CE 410
CIVIL ENGINEERING DESIGN

HIGHWAY PAVEMENTS AND DESIGN

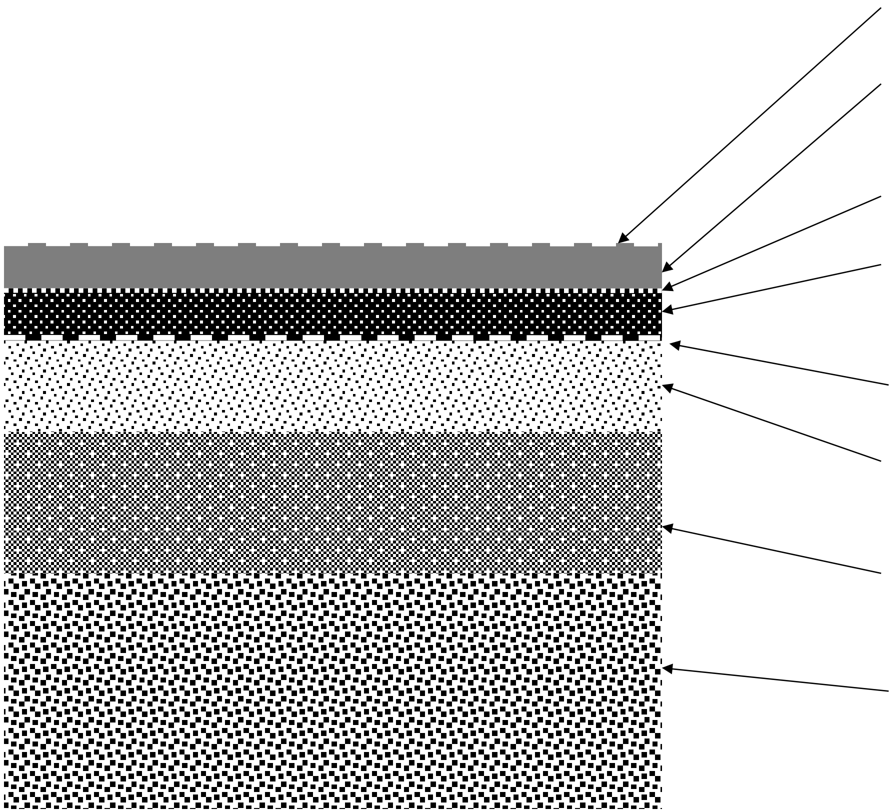
PAVEMENTS AND PAVEMENT DESIGN

- **Pavements according to use and location**
  - Highway Pavements
  - Pavements for parking lots
  - Airport Pavements (runways, taxiways and aprons)
  - Pavements of pedestrian ways

- **Pavements according to type**
  - Flexible Pavements (Asphaltic surface)
  - Rigid Pavements (PCC surface)
  - Composite pavements

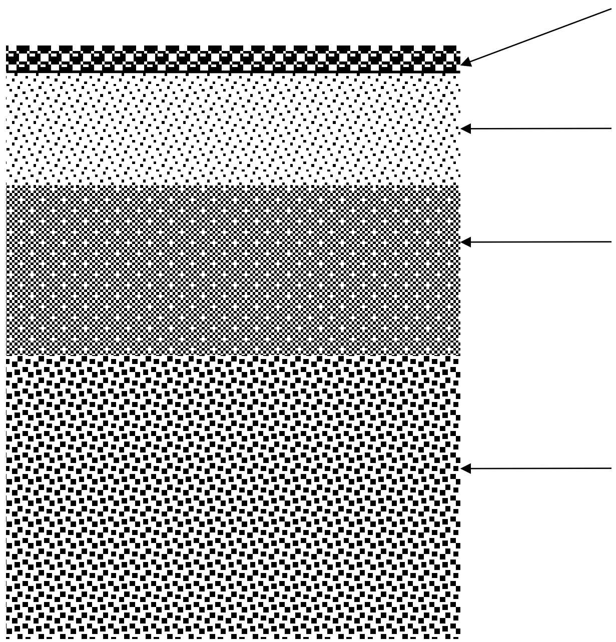
A) Flexible Pavements

i) Asphalt concrete surfaced



- Seal coat (spray application)
- Wearing course (dense asphalt-aggregate mix)
- Tack coat (spray application)
- Binder course (dense asphalt-aggregate
- Prime coat
- Base course (untreated or treated granular mat.)
- Subbase course (granular material)
- Subgrade (original soil or improved soil)

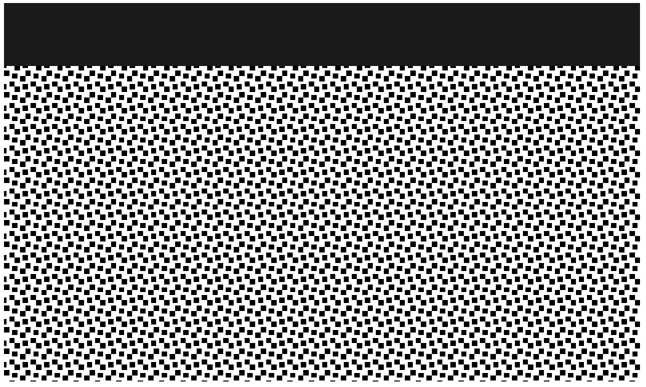
ii) Surface Treatment



- Surface dressing (treatment)
- Base course
- Subbase course
- Subgrade soil

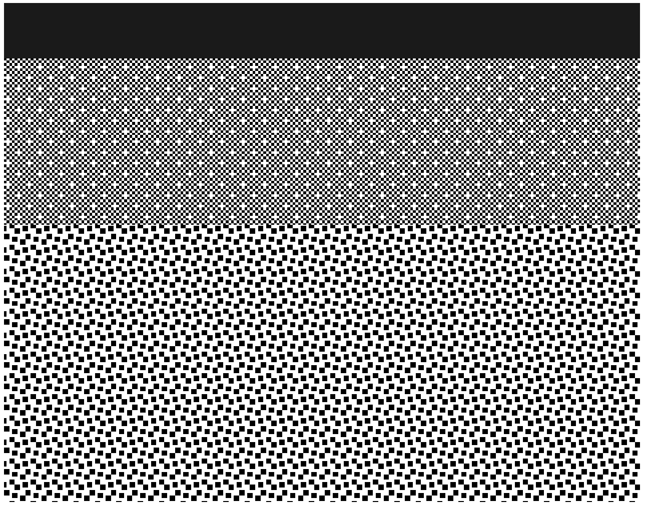
B) Rigid Pavements (plain concrete with dowel bars and temperature steel or reinforced concrete)

i) Without subbase



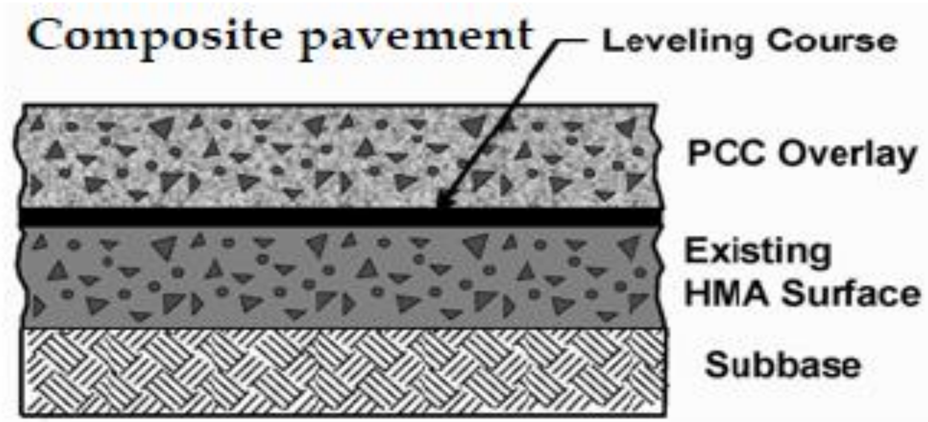
- PCC surface (jointed slabs)
- Stabilized or Improved soil

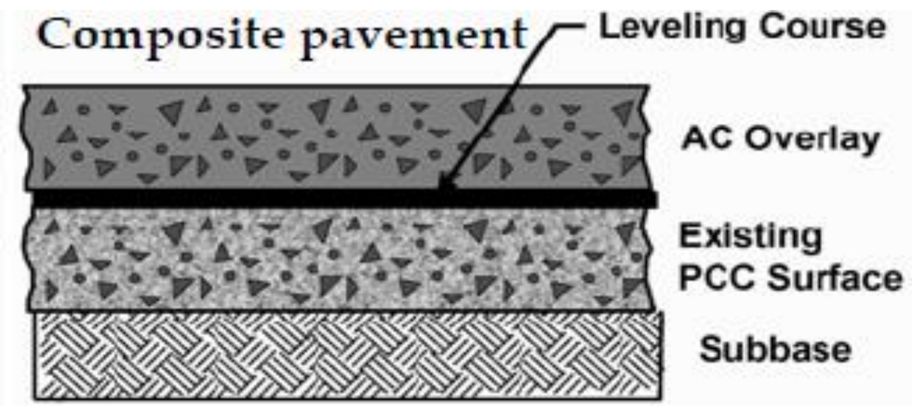
ii) With subbase



- PCC surface (jointed slabs)
- Subbase course (granular or treated)
- Soil (original or improved)

C) Composite Pavements





PAVEMENT PERFORMANCE AND PAVEMENT DISTRESSES

- **Requirements for Pavement Structure**
  - Sufficient thickness to spread loading to a pressure intensity tolerable by subgrade
  - Sufficient strength to carry imposed stress due to traffic load
  - Sufficient thickness to prevent the effect of frost susceptible subgrade
  - Pavement material should be impervious to penetration of surface water which could weaken subgrade and subsequently pavement
  - Pavement materials should be non-frost susceptible
  - Pavement surface should be skid resistant
  - Pavement surface material should be durable

- **Distresses in Pavements**

  Pavement distress can be defined as flaws such as cracks, potholes, material loss, etc. in a pavement structure

  Distress types according to cause:
  - Load-related
  - Temperature-related
  - Moisture-related
  - Failure due to frost heave
  - Age-related

- **Distresses in Flexible Pavements**

  A) Load related distresses

  i) Alligator or fatigue cracking

  ii) Permanent deformation or rutting

  B) Temperature cracks

  C) Moisture related distresses

  i) Strength loss of material

  ii) Stripping

  D) Failure due to frost heave

  E) Distresses due to aging

A) Load related distresses:

i) <u>Alligator or fatigue cracking:</u> Serious of interconnected surface cracks caused by fatigue failures in the asphalt bound layer or stabilized base course layer by repeated loading.

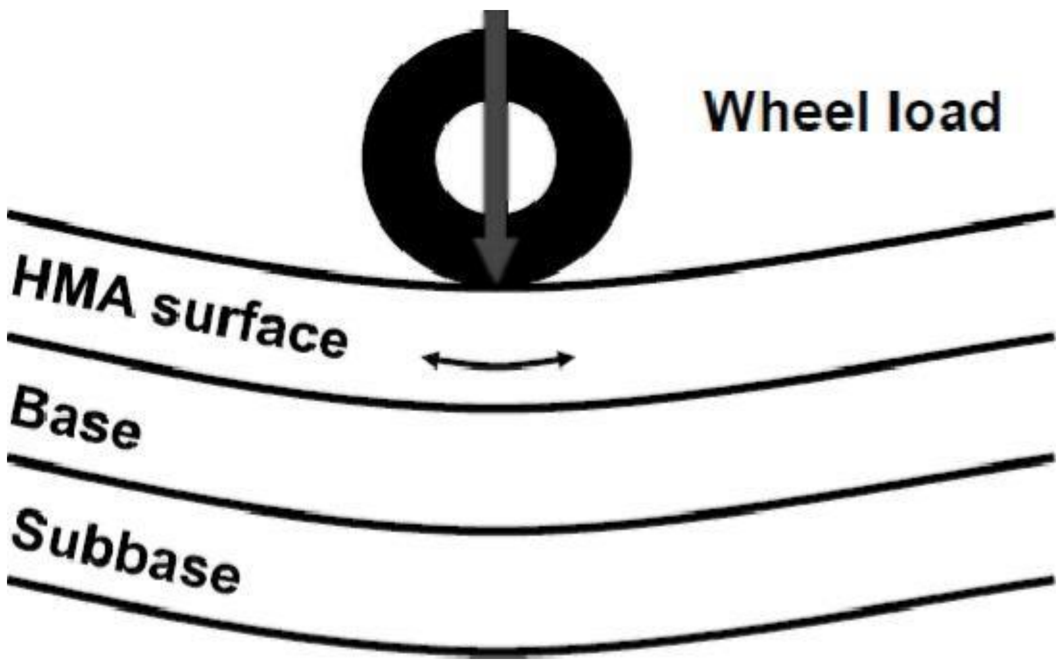


Figure: Mechanism for fatigue cracking

Figure: Fatigue cracks on an asphalt pavements

ii) Permanent deformation or rutting: Surface depression in the form of consolidation or lateral movement of the materials which can occur in any pavement layer.

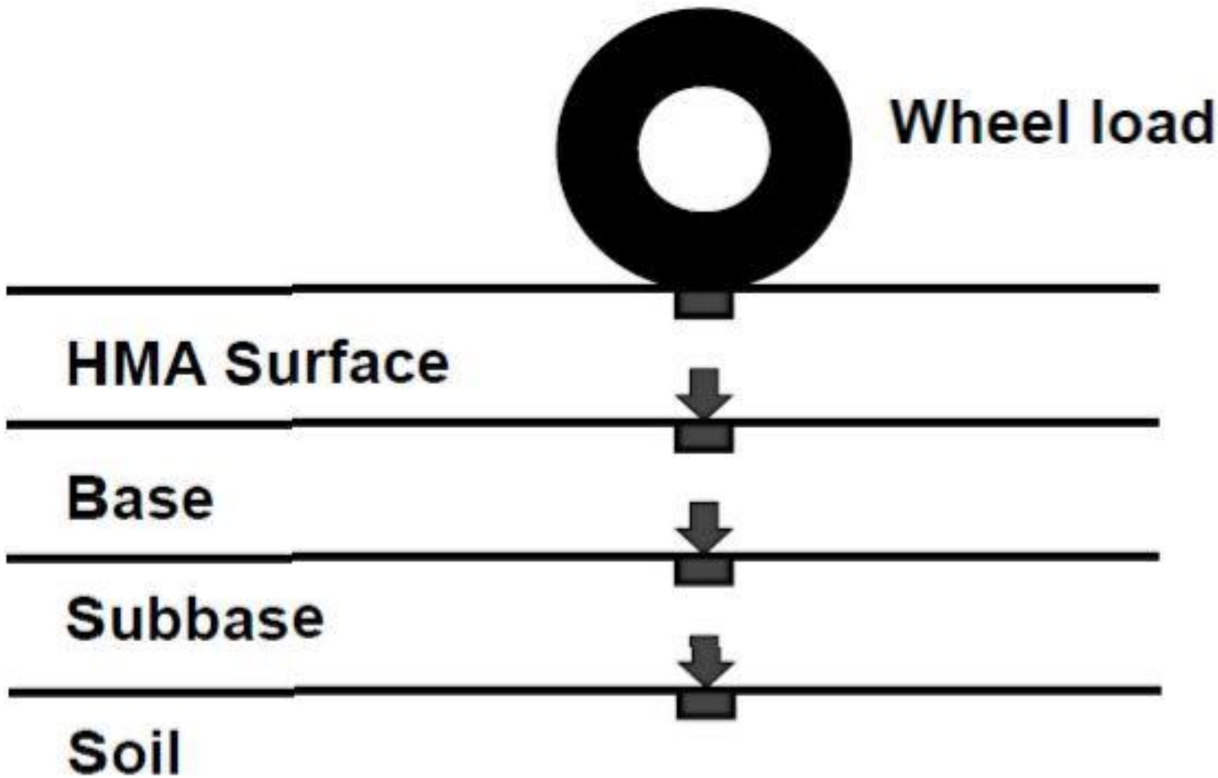


Figure: Mechanism for rutting

Figure: Severe rut formations on an asphalt pavement

B) Temperature cracks: formation of transverse cracks due to shrinkage of asphalt surface layer and daily cycling temperature changes

Figure: Transverse temperature cracking

C) Moisture related distresses:

i) <u>Strength loss in granular layers :</u> weakening of internal structure by erosion and lubricating effect of moisture

ii) <u>Strength loss in asphalt bound layers:</u> stripping due to loss of adhesion between asphalt binder and aggregate

D) Frost heave:

Strength loss due to freezing-thawing cycles by seasonal changes in pavement sub-layers (base, subbase or subgrade)

E) Distresses due to aging:

Cracking resulting from hardening of asphalt surface layer by the environmental effects (sun rays, heat snow, rain, air)

- **<u>Distresses In Rigid Pavements</u>**

  A) Load related distresses

  i) Fatigue cracking

  ii) Faulting

  B) Temperature related distresses

  i) Mid-slab cracking

  ii) Spalling

  iii) Blowup

  D) Moisture related distresses:

  i) Pumping

  ii) D-cracking

A) Load related distresses

i) <u>Fatigue cracking:</u> fatigue failures in PCC layer especially around slab shoulders under by repeated loading.

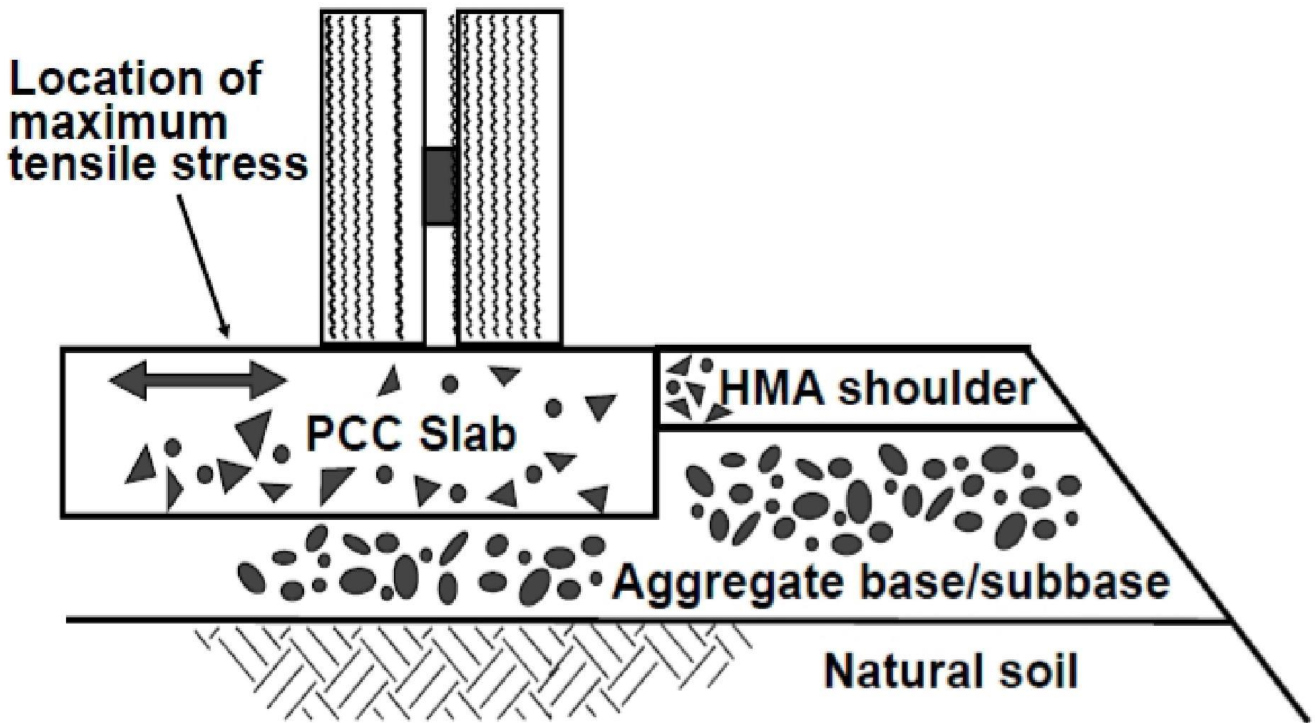


Figure: Mechanism in fatigue failure

ii) Faulting: cracks or disintegration at joints under traffic loading because of moisture infiltration

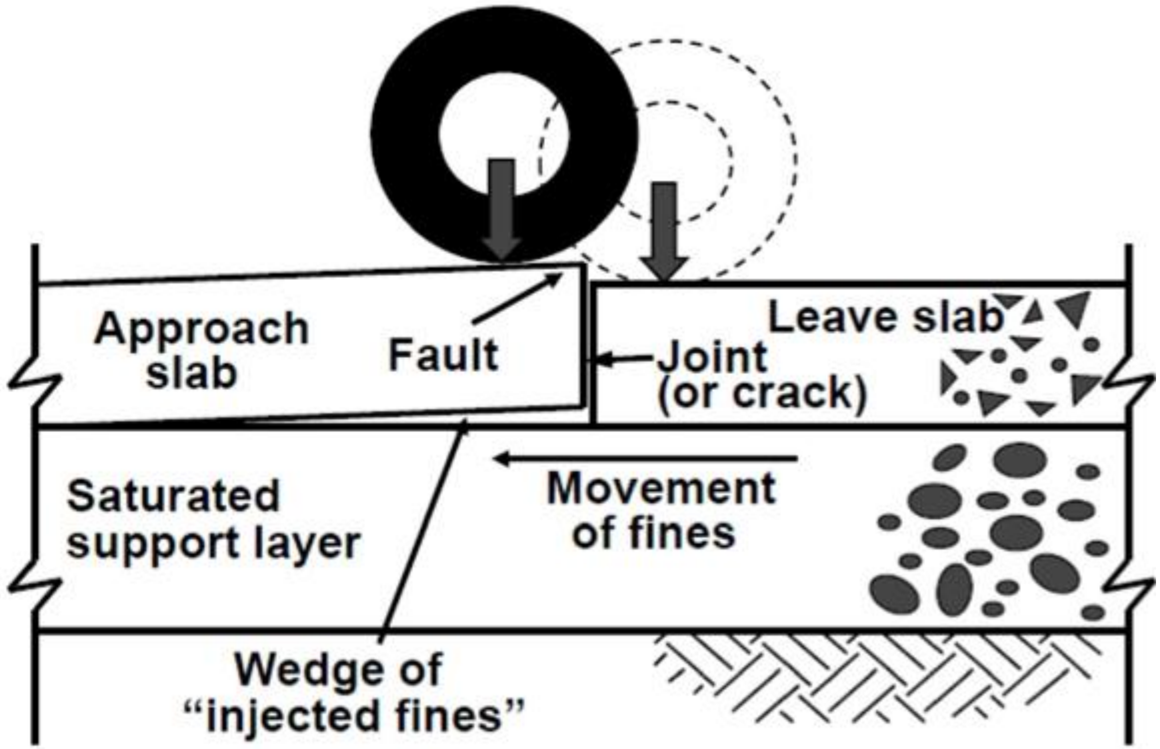


Figure: Mechanism in faulting

B) Temperature related distresses

i) Mid-slab cracking: Transverse cracks by the shrinkage of PCC layer

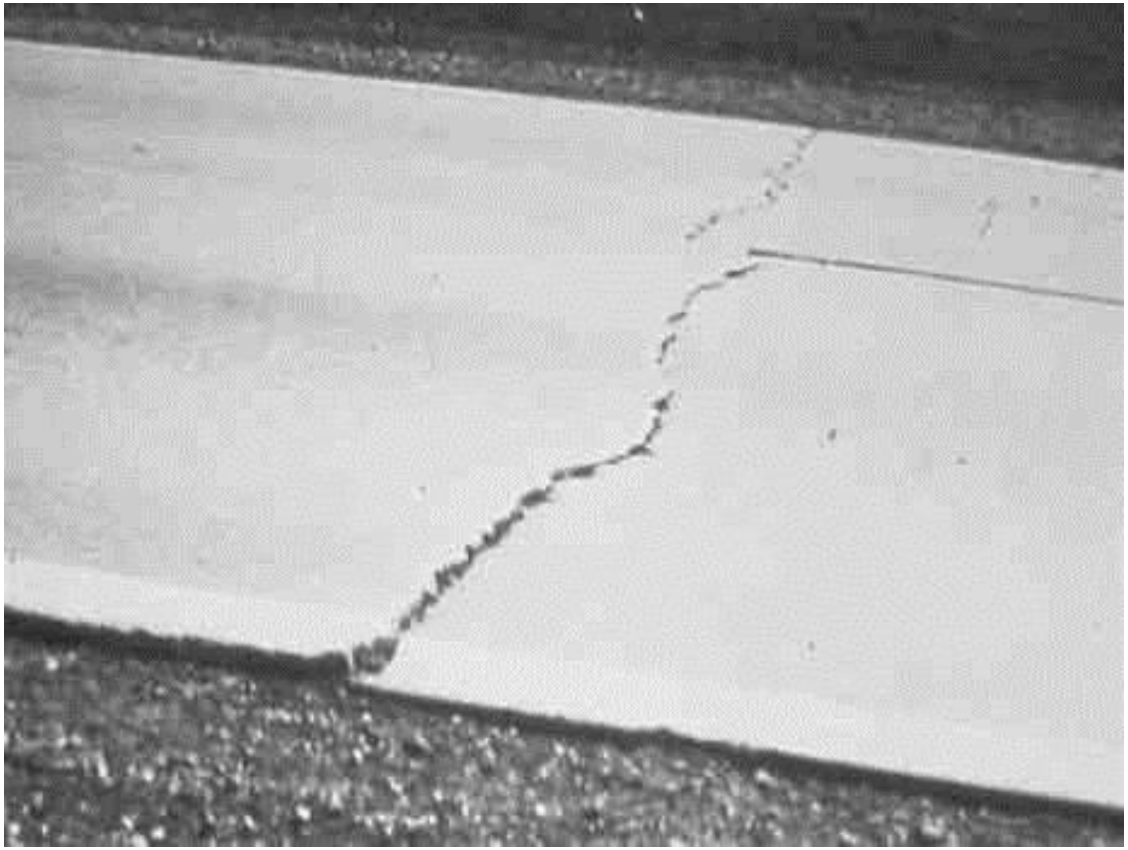


Figure: Mid-slab cracking

ii) Spalling: Joint failure by the extension of slabs due to high temperature

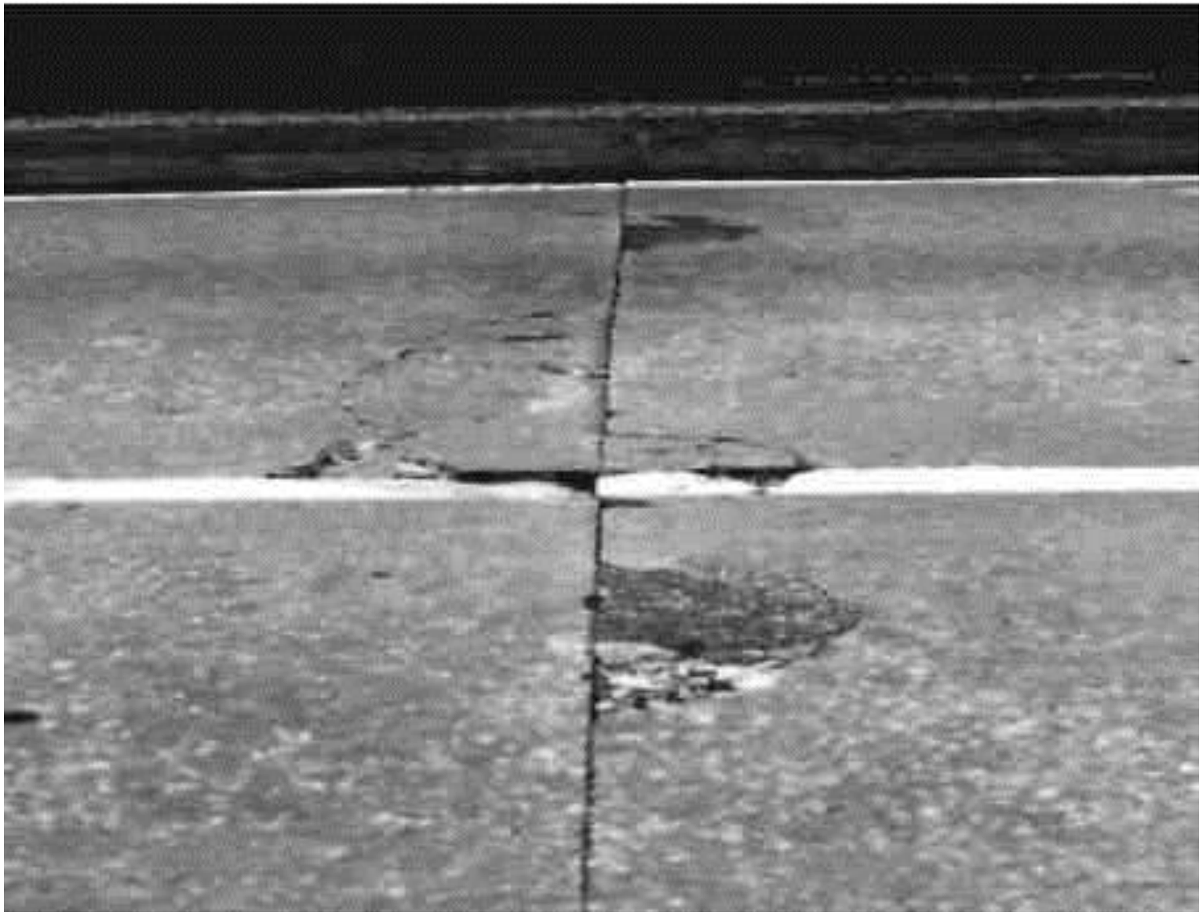


Figure: Spalling at joints and corners

iii) Blowup: Significant failures in PCC slabs because of large extensions under high temperature

Figure: Blowups at transverse joints

C) Moisture related distresses

i) Pumping: Failures by the erosion of fines underneath joints under the effect of repeated loading

ii) D-cracking: Cracking due to expansive forces generated within the pores of PCC slab by freezing of water (ice lenses in voids)

Figure: D-cracking along transverse joints

PAVEMENT DESIGN PROCESS

- **Functions of the Pavement Structure**
  - Reduce and distribute the traffic loading so as not to damage the subgrade
  - Provide safe, smooth and comfortable ride to road users without undue delays and excessive wear & tear
  - Meet environmental and aesthetics requirements
  - Limited noise and air pollution
  - Reasonable economic

- **Basic factors to be considered in pavement design process**
  - Magnitude and frequency of the load
  - Behavior and supporting capacity of subgrade under equilibrium conditions
  - The resilient or fatigue capacity of the foundation
  - The behavior and load distribution capacity of components of pavement
  - The resilient or the fatigue capacity of the pavement

- **Requirements for pavement Design process**
  - Selection of pavement type and materials
  - Proportioning of materials (mixtures)
  - Structural design (determination of layer thicknesses)

- **Methods of structural design**
  - Empirical Methods
  - Rational Methods (Mechanistic)
  - Mechanistic-empirical methods

- **Empiricism**

  The relations are empirical, based on little theory. They largely depend on experience, observations.

  The form of the empirical relation in the general sense:

  PSF = f (W, RSF, CRF, PCF)

  Where;

  PSF : Pavement structure factors (layer thicknesses and materials)

  W : Traffic

  RSF : Roadbed soil factors

  CRF : Climate related factors

  PCF : Pavement condition factors

  The relation can be expressed in an other form as:

  W = f (PSF, RSF, CRF, PCF)

- **Rationalism (Mechanistic approaches)**
  - Theories are used to predict the failure or distress parameters
  - Pertinent material properties necessary for the theory selected are evaluated and incorporated.
  - The relationship between the magnitude of the parameter in question to the failure or performance level is established.
- **Empirical-Mechanistic Methods**

  Non of the current design methods is fully empirical or fully theoretical (mechanistic). Modern design methods use both empiricism and theoretical approaches.

- **Factors effecting the performance of Pavements**

  1) Traffic
  - Axle load and tire pressure
  - Repetition of load
  - Speed
  - Axle (gear) and wheel configuration

  2) Material
  - Properties and classification of subgrade
  - Properties and classification of base and/or subbase
  - Properties and quality of surface courses

- **Factors effecting the performance of Pavements (continued)**

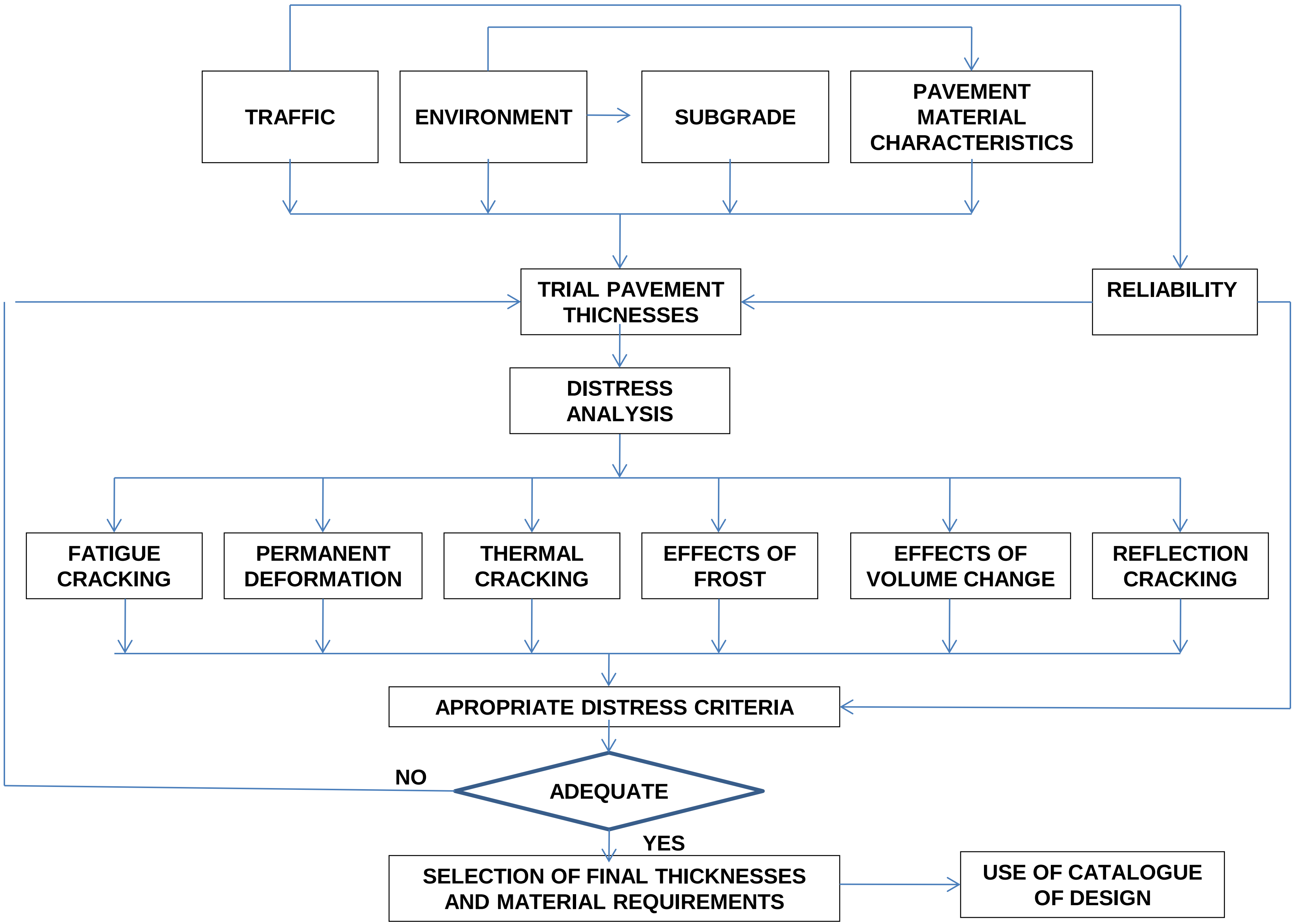
  <u>3) Climate</u>

  - Amount and seasonal distribution of rainfall
  - Level of frost depth and heave
  - Temperature regime (hourly seasonal variation)
  - Freezing and thawing periods

  <u>4) Geometry and existing situation</u>

  - Traffic distribution across the pavement (lane distribution)
  - Cut and fill sections
  - Landslide and other related problems
  - depth of soft deposits
  - Ground water table

BASIC PAVEMENT DESIGN FRAMEWOPRK



- **Traffic parameters for highway pavements**
  - Gross load and tire pressure
  - Axle configuration
  - Repetition

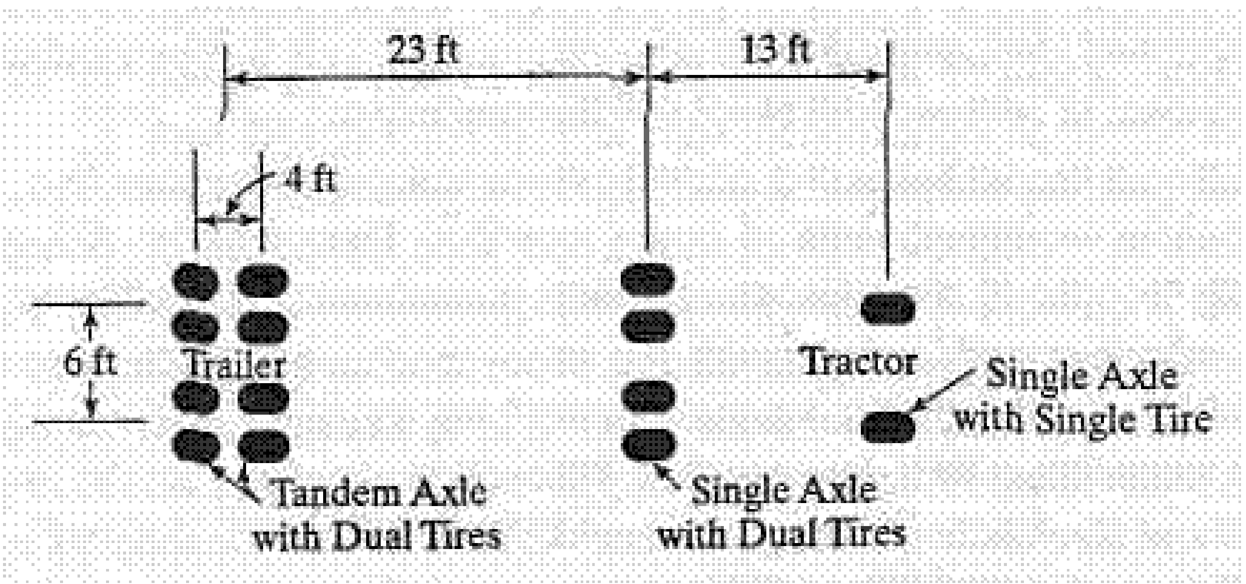


Figure: Wheel configuration for a typical semi-trailer unit

- **Pavement Rating systems : (Pavement surface condition)**

  Serviceability : Pavement serviceability can be briefly defined as the ability of a pavement section to serve traffic in its current condition

- Serviceability index (SI):

  In order to define serviceability in a quantitative manner a rating scale should be established to correlate quality of the surface (riding quality and comfort) to some Index numbers

- In general it will be function of roughness + surface distresses. Pavement serviceability index correlates subjective rating of a section with field measurements covering both roughness and distresses.
- Roughness Index: function of roughness characteristics

AASHTO FLEXIBLE PAVEMENT DESIGN (1993)

The basic design equation is exactly in the following form:

W x Fr= f (PSF, RSF, CRF, PCF)

Where, Fr : reliability factor

$$\mathrm{Log}(w_{18} * Fr) = 9.36Log(SN+1) - 0.20 + \frac{Log\left(\frac{P_0 - P_t}{4.4 - 1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32Log(Mr) - 8.07$$

w_{18} : Traffic in terms of equivalent single axle load (ESAL) for performance period

SN : Structural number (defining layer thicknesses and load carrying capacities)

P_0 , Pt : Initial and terminal serviceability index values (defining performance)

Mr : Roadbed resilient Modulus (psi)

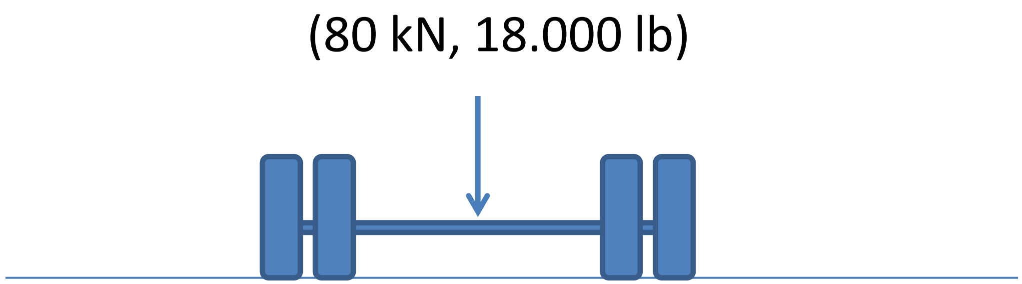
Fr : Reliability factor ($Fr = 10^{-Z_R * S_0}$)

Z_R : Standard normal deviate

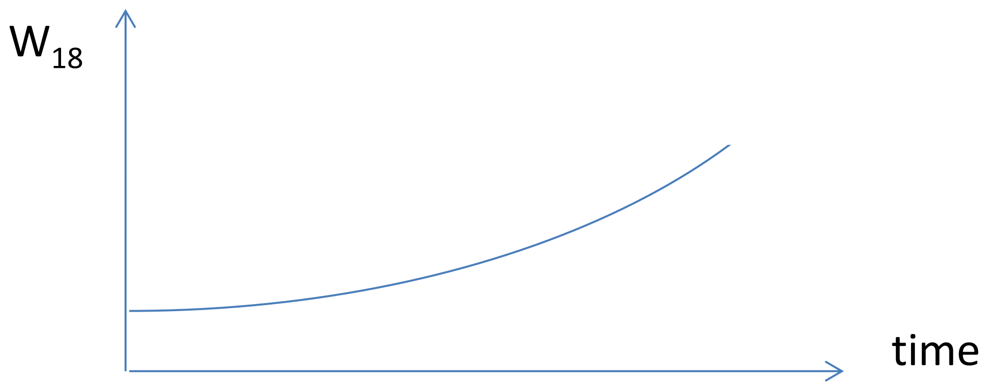
S_0 : Overall standard deviation

- **Standard axle load and ESAL (w_{18})**

  Standard axle load: 80 kN standard axle load composed of dual wheels.



  For the base year, traffic is determined in terms of repetitions of all axle type and load categories. Then they are converted to equivalent repetitions of standard axle load.



- **Roadbed resilient modulus**

  Roadbed resilient modulus values are obtained from laboratory resilient modulus tests (AASHTO T274) on representative samples in stress and moisture conditions those of the primary moisture seasons.

  Effective roadbed soil resilient Modulus **(M_R)** is calculated by a method that incorporates seasonal relative damages.

- **Structural number**

  $SN = a_{1*}m_{1*}D_1 + a_{2*}m_{2*}D_2 + a_{3*}m_{3*}D_3 + a_{4*}m_{4*}D_4 + a_{4*}m_{4*}D_4$

  Where,

  a_i : Layer coefficient of i^{th} layer (tabulated data for mat. Types)

  m_i : drainage coefficient of i^{th} layer (1.00 for asphalt bound layers)

  D_i : thickness of i^{th} layer (inch)

- **Material characterization and layer coefficients:**

  The materials are characterized by the parameters that expolains the behavior under loading. Several tests can be applied insitu or on laboratory samples to determine such material parameters.

Material	Parameters
Granular base or subbase	:CBR, R-value, Texas triaxial, modulus
Cement treated base	: Unconfined com. Strength, modulus
Bituminous treated base	: Marshall stability, stiffness modulus
Asphalt concrete	: Elastic resilient modulus (68 ^{o}F) .

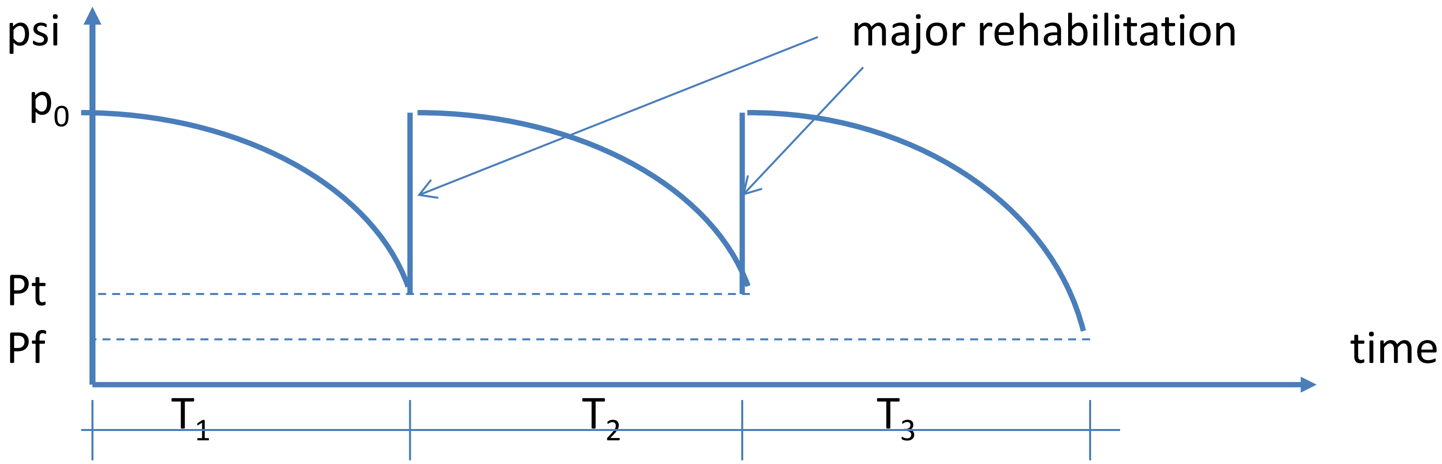
For each material type available charts or tabular data will be used to obtain layer coefficients.

- **Performance rating (serviceability)**

AASHTO established the following serviceability scaling

- <u>Index</u> <u>qualitative definition</u>

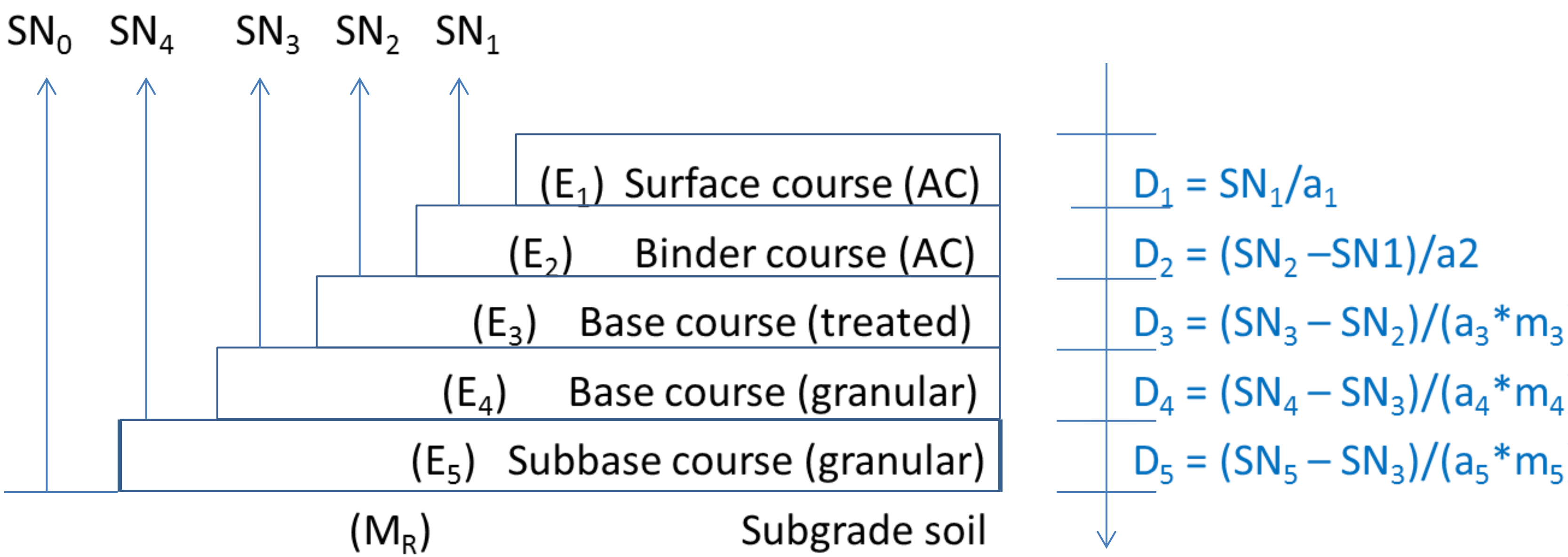
Index	qualitative definition
0	: impassible surface
0 – 1	: very poor
1 – 2	: good
2 – 3	: fair
3 – 4	: good
4 – 5	: very good
5	: excellent (practically impossible)



Design thicknesses:

$$\mathrm{Log}(w_{18} * Fr) = 9.36Log(SN + 1) - 0.20 + \frac{Log\left(\frac{P_0 - P_t}{4.4 - 1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32Log(Mr) - 8.07$$

The design equation should be solved a number of times depending on number of layers. Say, number of layers is five. Then it follows:

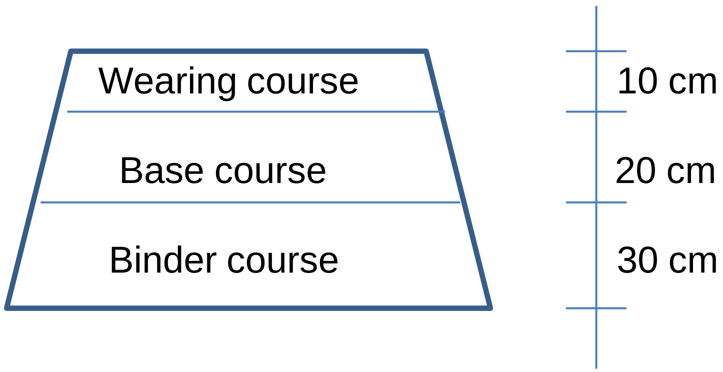


Note : - Solve the equation by taking M_R = M_R to obtain SN_0

- Solve the equation by taking $M_R = E_2$ to obtain SN_1 . And so on.

- Example:

For the below given flexible pavement cross-section calculate structural number SN (AASHTO)



<u>Layer coefficients</u>

wearing course : 0.42

Base course : 0.14

Subbase course : 0.11

Solution:

$$SN = \sum a_i m_i D_i$$

$$= 0.42 \times 1.0 \times 10/2.54 + 0.14 \times 1.0 \times 20/2.54 + 0.11 \times 30/2.54$$

$$= 4.06$$

- Example

The AASHTO Flexible design equation

$$\text{Log}(w_{18} * Fr) = 9.36Log(SN+1) - 0.20 + \frac{Log\left(\frac{P_0 - P_t}{4.4 - 1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32Log(Mr) - 8.07$$

is reduced to the following when the design inputs are inserted in the equation:

$$13.75 = 9.36 \text{ Log } (SN+1) - \frac{0.1526}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32\text{Log } (MR)$$

İf roadbed resilient modulus is 5000 psi, What is SN of the pavement (Answer 3.89)

MECHANISTIC-EMPRICAL DESIGN

- **Takes into account distress types that cause failure.**

- **Takes into account material characterization and behavior**

- **Appropriate distress criteria is incorporated into design to relate traffic loading to pavement life.**

- **The most critical distress types are:**

  - Fatigue of asphalt concrete

  - Rut formation due to permanent deformation of granular layers and subgrade soil.

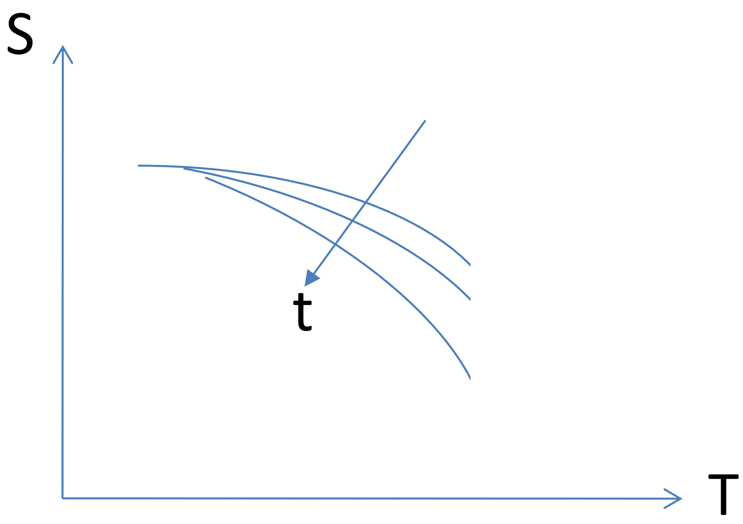
  - Low temperature cracking

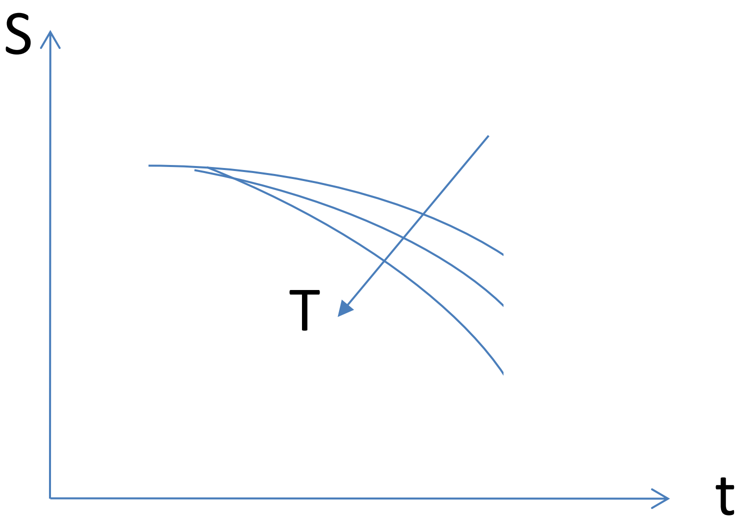
- **Stiffness modulus of asphalt concrete**

  Asphalt concrete is viscoelastic material. At the same time it is a termoplastic material. Its behavior under loading depens on both time of loading and temperature.

  Stiffness modulus of asphalt concrete defined as the rati of stress to strain is expressed by:

$$S_{mix}\,(t, T) = S_{t,T} = (\sigma / \varepsilon)_{t,T}$$





Fatigue and Permanent deformation (rut) subsystem

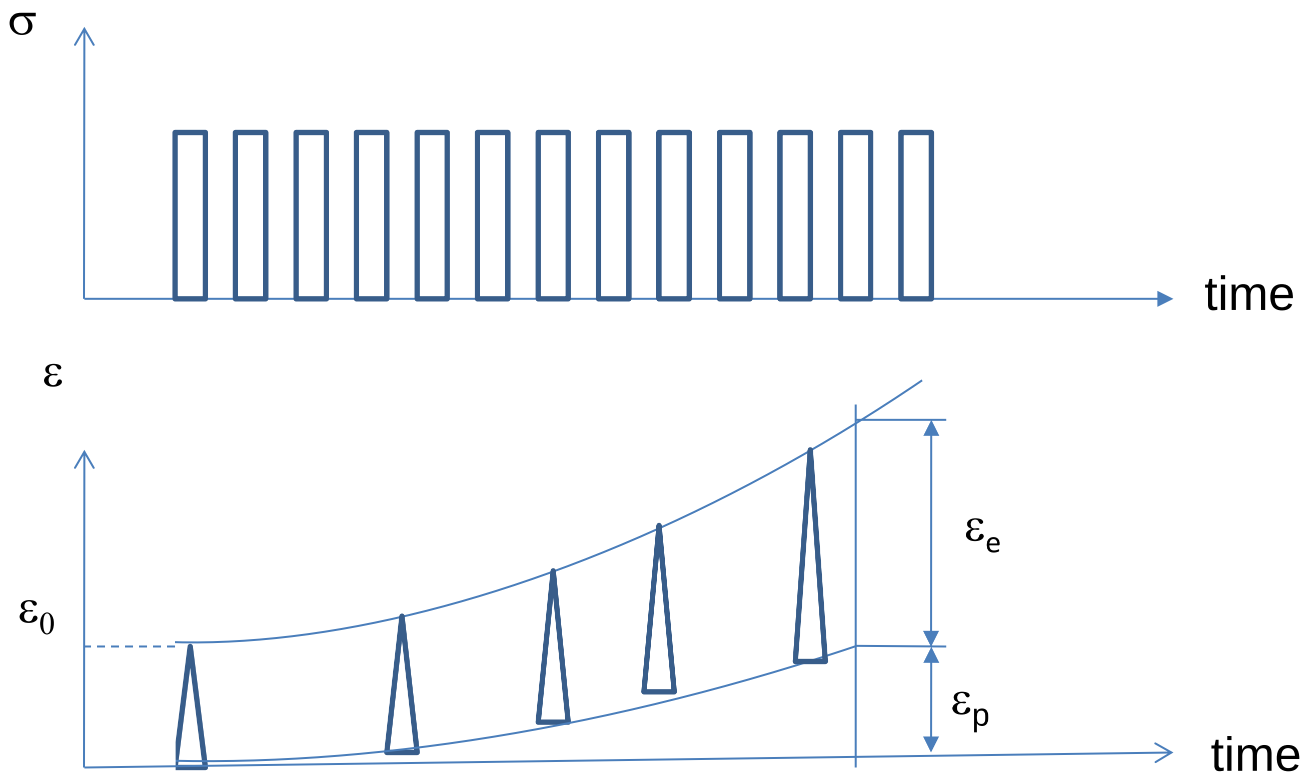
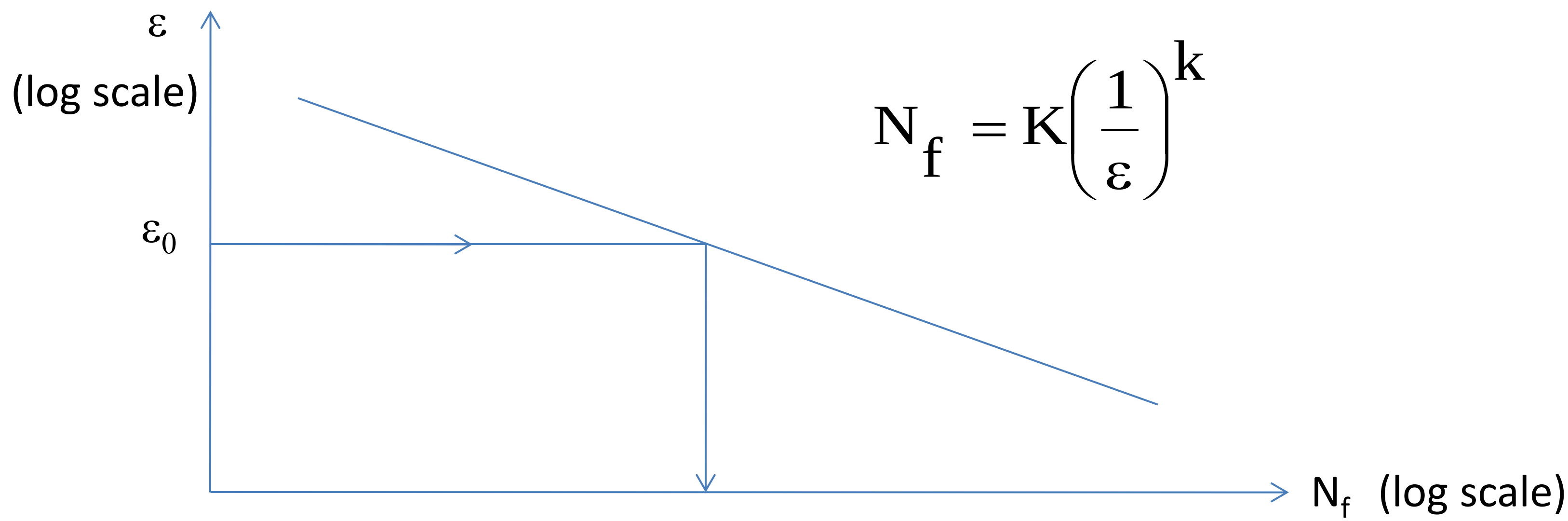
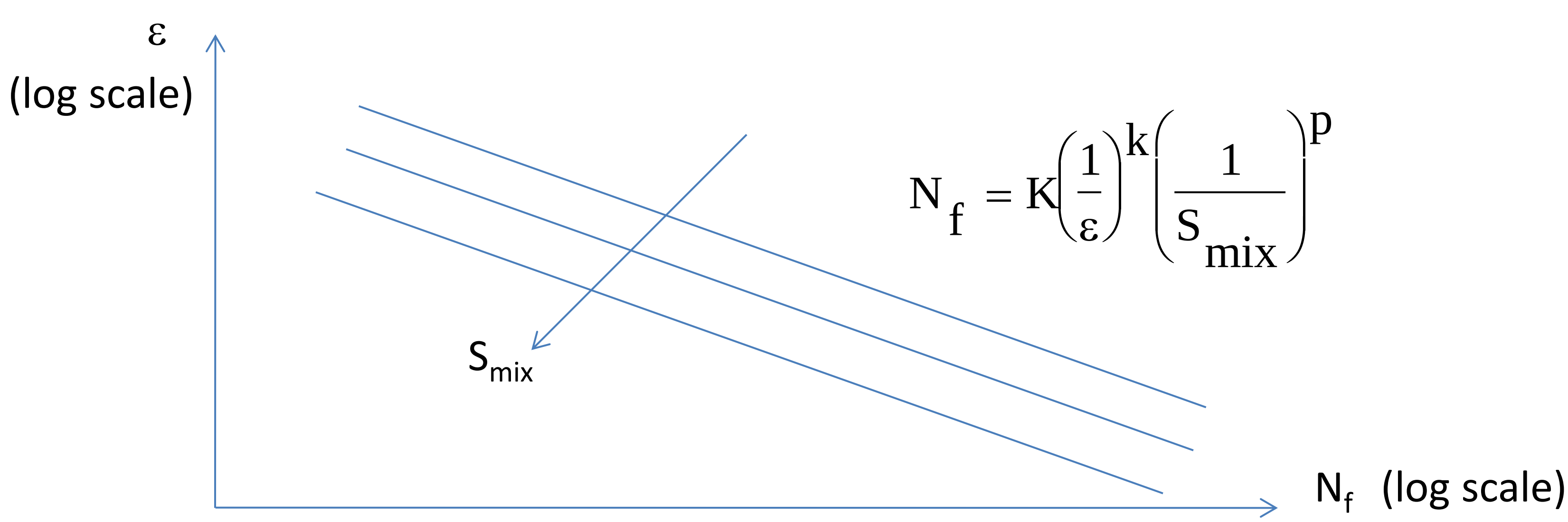


Figure : Behavior of asphalt concrete under controlled stress repeated loading

- **Fatigue of asphalt concrete under repeated loading**



$$N_f = K\left(\frac{1}{\varepsilon}\right)^k$$



$$N_f = K\left(\frac{1}{\varepsilon}\right)^k\left(\frac{1}{S_{mix}}\right)^p$$

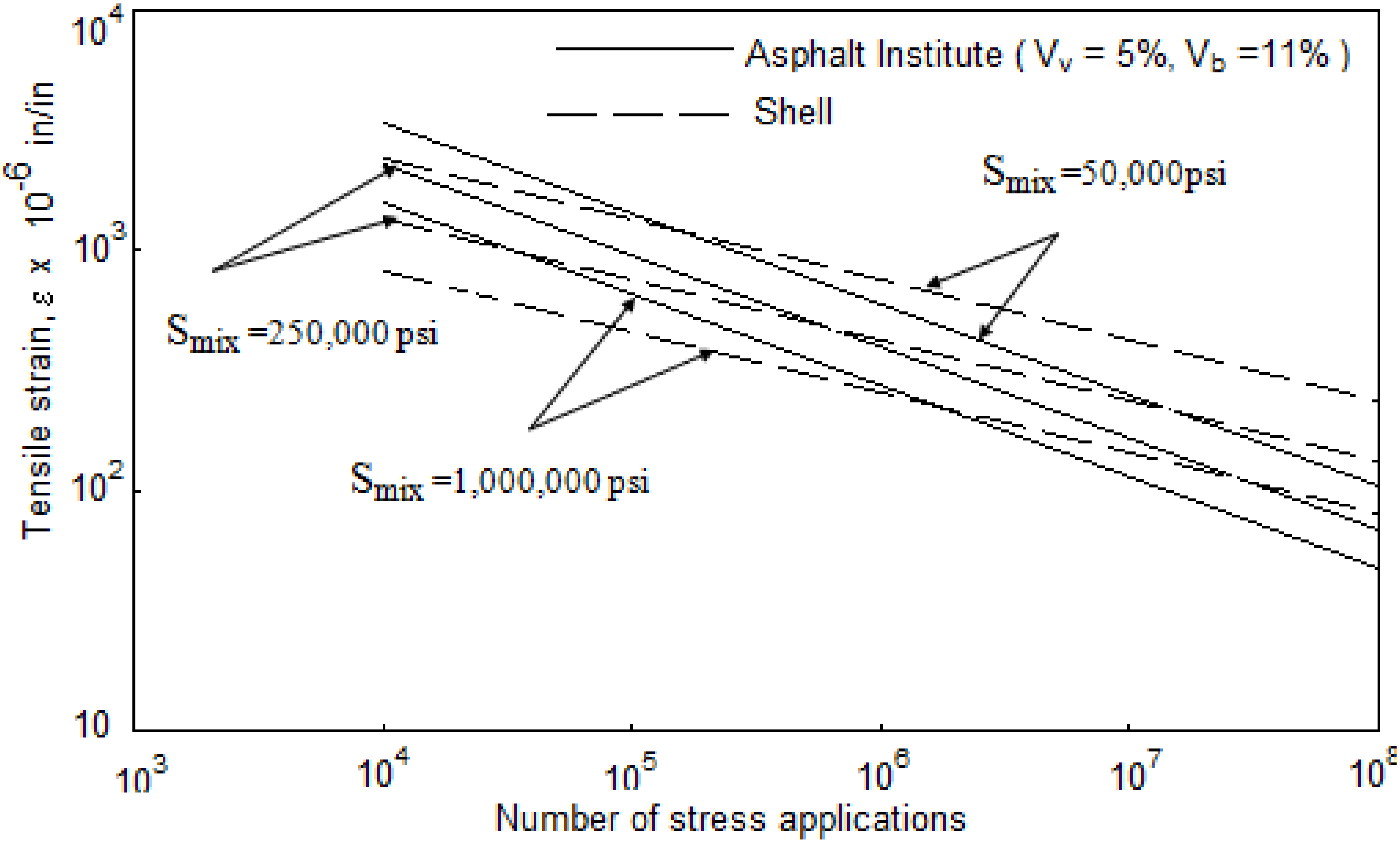
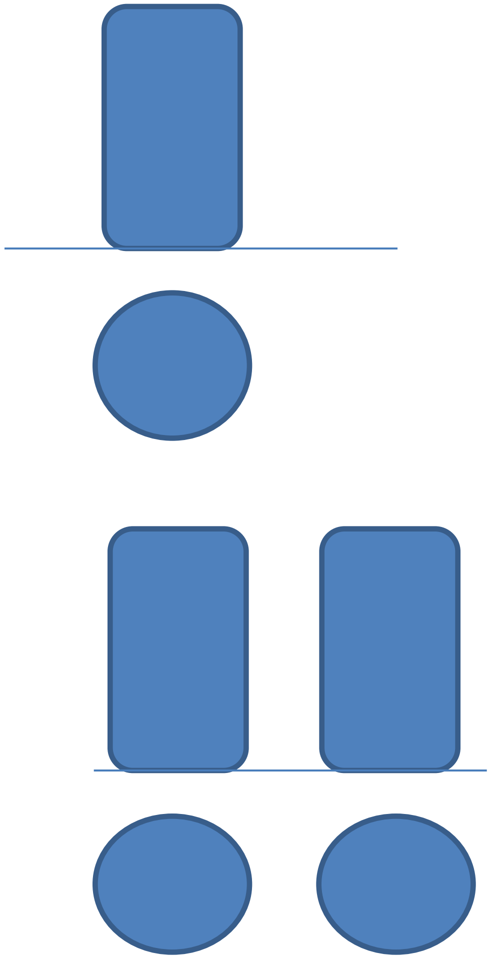
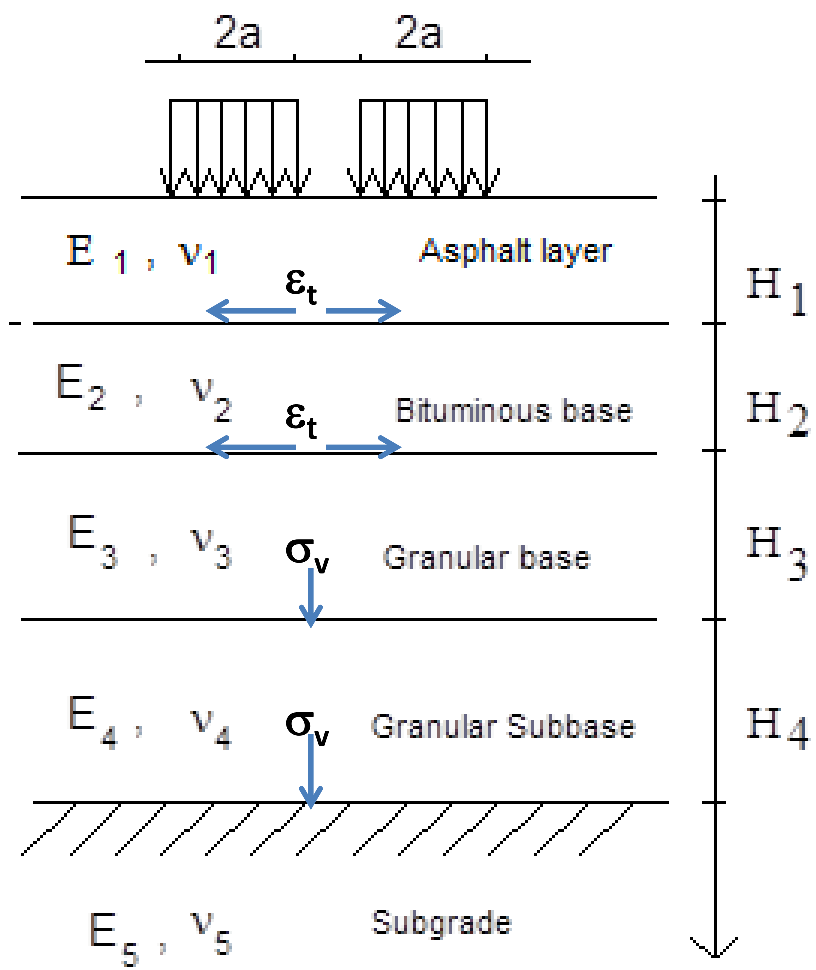


Figure: Comparison of Asphalt institute and Shell fatigue curves

Structural modelling and pavement responses



Circular tire imprints
Single axle single or dual tires,
tandem axle single oor dual tires.



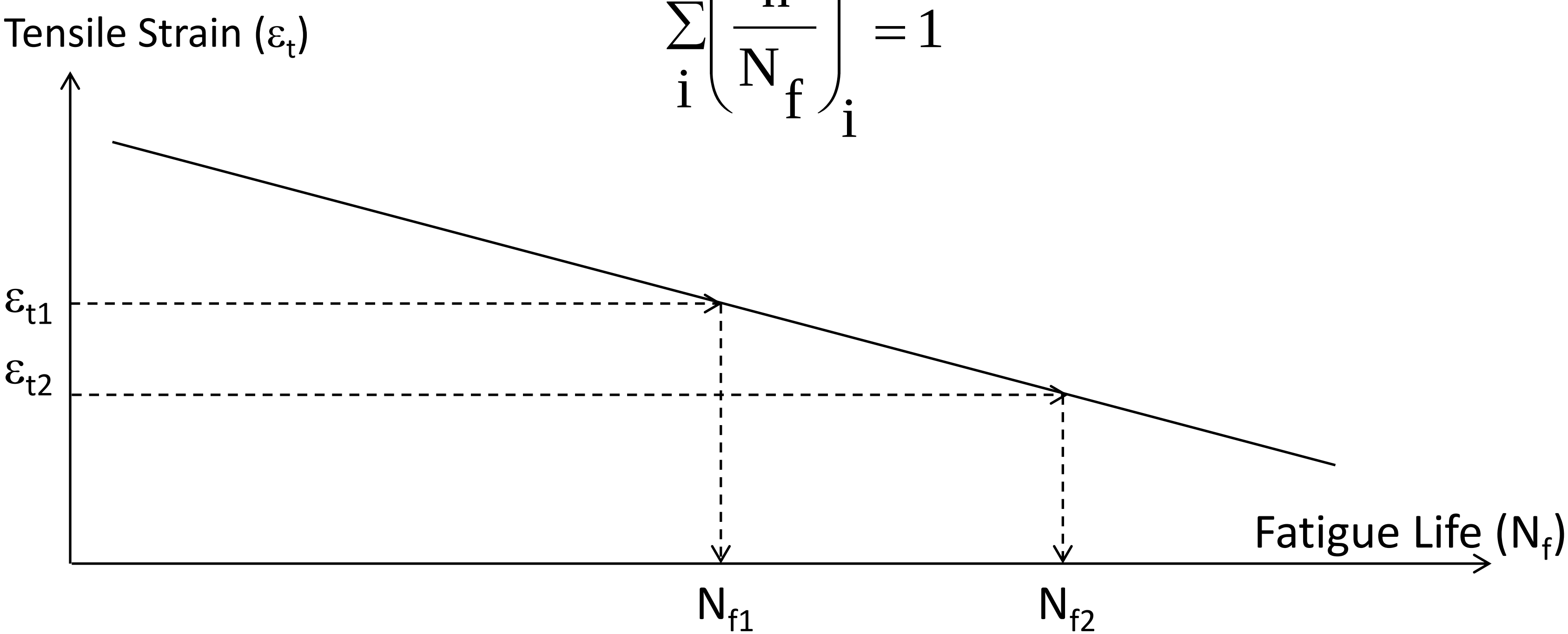
Elastic layered system

- **Fatigue life prediction (Miner's Hyphothesis)**

  Miner's Hyphothesis (Summation of cumulative damage ratios)

  Where, n is the actual number of load repetition for i[th] load condition

$$\sum_{i}\left(\frac{n}{N_f}\right)_i = 1$$



Load level	Stiffness	Tensile Stress	Nf	n	n/Nf
L_1	S_1	150×10^{-6}	9.2×10^{6}	5700	0.00062
L_1	S_2	320×10^{-6}	4.1×10^{6}	20.000	0.00490
…….	……..	…….	……..	…….	…….
L_2	S_1	……..	……..	……..	……..
L_2	S_2	……..	…….	…….	…….
………	…….	……..	…….	…….	…….

$\Sigma = \mathbf{0.750}$

This means 75 % of the life is exhausted. In other words the remaing life is 25 %.

- **Rut formation**

  Determine the permanent deformation as a function of load repetition for each constituent material based on laboratory tests.

  Then, rut depth can be calculated as follows:

$$\Delta = \int_{z} \varepsilon_p \, dz$$

  Where;

  Δ : permanent surface deformation (rut depth)

  ε_p : permanent strain as a function of depth

  z : depth

References:

1) AASHTO, Guide for Design of Pavement Structures (1993)
2) Yang H. Huang, *Pavement Analysis and Design,* Pearson, 2004
3) Lecture notes, *CE 4001- Introduction to Pavement design and Pavement Performance*