ASPHALT TECHNOLOGY
INTEGRATED INTO
ROAD ENGINEERING
FOR THE TROPICS


BRIDGING SCIENCE AND PRACTICE

By
Associate Prof. Dr. Ir. Hendro SUBROTO, MSc., PhD.

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Abbreviations:

AC	Asphalt Concrete
DAC	Dense Asphalt Concrete
PA	Porous Asphalt
SMA	Stone Mastic Asphalt
GAC	Gravel Asphalt Concrete
SAC	Stone Asphalt Concrete
OAC	Open Asphalt Concrete
AC-Surf	Asphalt Concrete Surface layer
AC-Bind	Asphalt Concrete Binder layer
AC-Base	Asphalt Concrete Base layer
AMP	Asphalt Mixing Plant
PR	Partial Recycling
PR-Asphalt	Partial Recycling Asphalt
C-Fix	Carbon Fixation
PMB	Polymer Modified Bitumen
SBS	Styrene Butadiene Styrene
EVA	Ethylene Vinyl Acetate
CBR	California Bearing Ratio
A/M-Ratio	Asphaltene/Maltene-Ratio
BANDS	Bitumen and Asphalt Nomographs Developed by Shell
SPDM	Shell Pavement Design Method
BISAR	Bitumen Stress Analysis in Roads
σ	Stress
σx, σy, σz	Stresses in the 3 orthogonal directions
σv	Stress in vertical direction
σr	Stress in radial direction
ε	Strain
εx, εy, εz	Strains in the 3 orthogonal directions
τ	Shear
τx, τy, τz	Shears in the 3 orthogonal directions
ν	Poisson ratio
φ	Angle
(m/m)	Mass on mass
(v/v)	Volume on volume
[cm]	Centimetre
[mm]	Millimetre
[µm]	Micrometer
[˚C]	Degree Celsius
[Kg]	Kilogram
[N]	Newton
[KN]	Kilo Newton
[MPa]	Mega Pascal
t	Time
tc	Traffic class
min. aggr.	Mineral Aggregate
Aggr.	Aggregate
Pen.	Penetration
Pm	Marshall Stability
Fm	Marshall Flow
Qm	Marshall Quotient
Emod	Modulus of Elasticity
Smod	Stiffness Modulus
Svert. Shor	Step's Dimension, Vertical Resp. Horizontal
4PB	Four-Point Bending
FWD	Falling Weight Deflectometer

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Introduction

Until a few decades ago, road engineering worldwide had mostly been carried out based on the purely empirical method of experience. In the last decades, however, some universities have been trying to improve the quality of road construction by doing research in their labs. Some local government offices dealing with road construction have also made some efforts to improve the quality of roads under their maintenance responsibility by approaching the construction more scientifically and by carrying out research.

In approaching road construction problems (deformation, ravelling, cracks, potholes etc.) more scientifically, one has to include Asphalt Technology, which gives more insight into the behaviour of mixtures produced with bitumen. An ***integrated*** approach using Road Construction theories and Asphalt Technology is necessary to better understand the problems and to minimise the problems may occur as much as possible. Furthermore, it is very important to learn from the results in practice, since some theories do not entirely match the real situation on the field due to variations in circumstances.

Unlike most municipalities worldwide, the city of Utrecht (the Netherlands) has been carrying out a lot of research regarding road construction and implementing Asphalt Technology. The city has also been implementing its own procedure in Road Engineering for the last decades. This procedure (Quality Controlled Road Engineering) is based on a scientific approach to Asphalt Technology in road construction and its implementation has revealed the eventualities of incorrectness in the asphalt mixtures, preventing a lot of mistakes and undesirable situations during its application and giving evidence of deficiencies within the construction.

This book is partly based on the scientific Road Engineering theories (lectured on at the Delft University of Technology), on the latest approaches to Road Construction and Asphalt Technology, on the road problems observed in the tropics, and mostly on the results monitored during more than 15 years in the Netherlands. These factors are linked as much as possible to better understand road construction problems, and at the same time emphasize the techniques which are also applicable for the tropics. By using common explanations, and summarising short texts and many figures, the author* has tried to make the asphalt technology, as well as the road engineering easier to understand, bridging science and practice. Complicated formulas are avoided as much as possible, and only what is necessary is presented. This book is meant as a guide for improving Road Engineering in the tropics, at university level as well as in the field.

**See back cover*

I. Asphalt Technology

Asphalt Technology deals with asphalt as material for road construction. As mentioned earlier, this subject will be integrated within road construction as a whole, since most changes herein also affect the strength of construction and, consequently, its longevity.
When considering this technology, the items (bitumen sort, structure, behaviour etc.) that determine the characteristics of the asphalt mixtures will be analysed.

Asphalt mixtures (usually) consist of the following components:

*Bitumen;
*Stone aggregate;
*Sand;
*Filler and
*Some additives that may be required.

Herein, bitumen is regarded as the most crucial component since it functions as the “glue” enabling the other components to work together and therefore determining the strength and longevity of the whole mixture.
The structure, the skeleton and the interactions between all of the components inside are also very important and have to be considered both separately and as a whole.

I.1. Bitumen

Within the asphalt mixture, the bitumen component functions as the “glue,” fixing all the other components to each other so they are able to cooperate as a whole. Bitumen is also the most expensive component in the mixtures and is on what the price of asphalt mostly depends.

For road construction purposes, the most crucial characteristic of bitumen is its penetration value. Penetration value refers to the value obtained from a bitumen penetration test (Fig. 1). Here, a special needle with 100 gram of mass is put into bitumen at 25 °C and the deformation/indention measured after 5 seconds is expressed in [0.1 mm], a factor of 10 is thus embedded in the registration.

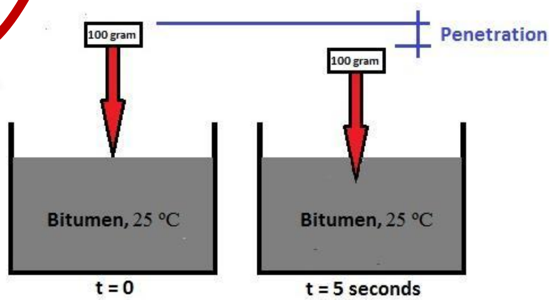


Fig. 1: Penetration Test for Bitumen

So, a 70/100 bitumen will give an indention between 7-10 mm, a 40/60 bitumen around 4-6 mm, etc. This means that a 70/100 bitumen is softer than 40/60. The higher the value, the softer the bitumen. High values denote less resistance to deformation and low values indicate higher stiffness, but also less flexibility and less *healing* capacity. Usually, bitumen sorts harder than 40/60 are not used for road construction since they are more crack sensitive.

For road construction purposes, bitumen sorts with penetration values of 70/100, 50/70 and 40/60 are usually used, depending on the situation and the local temperature. In hot climates, bitumen sorts with lower penetration values are recommended, as they possess higher resistance to deformation at certain temperatures and so can prevent extreme deformations.

In the past decades, recycled asphalt mixed with new asphalt has been used more and more. The older bitumen inside the recycled asphalt possesses a very low penetration value of about 25-30, due to oxidation.

As mentioned, one of the positive characteristics of bitumen is *healing*. This characteristic enables bitumen and asphalt mixtures to heal/recover from relatively small damages caused by stress and strain. The higher the penetration value, the higher the healing capacity of the bitumen and the asphalt mixtures composed with it.

I.1.1. Chemical Components

Bitumen can be produced from oil all around the world,. As the residue of crude oil, it is almost the last product of the refinery process. Due to its many places of origin, not all bitumen is produced in the same way. Chemical differences occur. However, when looking at the chemical components of bitumen, the most important components for asphalt mixtures are the *Asphaltenes* and the *Maltenes*, especially the ratio of them.

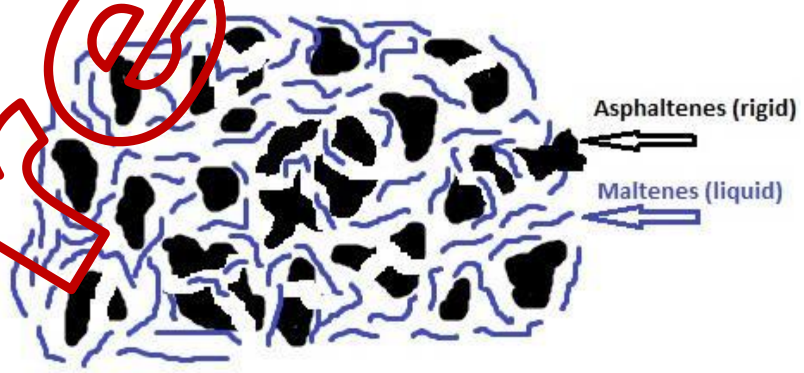


Fig. 2: Asphaltenes and Maltenes in Bitumen

Asphaltenes are black coloured and come in a powder form. They are the rigid particles in the bitumen.

Maltenes are the viscous/liquid parts of bitumen, and when they are in contact with air, they tend to evaporate, lessening their quantity, a phenomena known as *oxidation*. Due to this, the ratio of Asphaltenes/Maltenes (A/M-Ratio) will change, causing the bitumen to be more fragile and crack sensitive. A higher A/M-Ratio value means a relatively higher content of the rigid particles and, therefore, a higher crack sensitivity.

These effects can be seen using a penetration test (Fig. 1). On bitumen that was originally 70/100, penetration values as low as 25-30 can be recorded after some period of oxidation.

The followings are more detailed descriptions of both components:
(source: lloydminsterheavyoil.com)

Asphaltenes are complex hydrocarbons that have the following components:

- Condensed aromatic hydrocarbons with side chains up to C30.
- Hetero-aromatic compounds with sulfur present in benzothiophene rings and nitrogen in pyrrole and pyridine rings.
- Bi- or polyfunctional molecules with nitrogen as amines, amides, and oxygen in groups such as: ketones, armides, phenols, and carboxylic acids
- The metals nickel and vanadium complexed with pyrrole nitrogen atoms in porphyrin ring structures.

Maltenes constitute the fraction of asphalt which is soluble in n-alkane solvent, such as pentane and heptane. Their chemical characteristics are as follows:

- Contain smaller molecular weight versions of asphaltenes called "resins."
- Contain aromatic hydrocarbons with or without O, N and S (also called "first acidaffins").
- Contain straight chained or cyclic unsaturated hydrocarbons called oleifins (also called "second acidaffins").
- Contain cyclic saturated hydrocarbons known as naphthenes (also called "saturates").
- Contain straight or branch chain saturated hydrocarbons (also called "saturates").
- Their molecules are also known as "naphthene-aromatics."

Due to the more crack sensitive characteristics of "old" bitumen, the asphalt mixtures created with this bitumen inside will also show more crack sensitive behaviour.

The older the asphalt mixture, the more cracks will be seen.

Fig. 3: Cracks in Old Asphalt Mixture

This natural effect is very important to consider when *recycled asphalt* will be used in combination with new asphalt, resulting in the so-called Partial Recycling Asphalt, or *PR-Asphalt*.
The old bitumen coming from PR-Asphalt with a higher Asphaltene/Maltene-ratio is only thoroughly mixable with new bitumen above a certain temperature, depending on the state of both sorts of bitumen. Under a certain temperature and certainly at common air temperatures outside, however, both sorts of bitumen will tend to segregate and so micro-cracks in the mixtures will occur. Also the adhesive function of the bitumen as a glue and its healing characteristics will diminish.

I.1.2. Mechanical Behaviour of Bitumen

The mechanical behaviour of asphalt mixtures is almost entirely determined by the behaviour of bitumen, which is *visco-elastic*. This means that the behaviour of bitumen is strongly dependent on temperature and on loading time.
High temperatures will decrease the viscosity, and subsequently the strength and stiffness of the material (Fig. 4) to a certain level.

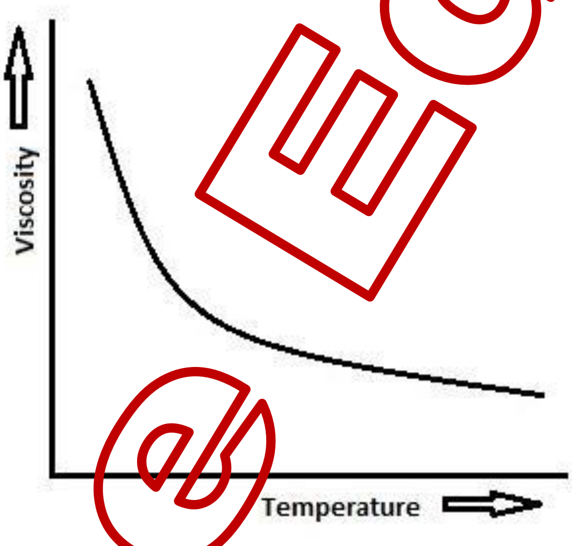


Fig. 4: Dependency of Bitumen on Temperature

Longer loading time will also affect the strength and stiffness of lower values (Fig. 5). When stress (σ) is applied and made constant, the strain (ε) will first jump up to a certain level due to the elastic part, and then will slowly grow to a certain level due to the viscous part. When "unloaded", the strain will jump downwards due to the elastic behaviour, and then slowly decrease to a certain level near zero due to the viscous behaviour.
When strain (ε) is brought to a certain level and kept constant as "load," the stress (σ) caused will first jump up to a certain level due to the elastic part and then slowly decrease to a certain level due to the viscous part. By "unloading,"

the stress will jump downwards, even reaching negative numbers, before slowly increasing to a certain level near zero.

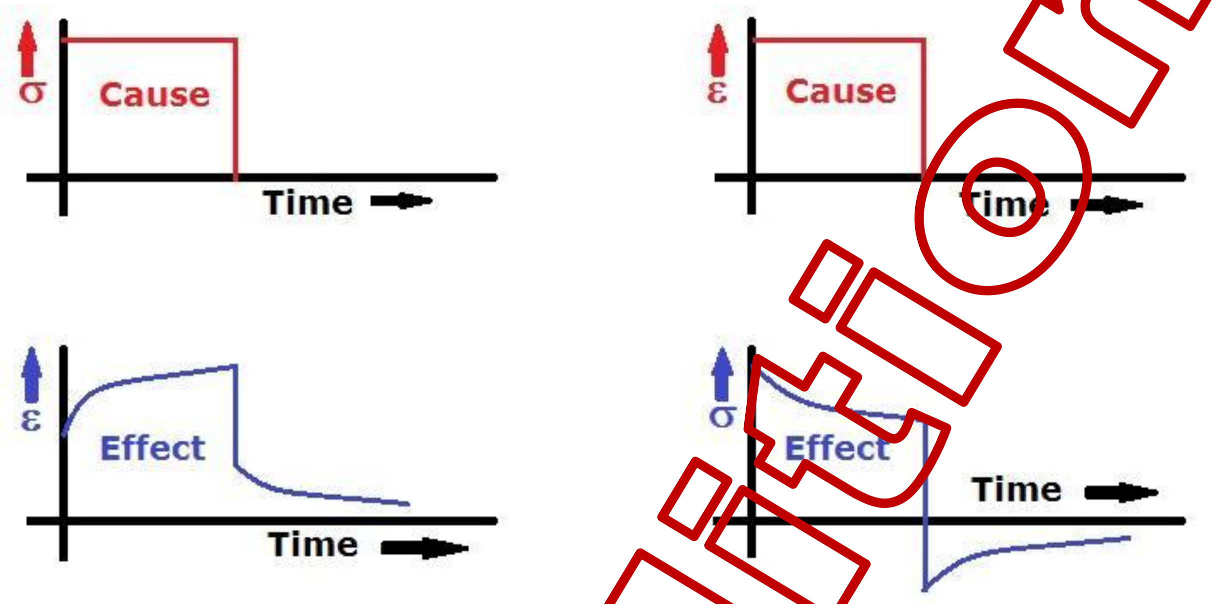


Fig. 5: Dependency of Bitumen on Loading Time (source: 35)

Due to this, it is very important to take the air temperature of the road's surroundings into account. So asphalt roads in the tropics must be designed with more strength than they are in places with colder climates.
This very crucial factor of temperature was not taken into account when outdated design methods like CBR (California Bearing Ratio) were used.

Also, in places where longer loading time is expected such as stop signs or stoplights, bus stops, parking lots, crossings, etc., this aspect must be taken into account at an early stage to minimise the development of damages.

I.2. Asphalt Mixtures

With the components:

*Bitumen: 70/100, 50/70, 40/60 etc.;
*Stone aggregate: on sieve 2 – 31.5 mm;
*Sand: on sieve 63 µm – 2 mm;
*Filler: < 63 µm, and
*Some additives that may be required

several sorts of asphalt mixtures can be developed (Fig. 6).

Fig. 6: Asphalt Mixtures

However, looking at these mixtures, there are actually 3 types of structures that can be distinguished, each with their own characteristics.

I.2.1. Structure

The structure of almost every asphalt mixture used nowadays can be divided into the following three (3) sorts, based on their skeleton (Fig. 7):

*Sand skeleton, *continuously graded*;
*Stone skeleton, *discontinuously graded* and
*Stone skeleton with mastic inside, *discontinuously graded*.

Fig. 7: Skeleton of Asphalt Mixtures

In asphalt mixtures with a sand skeleton as structure, the sand and other small particles form the skeleton by touching and supporting each other. This is only possible when the mixtures are *continuously graded*, which means that the gradation does not show a certain gap between the particles forming the skeleton. A typical sand skeleton mixture is Dense Asphalt Concrete (DAC) which has the following approximate specifications (Table 1):

Table 1: Specifications of Typical Dense Asphalt Concrete *(source: 11)*

Surface Layers										
Specification		DAC (Dense Asphalt Concrete).								
Grade		0/8			0/11			0/16		
on sieve (% m/m)		target	min.	max.	target	min.	max.	target	min.	max.
C 31.5										
C 22.4										
C 16									[illegible]	6.0
C 11.2						0.0	6.0		5.0	25.0
C 8			0.0	6.0		5.0	25.0			
C 5.6			10.0	30.0		[illegible]	[illegible]		30.0	55.0
2 mm		55.0	52.0	58.0	55.0	[illegible]	58.0	[illegible]	57.0	63.0
63 um		x	x-0.5	x+1.0	y	y-0.5	y+1.0	y	y-0.5	y+1.0
Bitumen										
Content (% m/m on	tc-2		6.6	7.0		6.4	6.8		6.2	6.6
100% min. aggr.)	tc-3		6.6	7.0		6.4	6.8		6.2	6.6
	tc-4					6.2	6.6		6.0	6.4
Penetration (0,1mm)	tc-2		*60/70*	100		*60/70*	100		*60/70*	100
	tc-3		*60/70*	100		*60/70*	100		*60/70*	100
	tc-4		40	60		40	60		40	60
Voids										
(% v/v)	tc-2			4.0			4.0			4.0
	tc-3			4.0			4.0			4.0
	tc-4			6.0			6.0			6.0
Marshall										
Stability Pm (N)	tc-2		6,500			6,500			6,500	
	tc-3		7,000			7,000			7,000	
	tc-4		7,500			7,500			7,500	
Flow Fm (mm)	tc-2		2.0	5.0		2.0	5.0		2.0	5.0
	tc-3		2.0	4.0		2.0	4.0		2.0	4.0
	tc-4		2.0	4.0		2.0	4.0		2.0	4.0
Quotient Qm (N/mm)	tc-2		2,000			2,000			2,000	
	tc-3		2,500			2,500			2,500	
	tc-4		3,000			3,000			3,000	
Filling grade										
(% v/v)	tc-2			87			87			87
	tc-3			83			83			83
	tc-4			80			80			80
	tc: traffic class									
m/m: mass/mass		*x = 100 - 8(filler's density/2700).*								
v/v: volume/volume		*y = 100 - 7(filler's density/2700).*								

In stone skeleton asphalt mixtures, the stone aggregates form the skeleton by touching each other and filling the spaces in between with air. These mixtures are designed with a certain gap in the gradation and known as *discontinuously graded* mixtures. The relatively high portion of voids enables better drainage of the asphalt surface and the mixtures produce much less noise hindrance. A typical sort of this kind of mixture is Porous Asphalt (PA) which, thanks to the stone skeleton, is less sensitive to high temperatures like in the tropics (see Table 2).

Table 2: Specifications of Typical Porous Asphalt *(source: 11)*

Surface Layers							
Specification		**PA (Porous Asphalt)**					
Grade		**0/11**			**0/16**		
on sieve (% m/m)		target	min.	max.	target	min.	max.
C 31.5							
C 22.4							
C 16						0.0	7.0
C 11.2			0.0	9.0		15.0	[illegible]
C 8			60.0	85.0		[illegible]	65.0
C 5.6			75.0	85.0		70.0	85.0
2 mm		85.0			85.0		
63 µm		95.5			95.5		
Bitumen							
Content (% m/m on	tc-2	4.5			4.5		
100% min. aggr.)	tc-3						
	tc-4						
Penetration (0,1mm)	tc-2		70	100		70	100
	tc-3						
	tc-4						
Voids							
(% v/v)	tc-2		[illegible]			20.0	
	tc-3						
	tc-4						
Marshall							
Stability Pm (N)	tc-2						
	tc-3						
	tc-4						
Flow Fm (mm)	tc-2						
	tc-3						
	tc-4						
Quotient Qm (N/mm)	tc-2						
	tc-3						
	tc-4						
Filling grade							
(% v/v)	tc-2						
	tc-3						
	tc-4						
	tc: traffic class						
m/m: mass/mass							
v/v: volume/volume							

In SMA, the skeleton is, like PA, formed by the stone aggregates. However, the spaces between the aggregates are filled with *mastic*, a mixture of bitumen, sand and filler. Like PA, these mixtures belong to the *discontinuously graded* mixtures. However, due to the presence of mastic, the portion of voids is relatively low. So in this kind of asphalt the glue function of the bitumen functions more effectively than in PA and, due to the stone skeleton structure, the mixture possesses a relatively high resistance to deformation (see Table 3).

Table 3: Specifications of Typical Stone Mastic Asphalt *(source: 11)*

Surface Layers																
Specification		SMA (Stone Mastic Asphalt).														
Grade		0/6			0/8						0/11					
					Type1			Type2			Type1			Type2		
on sieve (% m/m)		target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.
C 31.5																
C 22.4																
C 16																
C 11.2												0.0	8.0		[illegible]	8.0
C 8						0.0	8.0		0.0	8.0		[illegible]	[illegible]		[illegible]	55.0
C 5.6			0.0	8.0		40.0	60.0		45.0	65,0		[illegible]	70.0		60.0	75.0
2 mm		67.5	62.5	72.5	72.5	67.5	77.5	75.0	70.0	[illegible]	75.0	70.0	80.0	[illegible]	72.5	82.5
63 um		88.5	86.5	90.5	90.0	88.0	92.0	91.0	89.0	[illegible]	[illegible]	89.0	93.0	[illegible]	90.0	94.0
Bitumen																
Content (% m/m on	tc-2	8.0			7.4			7.4			7.0			7.0		
100% min. aggr.)	tc-3															
	tc-4															
Penetration (0,1mm)	tc-2		70	100		70	100		70	100		70	100		70	100
	tc-3															
	tc-4															
Voids																
(% v/v)	tc-2	4.0			4.0			5.0			4.0			5.0		
	tc-3															
	tc-4															
Marshall																
Stability Pm (N)	tc-2															
	tc-3															
	tc-4															
Flow Fm (mm)	tc-2															
	tc-3															
	tc-4															
Quotient Qm (N/mm)	tc-2															
	tc-3															
	tc-4															
Filling grade																
(% v/v)	tc-2															
	tc-3															
	tc-4															
	tc: traffic class															
m/m: mass/mass																
v/v: volume/volume																

For tropical areas, asphalt mixtures based on stone skeletons are more suitable because the structure of the stones which form the skeleton are less dependent on temperature than mixtures where the structure is based on a sand skeleton. DAC is more sensitive to hot tropical conditions and will show more and bigger deformations than SMA and PA.
Therefore, DAC is actually less suitable for the tropics.

PA is, however, more sensitive to *ravelling*, a phenomenon also known as the degradation of the mixtures caused by ongoing loss of stones (Fig. 8). This kind of mixture possesses a relatively high proportion of air holes and the bitumen does not work as well as glue. Especially in places with friction and shear forces (wheel breaking, curves, crossings, stop places etc.), ravelling will occur very rapidly and when it happens, it will create potholes after just weeks or months.

For city roads, where traffic causes more and more shear forces on asphalt than on highways, this kind of asphalt is actually not preferable. Due to the relatively high noise reduction capacity, however, some cities still use this kind of asphalt mixture, knowing that the costs for repair and construction are high. These decisions are usually based on local politics.

Fig. 8: Ravelling, an Ongoing Loss of Stones

SMA is actually between DAC and PA, and was invented by Germany some decades ago. Its structure is made up of a stone skeleton with *mastic* (a mix of bitumen, sand and filler) in between. Due to the stone skeleton, SMA possesses a relatively high resistance against deformation and is also less dependent on temperature. Therefore, it is very suitable for tropical areas.

The problem with this sort of mixture is the present lack of experience, based on which optimization of the mixture is hardly done. Another disadvantage is that bitumen drops off during transport and application works, resulting in less homogeneity of the mixture and causing damage that can be seen at a very early stage.
However, when using a proper composition that is properly mixed and applied, SMA is very durable and very suitable for tropical areas.

I.2.2. Mechanical Behaviour of Asphalt Mixtures

As already mentioned, the mechanical behaviour of asphalt mixtures is almost entirely determined by the behaviour of the bitumen used, which is visco-elastic. This means that the behaviour of asphalt mixtures is also very dependent on the temperature and loading time.

High temperatures will decrease the strength and stiffness of the mixture (Fig. 9) and greater loading time will lower the strength and stiffness (Fig. 10.a). If a certain stress (σ) is brought to a certain level and kept constant, the strain (ε) will increase due to the elastic part and then slowly increase to a certain level due to the viscous part. When strain (ε) is brought to a certain level and kept constant as "load", the stress (σ) caused will jump up (elastic part), and then slowly decrease to a certain level (viscous part).

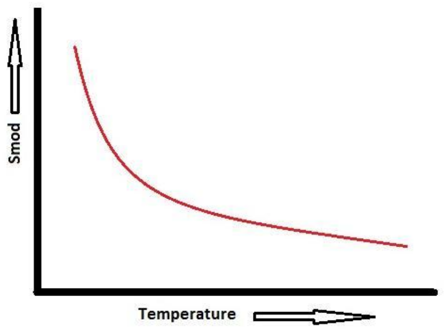


Fig. 9: Dependency of Asphalt Mixtures on Temperature

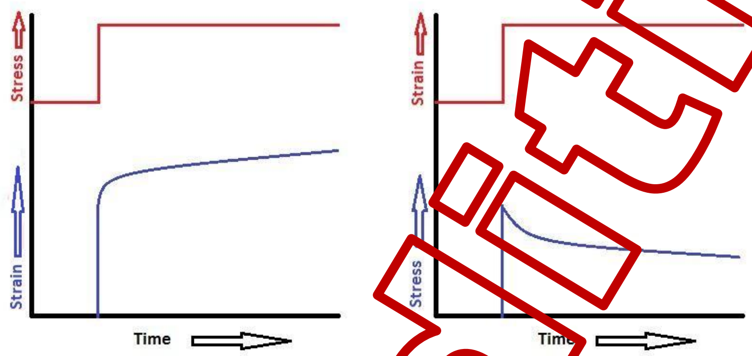


Fig. 10.a: Dependency of Asphalt Mixtures on Loading Time

The typical effects of both (temperature and loading time) on the permanent strain of asphalt can be seen in Fig. 10.b.

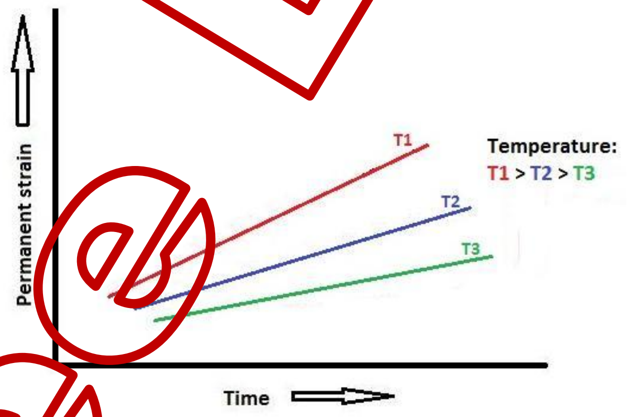


Fig. 10.b: Typical Effects of Temperature and Loading Time on Asphalt Permanent Strain

When soft bitumen as 70/100 is used, it is expected that heavy traffic will easily cause damages such as deformation, especially in tropical areas. Therefore, harder bitumen as 40/60 or bitumen with modification is preferable.

When using bitumen with modification, one has to take into account the changes in the characteristics of the bitumen. Modification by adding polymers usually increases the stiffness, but it also makes the mixture more sensitive to cracks and ravelling.

I.3. Asphalt Mixtures in Road Construction

Having learned that various sorts of asphalt mixtures can be created with various kinds of structures and compositions, which consequently result in various characteristics, several functions can be distinguished and allocated.

I.3.1. Functions of Asphalt Mixtures in Road Construction

The main function of the asphalt and the other layers (base and subbase) within road construction is to spread the 'load' gradually and thereby decrease the stresses and strains generated on the subgrade.
Fig.11 shows the typical load distribution pattern for road construction and, therefore, how the stiffness modulus (Smod) of each layer from the subgrade upwards needs to increase gradually, with the highest at the top.

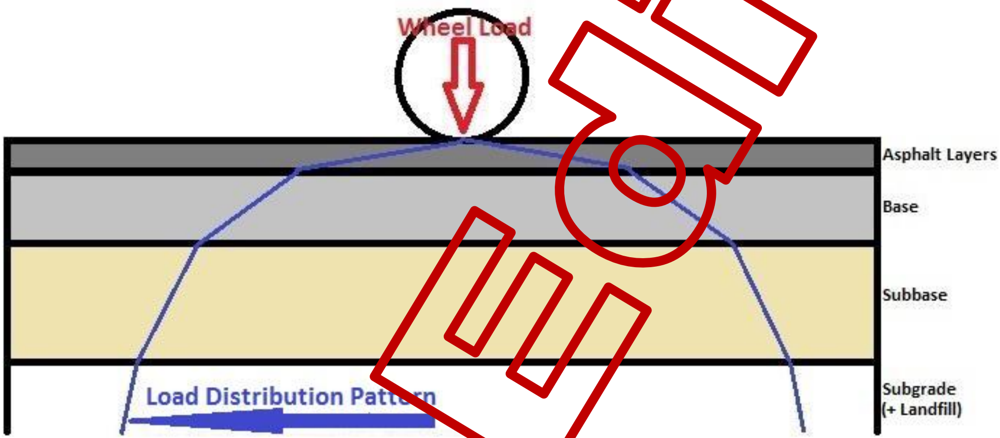


Fig. 11: Typical Load Distribution in Road Construction

To achieve this kind of load distribution pattern and to assure an optimal interaction, the layers should have the following stiffness modulus (Smod):

- *The asphalt layer: 2,000 - 10,000 (to 15,000 MPa. when modified);
- *The base layer: 400 - 1,000 MPa.;
- *The subbase layer: 80 - 200 MPa.;
- *The subgrade and landfill: usually up to 100 MPa.

The term stiffness modulus (Smod) is used instead of *modulus of elasticity* (Emod) since the behaviour of bitumen and asphalt mixtures is not *elastic* but *visco-elastic*, as already explained.

In road construction, the upper course of the pavement consists of asphalt concrete. Until some decades ago, only one sort of asphalt mixture with relatively high thickness had been used in this course.
However, looking at the paths of the vertical and radial stresses caused by traffic load within the road construction (Fig. 12.a), this upper course can actually be

optimised regarding the load distribution and divided into several layers with distinguishable functions.

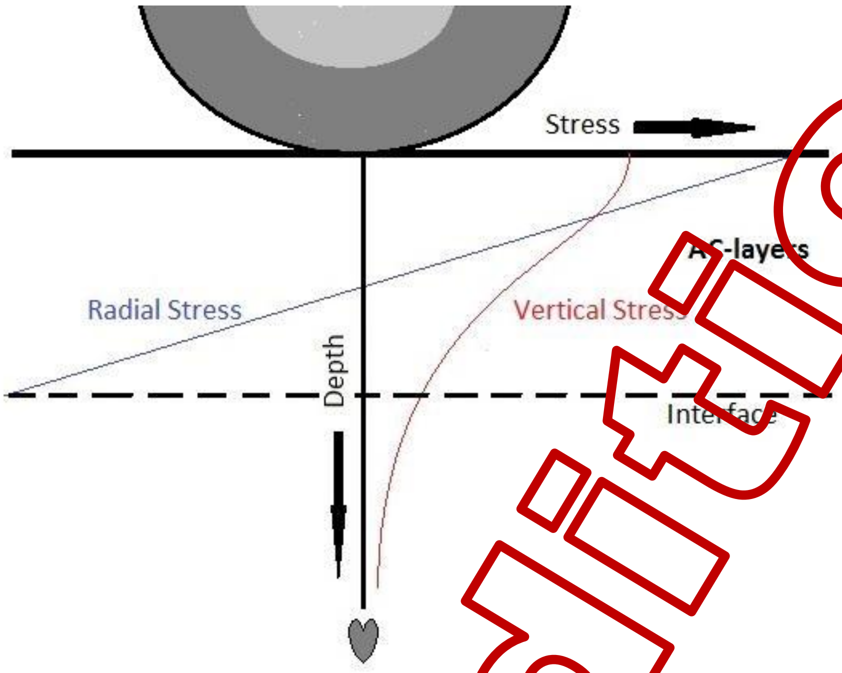


Fig. 12.a: Vertical and Radial Stresses in Asphalt Road Construction (source: 7+8)

The upper part of the upper course has to deal with relatively high radial stress (shear forces) and vertical stresses. However, since the path of the radial stress decreases more rapidly in a downward direction than the vertical one (Fig.12.a), the lower part of this upper course can be assigned another function.
So mechanically but also economically, it is better for the upper course to be divided into 3 parts with the following functions:

*The upper part with function A:
-Providing a comfortable and safe driving surface;
-Absorbing and spreading relatively high radial and vertical stresses.

*Lowest part with function B:
-Providing physical support to the asphalt layers above;
-Absorbing and spreading relatively low radial and vertical stresses.

*Middle part with function A↔B:
-Providing physical support to the asphalt layer above;
-Attaching the mixture above and under;
-Absorbing and spreading the local radial and vertical stresses.

For asphalt mixtures, 3 sorts of asphalt layers with different compositions and characteristics are necessary. These layers (Fig. 12.b) can be distinguished as the:

*Surface layer (AC-Surf), containing asphalt mixtures with function A ;
*Binder layer (AC-Bind), containing asphalt mixtures with function A↔B;
*Base layer (AC-Base), containing asphalt mixtures with function B.

Since these layers purely consist of asphalt concrete, the upper course will now be called the AC-layers.

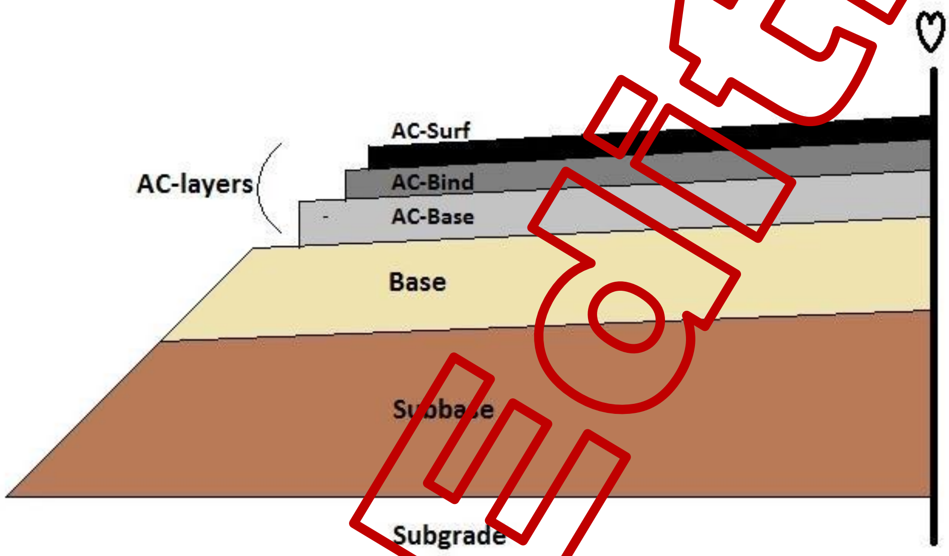


Fig. 12.b: Cross-Section of a Road Construction

Considering the functions and the compositions, it is evident that the price of producing the surface layer (AC-Surf) will be the highest, followed by the binder layer (AC-Bind). The AC-Base can be composed and produced with cheaper materials, e.g. mixed with *Partly Recycled Asphalt* (PR-Asphalt). A maximum of 50% of PR-Asphalt is recommended to preserve enough healing capacity. This means that the asphalt layers can be cheaper and more efficient.

In order to optimise the interaction between the asphalt layers consisting of different mixtures, *downsizing the gradation* upwards with a maximum factor of 2 is necessary, see II.1.1.
In the case that more thickness is required due to heavy traffic, two AC-Base layers can be applied on each other. The second AC-Base layer can be directly applied after the compaction of the first. Warm on warm will also improve the attachment.

I.3.2. Examples of Asphalt Mixtures

As already mentioned, various kinds of asphalt mixtures can be made. Almost every country has its own type of mixture. Distinguished examples of some asphalt mixtures are given below, with their variations in gradation and bitumen percentages:

+For the AC-Surf layers, function A.:

*Dense Asphalt Concrete (DAC), see Table 1, *continuously graded*;
*Stone Mastic Asphalt (SMA), see Table 3, *discontinuously graded*;
*Porous Asphalt (PA), see Table 2, *discontinuously graded*;

+For the AC-Bind and AC-Base layers, function A↔B. and B., (Table 4):

*Gravel Asphalt Concrete (GAC), function B., *continuously graded*;
*Stone Asphalt Concrete (SAC), function A↔B., *continuously graded*;
*Open Asphalt Concrete (OAC), function A↔B., *continuously graded*,

Table 4: Asphalt Mixtures for the AC-Bind & AC-Base Layers *(source: 11)*

AC-Bind & AC-Base Layers Specification		Gravel Asphalt Concrete (GAC)									Stone Asphalt Concrete (SAC)						Open Asphalt Concrete (OAC)											
Grade		0/16						0/32			0/16			0/22			0/11			0/16						0/22		
		Type1			Type2															Type2			Type3					
on sieve (% m/m)		target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.	target	min.	max.
C 31.5									[illegible]	[illegible]																		
C 22.4															0.0	6.0											0.0	4.0
C 16			0.0	6.0		0.0	[illegible]					0.0	[illegible]								0.0	4,0		0.0	4.0			
C 11.2									10.0	[illegible]					15.0	40.0		0.0	4.0					10.0	20.0		30.0	40.0
C 8			15.0	40.0		15.0	[illegible]					25.0	45.0								35.0	50.0						
C 5.6																		45.0	60.0					35,0	50,0			
2 mm		50.0	47.0	53.0	57.0	54.0	60.0	[illegible]	54.0	60.0	57.0	[illegible]	60.0	57.0	54.0	60.0	72.0	69.0	75.0	72,0	69,0	75,0	67.0	64.0	70.0	72.0	69.0	75.0
63 um		93.0	92.0	94.0	93.0	92.0	94.0	93.0	[illegible]	94.0	93.0	[illegible]	94.0	93.0	92.0	94.0	95.0	94.0	96.0	95.0	94.0	96.0	94.0	93.0	95.0	95.0	94.0	96.0
Bitumen																												
Content (% m/m on	tc-2		4.5	5.5		4.5	5.5		4.5	5.5		4.5	5.5		4.5	5.5	5.0	4.6	5.4	5.0	4.6	5.4	5.4	5.0	5.8	4.6	4.2	5.0
100% min. aggr.)	tc-3		4.0	5.0		4.0	5.0		4.0	5.0		4.0	5.0		4.0	5.0	5.0	4.6	5.4	5.0	4.6	5.4	5.4	5.0	5.8	4.6	4.2	5.0
	tc-4											4.0	5.0		4.0	5.0	5.0	4.6	5.4	4.9	4.4	5.4	5.3	4.8	5.8	4.5	4.0	5.0
	tc-5											4.0	5.0		4.0	5.0	5.0	4.6	5.4	4.9	4.4	5.4	5.3	4.8	5.8	4.5	4.0	5.0
Penetration (0,1mm)	tc-2		45/80	100		45/80	100		45/80	100		45	100		45	100		45	100		45	100		45	100		45	100
	tc-3		45	60		45	60		45	60		45	60		45	60		45	100		45	100		45	100		45	100
	tc-4											45	60		45	60		45	60		45	60		45	60		45	60
	tc-5											45	60		45	60		45	60		45	60		45	60		45	60
Voids																												
(% v/v)	tc-2			7.0			7.0			7.0			7.0			7.0			10.0			10.0			10.0			10.0
	tc-3			[illegible]			[illegible]			7.0			7.0			7.0			10.0			10.0			10.0			10.0
	tc-4												7.0			7.0			10.0			10.0			10.0			10.0
	tc-5												7.0			7.0			10.0			10.0			10.0			10.0
Marshall																												
Stability Pm (N)	tc-2		4,500			[illegible]			4,500			4,500			4,500			5,500			5,500			5,500			5,500	
	tc-3		5,000			5,000			5,000			5,000			5,000			6,500			6,500			6,500			6,500	
	tc-4											6,000			6,000			7,000			7,000			7,000			7,000	
	tc-5											7,000			7,000			7,500			7,500			7,500			7,500	
Flow Fm (mm)	tc-2		1.5	3.0		1.5	[illegible]		1.5	3.0		1.5	3.0		1.5	3.0		2.0	4.0		2.0	4.0		2.0	4.0		2.0	4.0
	tc-3		1.5	[illegible]		1.5	3.0		1.5	3.0		1.5	3.0		1.5	3.0		2.0	4.0		2.0	4.0		2.0	4.0		2.0	4.0
	tc-4											1.5	3.0		1.5	3.0		2.0	4.0		2.0	4.0		2.0	4.0		2.0	4.0
	tc-5											1.5	3.0		1.5	3.0		2.0	4.0		2.0	4.0		2.0	4.0		2.0	4.0
Quotient Qm (N/mm)	tc-2		2,000			2,000			2,000			2,000			2,000			2,000			2,000			2,000			2,000	
	tc-3		[illegible]			2,500			2,500			2,500			2,500			2,500			2,500			2,500			2,500	
	tc-4											3,000			3,000			3,000			3,000			3,000			3,000	
	tc-5											3,500			3,500			3,000			3,000			3,000			3,000	
Filling grade																												
(% v/v)	tc-2		[illegible]	75		50	75		50	75		50	75		50	75			77			77			77			77
	tc-3		50	72		50	72		50	72		50	72		50	72			75			75			75			75
	tc-4											50	68		50	68			72			72			72			72
	tc-5											50	65		50	65			70			70			70			70

tc: traffic class
m/m: mass/mass
v/v: volume/volume

In Table 5, one can also see several other international asphalt mixtures.

Table 5: Other International Asphalt Mixtures (source: 7)

Country			USA			Netherlands					French	German[illegible]		Fr[illegible]ch
Mix Type			Asphaltic Concrete, California	Lean Sand Asphalt	Dense Bitumen Macadam-1	Gravel Sand Asphalt	Lean Bitumen Macadam	Dense Asphaltic Concrete	Dense Bitumen Macadam-2	Rolled Asphalt Base	Gravel Bitumen	Asph[illegible] Ba[illegible] Cours[illegible]	Ri[illegible] Sand Sheet	Lean Sand As[illegible]lt
Mix Composition (as composed)														
Stone		% m/m	49.0	-	65.0	49.9	97.0	55.0	65.0	66.0	69.5	[illegible]	-	-
Sand		% m/m	47.0	83.0	29.5	42.2	-	35.0	29.5	34.0	22.0	24.5	[illegible]	84.0
Filler		% m/m	4.0	17.0	5.5	7.9	3.0	10.0	5.5	-	8.5	6.5	[illegible]	16.0
Bitumen	content	ph a	6.4	5.0	5.0	5.4	3.0	5.0	5.0	6.4	[illegible]	[illegible]	[illegible]	4.0
	grade		40/50	80/100	80/100	45/60	80/100	40/50	40/60	40/60	[illegible]	R80	[illegible]	20/30
Analysis of Aggregate														
ASTM Sieve	1"		-	-	-	100.0	-	-	-	-	[illegible]	[illegible]	-	-
	3/4"		100.0	-	100.0	94.0	-	-	100.0	[illegible]	[illegible]	79.5	-	-
	1/2"		97.0	-	89.0	83.0	100.0	100.0	89.6	[illegible]	[illegible]	64.4	-	-
	3/8"		87.0	-	71.2	73.0	70.7	88.0	[illegible]	[illegible]	64.0	[illegible]	-	-
	1/4"		74.0	-	58.8	62.0	31.8	76.0	58.7	[illegible]	[illegible]	42.5	-	-
	no. 4		64.0	-	50.7	57.0	13.5	67.0	51.3	[illegible]	44.0	40.3	-	-
	6		55.0	-	48.3	55.0	5.7	57.0	43.2	[illegible]	37.0	[illegible]	-	100.0
	10		45.0	100.0	33.9	54.0	5.2	45.0	[illegible]	[illegible]	30.0	30.7	100.0	98.0
	20		34.0	90.7	23.1	52.0	4.7	30.0	[illegible]	[illegible]	[illegible]	24.5	93.6	90.0
	30		29.0	72.6	18.7	50.0	4.6	26.0	18.4	21.0	17.0	22.5	84.5	60.0
	40		25.0	60.8	16.1	46.0	4.5	22.0	15.9	[illegible]	[illegible]	18.0	71.7	48.0
	50		21.0	47.8	12.2	38.0	4.4	18.0	[illegible]	9.0	[illegible]	12.3	49.1	40.0
	80		16.0	34.3	9.1	25.0	4.2	[illegible]	8.7	4.5	[illegible]	7.9	24.5	25.0
	100		15.0	30.1	8.2	21.0	4.2	13.0	[illegible]	4.0	[illegible]	7.4	21.9	20.0
	200		9.0	16.5	5.7	8.0	4.1	[illegible]	5.5	[illegible]	8.0	6.3	15.1	16,0
Mix Composition (as [illegible]ed)														
Stone		% m/m	55.0	-	66.1	46.0	[illegible]	[illegible]	65.9	[illegible]	70.0	69.3	-	2.0
Sand		% m/m	36.0	83.5	28.2	46.0	[illegible]	35.5	28.6	[illegible]	22.0	24.4	84.9	82.0
Filler		% m/m	9.0	16.5	5.7	8.0	[illegible]	[illegible]	[illegible]	[illegible]	8.0	6.3	15.1	16.0
Bitumen		ph a	6.2	5.1	4.7	5.6	2.9	4.9	4.7	6.3	4.0	3.9	9.8	4.0
Properties of Rec[illegible]ered Bitumen														
Softening Point			61	52	52	64	[illegible]	59	60.5	62.5	60	52	53.5	69
R & B		˚C	-	-	-	-	[illegible]	[illegible]	-	-	-	-	-	-
Penetration at 25˚C			38	61	59	26	68	36	[illegible]	34	27	58	60	22
Penetration Index			+0.6	-0.2	-0.3	+0.2	-0.2	+0.1	[illegible]	+0.6	0	-0.3	+0.1	+1.2

Due to the relatively high sensitivity to deformation, it is strongly recommended NOT to use Open Asphalt Concrete (OAC) as an AC-Bind layer if intensive heavy traffic is expected. In the past decades, however, this was done very often in the Netherlands. During lab tests as well as in practice, OAC appeared to continuously show deformation for a very long time, even years after application works.

A substitution can be made by using Stone Asphalt Concrete (SAC), which has much better resistance against deformation and appears to be able to properly connect the A. and B. function.

I.4. Effects of Vibrations, High Stiffness and Shear on Asphalt Mixtures

Having learned about the several sorts of asphalt mixtures and their characteristics, it is also necessary to consider the effects of vibrations, relatively high stiffness and shear on asphalt mixtures.

It sounds wonderful in theory, but in practice it's still a bit lacking. In the next section, some of these effects that have been observed in real-world situations will be mentioned, discussed and explained in the follow-up. For this, asphalt technology will be applied.

I.4.1. Effects of Vibrations

Depending on the amplitudes and frequencies, vibrations may cause cracks in any material. For asphalt mixtures with a stone skeleton for structure, the effects will be greater than on mixtures based on sand skeletons, where the total contact surface of the bitumen with the aggregates is much bigger.
As already mentioned, stone skeleton mixtures are based on a discontinue gradation of the aggregates and particles. Consequently, the role of the bitumen in the interaction, with the particles forming the skeleton, is not optimal (Fig. 13). This is especially needed for resistance against vibration, meaning that the mixtures are more sensitive to cracks since tensile stresses can hardly be absorbed.

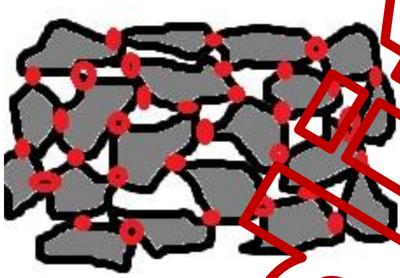


Fig. 13: Fixation Only at Contact Points (**o**)

For certain places where a relatively high amount of vibration is expected, it is recommended not to use asphalt mixtures that are based on stone skeleton structures due to their relatively higher sensitivity to (small) cracks which will grow into bigger ones.
Therefore, the use of PA and certain types of SMA are not recommended for places like bridges where the vibrations caused by traffic will last for an extra period, depending on bridge characteristics like span-length, thickness etc.

Also, during application it is recommended to avoid vibratory compaction, as this will prevent the generation of small cracks within the mixtures.

I.4.2. Effects of High Stiffness (C-Fix, PMB, PR and Combi-Surf)

It is a law of mechanics that material with high stiffness will attract more stresses from its surroundings than material with low stiffness, so highly stiff materials may absorb more stress than is calculated and planned. In practice, cracks in an earlier stadium have been monitored in several situations like this. Some items regarding high stiffness are discussed further on.
In all cases, one of the requirements for a successful application of mixtures with high stiffness is to make sure that the subgrade, subbase and base materials all have reasonable resistance to deformation, preventing stress concentration.

C-Fix

Asphalt mixtures composed using a 'hard binder' called *C-Fix* (Carbon Fixation) for bitumen have been tried for several years already. This hard binder/bitumen is the ultimate hard residue of crude oil and has penetration values of around 6 – 9. Due to these very low values, the mixtures possess a very high stiffness and are very suitable for heavy traffic. In long periods of low temperatures (like in Europe), however, the asphalt mixtures become vulnerable to cracks and ravelling, as observed after just 1 year (Fig.14.a).

Fig. 14.a: Ravelling on C-Fix

In the tropics, on the contrary, C-Fix asphalt mixtures can be recommended for application, especially for roads where heavy traffic is very intensive and at stopping points, parking lots etc.

PMB (Polymer Modified Bitumen)

The modification of the bitumen with some sorts of polymer will also push the stiffness up to relatively high levels. The most used modifications of bitumen in road constructions are SBS (*Styrene Butadiene Styrene*) and EVA (*Ethylene Vinyl Acetate*). However, in climate areas with low temperatures, cracks have been seen at very early stages.

PR-Asphalt

The stiffness of the bitumen and asphalt mixture can also be elevated by mixing it with *Partial Recycled Asphalt*, a type of asphalt where the bitumen has been oxidised and possesses a low penetration value of around 25. Due to the increase in the Asphaltene/Maltene-Ratio of the old bitumen, segregation of the new bitumen will occur, resulting in ravelling, cracks and potholes.

Combi-Surf

Efforts have also been made to push up the stiffness of an asphalt mixture by using *Combi-Surf* (PA injected with cement slurry). Cracks after just a few years have been observed (Fig. 14.b).

Fig. 14.b: Cracks in *Combi-Surf* (PA injected with cement slurry)

It is evident that asphalt mixtures have been sought which have relatively high stiffness, especially for roads in the tropics. However, the effects of ravelling and crack sensitiveness must be considered when choosing the asphalt types within the asphalt layers. Referring to the load distribution pattern in Fig. 11 and to the functions (I.3.1.), the surface layer, or AC-Surf, must possess the highest stiffness and the AC-base the lowest. Next to *downsizing the gradation* (I.1.1.), however, the difference between the stiffness has also to be limited in order to ensure the optimal cooperation and interactions between the asphalt layers. Factor 2 must be considered as maximum. So, when the AC-Base has a Smod of 3,000 MPa, the AC-Bind should consequently possess a Smod between 3,000 and 6,000 MPa and the AC-Surf should have a maximum of 12,000 MPa.

I.4.3. Effects of Shear

The effects of shear on asphalt constructions are usually seen on places where ravelling occurs. Due to the shear forces applied during wheel braking and turning, the stones on the surface are experiencing sideways force. Depending on the size of the aggregate gradation used on the surface layer (AC-Surface), these forces will generate minor or severe damage.
This kind of damage is mostly seen on roads within the city area. Due to the much higher driving speed, the highways experience this phenomenon on a much smaller scale.

In theory, the bigger the gradation is used, the rougher the surface will be. On a rough surface, shear can easily transfer its forces to the surface aggregate unevenly (Fig. 15), creating concentration spots. The stones on these spots will have to absorb the forces almost individually since the surface is rough, meaning that it is not evenly filled in the horizontal direction.
This effect will become stronger when discontinuously graded mixtures are used on the surface layer. Shear will grab the bigger stand-alone stones and pull them loose from the mixture. When the skeleton structure is damaged, potholes will rapidly occur.

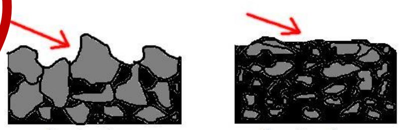


Fig. 15: Shear Forces Applied on Surface Stone Aggregate

To minimise this effect, it is recommended NOT to use a gradation bigger than 11 mm for city area. The most ideal gradation size is around 5-8 mm. Therefore, the application of PA and of some SMAs within the city area must be considered very carefully.
For highways, a maximum gradation of 16 mm is recommended.

II. <u>Asphalt Techno-Road Construction Design</u>

II.1. Theoretical Approach

The theoretical approach to road construction is given in this section, with a special focus on the construction structure, the gradation of the separate layers, the stresses and strains that occur and the application of *Mohr's Circle* in asphalt construction.

II.1.1. Construction Structure and Gradation of the Layers

Road constructions usually consist of several layers, where each layer has its own function. This is done to optimise the load distribution from the surface to the subgrade. Based on the theories from the mechanics and by taking the material characteristics into consideration, the road can be constructed as economically as possible.

From the road surface, the following layers can be distinguished (Fig. 16):

1. The Asphalt Concrete (AC) layers, consisting of:
    * AC-Surf: an asphalt concrete surface layer (also known as top layer or wearing course);
    * AC-Bind: an asphalt concrete intermediate layer that physically and functionally connects the surface and the under layer;
    * AC-Base: an asphalt concrete under layer, which might consist of 1 or 2 layer(s), depending on the traffic, the materials used and the subgrade;
2. The (unbound/bound) base layer;
3. The unbound subbase layer: *(in some situations, this layer is not necessary)*
4. The subgrade or natural soil.

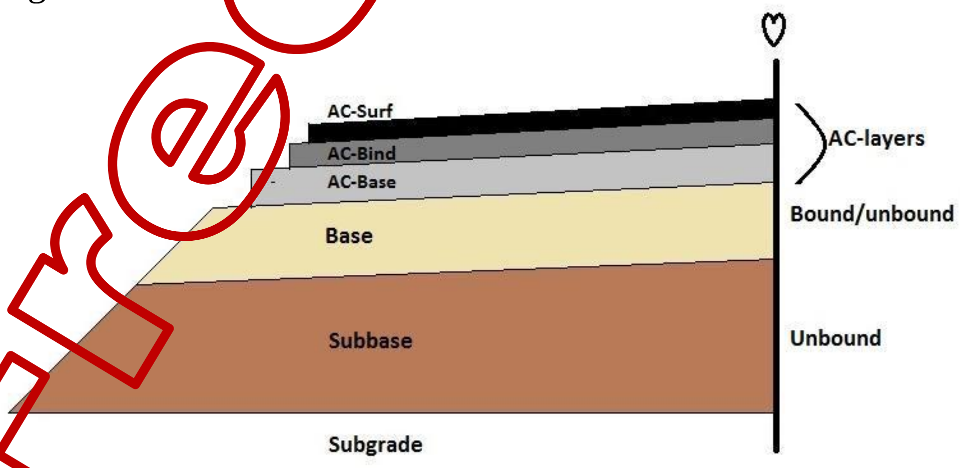


Fig. 16: Typical Cross-Section of a Road Construction

From the base layer up to the AC-Surf layer within the AC-layer, the gradation of the layers has to be *downsized*. This is necessary to optimise the interaction between all of these layers. Usually, it should be downsized from 40 mm at the base to 5 - 8 mm at the AC-Surf layer. It is recommended to use the factor 2 as the maximum ratio between the layers' gradation. So, when it is 40 mm at the base, the AC-Base should be at 20-25 mm, the AC-Bind at 10-15 mm and the AC-Surf at 5-8 mm.

Along with providing more comfort in driving, asphalt pavement is usually chosen due to the relatively lower initial construction cost and also a lower cost-lifetime ratio during a period of time when compared with, for example, concrete pavement.

Mechanically, the functions of the AC-layers are:

*To provide a comfortable and safe driving surface;

*To spread and transfer the axle-loads downwards as much as possible;

*To decrease the stresses and strains on the layers, especially on the subgrade, and

*To minimise the effects of deformation in the subgrade.

It is the responsibility of the road engineer in charge to make sure that the stresses and strains transferred are low and small enough, so as not to cause relevant deformation or damage to the subgrade.

The base layer has the function of physically supporting the AC-layers and also gradually decreasing the stresses and strains applied by axle-loads by transferring them to the subbase.

Unbound materials such as fine gravel, stones etc. are mostly used; however, when more bearing capacity is necessary partially bound materials can be applied. Finely graded materials from demolished brick or concrete walls have also been used and, when necessary, cement can be added.

Referring to the load distribution pattern in Fig. 11, the stiffness modulus of this base layer should be around 400 - 1,000 MPa.

The subbase actually forms the basis on which the road is physically constructed. It passes the "load" (which is already lowered by the layers above it) to the subgrade. However, in some places where the subgrade has enough bearing capacity (a Smod bigger than 100 MPa), due to sand, gravel, rocks etc., this layer is not necessary. The base layer can then be laid down directly on the subgrade. This can also be the case for a 'light' asphalt construction, used for pedestrian or bicycle paths.

The subbase layer usually consists of sand, finely graded and crushed stones, gravel, etc. It has to be unbound, enabling easier drainage and preventing the accumulation of water around the road construction. Referring to the load distribution in Fig.11, the stiffness modulus of this layer should be around 80 - 200 MPa. Although sand is usually used since it is cheap and available almost anywhere, other granulates between 63 µm – 2 mm on sieve can also be used. The bearing capacity expressed in the stiffness modulus of around 100 MPa or higher is recommended.

The subgrade is the natural ground or soil on which the whole road construction is laid down. The characteristics of this layer usually determine the alignment of the road in case replacement of the “soft” soil is not economically possible. If the stiffness modulus is less than 50 MPa., replacing it with a sand layer of about 50 cm thickness is recommended.

Caution must be taken when clay or pet soil (remnants of vegetation) is found in the subgrade. This kind of soil possesses a very low bearing capacity and will show deformation for a very long period; some kinds will even show it over a period of more than 30 years. When clay or pet soil is present in the surface/upper region of the subgrade and has a relative thickness of 50 cm or more, replacement with a sand layer that has a minimum of 50 cm is necessary.

II.1.2. Stresses and Strains and Mohr’s Circle

When a wheel applies its load to the asphalt construction, various situations can be considered regarding the stresses and strains that occur (Fig. 17). When rolling, certain friction forces will also occur on the surface, causing shear stresses within the construction.

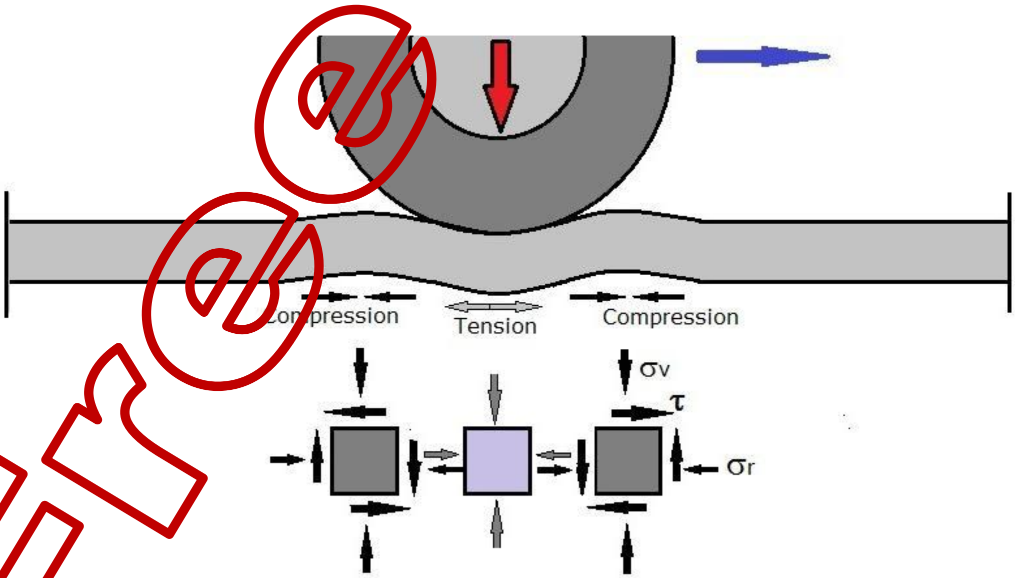


Fig. 17: *In Situ* Stresses Under a Rolling Wheel *(source: 7)*

Depending on the axle load, the contact surface, the tire pressure, the layers' thicknesses and the characteristics of the materials (especially the E-mod and the Poisson ratio ν), the stresses and strains that will occur right under the wheel can be calculated using the *theory of elasticity*. The local strains can then be derived from the stresses according to the well-known *Law of Hooke*:

$$\varepsilon x = 1/E\,[\sigma x - \nu(\sigma y + \sigma z)]$$

εx = strain in x-direction

σx, σy, σz = stresses in the 3 orthogonal directions

E = Elasticity/Young's modulus

ν = Poisson ratio.

(source: 7+8)

The variations of the vertical and radial stresses from under the wheel into the depth of the construction is given in Fig. 18.

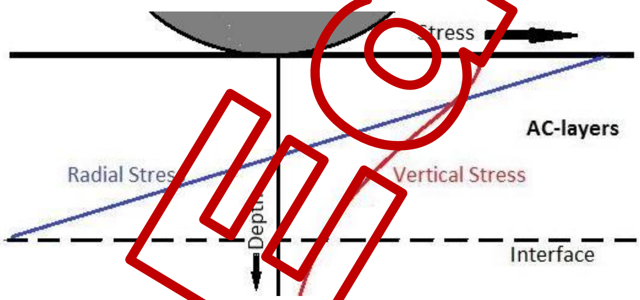


Fig. 18: Vertical and Radial Stresses in Asphalt Road Construction (source: 7+8)

The differences of the downward paths for the vertical (σv) and the radial stress (σr) are remarkable. The radial stresses decrease much faster than the vertical ones.
These stresses (σv and σr) can now be applied using *Mohr's circle* to determine the shear stresses (τ) and the *sliding line*, the tangent of both circles (Fig. 19).

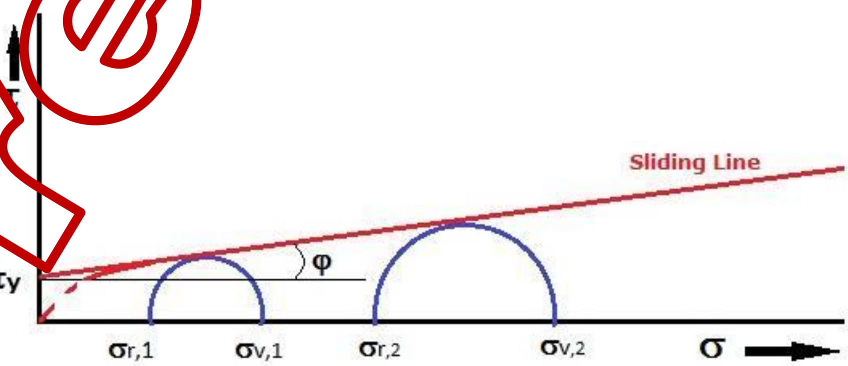


Fig. 19: Mohr's Circle of Asphalt Concrete (source: 7+8)

This line denotes the resistance of the material against sliding. At the point within the construction when the vertical stress (σ_v) and the radial stress (σ_r) create a circle that crosses this line, sliding will occur.
When the radial stress downwards decreases more quickly than the vertical stress (as seen in Fig. 18), sliding will occur.
In asphalt concrete, a *yield value* of shear stress (τ_y) is present, denoting an *initial resistance* against sliding. As seen in Fig. 19, this resistance increases along the sliding line, as determined by tangent **φ.**
The sliding line can be described by the following formula:

$$\tau = \tau_y + \sigma \cdot \text{tg}\ \varphi$$ (source: 7+8)

When the combination of σ_v en σ_r creates a shear stress (τ_y) that is bigger than ($\tau_y + \sigma \cdot \text{tg}\ \varphi$) at any point in the construction, then sliding will occur.
In asphalt concrete, the angle φ appears to be 25° or greater. At 25°, the initial resistance (τ_y) is about 0.1 MPa. If the deformation speed is very low (= longer loading time), τ_y is also very low, as seen in Fig. 19 with a dash-dot-line.

As seen in Fig. 18, from the surface to about 100 mm in the depth of the region, the radial stresses decrease much faster than the vertical ones.
In this region, there is a big risk of sliding. So attention must be paid when choosing the sort of asphalt mixture to be applied in this region. Asphalt mixtures like Open Asphalt Concrete (OAC) and Partial Recycled Asphalt (PR-Asphalt) are not recommended to be used as an intermediate/AC-Bind layer. OAC, as already mentioned, is very sensitive to deformation for a very long period of time and PR-Asphalt is very sensitive to the generation of cracks due to the presence of old/aged bitumen with a relatively high A/M-ratio.
PR Asphalt is also not recommended to be used as an AC-Surface layer. Based on the theoretical approach already mentioned and on experience (done in the Netherlands), cracks and ravelling will occur just few years after application works due to oxidation generating new and heavier segregation.

II.1.3. Stepwise Downsizing of the Asphalt layers Upwards

For completeness, the paths of the vertical and radial strains are given in the following Fig. 20.

The discontinuities of the paths (especially the vertical strains) are found at the interface positions and denote the differences in material characteristics. This fact also denotes that there is a big risk that the asphalt layers might get loose from each other, preventing the layers from properly working together.

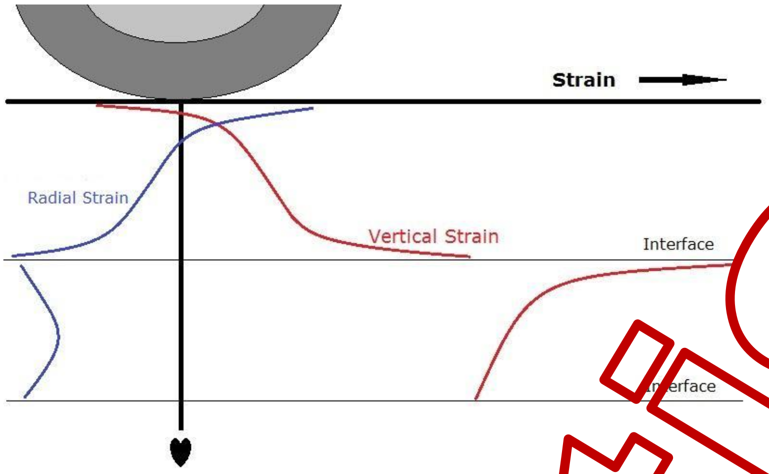


Fig. 20: Vertical and Radial Strains in Asphalt Road Construction (source: 7+8)

This problem is resolvable by *stepwise downsizing* of the gradation of the asphalt layers upwards, from the under layer to the surface layer. The optimum is to use a factor of 2 as a maximum ratio. So, when a gradation of 22 mm is used for the AC-Base layer, the gradation of the AC-Bind layer should not be less than 11 mm (11-16 is preferable). When a gradation of 11 mm is used for the AC-Bind layer, the AC-Surface layer should not have a gradation of less than 6 mm (6-8 is preferable).

By doing this, the risk that the attachment of the asphalt layers to each other will fail (causing less longevity), is significantly reduced.

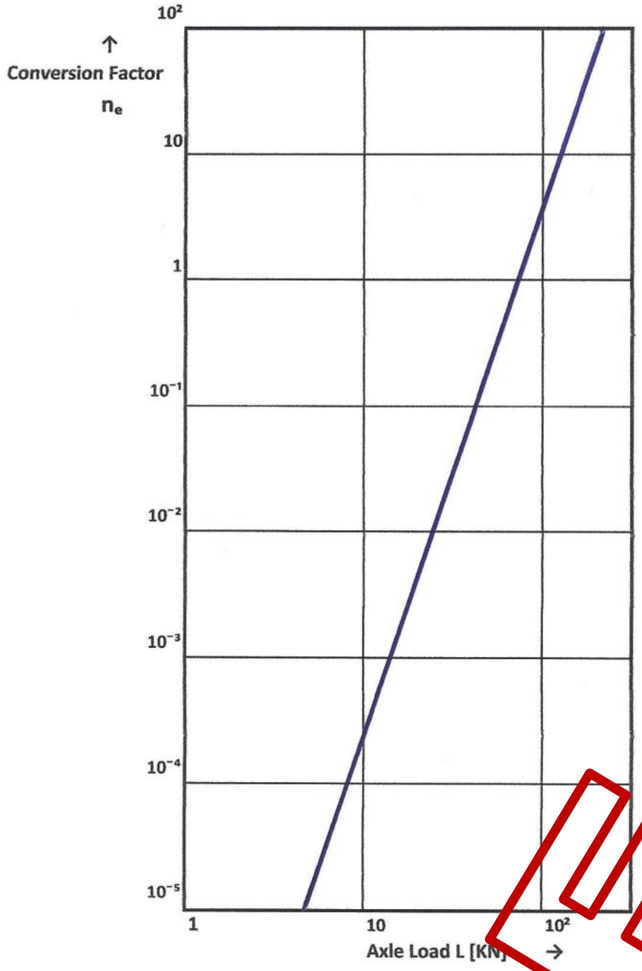
II.2. Data for Construction Calculation

Data necessary for the calculation of a road construction must be based on the:

*Traffic, causing the mechanical loads from above;
*Subgrade, supporting the loads from underneath;
*Construction materials applicable for the asphalt, base and subbase layers so that they will spread the traffic loads mechanically and minimise damage to the subgrade and the materials themselves.

II.2.1. Traffic

Traffic applies mechanical loads to asphalt construction and, next to the amount of weight (in Road Engineering this is usually expressed as Axle Load in KN), the intensities of the vehicles, especially heavy ones, are very important.
The axle load can be calculated to a standard value representing a 80 KN load. See Fig. 21 for the conversion factors of axle loads, according to research done by Shell and published in SPDM.



Axle Load L [KN]	Conversion Factor n_e
5	0.000015
9	0.000157
10	0.000240
20	0.00384
27	0.0127
30	0.019
40	0.061
44	0.090
50	0.15
60	0.31
62	0.35
70	0.58
80	1.00
90	1.57
100	2.40
110	3.51
120	4.98
130	6.85
140	9.22
150	12.15
160	15.73
170	20.05
180	25.19
190	31.28
200	38.40

Fig. 21: Axle Load - Conversion Factors, According to Shell SPDM (source: 14)

As can be seen, the effects of an axle load of 140 KN can be calculated by using the multiplication factor of 9.22 to equalise the effects of 80 KN.
Next to from the table, the conversion factor (ne) itself can also be found by the formula:

ne = $2.4 \times 10^{-8} \times L^4$, where L is the Axle Load in KN. (source: 14)

This conversion factor refers to the damage to the asphalt construction caused by the axle load. This means that the damage caused by an axle load of 100 KN is around 10,000 times the damage caused by an axle load of 10 KN:

$(100 \text{ KN} / 10 \text{ KN})^4 = 10^4 = 10{,}000)$

A loaded truck/bus will cause about 10,000 times more severe damage than a personal car.

As can be seen from the factors, the intensity of heavy traffic will be very crucial for road construction. Heavy traffic will also cause high strains where the maximums are dependent on temperature and load repetition/fatigue (Fig. 22). Therefore, when calculating the road construction, at least some manual checks of some strains on "fatigue" regarding heavy load are necessary to prevent failure. For this, the formula of "*Mine*r" can be used.

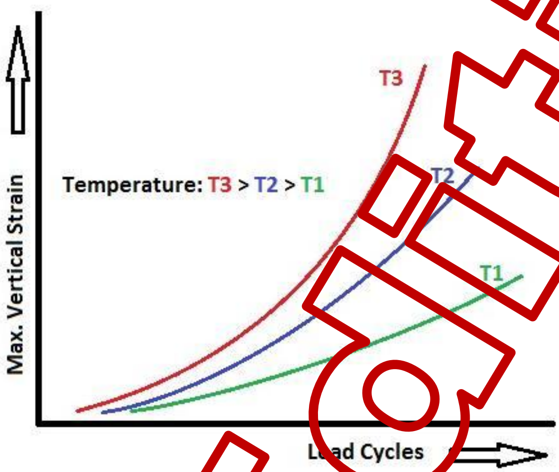


Fig. 22: Effects of Temperature and Load Repetition on Max. Vertical Strains

II.2.2. Subgrade

The subgrade also determines the suitable road construction since its characteristics limit the possibilities and the strength of the construction.

Usually, the subgrade consists of the following sorts of soil, classified below from the softest to the hardest:

*Peat soil (remnants of vegetation);
*Clay;
*Sand;
*Gravel;
*Rock
etc.

Especially when dealing with the first 2 sorts (peat soil and clay), it might be necessary to replace the subgrade at a certain depth. It can be replaced by sand, which is available in almost every country and relatively cheap.
For light traffic, a replacement could be avoided by injecting some stabilisers that improve the strength and bearing capacity.
When the subgrade consists of sand, gravel or rock, no improvement is usually

necessary. However, checking the modulus of stiffness (Smod in MPa.) in a lab to see whether it possesses values above 100 MPa is strongly recommended.

II.2.3. Applicable Materials for Base and Subbase Layers

The material used is mostly determined by the availability at the moment of construction. Many countries have to import such material, making the costs higher.

The following materials are usually applied:

*Sand: -For the subbase;
-Almost available everywhere and relatively cheap;
-Water permeable, preventing the accumulation of water in and around the construction;

*Gravel: -For the base;
-Relatively high support capacity;

*Crushed stone: -For the base;

*Crushed aggregate: -For the base;
-For the subbase when crushed to sand fraction;

*Recycled granulates: -For the base;
-Produced from demolished brick & concrete walls and cheaper than gravel.

(*For AC: filler, sand, stone aggregate, bitumen and some additives).

As already mentioned, the gradual downsizing of the gradation from the base layer to the AC-layers is necessary to optimise the interaction of those layers. A maximum factor of 2 can be used, dividing the gradation size upwards.

It is strongly recommended to pay attention to the state of compaction of the materials used in road construction. Due to the dynamic load situation, the road construction might rapidly fail due to deformations and cracks.
One of the easiest ways to control the state of compaction on site is using a nuclear test apparatus (Fig. 23). The results can be seen almost directly, so extra measurements can be inserted right during the construction.

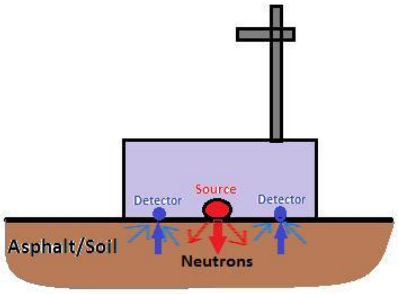


Fig. 23: Nuclear Test Apparatus, Testing the Compaction on Site

When a relative amount of clay or peat soil is present at the upper region of the subgrade, replacing it with e.g. 50 cm in thickness of sand layer may be necessary. In all circumstances, it is better to check the stiffness of all materials used for the base and subbase layers in the lab and it is highly recommended to do the compaction anyway.

II.3. Construction Calculation Using Software

The calculation of asphalt road construction can be done with several methods, from the CBR (California Bearing Ratio) using graphics, to the modern ones using computer software.
In this book, SPDM (Shell Pavement Design Method) is chosen, which has been applied internationally in several countries.

The SPDM calculation software consists of three (3) modules:

*The BANDS: enabling the calculation of the characteristics of the bitumen and the asphalt mixtures that will be applied;
*The SPDM: giving estimation regarding the total thickness needed for the specific road construction;
*The BISAR: calculating the stresses and strains at every point in the construction after detailing the asphalt layers, putting their characteristics as input and supplying the traffic characteristics.

In the following examples, the versions BANDS 2.0, SPDM 3.0 and BISAR 3.0 are used: (source: *15*)

II.3.1. BANDS 2.0:

Calculating the Bitumen Stiffness (SBIT) with e.g. the following input parameters (Fig. 24):
*Time of Loading;
*Bitumen Temperature;
*Softening Point:
*Penetration Value and
*Penetration Temperature,
resulting in:
+Bitumen stiffness and
+Penetration Index.
These parameters can be replaced by others, depending on what is already known.

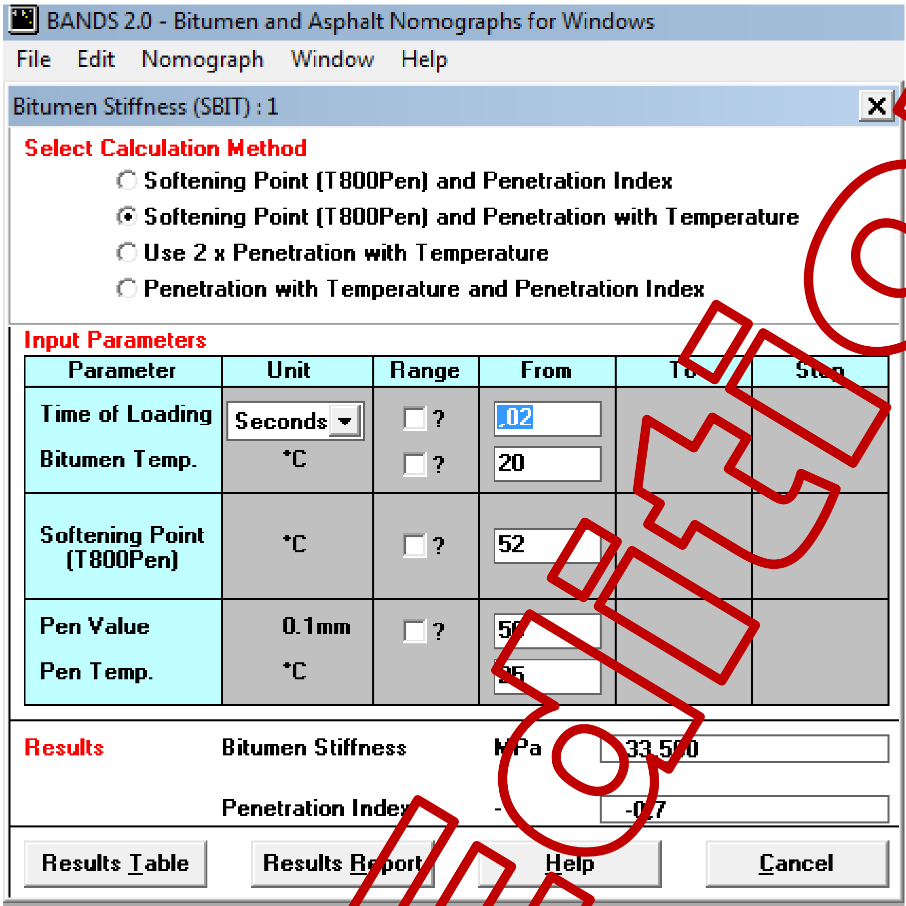


Fig. 24: Calculating the Bitumen Stiffness (source: 15)

The Asphalt Mix Stiffness (SMIX) can be calculated using the following input parameters (Fig. 25):

*Bitumen Stiffness;

*Volume Percentage Bitumen and

*Volume Percentage Aggregate,

resulting in:

+Percentage Voids and

+Mix Stiffness.

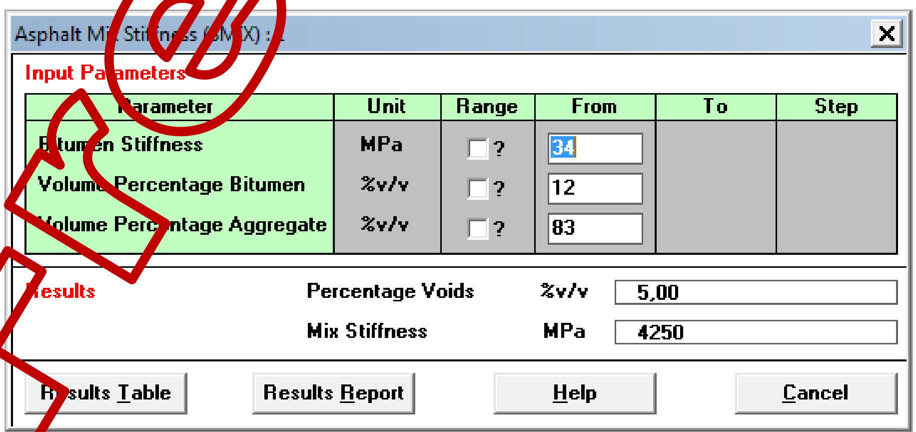


Fig. 25: Calculating the Asphalt Mix Stiffness (source: 15)

Calculating the Fatigue Life Asphalt Mix (NFAT) is based on the following input parameters (Fig. 26):

*Volume Percentage Bitumen;
*Asphalt Mix Stiffness and
*Fatigue Strain,

resulting in:

+Fatigue Life.

Fatigue Strain can be replaced by Fatigue Life when the other is desired.

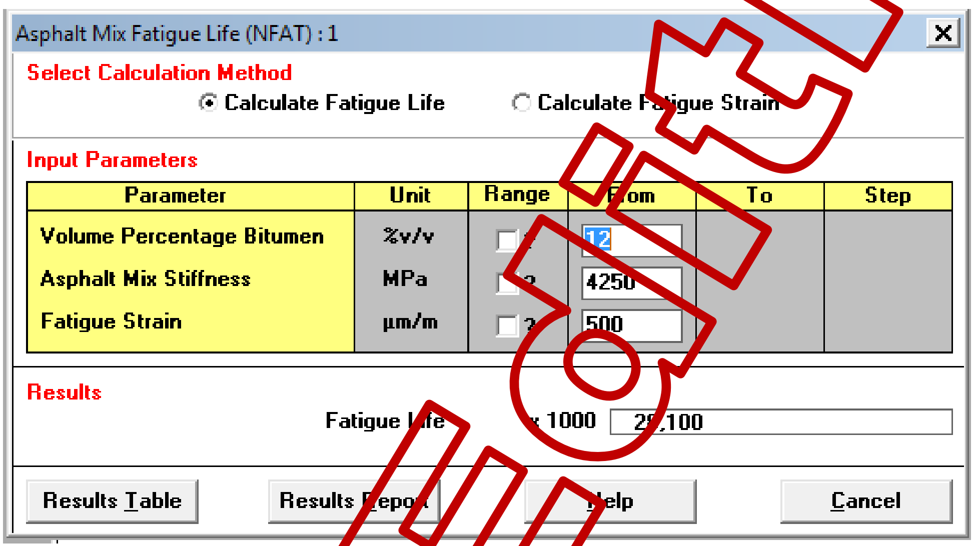


Fig. 26: Calculating the Fatigue Life Asphalt Mix (source: 15)

Calculating the Asphalt Mix Performance (COMB) uses the following input parameters (Fig. 27):

*Loading Time;
*Temperature of Bitumen;
*Penetration Value;
*Penetration Temperature;
*Softening Point;
*Volume Percentage Bitumen;
*Volume Percentage Aggregate and
*Fatigue Strain,

resulting in:

+Penetration Index;
+Bitumen Stiffness;
+Asphalt Mix Stiffness and
+Fatigue Life.

Fatigue Strain can be replaced by Fatigue Life, depending on what is already known.

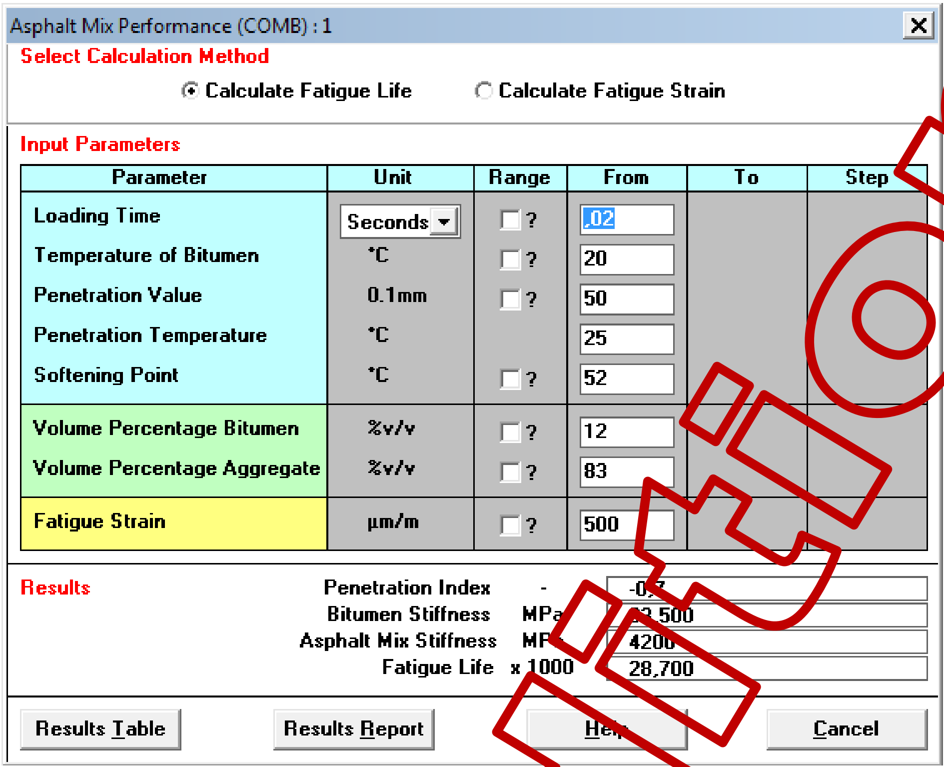


Fig. 27: Calculating the Asphalt Mix Performance (source: 15)

II.3.2. SPDM 3.0

With this module, calculations can be made regarding (Fig. 28):
*Thickness Design;
*Rutting and
*Overlay Design.

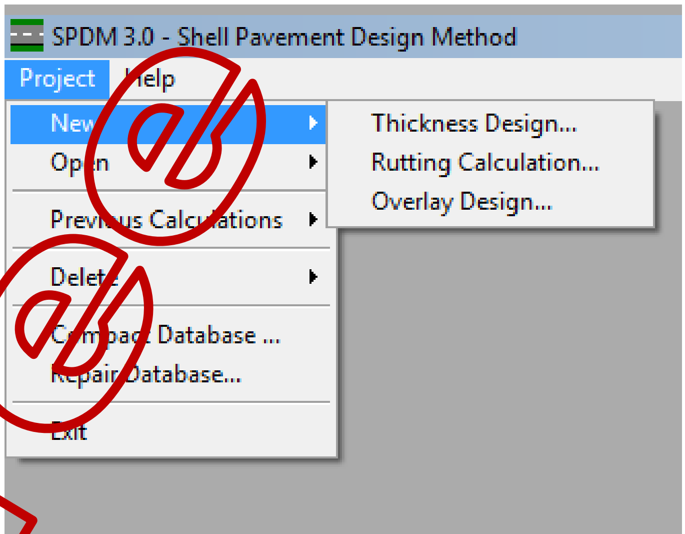


Fig. 28: Calculations with SPDM 3.0 (source: 15)

For Thickness Design, the following blocks of parameters are taken into account:

*Climate (Fig. 29):

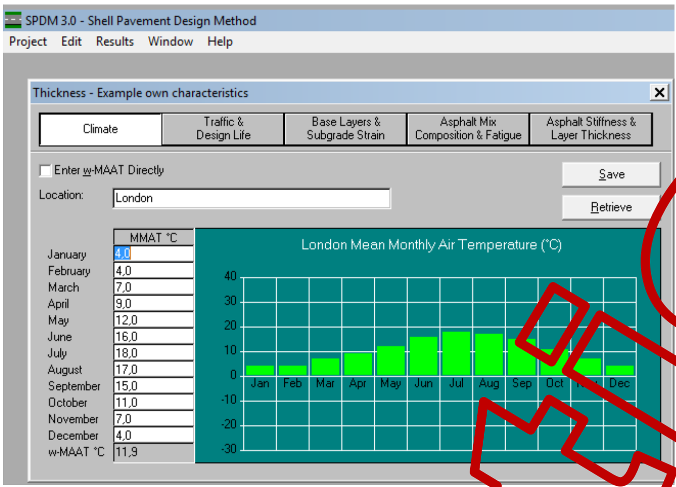


Fig. 29: Climate As Input (source: 15)

*Traffic and Design Life (Fig. 30):

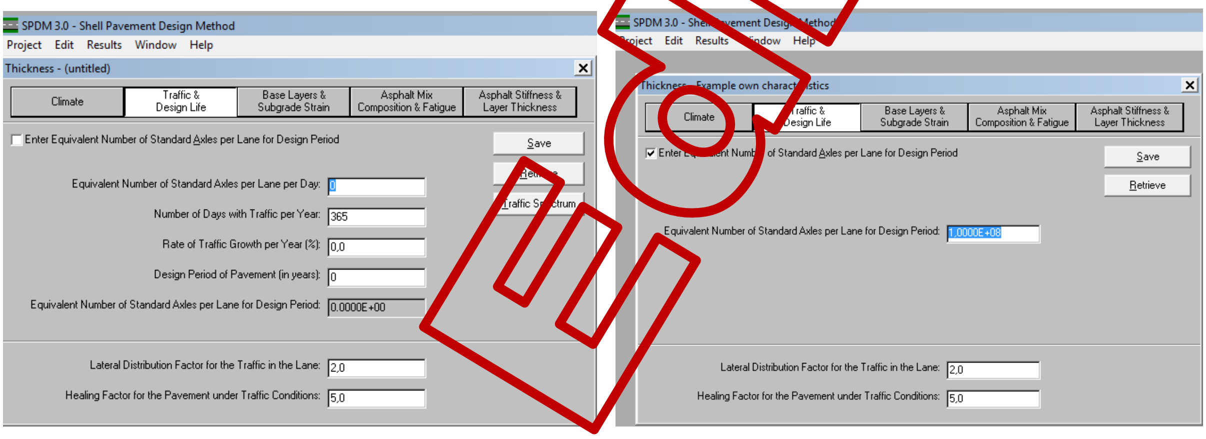


Fig. 30: Traffic and Design Life As Inputs (source: 15)

*Base Layers and Subgrade Strain (Fig. 31):

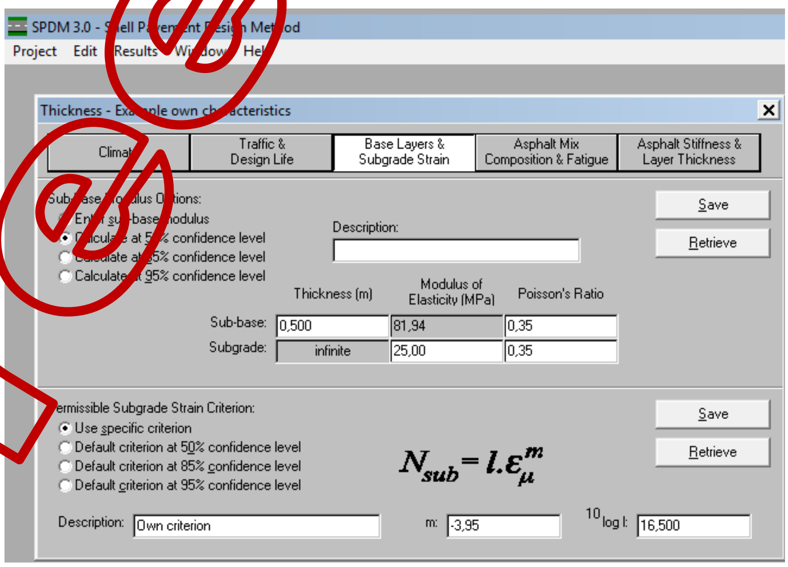


Fig. 31: Base Layers and Subgrade Strain as Inputs (source: 15)

*Asphalt Mix Composition and Fatigue (Fig. 32):

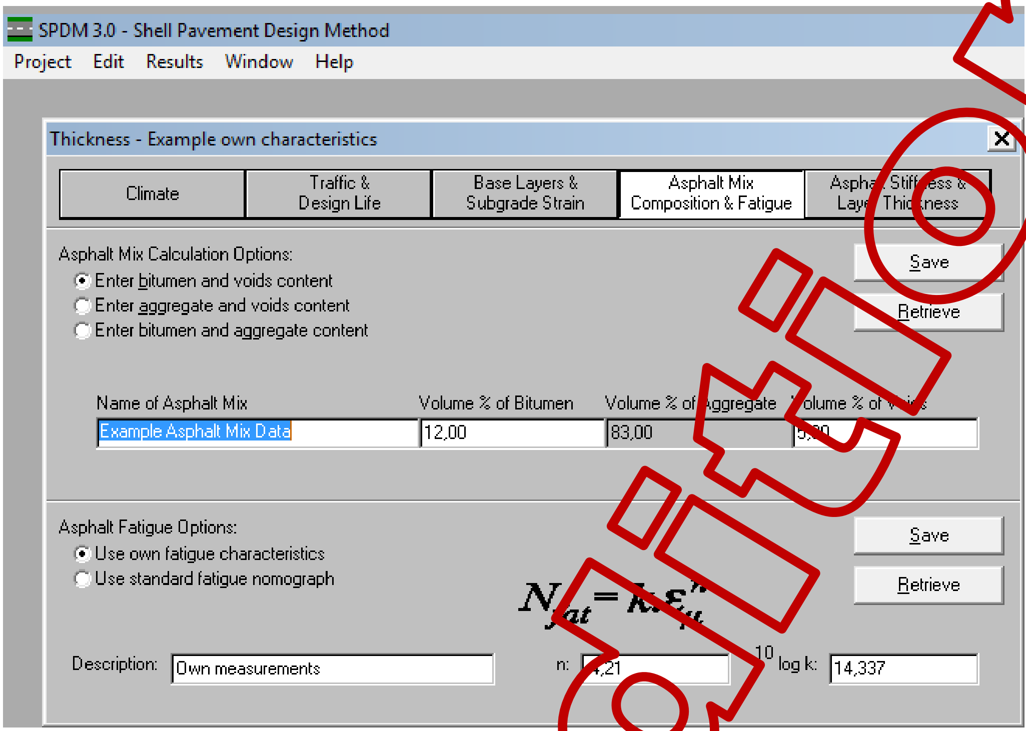


Fig. 32: Asphalt Mix Composition and Fatigue as Inputs (source: 15)

*Asphalt Stiffness and Layer Thickness (Fig. 33):

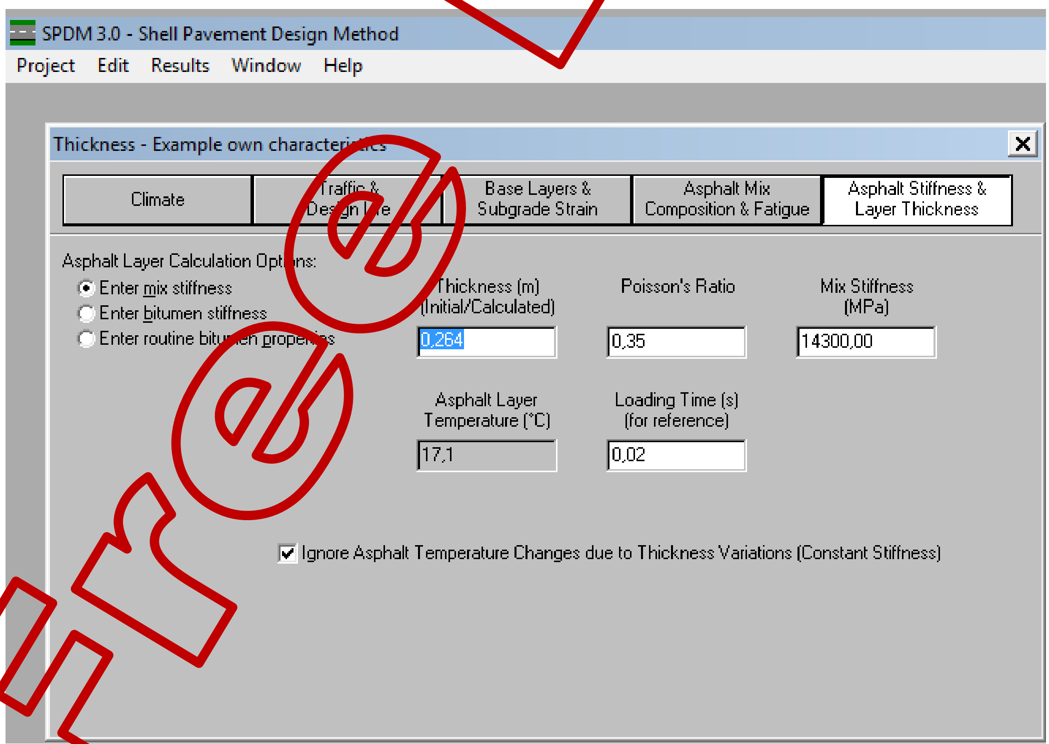
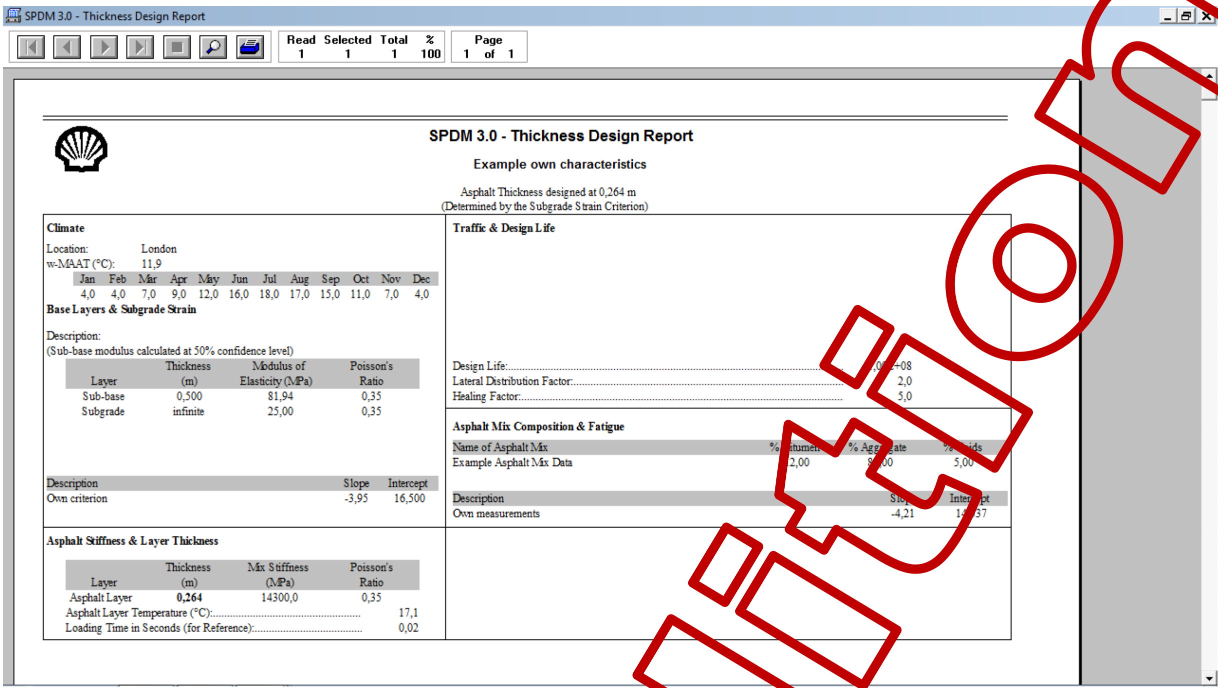


Fig. 33: Asphalt Stiffness and Layer Thickness as Inputs (source: 15)

resulting in the following data (Fig. 34 and 35):


SPDM 3.0 - Thickness Design Report

Read 1 | Selected 1 | Total 1 | % 100 | Page 1 of 1

SPDM 3.0 - Thickness Design Report

Example own characteristics

Asphalt Thickness designed at 0,264 m
(Determined by the Subgrade Strain Criterion)

Climate

Location: London
w-MAAT (°C): 11,9

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4,0	4,0	7,0	9,0	12,0	16,0	18,0	17,0	15,0	11,0	7,0	4,0

Base Layers & Subgrade Strain

Description:
(Sub-base modulus calculated at 50% confidence level)

Layer	Thickness (m)	Modulus of Elasticity (MPa)	Poisson's Ratio
Sub-base	0,500	81,94	0,35
Subgrade	infinite	25,00	0,35

Description	Slope	Intercept
Own criterion	-3,95	16,500

Asphalt Stiffness & Layer Thickness

Layer	Thickness (m)	Mix Stiffness (MPa)	Poisson's Ratio
Asphalt Layer	**0,264**	14300,0	0,35

Asphalt Layer Temperature (°C): 17,1
Loading Time in Seconds (for Reference): 0,02

Traffic & Design Life

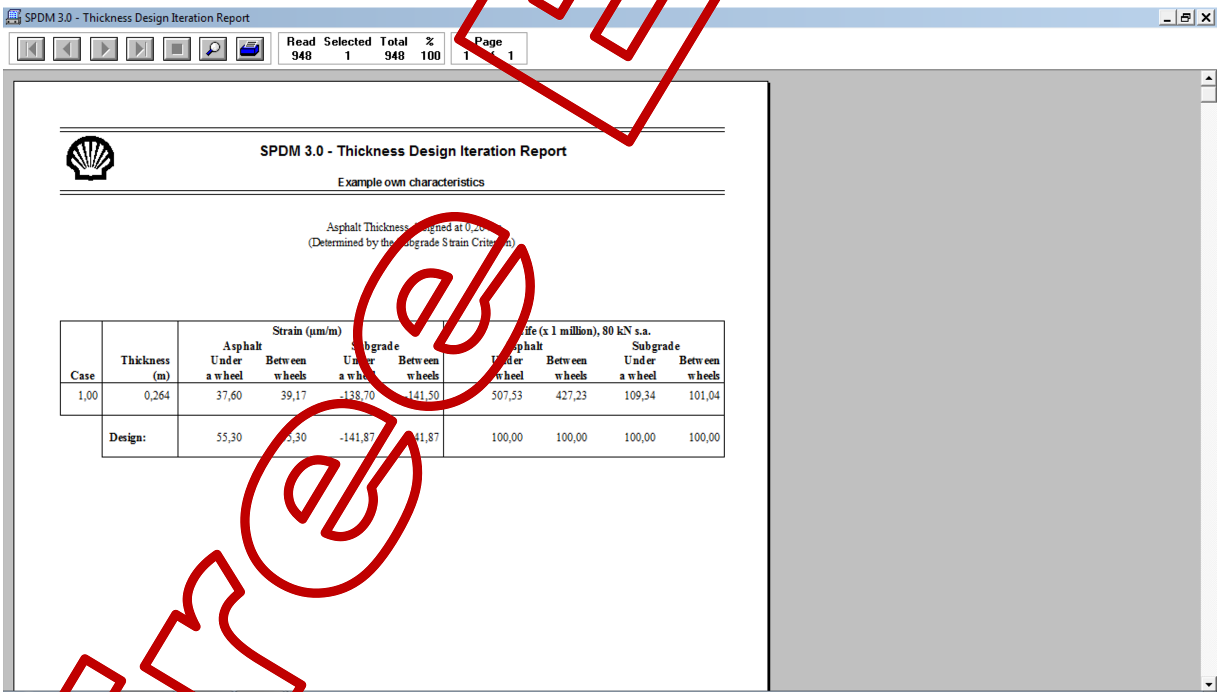
Design Life: [illegible]+08
Lateral Distribution Factor: 2,0
Healing Factor: 5,0

Asphalt Mix Composition & Fatigue

Name of Asphalt Mix	% Bitumen	% Aggregate	% Voids
Example Asphalt Mix Data	[illegible]2,00	[illegible]	5,00

Description	Slope	Intercept
Own measurements	-4,21	[illegible]

Fig. 34: Results of SPDM Calculation, Input Data (source: 15)


SPDM 3.0 - Thickness Design Iteration Report

Read 948 | Selected 1 | Total 948 | % 100 | Page 1 of 1

SPDM 3.0 - Thickness Design Iteration Report

Example own characteristics

Asphalt Thickness designed at 0,2[illegible]
(Determined by the Subgrade Strain Criterion)

Case	Thickness (m)	Strain (µm/m) Asphalt Under a wheel	Strain Asphalt Between wheels	Strain Subgrade Under a wheel	Strain Subgrade Between wheels	Life (x 1 million), 80 kN s.a. Asphalt Under a wheel	Life Asphalt Between wheels	Life Subgrade Under a wheel	Life Subgrade Between wheels
1,00	0,264	37,60	39,17	-138,70	-141,50	507,53	427,23	109,34	101,04
	Design:	55,30	[illegible],30	-141,87	[illegible]41,87	100,00	100,00	100,00	100,00

Fig. 35: Results of SPDM Calculation, Calculated Data (source: 15)

II.3.3. BISAR 3.0

After using SPDM, the BISAR module can be used as a tool to check the results. There are 3 modes within this software module: *Loads*, *Layers* and *Positions*.

With the mode *Load*, a combination of *stress*, *load* and *radius* regarding the axle loads can be applied as inputs, depending on what is already known (Fig. 36).

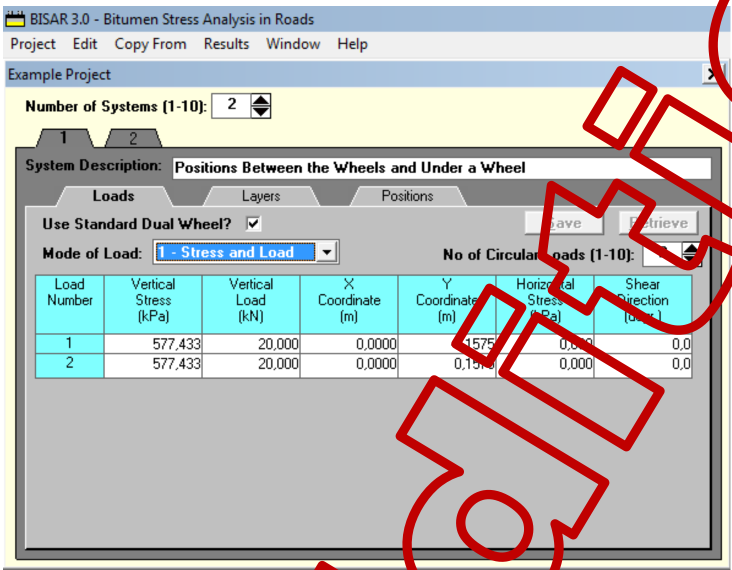


Fig. 36: The Load Mode of BISAR (source: 15)

In the *Layers* mode (Fig. 37), each layer within the construction must be filled in with its characteristics, such as *Thickness*, *Modulus of Elasticity* and *Poisson's Ratio*, including the several sorts of asphalt (AC-Surface, -Binder & -Base) which are designed to be applied as an Asphalt Concrete layer.
Due to this, it is possible to analyse the state of the stresses and strains within the whole construction before the start of the construction work.

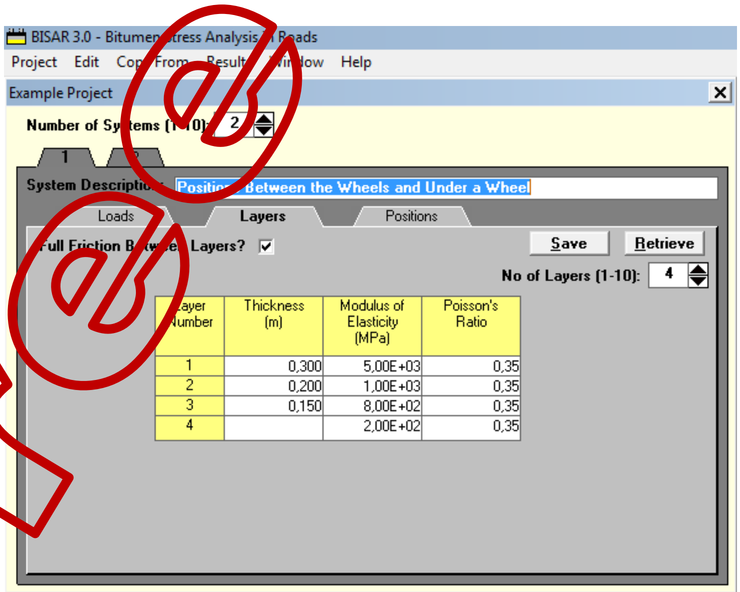


Fig. 37: The Layers Mode of BISAR (source: 15)

Within the *Positions* mode (Fig. 38), the coordinates of each position within the construction at which the stress and strain will be calculated can be pointed out.

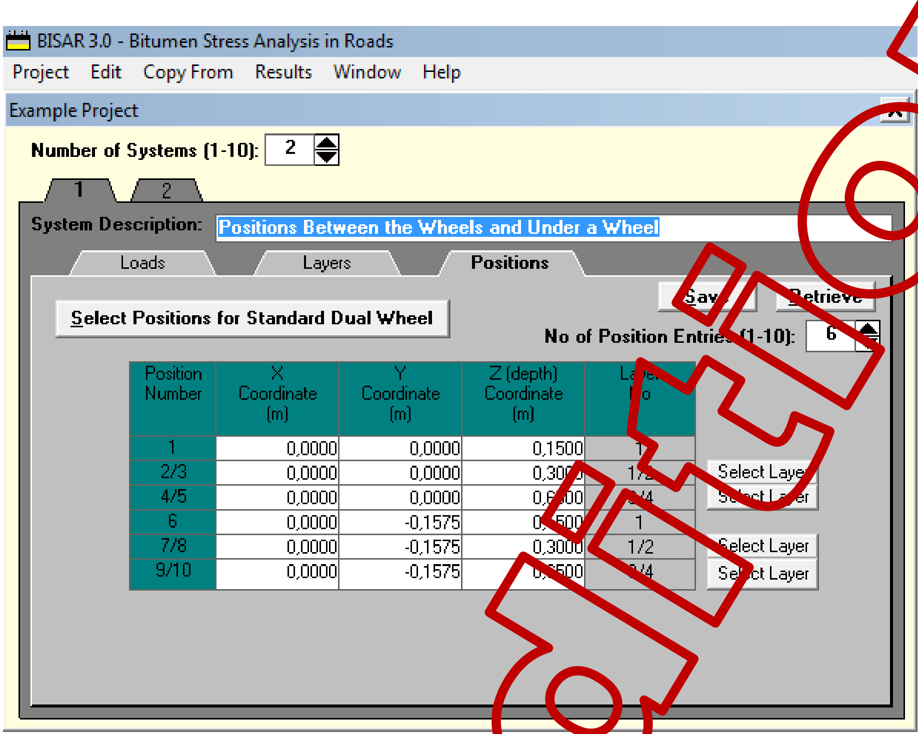


Fig. 38: The Positions Mode of BISAR (source: 15)

In the end, these modes will show an overview of stresses and strains across the construction in a *Block Report* (Fig. 39).

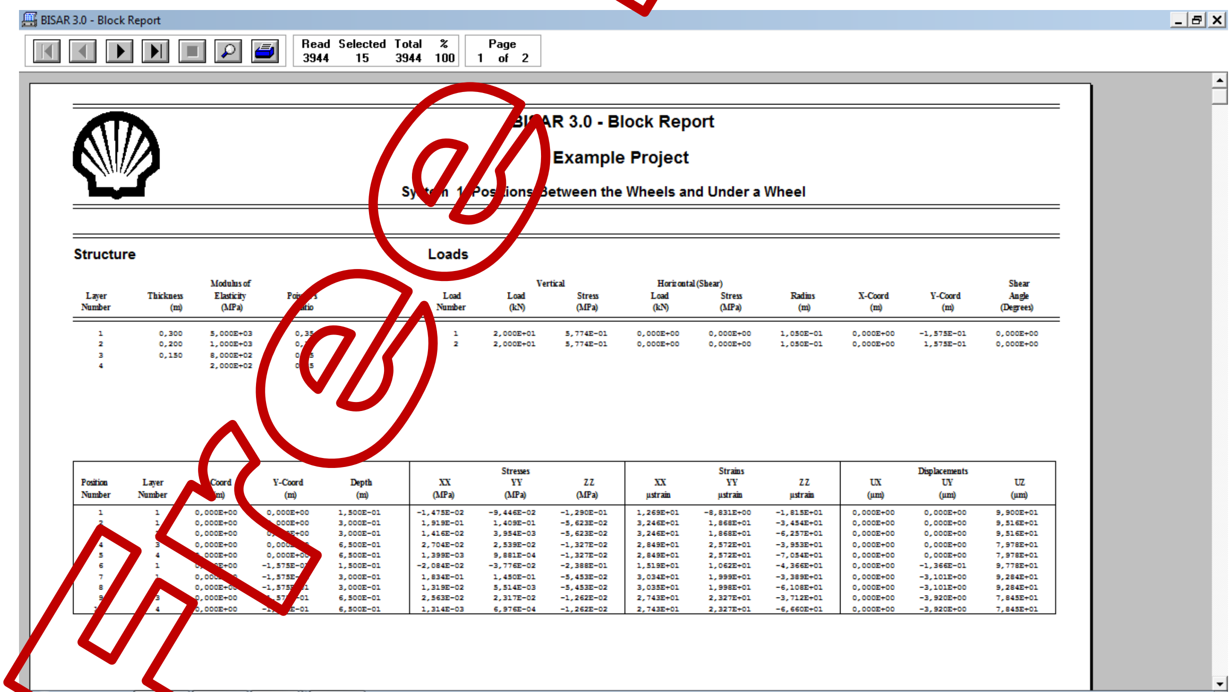


Fig. 39: Overview of Stresses and Strains, Calculated by BISAR (source: 15)

More details are available in a *Detailed Report* (Fig. 40).

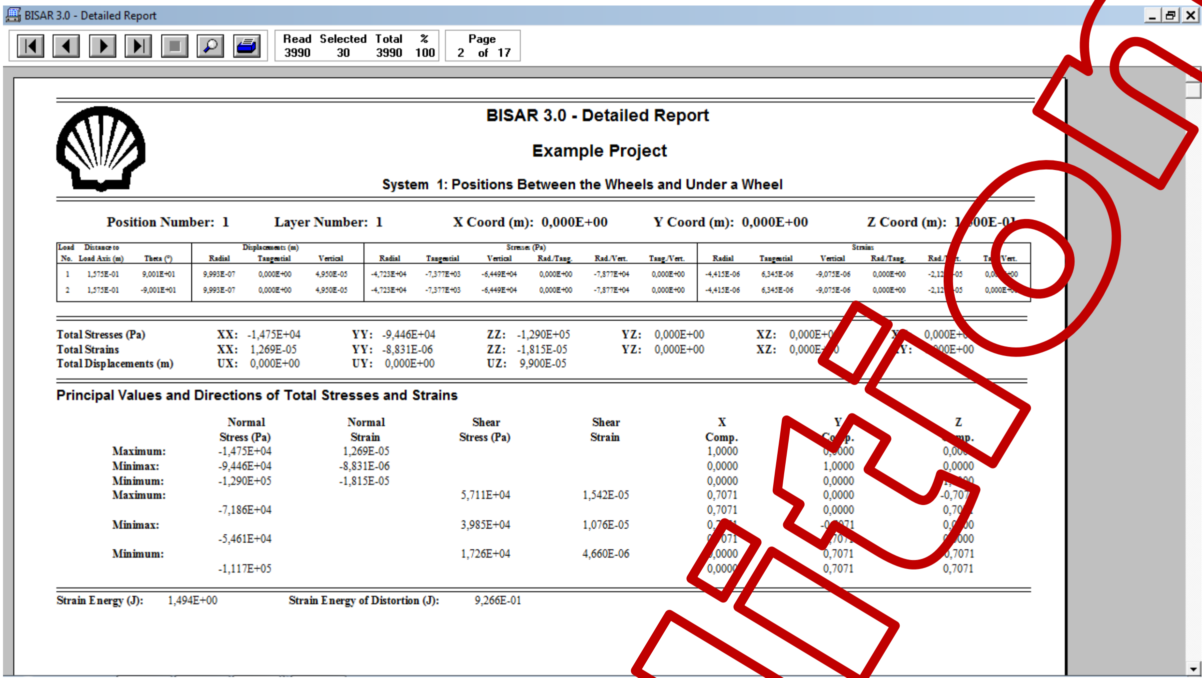


Fig. 40: Detailed Report of Stresses and Strains from BISAR (source: 15)

To avoid possible mistakes, made by the computer or due to wrong inputs, it is strongly recommended to manually check the biggest strains from BISAR, using the fatigue formula (e.g. Miner) for asphalt.

II.4. Drainage and Maintenance

In completing the design and construction of a road, the aspects of drainage and maintenance will be considered. These aspects also determine the longevity of the construction and will subsequently save a lot of work and money, as well as hindrances caused by the surroundings.

II.4.1. Drainage

When designing a road construction, drainage is one of the most important factors regarding the longevity of the total construction. Water must be given the opportunity to drain as soon as possible, since it will damage the construction.

This can be done by creating a slope of about 2-3% (depending on the amount of local rainfall per year), so water can run off the road. It is also necessary to create shoulders that prevent the accumulation of water along the sides (Fig. 41).

In relation to groundwater, the base layer must in all circumstances be above the level to prevent water from infiltrating into the construction after a period of time.

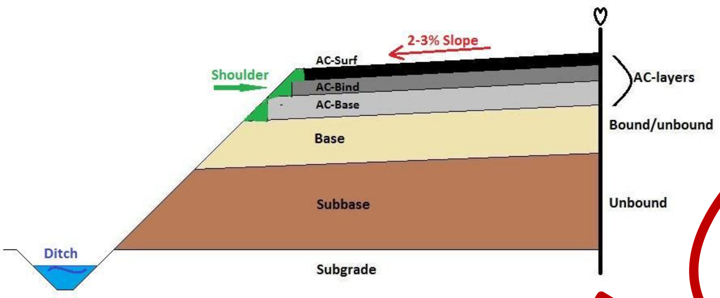


Fig. 41: Drainage

When PA is used, the edges of this layer must be kept open, so that water running inside the PA is able to drain away. This also means that regular cleaning of the edges is necessary.

II.4.2. Maintenance (small and big repair/reconstruction)

Maintenance is mostly neglected, especially when the budget is very narrow. However, carrying out regular maintenance will save a lot of work and money. Most damages on asphalt can be easily repaired when done in time.
In the case of a stone skeleton, when an asphalt mixture is used as the surface layer (AC-Surf), repairs of damage should be done as soon as possible, since the mixture is dependent on the skeleton which is discontinuously graded. A small pothole can rapidly grow to a bigger one within a relatively short period of time. This is seen very often with PA.

Small Repair

In all sorts of asphalt mixtures, repair should be carried out (Fig. 42.a) by cutting and taking away the edges of the damaged spots, up to around 10 cm. Just filling with *repair asphalt* (several sorts are available) will only last for a very short period. The damaged spots must be cleaned, dried and filled in with repair asphalt. Hot repair asphalt is preferable to cold due to its better adhesive capacity and usually longer longevity. Repair asphalt of the same sort (e.g. SMA with SMA) and the same sieve grade or lower (avoid higher) is recommended.
After compaction, the edges of the damage hole at the surface must be sealed with bitumen 70/100 or another sealing slurry to prevent the infiltration of water and improve the interaction between the new repair asphalt with the existing asphalt. Small cracks can also be repaired by sealing with bitumen 70/100.

Fig. 42.a: Maintenance, Cutting the Edges

Big Repair and Reconstruction

When the damage has already grown to a pothole, it is recommended to also renew the AC-Bind layer. Usually, this intermediate layer has also been affected and is showing some crack spots. When not removed, these crack spots will generate cracks in the new AC-Surface layer within months.

When the damaged asphalt has been cut and removed, attention must be given to the 'connecting borders' with the existing asphalt since the repair is relatively deep compared to the thickness of the new surface layer. In this case, the borders must be cut and provided with a "step" S with the following dimensions:

*$S_{vertical-1}$:	thickness of the first layer (AC-Surf);
*$S_{horizontal-1}$:	5 to 7 x thickness of the layer to be applied (AC-Surf);
*$S_{vertical-2}$:	thickness of the second layer (AC-Bind)

So, when a new AC-Surface of 30 mm thickness on a new AC-Bind with 50 mm thickness is applied, the step S at the connecting borders (Fig. 42.b) should have the following dimensions: S_{vert-1}= 3 cm; S_{hor-1}= 15-20 cm and S_{vert-2}= 5 cm.

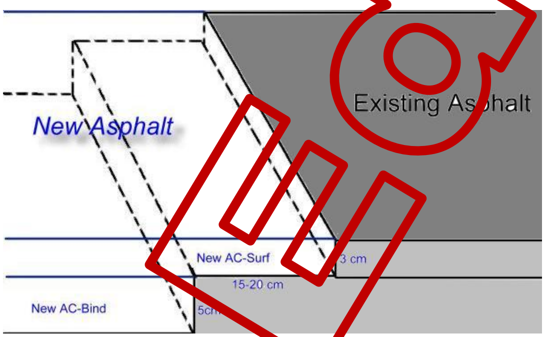


Fig. 42.b: Step S at Connecting Borders

This "step" at the connecting border is also necessary for every connecting border where the total thickness of the new asphalt layers is relatively high (= more than 5 cm). This step will create an optimal interaction between the old and the new asphalt mixtures, since their stiffness is not equal. Without this step, the border will show a gap within some months, allowing water to come into the asphalt construction and consequently destroying the whole construction. In addition, it is recommended to seal the borders at the surface with bitumen 70/100, to both ensure that water infiltration is prevented and equalise the surface for a better transfer of the stresses applied by the traffic wheels.

Take an example where a part of a road has to be partly renewed (a *reconstruction*) and the total thickness of the new asphalt layers is 15 cm, containing of 3 asphalt layers, respectively 30 mm AC-Surf on 50 mm AC-Bind on 70 mm AC-Base. 2 steps should be created at the border with the following dimensions: S_{vert-1} = 3 cm; S_{hor-1} = 15 - 20 cm; S_{vert-2} = 5 cm; S_{hor-2} = 30 cm and S_{vert-3} = 7 cm.

III. <u>Upgrading and Testing Asphalt Mixtures</u>

In this chapter, some methods in upgrading asphalt mixtures are going to be considered, followed by examples.
Some tests (and the apparatus) which are used very often on asphalt will also be presented and discussed here.

III.1. Theoretical Approach

Since asphalt mixtures merely consist of aggregates and bitumen, one usually follows the *gradation*-line or the *bitumen*-line when upgrading an asphalt mixture.

*.<u>Gradation-line</u>:

With the gradation-line, the aggregate and sand fraction and their percentages are optimised to achieve the purpose goal based on a certain percentage of bitumen. The purpose goal is to find an optimum composition for the percentages of each aggregate component. Using this method, the mixture will be more compact and will possess higher resistance to deformation.

In the past, this has led to the so-called *volumetric design* for SMA, where optimisation of the volume of the mixture is taken into priority. Some efforts have resulted in more compacted mixtures that have higher stiffness and quality.

*<u>Bitumen-line</u>:

In the bitumen-line (Fig. 43), the bitumen is usually modified by putting in some additives and by optimising the bitumen percentage. The bitumen percentage is hereby varied to find the optimum area, based on a certain composition regarding the aggregates. During the optimisation process, however, some shifts in the aggregate percentages have to be made.
A decrease in the amount of bitumen will increase the stiffness of the mixtures and therefore the resistance to deformation, but it will also increase the sensitivity to cracks and ravelling. Similarly, an increase of the bitumen percentage will push up the resistance to cracks and ravelling, but it will also decrease the resistance to deformation.

As several kinds of mixtures are very dependent on the percentage of bitumen, and as bitumen is the most expensive component, this method will also affect production costs.

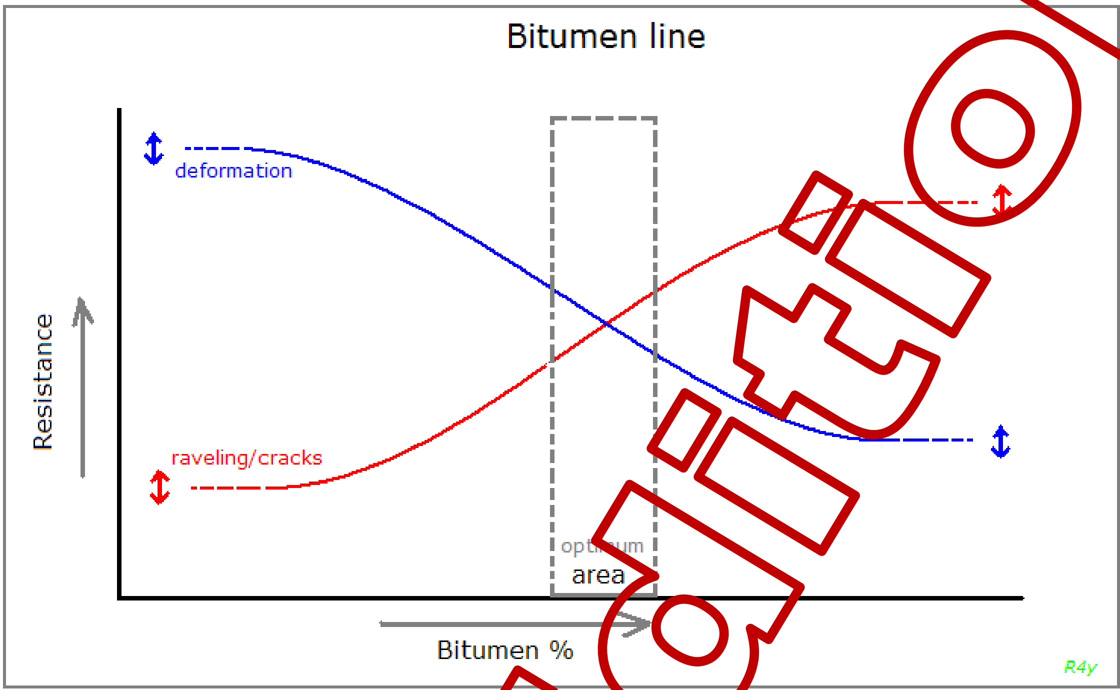


Fig. 43: Bitumen-line

The results of upgrading SMA using this method have shown that it has the advantage of improving the stiffness, the strength, the longevity and also the cost by reducing the bitumen percentage to a certain optimum bandwidth.

III.2. Examples – Upgrading Stone Mastic Asphalt (SMA)

Here, examples of upgrading asphalt mixture SMA are given, which is used as a surface layer, although the theory is applicable to most other mixtures.

As already mentioned, there has been (and is still) a lack of regulation regarding SMA. Each country uses its own SMA when available.
In 2000, the city of Utrecht in the Netherlands took the opportunity and the risk of upgrading the Dutch SMA to MODUS and DESA asphalt. The upgrade was done following the Bitumen-line, rather than the Gradation-line.
Unlike other mixtures, SMA theoretically has a very narrow optimum area regarding the resistance to deformation on one side and the resistance to crack on the other side. So, it is not easy to optimise. However, this sort of mixture has proven to have a high grade of longevity and, as it very suitable for the tropics due to its structure, it is worth trying.

III.2.1. MODUS

MODUS is derived from the Dutch SMA 0/8 from the year 2000. It is an abbreviation for MODified Utrechts Sma, using 70/100 bitumen and designed for the asphalt surface layer (AC-Surf) for city traffic.

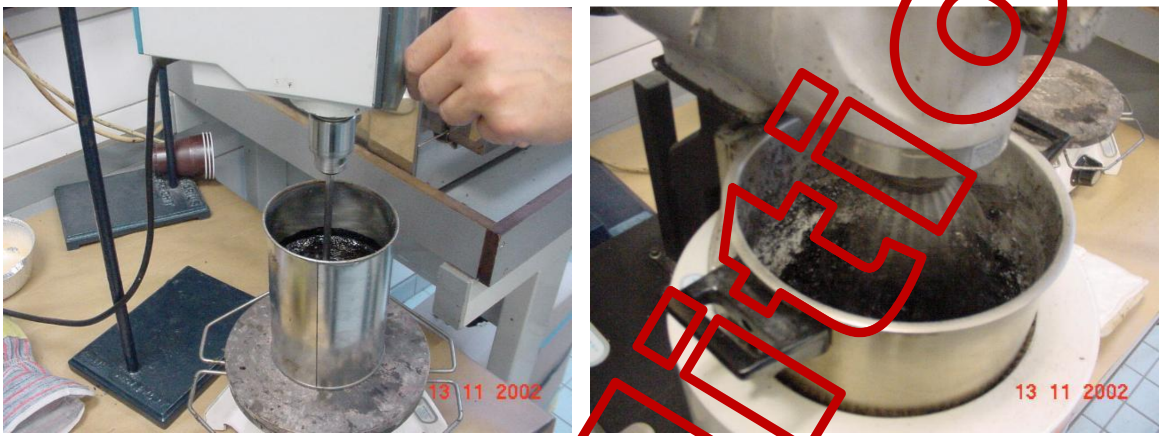


Fig. 44: Development of MODUS in the Lab

By varying the bitumen percentages, shifting the gradation, putting in some additives and removing some components, the following results were achieved:

	Dutch SMA2000:	MODUS:	Δ (%):
*Marshall-Stability (Pm in N):	4,350	5,500	+26
*Marshall-Flow (Fm in mm):	2.8	2.0	-28
*Marshall-Quotient (Qm in N/mm):	1,550	2,750	+77

During lab trials (Fig. 44), the Marshall-Flow was kept from decreasing further than around 2.0 to maintain the flexibility and healing capacity of the mixture and also to prevent the increase of crack sensitivity.

After the success of the first test lane in 2003, more and more roads within the city of Utrecht were covered by MODUS as an AC-Surf layer (wearing course). Up until now (more than 11 years), no maintenance has been necessary since there were still no damages detected.

III.2.2. DESA

After MODUS, a second version called DESA was developed (Fig. 45). DESA is also derived from Dutch SMA 0/8, an abbreviation for Double Enforcements in Stone mastic Asphalt, which uses harder bitumen 40/60 and is designed for heavy city traffic.

Fig. 45: Development of DESA in the Lab

Bitumen-line was also used to upgrade the mixture, and after varying the bitumen percentages, shifting the gradation, putting in some additive and removing some components, the following results were achieved:

	Batch SMA_{2000}:	DESA:	Δ (%):
*Marshall-Stability (Pm in N):	4,350	6,000	+38
*Marshall-Flow (Fm in mm):	2.8	2.0	-28
*Marshall-Quotient (Qm in N/mm):	1,550	3,000	+94

During lab trials, the Marshall-Flow was also prevented from decreasing further than around 2.0 to maintain the flexibility and healing capacity of the mixture and also preventing the increase of crack sensitivity.

The first test lane in 2007 was also very successful and subsequently, more and more roads within the city of Utrecht and outside – even the highways belonging to the central government – are using DESA as an AC-Surf layer (wearing course). Up until now (after 7 years), no maintenance has been necessary.

The use of MODUS and DESA in the Netherlands has been spreading since 2009. In other cities and on many highways belonging to the central government, many roads are now covered by these mixtures, especially due to their already proven and expected longevity and because of environmental factors such as lower CO_2 for production and a noise reduction of about 2 dB(A). *(note: 3dB(A) means a halving).*
More info can be found on Google by searching "*modus desa asphalt*."

Although these asphalt mixtures are also suitable for the tropics due to their structures, small adjustments might be necessary when using local materials from tropical areas. The mixtures are patented in the Netherlands.

Meanwhile, a red coloured version of MODUS and DESA (Fig. 46) has also been developed, designed for use as a bicycle lane with potential to be used for heavy traffic.

Fig. 46: Red Version of MODUS and DESA

III.3. Testing Asphalt Mixtures

When testing the characteristics of asphalt mixtures, there are a lot of new methods and apparatus available today. This, however, makes the comparison of the results very confusing.
Some of the most known and still used tests are given below.

III.3.1. Marshall

In the past, the Marshall Test has been used in almost every country all around the world. All the apparatuses (Fig. 47) have been standardised, from the sieve and the mixing machine to how the result/registration must be analysed, so comparison is much easier.

Fig. 47: Marshall Mixing Machine and Block Rings

To get rid of the water film which might be present around the particles, the aggregates are raised to temperatures around 105-110 ºC. After cooling down and sieving, weighing of each sieve portion can be done, as well as removing the particles on sieve 31.5 mm.

At least four (4) Marshall blocks of each mixture must be created and tested. Each block should contain about 1 Kg of aggregate, sand and filler in order to create a block with height of around 62-65 mm.
The aggregate, sand, filler, the Marshall rings and the bitumen are then brought to a mixing temperature of about 150-180 ºC, depending on the sort of bitumen used. Mixing should be done by machine in a bowl (which has also already been brought to temperature) and will last for 90 seconds. After putting the mixed sample into the Marshall rings, compaction can be carried out by machine, stamping 50 times twice, on both sides.

After cooling down, the Marshall blocks can be tested with the Marshall pressing machine, resulting in registration of the Marshall Loads at the vertical axis in KN and Marshall Flow at the horizontal axis in mm (Fig. 48). The Marshall Loads denote the stability and the Marshall Flow denotes the deformation.

Fig. 48: Marshall Blocks, Pressing Machine and Registration

Depending on the heights of the samples, correction factors have to be applied on the Marshall Stability (Pm). The Marshall Quotient (Qm in N/mm) can then be found by dividing the corrected Marshall Stability (Pm in N) by the Marshall Flow (Fm in mm). If deviations of 15% or more at Pm or 20% or more at Fm occur, the tests have to be repeated.
From the 4 samples, the final results can be validated by taking the average of the calculated Pm, Fm and Qm.

III.3.2. Four-Point Bending (4PB)

To conform to the European Union regulations, the Marshall test was replaced by the Four-Point Bending (4PB) test in 2008. The aim of this test (Fig. 49) is to predict the fatigue lifetime of asphalt mixtures by measuring the fatigue resistance, which corresponds with the number of load cycles to failure with the strain level applied. The results of these kinds of fatigue tests are expressed in terms of the number of cycles for the tensile strain level applied.

Along with this, the 4PB test also measures the stiffness modules of the asphalt mixtures dynamically.

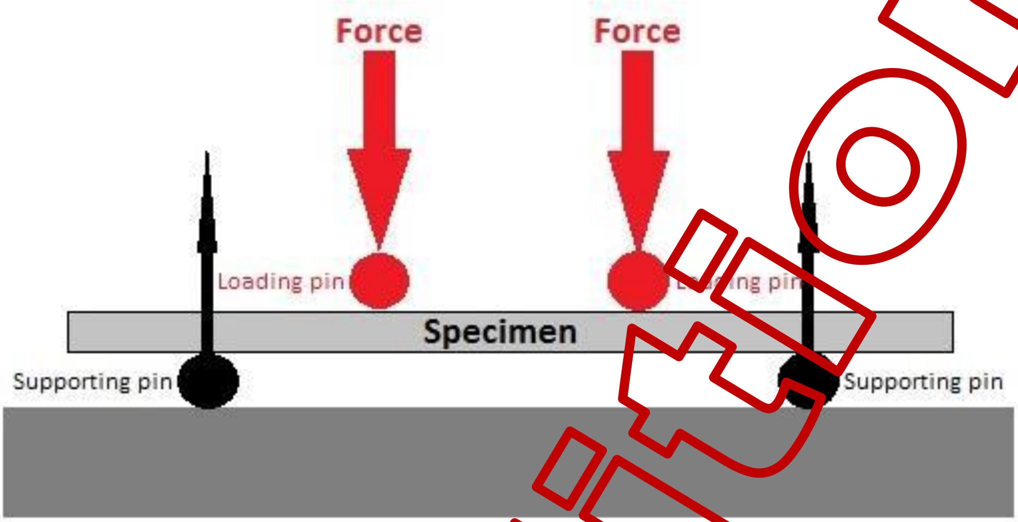


Fig. 49: Four-Point Bending (4PB) Test

A rectangular beam (305x45x50 mm) produced and cut from an asphalt concrete plate is used, which is subjected to sinusoidal loading in either controlled strain or controlled stress.

The results from this dynamic test apparatus have a relatively high accuracy, for the fatigue resistance as well as for the stiffness.

III.3.3. Rolling Bottle

With the *rolling bottle test* (Fig. 50), it is possible to get some information in advance regarding the adhesiveness of some sort of bitumen on some sorts of stone aggregates, before deciding to produce Marshall blocks or asphalt beams for the 4-Point-Bending test.

Several stone aggregates which have already been mixed with several sorts of bitumen are put into the bottles and mixed with water. By rotating the bottles at the same conditions (speed, temperature etc.) for some hours/days, the bitumen will be segregated / peeled off from the stone aggregates. For several samples, the time needed for this will reveal which combinations are better to use based on the adhesiveness.

This test is actually a necessity for preventing ravelling, cracks and potholes in advance.

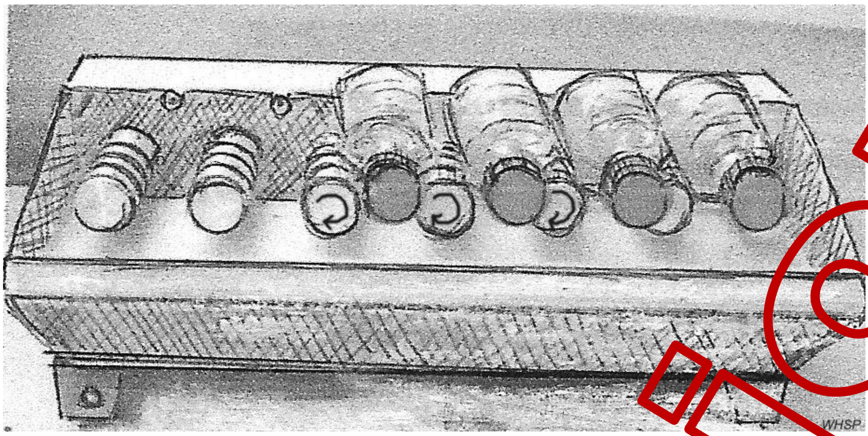


Fig. 50: Rolling Bottle Test

III.3.4. Deflection (FWD)

Deflection tests have been carried out for decades already. The aim of this test is to predict the bearing capacity still present in an existing road construction. This method is a non-destructive one and can be carried out very quickly.

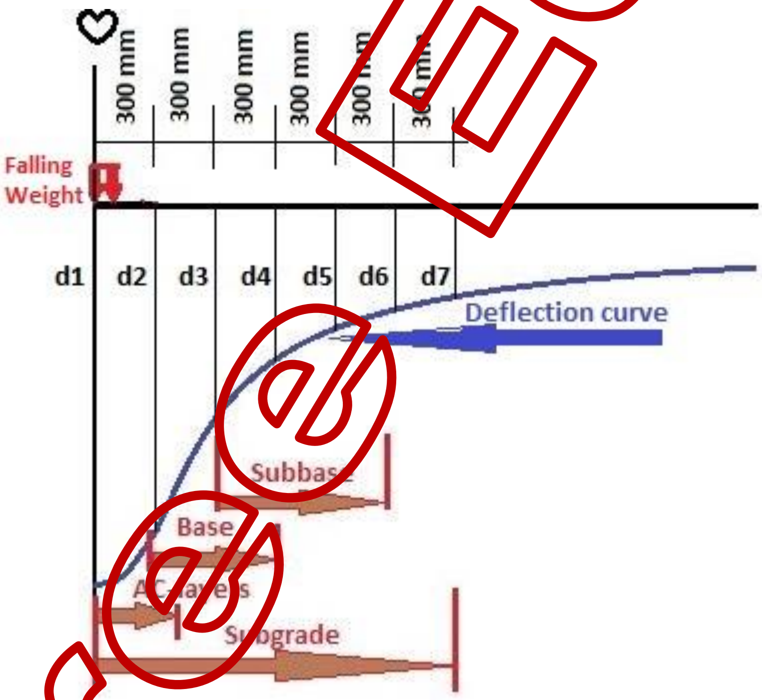


Fig. 51: Deflection Measuring Method (FWD)

The measuring apparatus of this method (Fig. 51) is also known as a Falling Weight Deflectometer (FWD), which uses readings from a series of geophones to detect the very small deflections at the pavement surface.

A mass of 50–350 Kg (the choice depends on the kind of pavement to be investigated) is dropped at 40-400 mm height (also depending on the pavement) on a steel plate with 300 mm diameter. The impact on the asphalt will cause the biggest deflection at the centre, but also at its edges. By using 7 geophones to also measure the deflection at the surroundings, each with a distance of 300 mm, the curve of the deflections can be determined.

As can be seen in Fig. 52, the results of the measurements are also dependent on the temperature. At lower temperatures, the deflections measured will be smaller.
For accuracy, several measurements have to be taken.

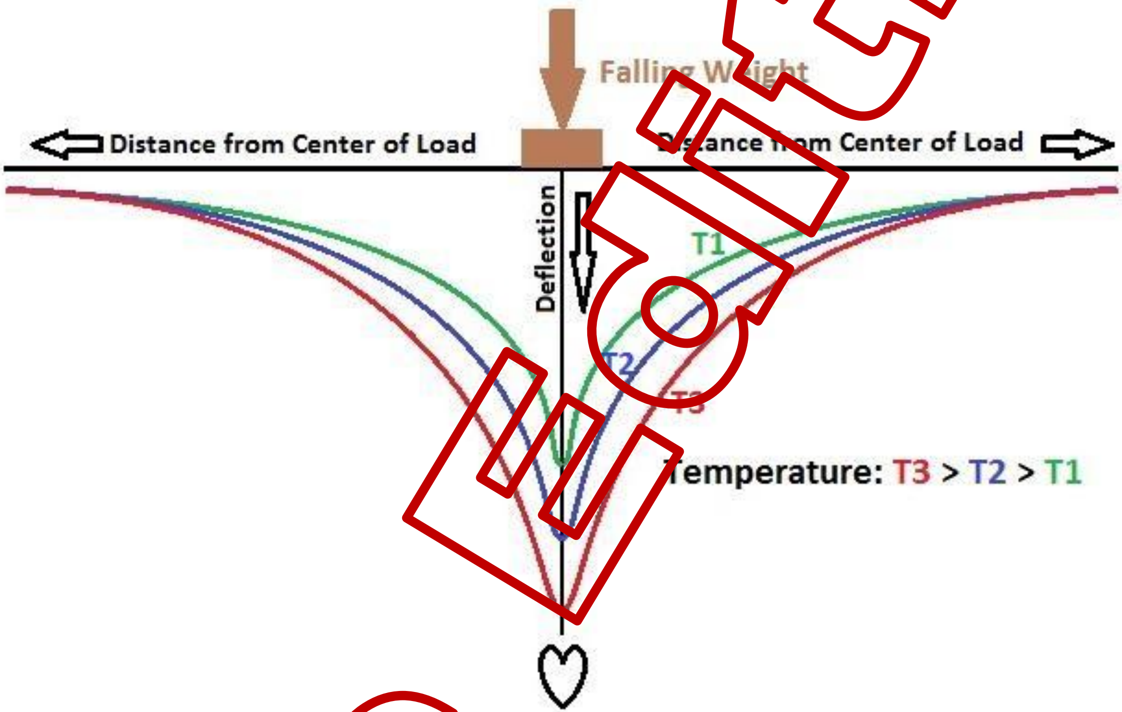


Fig. 52: Typical Measuring Results at Various Temperatures

It is known from the mechanics that deflections are directly related to the stiffness of the material.
Therefore, FWD is essential in estimating the *in situ* stiffness properties of the pavement layers through analysis of the deflection data by back-calculation of the layers' stiffness modulus value.
Finally, based on these stiffness modules and the traffic prognosis, the rest service life of the road can be estimated.

IV. Implementation in Tropical Road Engineering

The basic items of "Asphalt Technology Integrated into Road Engineering" have been discussed in Chapters I – III. This integration is also applicable to road engineering in the tropics. In addition, Chapter IV will support the quality improvement.

IV.1. Implementation

Based on decades of observations and involvements regarding road construction in South and Central America, South and North Africa, Southeast Asia and Oceania and the items as discussed in Chapters I – III, it can be noticed that many roads in the tropics:

*Are not provided with a base and/or subbase layer, causing irresponsible load distribution patterns within the construction;
*Have asphalt mixtures which are composed of materials chosen without involving the basic principles of physics/mechanics;
*Are calculated without integrating the crucial parameters as 'temperature', 'loading time' etc;
*Have asphalt layers that only consist of one layer, which is relatively thin and has high stiffness (due to some modifications) and so behaves like a "*plate of glass on small stones*", creating stress spots;
*Are not gradually downsized, regarding the gradation;
*Use oversized gradation with a certain discontinuity;
*Experience a lack of control/supervision during application works etc.

All of these have apparently affected the longevity for many tropical roads, which can be regarded as very low (1-3 years). This must and can be improved.

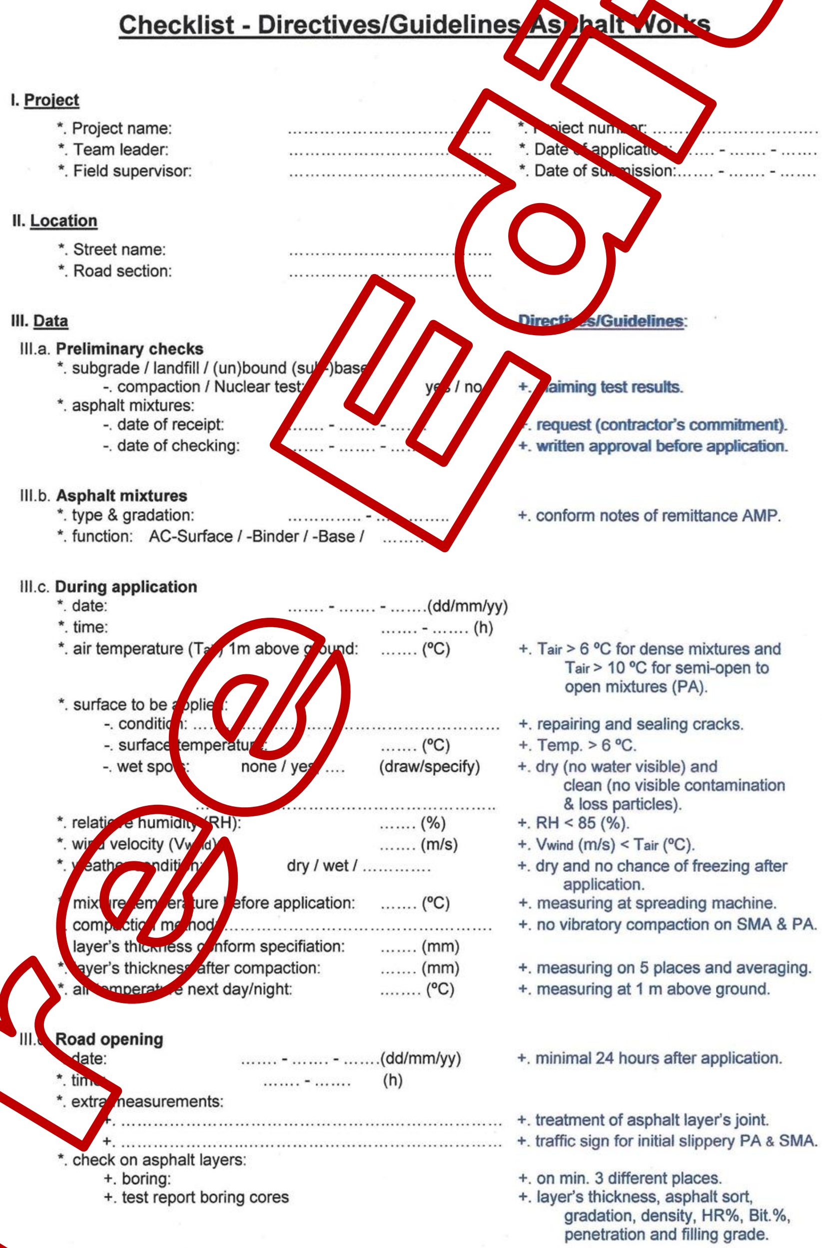
The crucial factor in the tropics is the 'temperature' and this factor has been made variable in the previous chapters. When choosing the bitumen type, the theoretical approaches mentioned should also consider high temperatures and its consequences to the strength, stiffness, longevity/lifespan etc. The suggested software for calculating the construction deals with high temperatures and so is more suitable for tropical areas than, for example, the CBR method. So, Chapters I – III can be used as guidance when constructing an asphalt road in the tropics on a more scientific basis, which should prolong the lifespan.

IV.2. Quality Controlled Road Engineering

As already mentioned in the introduction, the city of Utrecht in the Netherlands has been implementing its own procedure when applying asphalt. This procedure (Quality Controlled Road Engineering) is based on the scientific approach of Asphalt Technology into road construction and implementation has revealed the eventualities of incorrectness in the asphalt mixtures, preventing a lot of mistakes and undesirable situations during application and giving evidence of deficiencies within the construction.

After designing and calculating the road construction, preliminary checks on the subgrade, subbase and base layers are carried out. Preliminary checks on the asphalt mixtures are also done before carrying out the application.

During the application, several items regarding the conditions on the spot are considered and registered, which are necessary to back-analyse the road constructed. All of these items are mentioned in the *Checklist Asphalt Works* where some *directives/guidelines* are also given on the right side (Fig. 53).



Checklist - Directives/Guidelines Asphalt Works

I. Project

*. Project name: .... *. Project number: ....
*. Team leader: .... *. Date of application: .... - .... - ....
*. Field supervisor: .... *. Date of submission: .... - .... - ....

II. Location

*. Street name: ....
*. Road section: ....

III. Data — Directives/Guidelines:

III.a. **Preliminary checks**
*. subgrade / landfill / (un)bound (sub-)base
-. compaction / Nuclear test: yes / no — +. claiming test results.
*. asphalt mixtures:
-. date of receipt: .... - .... - .... — +. request (contractor's commitment).
-. date of checking: .... - .... - .... — +. written approval before application.

III.b. **Asphalt mixtures**
*. type & gradation: .... - .... — +. conform notes of remittance AMP.
*. function: AC-Surface / -Binder / -Base / ....

III.c. **During application**
*. date: .... - .... - ....(dd/mm/yy)
*. time: .... - .... (h)
*. air temperature (T_{air}) 1m above ground: .... (ºC) — +. T_{air} > 6 ºC for dense mixtures and T_{air} > 10 ºC for semi-open to open mixtures (PA).
*. surface to be applied:
-. condition: .... — +. repairing and sealing cracks.
-. surface temperature: .... (ºC) — +. Temp. > 6 ºC.
-. wet spots: none / yes .... (draw/specify) — +. dry (no water visible) and clean (no visible contamination & loss particles).
....
*. relative humidity (RH): .... (%) — +. RH < 85 (%).
*. wind velocity (V_{wind}): .... (m/s) — +. V_{wind} (m/s) < T_{air} (ºC).
*. weather condition: dry / wet / .... — +. dry and no chance of freezing after application.
*. mixture temperature before application: .... (ºC) — +. measuring at spreading machine.
*. compaction method: .... — +. no vibratory compaction on SMA & PA.
*. layer's thickness conform specifiation: .... (mm)
*. layer's thickness after compaction: .... (mm) — +. measuring on 5 places and averaging.
*. air temperature next day/night: .... (ºC) — +. measuring at 1 m above ground.

III.d. **Road opening**
*. date: .... - .... - ....(dd/mm/yy) — +. minimal 24 hours after application.
*. time: .... - .... (h)
*. extra measurements:
+. .... — +. treatment of asphalt layer's joint.
+. .... — +. traffic sign for initial slippery PA & SMA.
*. check on asphalt layers:
+. boring: — +. on min. 3 different places.
+. test report boring cores — +. layer's thickness, asphalt sort, gradation, density, HR%, Bit.%, penetration and filling grade.

Fig. 53: Checklist – Directives/Guidelines for Asphalt Works

The Team Leader and the Field Supervisor of the project are responsible for the correctness of the data filled in. With this kind of data, continuous improvement of the quality of the road construction can be made. In case of failure an analysis can easily be made to trace the causes and to find an adequate solution. As can be seen, the weather conditions are mentioned several times in the checklist, especially regarding water, since water can never mix with oil, the origin of bitumen. To minimise water's negative effect on the attachment between bitumen and the other components, a dry condition during application is necessary for a proper quality of the asphalt mixture.

This checklist with directives/guidelines is designed for the Dutch conditions; however, it is applicable to all regions in the world.
Especially when regarding the high temperatures in tropical areas, one has to realize that the 'hot' asphalt mixtures just after application do not yet possess the strength and stiffness as they are supposed to (see I.2.2). This warmth must be eliminated, which can be done by the implementation of a certain period to cool down, the *cooling down period*. Usually, a minimum period of 24 hours is sufficient before opening the road to traffic.

IV.3. Example of Calculation and Application

An example of a road construction calculation for an imaginary tropical road ("Tropika Road") is presented in Fig. 54.a and 54.b.

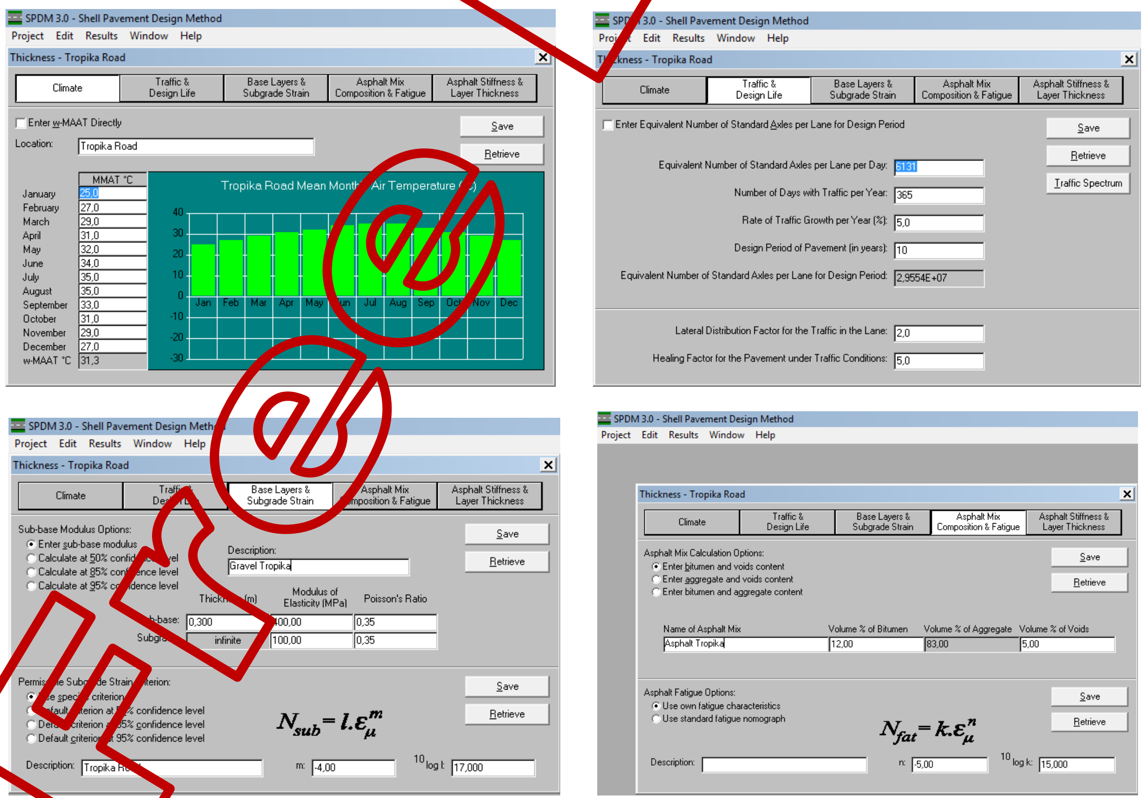
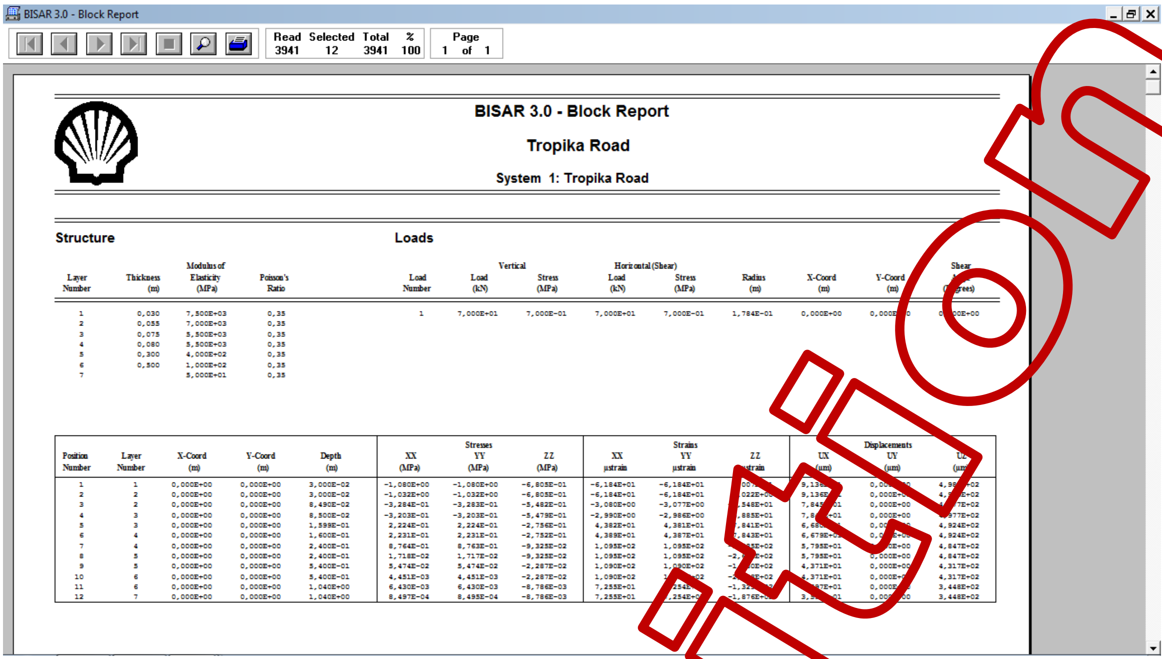


Fig. 54.a: Example of Calculation, "Tropika Road" (source: 15)



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BISAR 3.0 - Block Report

Tropika Road

System 1: Tropika Road

Structure

Layer Number	Thickness (m)	Modulus of Elasticity (MPa)	Poisson's Ratio
1	0,030	7,500E+03	0,35
2	0,055	7,000E+03	0,35
3	0,075	5,500E+03	0,35
4	0,080	5,500E+03	0,35
5	0,300	4,000E+02	0,35
6	0,500	1,000E+02	0,35
7		5,000E+01	0,35

Loads

Load Number	Vertical Load (kN)	Vertical Stress (MPa)	Horizontal (Shear) Load (kN)	Horizontal (Shear) Stress (MPa)	Radius (m)	X-Coord (m)	Y-Coord (m)	Shear [illegible]
1	7,000E+01	7,000E-01	7,000E+01	7,000E-01	1,784E-01	0,000E+00	[illegible]	[illegible]

Position Number	Layer Number	X-Coord (m)	Y-Coord (m)	Depth (m)	Stresses XX (MPa)	Stresses YY (MPa)	Stresses ZZ (MPa)	Strains XX µstrain	Strains YY µstrain	Strains ZZ µstrain	Displacements UX (µm)	Displacements UY (µm)	Displacements UZ (µm)
1	1	0,000E+00	0,000E+00	3,000E-02	-1,080E+00	-1,080E+00	-6,805E-01	-6,184E+01	-6,184E+01	[illegible]	[illegible]	[illegible]	[illegible]
2	2	0,000E+00	0,000E+00	3,000E-02	-1,032E+00	-1,032E+00	-6,805E-01	-6,184E+01	-6,184E+01	[illegible]	[illegible]	[illegible]	[illegible]
3	2	0,000E+00	0,000E+00	8,490E-02	-3,284E-01	-3,283E-01	-5,482E-01	-3,080E+00	-3,077E+00	[illegible]	[illegible]	0,000E+00	[illegible]
4	3	0,000E+00	0,000E+00	8,500E-02	-3,203E-01	-3,203E-01	-5,479E-01	-2,990E+00	-2,986E+00	[illegible]	[illegible]	0,000E+00	[illegible]
5	3	0,000E+00	0,000E+00	1,599E-01	2,224E-01	2,224E-01	-2,756E-01	4,382E+01	4,381E+01	[illegible]	[illegible]	[illegible]	4,924E+02
6	4	0,000E+00	0,000E+00	1,600E-01	2,231E-01	2,231E-01	-2,752E-01	4,389E+01	4,387E+01	[illegible]	6,679E+01	[illegible]	4,924E+02
7	4	0,000E+00	0,000E+00	2,400E-01	8,764E-01	8,763E-01	-9,325E-02	1,095E+02	1,095E+02	[illegible]	5,795E+01	[illegible]	4,847E+02
8	5	0,000E+00	0,000E+00	2,400E-01	1,718E-02	1,717E-02	-9,325E-02	1,095E+02	1,095E+02	[illegible]	5,795E+01	0,000E+00	4,847E+02
9	5	0,000E+00	0,000E+00	5,400E-01	5,474E-02	5,474E-02	-2,287E-02	1,090E+02	1,090E+02	[illegible]	4,371E+01	0,000E+00	4,317E+02
10	6	0,000E+00	0,000E+00	5,400E-01	4,451E-03	4,451E-03	-2,287E-02	1,090E+02	[illegible]	[illegible]	4,371E+01	[illegible]	4,317E+02
11	6	0,000E+00	0,000E+00	1,040E+00	6,430E-03	6,430E-03	-8,786E-03	7,255E+01	[illegible]	[illegible]	[illegible]	[illegible]	3,448E+02
12	7	0,000E+00	0,000E+00	1,040E+00	8,497E-04	8,495E-04	-8,786E-03	7,255E+01	[illegible]	[illegible]	[illegible]	[illegible]	3,448E+02

Fig. 54.b: Result of the Example of Calculation, "Tropika Road" (source: 15)

To ensure a proper result, it is recommended to pick up some of the maximal strains calculated and manually check them on fatigue.
As can be seen, this calculation has resulted in:

*30 mm AC-Surf. on 55mm AC-Bind on 75mm+80mm AC-Base;
*300 mm Base layer;
*500 mm Subbase layer.

Some examples of application of MODUS and DESA for AC-Surf, are shown in Figs. 55-57.

Fig. 55: MODUS on a City Main Road, containing: 30 mm MODUS as AC-Surf. +
45 mm AC-Bind. (0/16) +
60 mm+80 mm AC-Base (0/22) +
250 mm Base layer (Mixed Aggr. 0/40) +
500 mm Subbase layer (Sand)

Fig. 56: DESA on a City Access Road, containing:30 mm DESA as AC-Surf.+
40 mm AC-Bind. (0/16) +
65 mm AC-Base (0/22) +
250 mm Base layer (Mixed Aggr. 0/40) +
500 mm Subbase layer (Sand)

Fig. 57: DESA on Highways

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MODUS Asphalt

DESA Asphalt