Advanced Pavement Design

Postgraduate Studies
Highways Engineering

Prepared By:

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Syllabus of:
Advanced Pavement Design

Syllabus of Advanced Pavement Design

1. **Principles of Pavement Design: .... (1.5 Weeks)**
   - 1.1. Types of Pavements
   - 1.2. Concept of Pavement Performance,
   - 1.3. Design Factors.
   - 1.4. Structural and Functional Failures of Pavements
   - 1.5. Vehicle Types
   - 1.6. Axle Configurations
   - 1.7. Contact Area Shapes and Contact Stress Distributions
   - 1.8. Concept of Standard Axle Load
   - 1.9. Vehicle Damage Factor
   - 1.10. Estimation of Design Traffic
2. **Flexible Pavement...(2.5 Weeks)**

2.1. Analysis of: Stress, Strain and Deflection in Flexible Pavement
2.1.1. One Layer System
2.1.1.1. Point loading
2.1.1.2. Circular Loading
2.1.1.3. Methods of solutions.
2.1.2. Layard Systems
2.1.2.1. Two Layers System
2.1.2.2. Three Layers System.
2.2. Equivalent Thickness Method (OdeMark's Concept)

3. **Rigid Pavement ....(2 Weeks)**
   - 3.1. Analysis of: Stress, Strain and Deflection in Rigid Pavement,
   - 3.2. Type of Stresses

3.2.1. Due to Temperature Variations
3.2.2 Due to Load (Westergard Method)
3.2.2.1. Effect of Dual Tires.
3.2.3. Due to Subgrade Friction.
3.2.3.1. Steel Stress
3.2.3.2. Tie-Bars.
   - 3.3. Design of Dowel-Bars
   - 3.4. Design of Joints.

4. **Flexible Pavement Design Method (AASHTO 1993 Method) ...(2.5 weeks)**

4.1. Design Considerations
4.1.1. Pavement Performance (Loss of Serviceability)
4.1.2. Traffic
4.1.3. Roadbed Soil Properties
4.1.4. Materials for Construction
4.1.4.1. For Flexible Pavement
4.1.4.2. For Rigid Pavement
4.1.5. Environmental Effects
4.1.6. Drainage
4.1.7. Reliability
4.2. Flexible Pavement Design Solved Example.
4.3. Flexible Pavement Overlay Design.

5. Rigid pavement design method (AASHTO 1993 Method) ……………………………(1.5 Weeks)

5.1. Design Considerations

6. Mechanistic Empirical Design Method (ME-Method) ……………………………………(2 Weeks)

6.1. ME for Flexible Pavement.

6.2. ME for Rigid pavement.

Text Books:

1. Yang H. Huang " Pavement Analysis and design", Second Edition, 2004, Published by Pearson Education Inc.
2. A.T. Papagiannakis and E. A. Masad "Pavement Design and Materials", 2008, Published by john Wiley & Sons, Inc.
3. AASHTO Guide for Design of Pavement Structures, 1993, Published by American Association of State Highway and Transportation Officials.
4. E. J, Yoder and M. W. Witczak "Principles of Pavement Design", 1975, Published by john Wiley & Sons, Inc.

Marks Distribution:

Final exam: 70%

Midterm and Progressive Examinations: 20%

Presentation Paper: 6%

Quiz and H.W. : 4%

Location, Day, Time, Duration and First Lecture Date:

Highway Lab, Thursday, 8:30 am., Three Hours, 4/2/2019.

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1. **Principles of Pavement Design: .... (1.5 Weeks)**
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    1.5. Vehicle Types
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1.1. Types of Pavement

There are three major types of pavement: flexible or asphalt pavements, rigid or concrete pavements, and composite pavements .

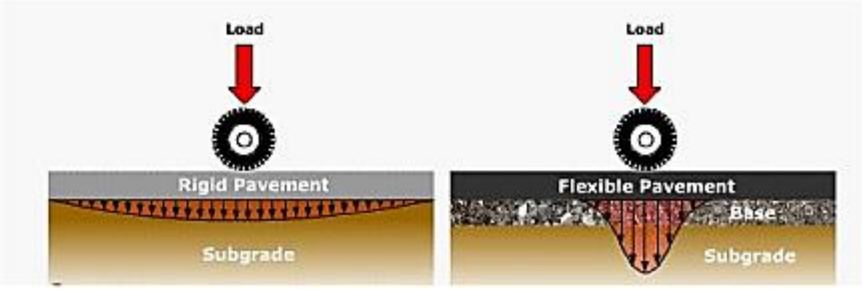
Flexible pavements are layered systems with better materials on top where the intensity of stress is high and inferior (low quality) materials at the bottom where the intensity is low . Figure 1.1 shows the cross section of a conventional flexible pavement . Starting from the top, the pavement consists of, surface course, tack coat, binder course(optional), prime coat, base course(Hot Mix Asphalt (HMA) or untreated granular materials), subbase course, and natural subgrade. Each of these layers contributes to structural support. The use of the various courses is based on either necessity or economy, and some of the courses may be omitted .

The surface course is made of hot-mix asphalt (HMA), it typically is the stiffest (as measured by elastic modulus) layer and may contribute the most (depending upon thickness) to pavement strength. The underlying layers are less stiff but are still important to pavement strength as well as drainage and frost protection.

Figure 1.1.

Rigid Pavement

- A rigid pavement structure is composed of a hydraulic cement concrete surface course or Portland Cement Concrete (PCC) pavement, produced from aggregates and cement as bonding material, and underlying of subbase courses. The surface course (concrete slab) is the stiffest layer and provides the majority of strength. The subbase layer is orders of magnitude less stiff than the PCC surface but still make important contributions to **uniformity of support**, **pavement drainage**, and **frost protection**, and **provide a working platform for construction equipment.**
- Rigid pavements are substantially 'stiffer' than flexible pavements due to the high modulus of elasticity of the PCC material, resulting in **very low deflections under loading**. The rigid pavements can be analyzed by the plate theory. **Rigid pavements can have reinforcing steel, which is generally used to handle thermal stresses to reduce or eliminate joints and maintain tight crack widths**. Figure 1.2 shows a typical section for a rigid pavement.



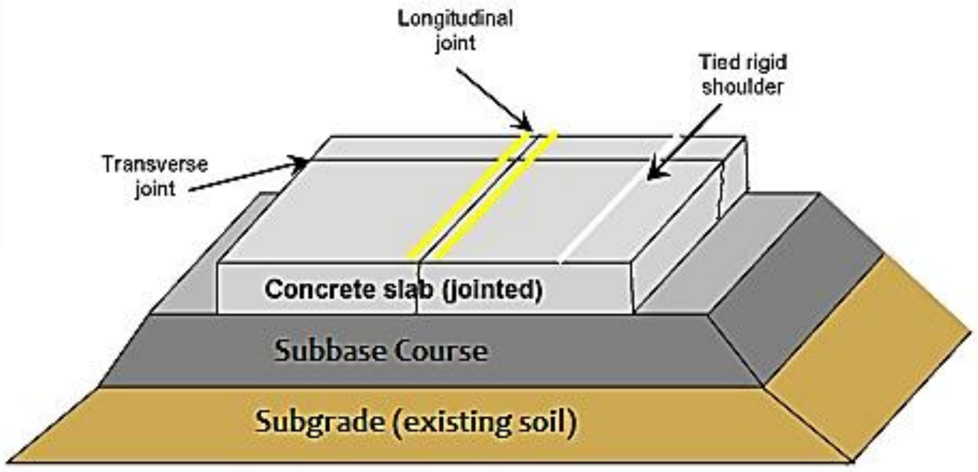


Figure 1.2 Typical Rigid Pavement

Composite Pavement

A composite pavement is composed of both hot-mix asphalt (HMA) and hydraulic cement concrete. Typically, composite pavements are asphalt overlays on top of concrete pavements. The HMA overlay may have been placed as the final stage of initial construction, or as part of a rehabilitation or safety treatment. Composite pavement behavior under traffic loading is essentially the same as rigid pavement.

1.2. Concept of Pavement Performance

- Different agencies as Asphalt Institute suggested the use of:

1- **Vertical compressive strain on the surface of subgrade as a failure criterion to reduce permanent deformation, and**

2-**Horizontal tensile strain at the bottom of asphalt layer to minimize fatigue cracking,** as shown in Figure 1.3. The use of vertical compressive strain to **control permanent deformation(Rutting)** is based on the fact that plastic strains are proportional to elastic strains in paving materials .

- **The principal structural requirements are as follows** :

(1) The subgrade should be able to sustain traffic loading without excessive deformation; this is controlled by the vertical compressive stress or strain at this level.

(2) Bituminous materials and cement-bound materials used in road-base design should not crack under the influence of traffic; this is controlled by the horizontal tensile stress or strain at the bottom of the bound layer.

(3) The road-base is often the main structural layer of the pavement, required to distribute the applied traffic loading so that the underlying materials are not overstressed. It must be able to sustain the stress and strain generated within itself without excessive or rapid deterioration of any kind. To control fatigue cracking caused by load repetitions.

(4) In pavements containing bituminous materials, the internal deformation of these materials must be limited.

(5) The load spreading ability of granular sub-base and formation layers must be adequate to provide a satisfactory construction platform.

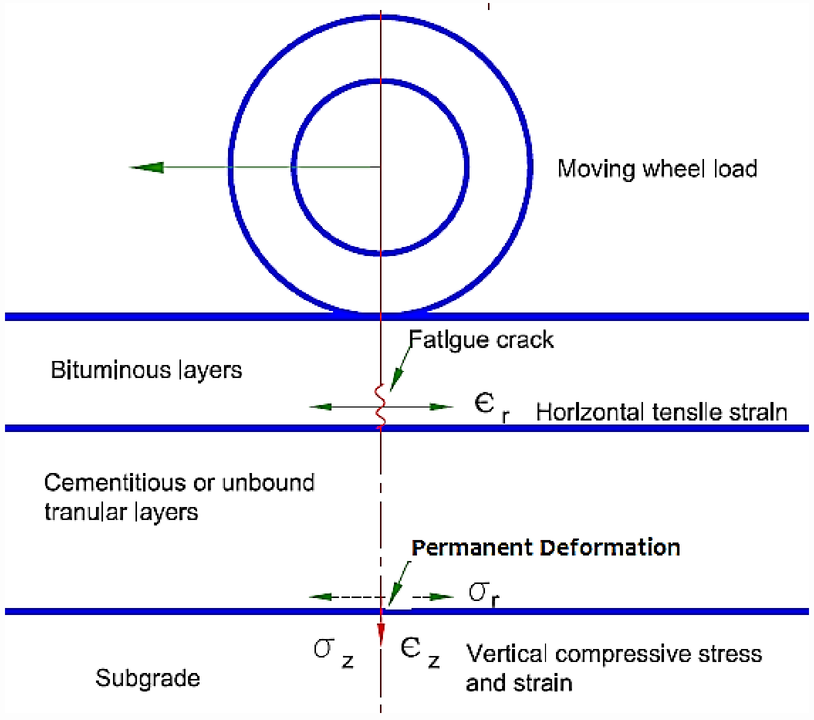


Figure 1.3. Concept of Pavement Performance

1.3. Design Factors.

Design factors can be divided into five categories :

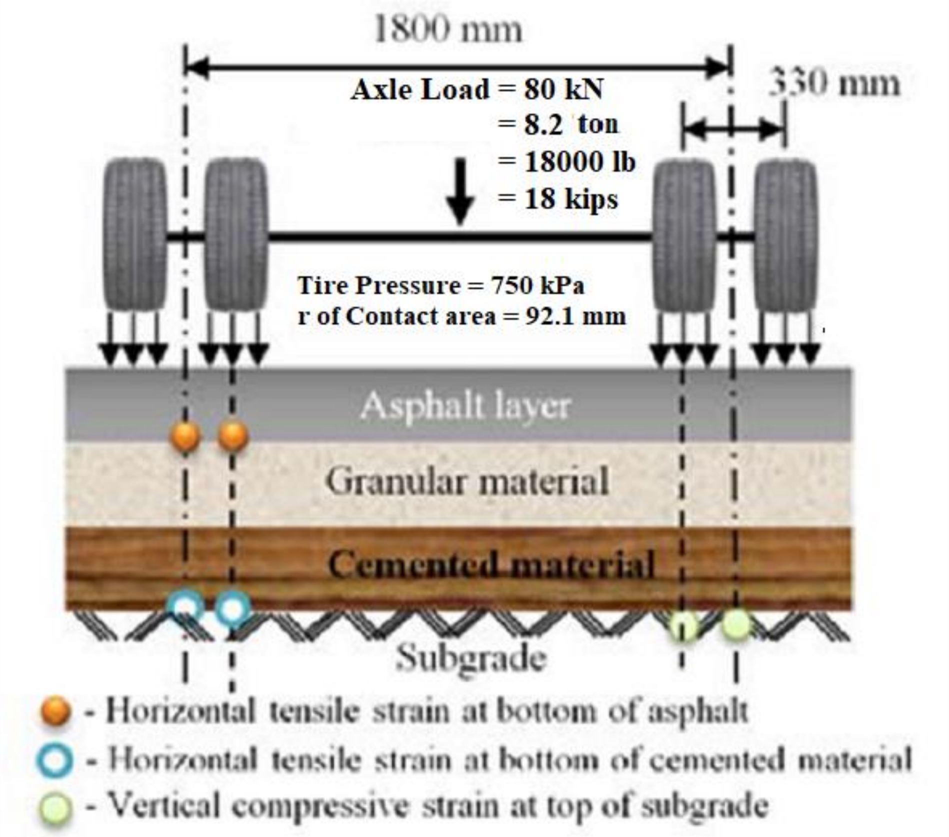
- ✓ **Traffic and loading**
- ✓ **Environment factors**
- ✓ **Materials characteristics**
- ✓ **Design Method.**
- ✓ **Economic considerations**

1.3.1. Traffic and Loading

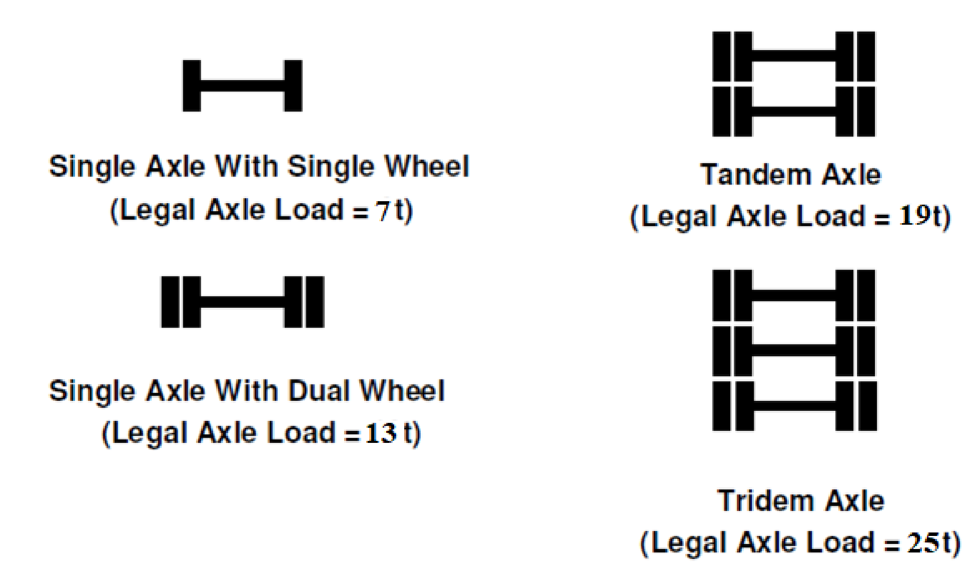
- ➢ ***axle loads***
- ➢ ***the number of load repetitions***
- ➢ ***tire-contact areas***
- ➢ ***vehicle speeds .***

➢ *Axle loads*

❑ The total weight of vehicle is carried by axels, and the load on axels transformed to the wheels and than to the pavement.



1.5. Characteristics of Standard Axels load



1.4. Legal Axels load and Configurations for Iraq

❑ Standard Axle Load:

Single axle with dual wheels carrying a load of 80 kN (8.2 tonnes) is defined as standard axle as shown in Figure (1.5)

➢**Note: Effect of Wheel Configuration**: The design may be unsafe if the tandem and tridem axles are treated as a group and considered as one repetition. The design is too conservative if each axle is treated independently and considered as one repetition.

➢ ***Number of load repetitions***

- ✓ The damage caused by each axle depends on its load, configuration and repetitions
- ✓ It is possible to evaluate the damage caused by the repetitions of each axle load group; so, they can be converted into equivalent repetitions of a **standard axle (W_{18})** using **Equivalent Standard Axle Load (ESAL)** factor.

➢ ***Tire pressure and contact areas***

It is necessary to know the contact area between tire and pavement, so the axle load can be assumed to be uniformly distributed over the contact area which is known as **contact pressure**. In pavement design, the **contact pressure** is generally assumed to be equal to the **tire pressure (pressure of air inside the tire)**; because using of tire pressure as the contact pressure will be more safe.

Contact areas

- ✓ The approximate shape of contact area for each tire is elliptical shape and can be approximated to a compound of a rectangle and two semicircles, Figure 1.6.

Contact area A_c is given by:

$$A_c = \pi\,(0.3L)^2 + (0.4L)(0.3L) = 0.5227\ L^2$$

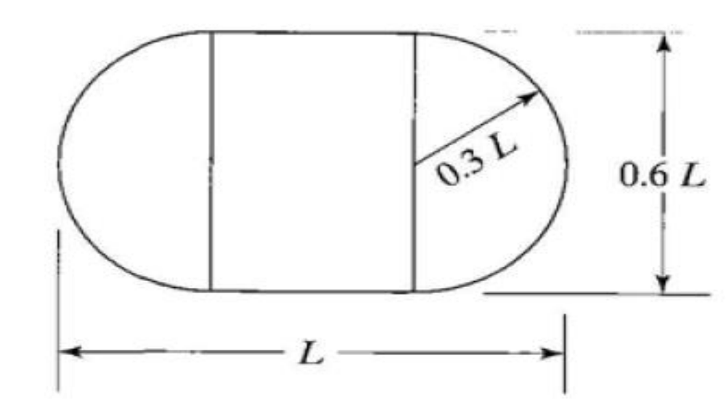


Figure 1.6. Shape of Contact Area

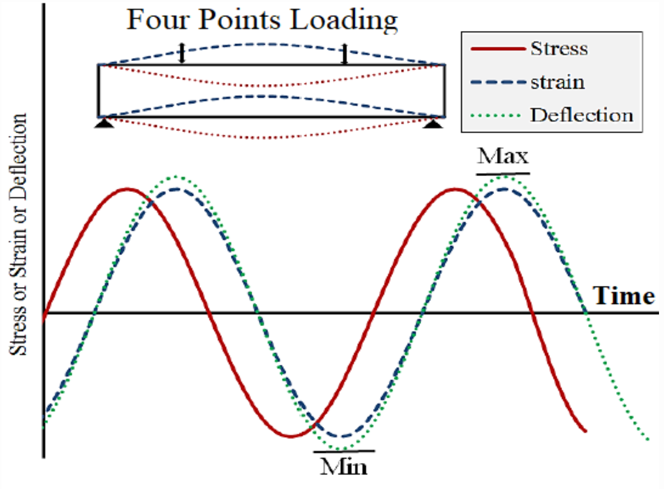
➢ *Vehicle speed*

- ✓ Speed of vehicles is directly related to the duration of loading on viscoelastic layers.
- ✓ For elastic layers, the resilient modulus of each layer should be selected based on the vehicle speed
- ✓ Greater the speed, the larger the modulus, and the smaller the strains in the pavement

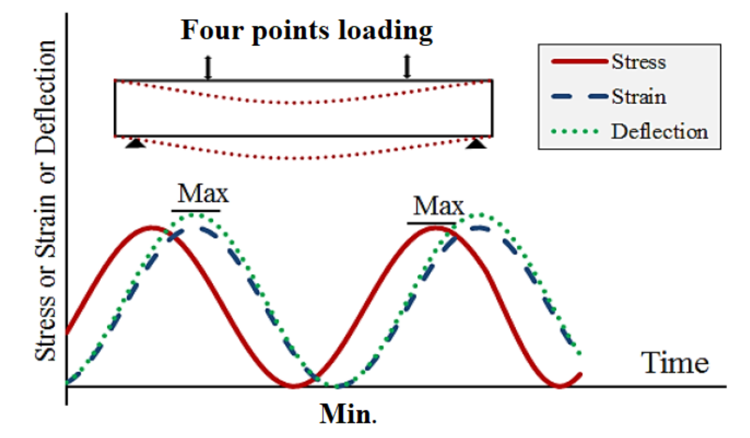
❑ *Lab Test Loading Shape*

There are two types of loading shapes used in four points test, Figure 1.7.

- Haversine waveform loading
- Sinusoidal Waveform loading



Sinusoidal waveform loading shape



Haversine Loading Shape

Figure 1.7. Test Loading Shapes

▪ In field, the intensity of load varies with time according to a haversine function, as shown in Figure 1.8. With t = 0 at the peak, the load function is expressed as in Equation 1.1.

$$L(t) = q \sin^2\left(\frac{\pi}{2} + \frac{\pi t}{d}\right) \quad \text{..................................(1.1)}$$

Where: d is the duration of load, *the load intensity is q and t is the time*. When the load is at a considerable distance from a given point,

t = ±d/2, the load above the point is zero, or L(t) = 0.

When the load is directly above the given point (a), or *t = 0, the load intensity is* ***q***.

The duration of load depends on the vehicle speed **S** and the tire contact radius **a**. A reasonable assumption is that the load has practically no effect when it is at a distance of **6a** from the points (**b** and **c**), or **d** expressed as in Equation 1.2.

$$d = \frac{12a}{s} \quad \text{...(1.2)}$$

For example: If a = 6 in . and s = 40 mph (64 km/h) = 58 .7 ft/s (17.9 m/s),
d = 0.1 s .
So the loading frequency is:
f = 1/time   where f in Hz and t in second. time = d = 0.1 s.
f = (1/0.1) = 10 Hz.
Note: 1 Hz = 1 cycle per second. So in this example the frequency is 10 cyc/sec.

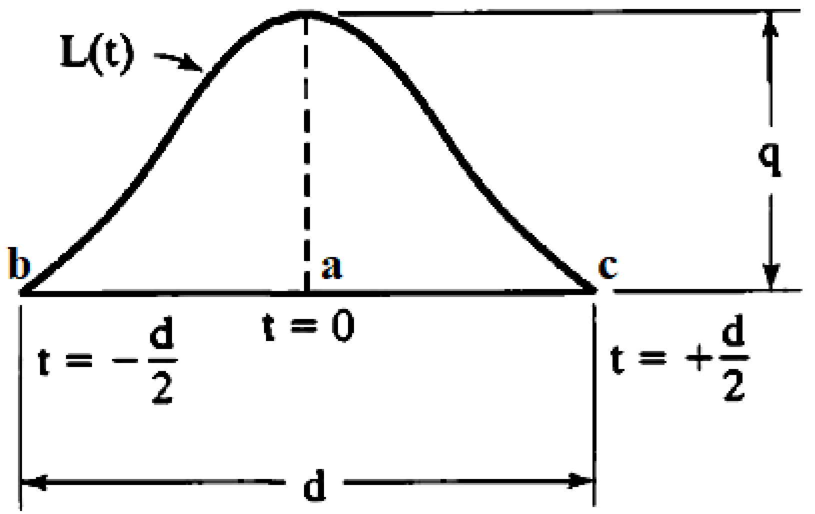


Figure 1.8. Moving load as a function of time

1.3.2. Environmental Factors

- ***Temperature***
- ***Precipitation and Moisture Variations***

➢ *Temperature*

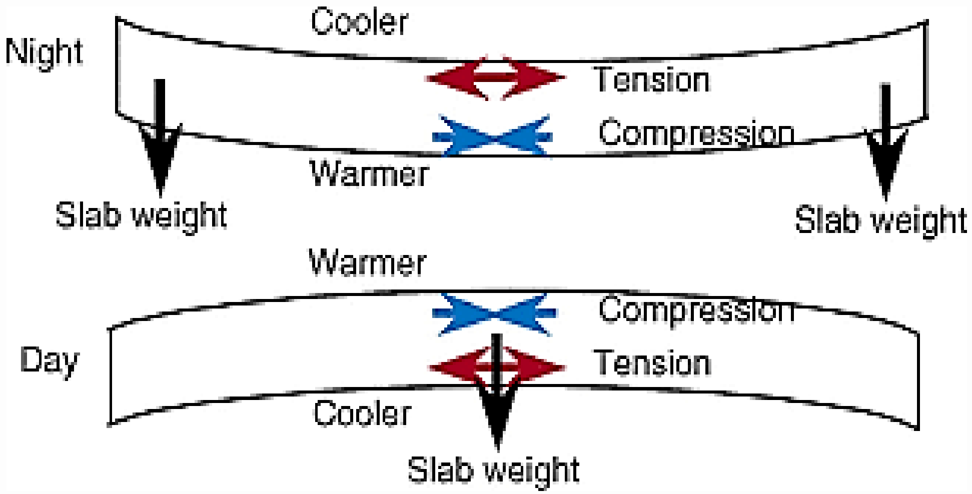
✓ *Effect on Asphalt Layer (Flexible Pavement)*

- Asphalt is a viscoelastic materials, when the atmosphere temperature changes asphalt's behaviour changes.
- During the winter, when temperature is low, the HMA becomes rigid (elastic) and the vertical compressive strain reduces in the pavement, less fatigue life and causes asphalt pavements to crack.
- During summer, hot temperature makes the asphalt layer hotter than atmosphere temperature causing asphalt softer to build up permanent deformation (rutting).

✓ *Effect on Concrete Slab (Rigid Pavement)*

▪During the day, when the temperature at top is higher than that at bottom, the slab curls down so that its interior. At night, when the temperature at top is lower than that at bottom, the slab curls upward as shown in Figure 1.7.

The change between maximum and minimum temperatures also determines the joint and crack openings and affects the efficiency of load transfer .



1.7. Curling phenomena in rigid pavement

✓ *Frost Penetration*

- The freezing of pore water and the melting of pore ice result in significant pavement layer volume changes, which over time and under the action of traffic loads reduce pavement serviceability.
- Frost penetration in cold climate results in a stronger subgrade in the winter but a much weaker subgrade in the spring causing differential settlements; where the ice melts in spring causes the subgrade to be in a saturated condition.
- To protect the subgrade from frost action, it is desirable to use non-frost-susceptible materials such as sand and gravel or mix of them which omit or eliminate the capillary property of the layer beneath the base course.

✓ *Freezing Index*

- Freezing index is an indicator used to express the severity of frost of a given region on the pavement in terms of mean degree days which is equal to the average of the highest and lowest air temperatures during the day.
- The freezing index has been correlated with the depth of frost penetration and can be used as a factor of pavement design and evaluation.

➢ *Precipitation and Moisture Variations*

- The precipitation from rain and snow affects the quantity of surface water infiltrating into the subgrade and the location of the groundwater table. The water table should be kept at least 3 ft (0.91 m) below the pavement surface. Every effort should be made to improve the drainage to drain out the rainfalls within a short time, its effect can be minimized, even in regions of high precipitation.
- Moisture variations in pavement layers may be caused due to precipitation or a high ground water table. Proper surface and subsurface drainage will reduce the moisture variations in pavement layers. The bad effects of poor drainage include loss of subgrade stiffness in flexible pavements and pumping and loss of support in rigid pavements

1.4. Materials Characteristics

- In the pavement design methods, the properties of materials which are used in the construction of the pavement layers must be strongly considered, so that the responses of the pavement layers due to axel load or traffic motion such as, stresses, strains, and deflection can be determined. These responses are then used in the analysis and design process .
- The general engineering properties of materials for subgrade, embankment soil, and each layer which are considered in the design are:

1. **Modulus of elasticity (E).**
2. **Poisson ratios (μ)**
3. **Resilient modulus (M_R) (the elastic modulus under repeated loads).**
4. **Nonlinear elastic moduli.**

➢ **The data required in design:**

❑ **Fixable pavement**

✓ Hot mix asphalt is viscoelastic materials (Creep compliance (moduli at various loading times), Time–temperature shift factor (the sensitivity of asphalt mixtures to temperature)).

✓ Fatigue properties of asphalt mixtures (design based on the fatigue failure criteria)

✓ Rut depth (the permanent deformations over all layers), the permanent deformation parameters of each layer must be specified for design based on rutting failure criteria.

✓ Low-temperature cracking (asphalt stiffness at the winter design temperature).

- **Rigid pavement**
  - The modulus of subgrade reaction.
  - Coefficient of thermal expansion (the effect of temperature curling).
  - Fatigue cracking distress (the modulus of rupture).
  - Other distresses.

1.5. Design Methods

- **Empirical method** : Empirical method are used to relate observed or measurable phenomena (pavement characteristics) with outcomes (pavement performance) , i.e. empirical equations,. An example: AASHTO Guide design, Group Index method and CBR method (Asphalt Institute).
- **Mechanistic–Empirical Methods**: The mechanistic–empirical method of design is based on the mechanics of materials that relates an input, such as a wheel load, to an output or pavement response, such as stress or strain.

1.6. Structural and Functional Failures of Pavements

1.6.1 Structural failure : Structural failure is a collapse of the pavement structure or a breakdown of one or more of the pavement components to make the pavement incapable of sustaining the loads imposed upon its surface. For example: collapse of box Calvert, embankment, depending of the degree of distress severity such as high severity of rutting and cracking.

1.6.2. Functional failure: Functional failure is a failure that is taken place in the pavement surface causing uncomfortable for the riders such as rutting, cracking, potholes, roughness, opening of joints in rigid pavement, etc.

1.7. Vehicle Damage Factor

The vehicle damage factor (VDF) is a multiplier for converting the number of commercial vehicles of different axle loads and axle configurations to the number of standard axle-load repetitions. It is defined as equivalent number of standard axles per commercial vehicle. The VDF varies with the axle configuration, axle loading, terrain, type of road, and from region to region. The Equivalent Standard Axle Load (ESAL) factor is used to convert different axle load repetitions into equivalent standard axle load repetitions. The exact VDF values are arrived after extensive field surveys. The load equivalency factor (LEF) is a number which relate the amount of equivalent damage caused by a given load of axel to the standard axel load. $LEF = [W_m/W_{std.}]^4$

Where : W_m is axel load , W_{std}. Is the standard axel load.

1.8. Estimation of Design Traffic

- Traffic is a mix of different vehicles types having different type and configurations of axels. In the pavement design criteria it is necessary to account the number and types of vehicles moving along the highway.
- The account of the traffic volume and types is daily, weekly, monthly and annually . Annually average daily traffic (AADT) is one of the important account. It is depends on account the traffic volume and type per hour along the day and then the account operation is continued from many days to several months arriving to a year.
- The total account of a one year is divided by (365) days to get the AADT.
- Then, the AADT is converted to standard axle load ($\mathbf{W_{18/day}}$) using Load Equivalency factor.
- The Equivalency factors have different values based on the axles, configurations and conditions of the pavement.
- ($\mathbf{W_{18/day} \times 365\ days = W_{18/year}}$). Where $\mathbf{W_{18/year}}$ is the amount of the standard axel loads of the base year used in the design.
- A growth rate (G) is used to estimate the total amount of the standard axle loads which can be passed over the highway during the design life. Where: r is the annual growth rate (e.g. (3%), r = 0.03), t is design life in year of the pavement in years.

Example: $W_{18/day}$ = 1050, r = 3%, t= 20 year

$W_{18/year}$ = 1050 × 365 = 383250 per year

G = $((1+0.03)^{(20)}-1)/0.03$ = 26.87

Estimated W_{18} which pass over the pavement within 20 years = 26.87 × 383250 = 10.3×10^6

$$G = \frac{(1+r)^t - 1}{r}$$

Thank you for your attention