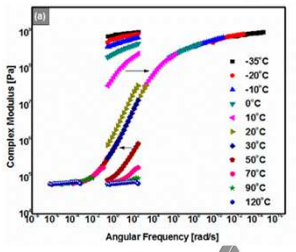
Dynamic Modulus

- Carried out in the asphalt mix performance tester (AMPT) as per AASHTO TP~~79~~ 378 - Replaced
- Values at various ***temperatures*** and ***frequencies*** - combined into ***master curve***
- Required for advanced ***pavement design***



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Dynamic modulus

- Asphalt - linear ***visco-elastic*** material
- Stress-strain relationship under continuous sinusoidal loading defined by complex dynamic modulus

$$E^* = \frac{\sigma_0 . \sin(\omega t)}{\varepsilon_0 \cos(\omega t - \delta)}$$

Where:

E* is the complex modulus
σ_0 peak stress
ε0 peak strain
δ phase angle (degrees)
ω angular velocity
t time (seconds)

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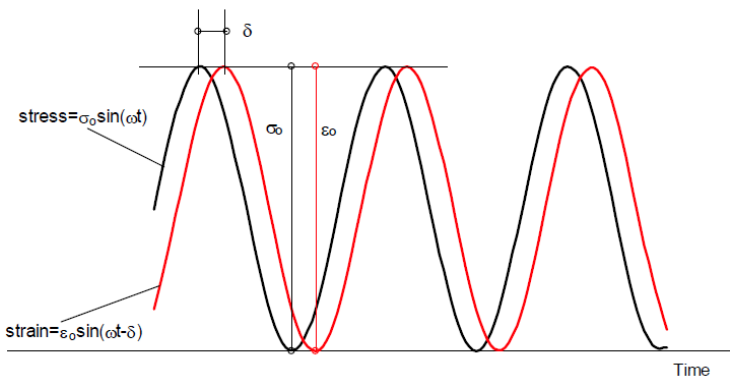
Stress / strain



For purely elastic materials, δ = 0
For purely viscous materials, δ = 90°

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Dynamic modulus procedures

- Conducted at ***frequency sweeps*** of 0.1, 0.5, 1, 5, 10, and 25 Hz.
- For ***Level II***, the sweep is carried out at one test temperature of ***20°C***.
- At ***Level III*** design, a full factorial test of dynamic modulus is conducted at the five frequencies above and at five temperatures ***(-5, 5, 20, 40 and 55°C)***

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Evaluation of rutting performance

- Best correlated to ***wheel tracking tests***:
- At ***Level I*** design
  – ***Dynamic Creep Modulus***
- At ***Levels II, III*** design
  - Hamburg Wheel Tracking Test (***HWTT)*** - for ***design***
  - Model Mobile Load Simulator (***MMLS***) - for ***field validation***

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Dynamic creep test

- Conditioned specimen (100 mm dia., 50 mm high) - subjected to a 100kPa ***cyclical load at 0.5 Hz at 40°C***
- The initial strain is measured after 1 minute as datum
- After 3 600 load repetitions the dynamic modulus is calculated using the measured strain.

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HWTT

- Indicates susceptibility to premature failing due to:
  - weak ***aggregate structure***
  - inadequate ***binder stiffness***
  - ***moisture damage***
  - inadequate ***adhesion*** between ***aggregate and binder***.
- The test outputs :
  - post-compaction consolidation (at 1 000 wheel passes)
  - creep slope
  - stripping slope
  - stripping inflection point

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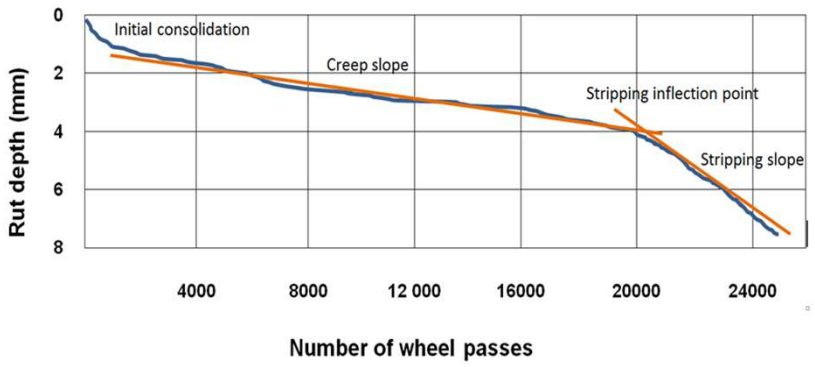
Definition of HWTT outputs



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HWTT

- This requirement set out in Manual 35
- Compliance criteria are ***provisional***
- No evidence at this stage to suggest that revisions are in the offing

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Assessing performance

- Importantly, it is noted in Manual 35 that ***recording and assessing mix performance on the basis of the final data after 20,000 wheel passes only might be misleading***
- Data assessment should cover:
  - Post compaction consolidation
  - creep slope (number of wheel passes per mm rut depth)
  - stripping inflection point and slope

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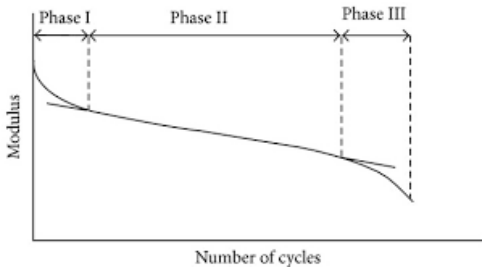
Fatigue

- ***Effective stiffness*** of asphalt ***decreases*** throughout the crack developing
- Plot of the ***stiffness*** versus ***loading cycle*** of an asphalt mixture during fatigue testing exhibits ***three phases*** of development



Phase I – rapid decrease in stiffness
Phase II – gradual decrease in stiffness
Phase III – acceleration of micro-cracks into observable macro-cracks

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Fatigue tests

- Carried out with the ***4-Point Beam Bending Test*** as per AASHTO T321
- In general, fatigue life is defined as the load cycle (n) at which $\boldsymbol{S \times n}$ ***is a max***.
- At this point the rate of change of dissipated energy changes
- ***Micro-cracks*** have propagated and coalesced to form ***macro - cracks***

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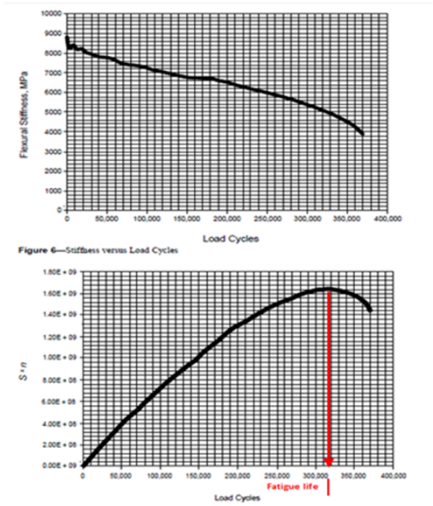
Fatigue life



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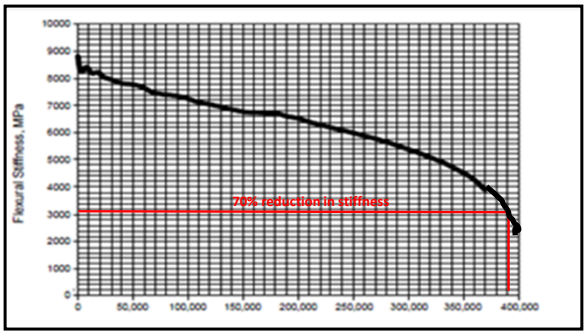
Exception

- Plots of S x n of some mixes may not display a peak value
- In such cases fatigue life is defined as the number of cycles at which the specimen flexural stiffness is reduced by 70%



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Summary of tests

Property	Test conditions	No. of specimens	Test method
Workability	Superpave gyratory compactor, air voids after specified number of gyrations	3	AASHTO T312
Durability	Modified Lottman test conditions	6	ASTM D 4867M
Stiffness/ (dynamic modulus)	AMPT dynamic modulus at temperatures of -5, 5, 20, 40, 55°C; loading frequencies of 25, 10, 5, 1, 0.5, 0.1 Hz	5	AASHTO TP 79
Permanent deformation	HWTT at relevant number of passes.	2[1]	AASHTO T 324
Fatigue	Four-point beam fatigue test at maximum of three strain levels and three temperatures.	9[2]	AASHTO T 321

[1] Number of specimens per binder content
[2] Max number of specimens for Level II – for Level III 18 specimens may be required

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Appropriate limits Levels II & III

Compliance limits for
- Dynamic modulus
- Fatigue life
- Resistance to rutting

Determined by structural design requirements
- ***Specific project***

OR
- ***Range of operating conditions***
  - Climate
  - Traffic
  - Pavement response and damage characteristics

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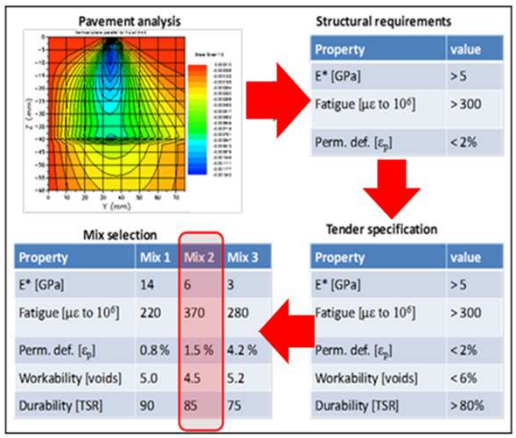
The system

- ***Basis*** for ***tender*** documentation
- ***Plus*** requirements:
  - workability
  - durability
  - Functional requirements (e.g. skid resistance for wearing course)



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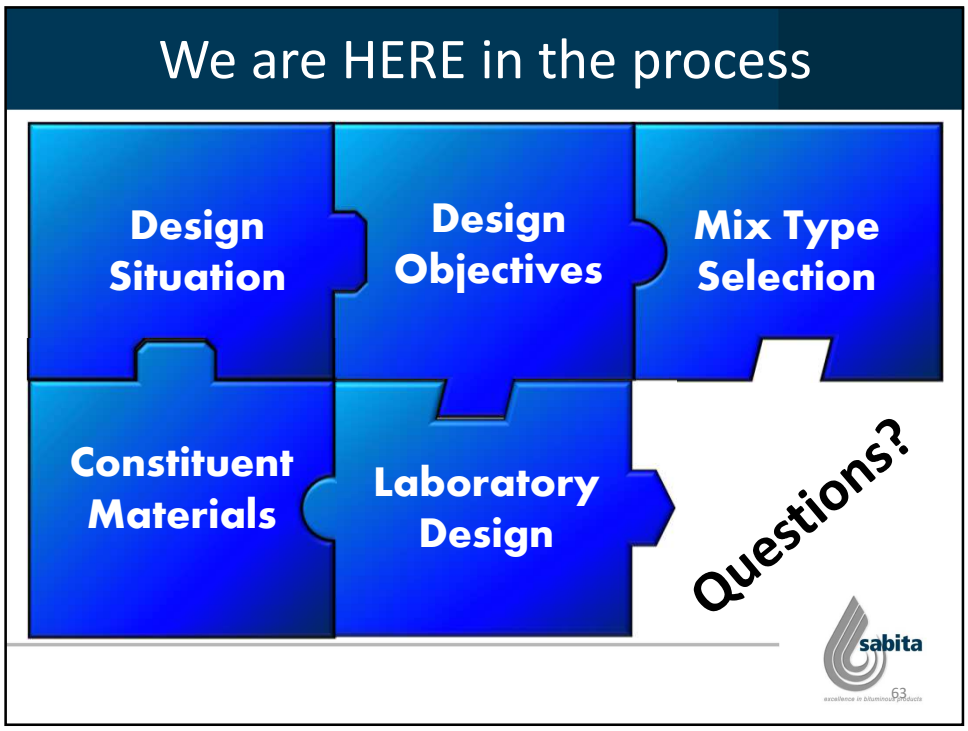
We are HERE in the process
Design Situation
Design Objectives
Mix Type Selection
Constituent Materials
Laboratory Design
Questions?
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