Chapter 27

Flexible pavement design

27.1 Overview

Flexible pavements are so named because the total pavement structure deflects, or flexes, under loading. A flexible pavement structure is typically composed of several layers of materials. Each layer receives loads from the above layer, spreads them out, and passes on these loads to the next layer below. Thus the stresses will be reduced, which are maximum at the top layer and minimum on the top of subgrade. In order to take maximum advantage of this property, layers are usually arranged in the order of descending load bearing capacity with the highest load bearing capacity material (and most expensive) on the top and the lowest load bearing capacity material (and least expensive) on the bottom.

27.2 Design procedures

For flexible pavements, structural design is mainly concerned with determining appropriate layer thickness and composition. The main design factors are stresses due to traffic load and temperature variations. Two methods of flexible pavement structural design are common today: Empirical design and mechanistic empirical design.

27.2.1 Empirical design

An empirical approach is one which is based on the results of experimentation or experience. Some of them are either based on physical properties or strength parameters of soil subgrade. An empirical approach is one which is based on the results of experimentation or experience. An empirical analysis of flexible pavement design can be done with or with out a soil strength test. An example of design without soil strength test is by using HRB soil classification system, in which soils are grouped from A-1 to A-7 and a group index is added to differentiate soils within each group. Example with soil strength test uses McLeod, Stabilometer, California Bearing Ratio (CBR) test. CBR test is widely known and will be discussed.

27.2.2 Mechanistic-Empirical Design

Empirical-Mechanistic method of design is based on the mechanics of materials that relates input, such as wheel load, to an output or pavement response. In pavement design, the responses are the stresses, strains, and deflections within a pavement structure and the physical causes are the loads and material properties of the pavement structure. The relationship between these phenomena and their physical causes are typically described using some mathematical models. Along with this mechanistic approach, empirical elements are used when defining what value of the calculated stresses, strains, and deflections result in pavement failure. The relationship between physical phenomena and pavement failure is described by empirically derived equations that compute the number of loading cycles to failure.

27.3 Traffic and Loading

There are three different approaches for considering vehicular and traffic characteristics, which affects pavement design.

Fixed traffic: Thickness of pavement is governed by single load and number of load repetitions is not considered. The heaviest wheel load anticipated is used for design purpose. This is an old method and is rarely used today for pavement design.

Fixed vehicle: In the fixed vehicle procedure, the thickness is governed by the number of repetitions of a standard axle load. If the axle load is not a standard one, then it must be converted to an equivalent axle load by number of repetitions of given axle load and its equivalent axle load factor.

Variable traffic and vehicle: In this approach, both traffic and vehicle are considered individually, so there is no need to assign an equivalent factor for each axle load. The loads can be divided into a number of groups and the stresses, strains, and deflections under each load group can be determined separately; and used for design purposes. The traffic and loading factors to be considered include axle loads, load repetitions, and tyre contact area.

27.3.1 Equivalent single wheel load

To carry maximum load with in the specified limit and to carry greater load, dual wheel, or dual tandem assembly is often used. Equivalent single wheel load (ESWL) is the single wheel load having the same contact pressure, which produces same value of maximum stress, deflection, tensile stress or contact pressure at the desired depth. The procedure of finding the ESWL for equal stress criteria is provided below. This is a semi-rational method, known as Boyd and Foster method, based on the following assumptions:

- equalancy concept is based on equal stress;
- contact area is circular;
- influence angle is 45^o; and
- soil medium is elastic, homogeneous, and isotropic half space.

The ESWL is given by:

$$\log_{10} ESWL = \log_{10} P + \frac{0.301 \log_{10}\left(\frac{z}{d/2}\right)}{\log_{10}\left(\frac{2S}{d/2}\right)} \tag{27.1}$$

where P is the wheel load, S is the center to center distance between the two wheels, d is the clear distance between two wheels, and z is the desired depth.

Example 1

Find ESWL at depths of 5cm, 20cm and 40cm for a dual wheel carrying 2044 kg each. The center to center tyre spacing is 20cm and distance between the walls of the two tyres is 10cm.

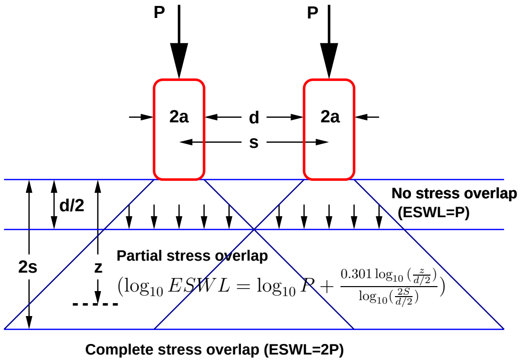

Figure 27:1: ESWL-Equal stress concept

Solution For desired depth z=40cm, which is twice the tyre spacing, ESWL = 2P=2×2044 = 4088 kN. For z=5cm, which is half the distance between the walls of the tyre, ESWL = P = 2044kN. For z=20cm, $\log_{10} ESWL = \log_{10} P + \frac{0.301 \log_{10}(\frac{z}{d/2})}{\log_{10}(\frac{2S}{d/2})}$ =$\log_{10} ESWL = \log_{10} 2044 + \frac{0.301 \log_{10}(\frac{20}{10/2})}{\log_{10}(\frac{2\times 20}{10/2})}$ =3.511. Therefore, ESWL = antilog(3.511)= 3244.49 kN

27.3.2 Equivalent single axle load

Vehicles can have many axles which will distribute the load into different axles, and in turn to the pavement through the wheels. A standard truck has two axles, front axle with two wheels and rear axle with four wheels. But to carry large loads multiple axles are provided. Since the design of flexible pavements is by layered theory, only the wheels on one side needed to be considered. On the other hand, the design of rigid pavement is by plate theory and hence the wheel load on both sides of axle need to be considered. *Legal axle load:* The maximum allowed axle load on the roads is called legal axle load. For highways the maximum legal axle load in India, specified by IRC, is 10 tonnes. *Standard axle load:* It is a single axle load with dual wheel carrying 80 KN load and the design of pavement is based on the standard axle load.

Repetition of axle loads: The deformation of pavement due to a single application of axle load may be small but due to repeated application of load there would be accumulation of unrecovered or permanent deformation which results in failure of pavement. If the pavement structure fails with N_1 number of repetition of load W_1 and for the same failure criteria if it requires N_2 number of repetition of load W_2, then W_1N_1 and W_2N_2 are considered equivalent. Note that, W_1N_1 and W_2N_2 equivalency depends on the failure criterion employed.

Equivalent axle load factor: An equivalent axle load factor (EALF) defines the damage per pass to a pavement by the i^{th} type of axle relative to the damage per pass of a standard axle load. While finding the EALF, the failure criterion is important. Two types of failure criterias are commonly adopted: fatigue cracking and ruttings. The fatigue cracking model has the following form:

$$N_f = f_1 (\epsilon_t)^{-f_2} \times (E)^{-f_3} or N_f \propto \epsilon_t{}^{-f_2} \tag{27.2}$$

where, N_f is the number of load repetition for a certain percentage of cracking, ϵ_t is the tensile strain at the bottom of the binder course, E is the modulus of elasticity, and f_1, f_2, f_3 are constants. If we consider fatigue cracking as failure criteria, and a typical value of 4 for f_2, then:

$$EALF = \left(\frac{\epsilon_i}{\epsilon_{std}}\right)^4 \tag{27.3}$$

where, i indicate i^{th} vehicle, and std indicate the standard axle. Now if we assume that the strain is proportional to the wheel load,

$$EALF = \left(\frac{W_i}{W_{std}}\right)^4 \tag{27.4}$$

Similar results can be obtained if rutting model is used, which is:

$$N_d = f_4 \left(\epsilon_c\right)^{-f_5} \tag{27.5}$$

where N_d is the permissible design rut depth (say 20mm), ϵ_c is the compressive strain at the top of the subgrade, and $f_4,\ f_5$ are constants. Once we have the EALF, then we can get the ESAL as given below.

$$\text{Equivalent single axle load, ESAL} = \sum_{i=1}^{m} F_i n_i \tag{27.6}$$

where,m is the number of axle load groups, F_i is the $EALF$ for i^{th} axle load group, and n_i is the number of passes of i^{th} axle load group during the design period.

Example 1

Let number of load repetition expected by 80 KN standard axle is 1000, 160 KN is 100 and 40 KN is 10000. Find the equivalent axle load.

Solution: Refer the Table 27:1. The ESAL is given as $\sum F_i n_i = 3225\ kN$

Table 27:1: Example 1 Solution

i	Axle Load (KN)	No.of Load Repetition (n_i)	EALF (F_i)	$F_i n_i$
1	40	10000	$(40/80)^4 = 0.0625$	625
2	80	1000	$(80/80)^4 = 1$	1000
3	160	100	$(160/80)^4 = 16$	1600

Example 2

Let the number of load repetition expected by 120 kN axle is 1000, 160 kN is 100, and 40 kN is 10,000. Find the equivalent standard axle load if the equivalence criteria is rutting. Assume 80 kN as standard axle load and the rutting model is $N_r = f_4 \epsilon_c^{-f_5}$ where f_4 =4.2 and f_5 =4.5.

Solution Refer the Table 27:2. The ESAL is given as $\sum F_i n_i = 8904.94\ kN$

Table 27:2: Example 2 Solution

i	Axle Load (KN)	No.of Load Repetition (n_i)	EALF (F_i)	$F_i n_i$
1	120	1000	$(120/80)^{4.5} = 6.200$	6200
2	160	100	$(160/80)^{4.5} = 22.63$	2263
3	40	10000	$(40/80)^{4.5} = 0.04419$	441.9

Example 3

Let number of load repetition expected by 60kN standard axle is 1000, 120kN is 200 and 40 kN is 10000. Find the equivalent axle load using fatigue cracking as failure criteria according to IRC. Hint:$N_f = 2.21 \times 10^{-4}(\epsilon_t)^{-3.89}(E)^0.854$

Solution Refer the Table 27:3. The ESAL is given as $\sum F_i n_i = 6030.81\ kN$

Table 27:3: Example 3 Solution

i	Axle Load (KN)	No.of Load Repetition (n_i)	EALF (F_i)	$F_i n_i$
1	40	10000	$(40/60)^{3.89} = 0.2065$	2065
2	60	1000	$(60/60)^{3.89} = 1$	1000
3	120	200	$(120/60)^{3.89} = 14.825$	2965.081

27.4 Material characterization

It is well known that the pavement materials are not perfectly elastic but experiences some permanent deformation after each load repetitions. It is well known that most paving materials are not elastic but experience some permanent deformation after each load application. However, if the load is small compared to the strength of the material and the deformation under each load repetition is almost completely recoverable then the material can be considered as elastic.

The Figure 27:2 shows straining of a specimen under a repeated load test. At the initial stage of load applications, there is considerable permanent deformation as indicated by the plastic strain in the Figure 27:2. As the number of repetition increases, the plastic strain due to each load repetition decreases. After 100 to 200 repetitions, the strain is practically all-recoverable, as indicated by ϵ_r in the figure.

27.4.1 Resilient modulus of soil

The elastic modulus based on the recoverable strain under repeated loads is called the resilient modulus M_R, defined as $M_R = \frac{\sigma_d}{\epsilon_r}$. In which σ_d is the deviator stress, which is the axial stress in an unconfined compression

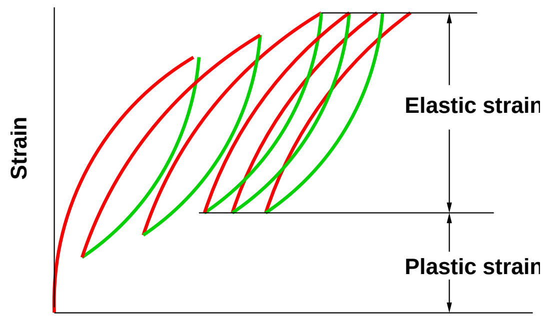

Figure 27:2: Recoverable strain under repeated loads

test or the axial stress in excess of the confining pressure in a triaxial compression test.

In pavements the load applied are mostly transient and the type and duration of loading used in the repeated load test should simulate that actually occurring in the field. When a load is at a considerable distance from a given point, the stress at that point is maximum. It is therefore reasonable to assume the stress pulse to be a haversine or triangular loading, and the duration of loading depends on the vehicle speed and the depth of the point below the pavement surface. Resilient modulus test can be conducted on all types of pavement materials ranging from cohesive to stabilized materials. The test is conducted in a triaxial device equipped for repetitive load conditions.

27.4.2 Dynamic complex modulus

When the loading wave form is sinusoidal and if there is no rest period, then, the modulus obtained is called dynamic complex modulus. This is one of the way of explaining the stress-strain relationship of visco-elastic materials. This modulus is a complex quantity and the absolute value of the complex modulus is called the dynamic modulus. This complex modulus test is usually conducted on cylindrical specimens subjected to a compressive haversine loading. The test setup is similar to resiliant modulus. The dynamic modulus varies with the loading frequency. Therefore, a frequency that most closely simulates the actual traffic load should be selected for the test.

27.4.3 Correlations with other tests

Determination of resiliant modulus is often cumbersome. Therefore, various empirical tests have been used to determine the material properties for pavement design. Most of these test measure the strength of the material and are not a true representation of the resiliant modulus. Accordingly, various studies has related empirical tests like CBR test, Tri-axial test etc are correlated to resiliant modulus.

27.5 Mechanistic-empirical analysis

Mechanics is the science of motion and action of forces on bodies. In pavement design these phenomena are stresses, strains, and deflections within a pavement structure and the physical causes are loads and material properties of the pavements structure. The relationship between these phenomena and their physical causes is described by a mathematical model. The most common of them is layered elastic model.

27.5.1 Advantages

The basic advantages of the Mechanistic-Empirical pavement design method over a purely empirical one are:

1. It can be used for both existing pavement rehabilitation and new pavement construction
2. It can accommodate changing load types
3. It can better characterize materials allowing for
    - better utilization of available materials
    - accommodation of new materials
    - improved definition of existing layer proportion
4. It uses material proportion that relates better with actual pavement performance
5. It provides more reliable performance predictions
6. It defines role of construction in a better way
7. It accommodates environment and aging effect of materials in the pavement

27.5.2 Mechanistic model

Mechanistic models are used to mathematically model pavement physics. There are a number of different types of models available today (e.g., layered elastic, dynamic, viscoelastic) but this section will present the layered elastic model.

Layered elastic model

A layered elastic model can compute stresses, strains and deflections at any point in a pavement structure resulting from the application of a surface load. Layered elastic models assume that each pavement structural layer is homogeneous, isotropic, and linearly elastic. In other words, it is the same everywhere and will rebound to its original form once the load is removed. This section covers the basic assumptions, inputs and outputs from a typical layered elastic model.

Assumptions in layered elastic model

The layered elastic approach works with relatively simple mathematical models and thus requires following assumptions

- Pavement layer extends infinitely in the horizontal direction
- The bottom layer (usually the subgrade) extends infinitely downwards
- Materials are not stressed beyond their elastic ranges

Inputs

A layered elastic model requires a minimum number of inputs to adequately characterize a pavement structure and its response to loading. These inputs are:

- Material properties of each layer, like modulus of elasticity (E), Poisson's ratio (ν),
- Pavement layer thicknesses, and
- Loading conditions which include the total wheel load (P) and load repetitions.

Output

The outputs of the layered elastic model are the stresses, strains and deflections in the pavements.

- **Stress**. The intensity of internally distributed forces experienced within the pavement structure at various points. Stress has units of force per unit area(pa)
- **Strain**. The unit displacement due to stress , usually expressed as a ratio of change in dimension to the original dimension (mm/mm)
- **Deflection**. The linear change in dimension. Deflection is expressed in units of length (mm)

Failure criteria

The main empirical portions of the mechanistic-empirical design process are the equations used to compute the number of loading cycles to failure. These equations are derived by observing the performance of pavements and relating the type and extent of observed failure to an initial strain under various loads. Currently, two types of failure criteria are widely recognized, one relating to fatigue cracking and the other to rutting initiating in the subgrade.

27.6 Summary

Basic concepts of flexible pavement design were discussed. There are two main design procedures- empirical and mechanistic empirical design. For design purposes, equivalent single wheel load and equivalent single axle load concepts are used.

27.7 Problems

1. A set of dual tyres has a total load of 4090 kg, a contact radius a of 11.4 cm and a center to center tyre spacing of 34.3 cm. Find the ESWL by Boyd & Foster method for a depth of 34.3 cm. [Ans: 3369.3 kg]
2. Calculate ESWL by equal stress criteria for a dual wheel assembly carrying 2044 kg each for a pavement thickness of 5, 15, 20, 25 and 30 cms. The distance between walls of the tyre is 11 cm. Use either graphical or functional methods. (Hint: P=2044kg, d=11cm, s=27cm). [Ans: 2044, 2760, 3000, 3230 and 4088]
3. Let number of load repetition expected by 60kN standard axle is 1000, 120kN is 200 and 40 kN is 10000. Find the equivalent axle load using fatigue cracking as failure criteria according to IRC. Hint:$N_f = 2.21 \times 10^{-4}(\epsilon_t)^{-3.89}(E)^{0.854}$