The pavements can be classified based on the structural performance into two, flexible pavements and rigid pavements. In flexible pavements, wheel loads are transferred by grain-to-grain contact of the aggregate through the granular structure. The flexible pavement, having less flexural strength, acts like a flexible sheet (e.g. bituminous road). On the contrary, in rigid pavements, wheel loads are transferred to sub-grade soil by flexural strength of the pavement and the pavement acts like a rigid plate (e.g. cement concrete roads). In addition to these, composite pavements are also available. A thin layer of flexible pavement over rigid pavement is an ideal pavement with most desirable characteristics. However, such pavements are rarely used in new construction because of high cost and complex analysis required

**Types of pavements**

## Flexible Pavements:

Flexible pavement can be defined as the one consisting of a mixture of asphaltic or bituminous material and aggregates placed on a bed of compacted granular material of appropriate quality in layers over the subgrade. Water bound macadam roads and stabilized soil roads with or without asphaltic toppings are examples of flexible pavements.

The **design of flexible pavement** is based on the principle that for a load of any magnitude, the intensity of a load diminishes as the load is transmitted downwards from the surface by virtue of spreading over an increasingly larger area, by carrying it deep enough into the ground through successive layers of granular material.



## Rigid Pavements:

A rigid pavement is constructed from cement concrete or reinforced concrete slabs. Grouted concrete roads are in the category of semi-rigid pavements.

The design of rigid pavement is based on providing a structural cement concrete slab of sufficient strength to resists the loads from traffic. The rigid pavement has rigidity and high modulus of elasticity to distribute the load over a relatively wide area of soil.



Fig: Rigid Pavement Cross-Section

Minor variations in subgrade strength have little influence on the structural capacity of a rigid pavement. In the design of a rigid pavement, the flexural strength of concrete is the major factor and not the strength of subgrade. Due to this property of pavement, when the subgrade deflects beneath the rigid pavement, the concrete slab is able to bridge over the localized failures and areas of inadequate support from subgrade because of slab action.

## Difference between Flexible Pavements and Rigid Pavements:

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|  | **Flexible Pavement** | **Rigid Pavement** |
| **1.** | It consists of a series of layers with the highest quality materials at or near the surface of pavement. | It consists of one layer Portland cement concrete slab or relatively high flexural strength. |
| **2.** | It reflects the deformations of subgrade and subsequent layers on the surface. | It is able to bridge over localized failures and area of inadequate support. |
| **3.** | Its stability depends upon the aggregate interlock, particle friction and cohesion. | Its structural strength is provided by the pavement slab itself by its beam action. |
| **4.** | Pavement design is greatly influenced by the subgrade strength. | Flexural strength of concrete is a major factor for design. |
| **5.** | It functions by a way of load distribution through the component layers | It distributes load over a wide area of subgrade because of its rigidity and high modulus of elasticity. |
| **6.** | Temperature variations due to change in atmospheric conditions do not produce stresses in flexible pavements. | Temperature changes induce heavy stresses in rigid pavements. |
| **7.** | Flexible pavements have self healing properties due to heavier wheel loads are recoverable due to some extent. | Any excessive deformations occurring due to heavier wheel loads are not recoverable, i.e. settlements are permanent. |

**Introduction to pavement design**

**Overview**

A highway pavement is a structure consisting of superimposed layers of processed materials above the natural soil sub-grade, whose primary function is to distribute the applied vehicle loads to the sub-grade. The pavement structure should be able to provide a surface of acceptable riding quality, adequate skid resistance, favorable light reflecting characteristics, and low noise pollution. The ultimate aim is to ensure that the transmitted stresses due to wheel load are sufficiently reduced, so that they will not exceed bearing capacity of the sub-grade. Two types of pavements are generally recognized as serving this purpose, namely flexible pavements and rigid pavements. This chapter gives an overview of pavement types, layers, and their functions, and pavement failures. Improper design of pavements leads to early failure of pavements affecting the riding quality.

**Factors affecting pavement design**

There are many factors that affect pavement design which can be classified into four categories as traffic and loading, structural models, material characterization, environment.

**Traffic and loading**

Traffic is the most important factor in the pavement design. The key factors include contact pressure, wheel load, axle configuration, moving loads, load, and load repetitions.

**Contact pressure:**

The tyre pressure is an important factor, as it determine the contact area and the contact pressure between the wheel and the pavement surface. Even though the shape of the contact area is elliptical, for sake of simplicity in analysis, a circular area is often considered.

**Wheel load:**

The next important factor is the wheel load which determines the depth of the pavement required to ensure that the subgrade soil is not failed. Wheel configuration affect the stress distribution and deflection within a pavemnet. Many commercial vehicles have dual rear wheels which ensure that the contact pressure is within the limits. The normal practice is to convert dual wheel into an equivalent single wheel load so that the analysis is made simpler.

**Axle configuration:**

The load carrying capacity of the commercial vehicle is further enhanced by the introduction of multiple axles.

**Moving loads:**

The damage to the pavement is much higher if the vehicle is moving at creep speed. Many studies show that when the speed is increased from 2 km/hr to 24 km/hr, the stresses and deflection reduced by 40 per cent.

**Repetition of Loads:**

The influence of traffic on pavement not only depend on the magnitude of the wheel load, but also on the frequency of the load applications. Each load application causes some deformation and the total deformation is the summation of all these. Although the pavement deformation due to single axle load is very small, the cumulative effect of number of load repetition is significant. Therefore, modern design is based on total number of standard axle load (usually 80 kN single axle).

**Environmental factors**

Environmental factors affect the performance of the pavement materials and cause various damages. Environmental factors that affect pavement are of two types, temperature and precipitation and they are discussed below:

**Temperature**

The effect of temperature on asphalt pavements is different from that of concrete pavements. Temperature affects the resilient modulus of asphalt layers, while it induces curling of concrete slab. In rigid pavements, due to difference in temperatures of top and bottom of slab, temperature stresses or frictional stresses are developed. While in flexible pavement, dynamic modulus of asphaltic concrete varies with temperature. Frost heave causes differential settlements and pavement roughness. Most detrimental effect of frost penetration occurs during the spring break up period when the ice melts and subgrade is a saturated condition.

**Precipitation**

The precipitation from rain and snow affects the quantity of surface water infiltrating into the subgrade and the depth of ground water table. Poor drainage may bring lack of shear strength, pumping, loss of support, etc.

**Flexible pavement design**

**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.

**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.

**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.

**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.

**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.

**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; and

soil medium is elastic, homogeneous, and isotropic half space.

The ESWL is given by:

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| $\displaystyle \log_{10}{ESWL}=\log_{10}P+\frac{0.301\log_{10}{(\frac{z}{d/2})}}{\log_{10}(\frac{2S}{d/2})}$ |   |   | (1) |

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

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| \begin{figure}\centerline{\epsfig{file=../../../figeps/p25-equivalent-single-wheel-load.eps,width=7cm}}\end{figure} |
| Figure 1: ESWL-Equal stress concept |

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.

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| SolutionFor desired depth z=40cm, which is twice the tyre spacing, ESWL = 2P=2$\times$2044 = 4088 kN. For z=5cm, which is half the distance between the walls of the tyre, ESWL = P = 2044kN. For z=20cm,$\log_{10}{ESWL}=\log_{10}P+\frac{0.301\log_{10}{(\frac{z}{d/2})}}{\log_{10}(\frac{2S}{d/2})}$ = $\log_{10}{ESWL}=\log_{10}2044+\frac{0.301\log_{10}{(\frac{20}{10/2})}}{\log_{10}(\frac{2\times20}{10/2})}$ =3.511. Therefore, ESWL = antilog(3.511)= 3244.49 kN |

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**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.

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| 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 $W_1 N_1$ and $W_2 N_2$ are considered equivalent. Note that, $W_1 N_1$ and $W_2 N_2$ 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:

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| \begin{displaymath}{N_f} = {f_1}\left({\epsilon_t}\right)^{-{f_2}}\times \left({E}\right)^{-{f_3}} or {N_f}\propto{\epsilon_t}^{-{f_2}} \end{displaymath} | (1) |

where, ${N_f}$ is the number of load repetition for a certain percentage of cracking, ${\epsilon_t}$ 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:

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| \begin{displaymath} EALF = \left(\frac{\epsilon_i}{\epsilon_{std}}\right)^4 \end{displaymath} | (2) |

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,

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| \begin{displaymath} EALF = \left(\frac{W_i}{W_{std}}\right)^4 \end{displaymath} | (3) |

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

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| \begin{displaymath} {N_d} = {f_4}\left({\epsilon_c}\right)^{-{f_5}} \end{displaymath} | (4) |

where $N_d$ is the permissible design rut depth (say 20mm), $\epsilon_c$ 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.

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| \begin{displaymath} \mbox{Equivalent single axle load, ESAL} =\sum_{i=1}^{m} F_{i}n_i \end{displaymath} | (5) |

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

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| Example 1Let 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 [1](http://nptel.ac.in/courses/105101087/27-Ltexhtml/p9/p.html#qtEg1). The ESAL is given as $\sum{{F_i}{n_i}}=3225~kN$

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| Table 1: Example 1 Solution |
|   | Axle | No.of Load | EALF |   |
|   | Load | Repetition |   |   |
| i | (KN) | (${n_i}$) | (${F_i}$) | ${F_i}{n_i}$ |
| 1 | 40 | 10000 | $\left({40/80}\right)^4$ = 0.0625 | 625 |
| 2 | 80 | 1000 | $\left({80/80}\right)^4$ = 1 | 1000 |
| 3 | 160 | 100 | $\left({160/80}\right)^4$ = 16 | 1600 |

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IRC 37:2001) Design of flexible pavements

The Pavement designs given in the previous edition IRC:37-1984 were applicable to design traffic upto only 30 million standard axles (msa). The earlier code is empirical in nature which has limitations regarding applicability and extrapolation. This guidelines follows analytical designs and developed new set of designs up to 150 msa.

Scope

These guidelines will apply to design of flexible pavements for Expressway, National Highways, State Highways, Major District Roads, and other categories of roads. Flexible pavements are considered to include the pavements which have bituminous surfacing and granular base and sub-base courses conforming to IRC/ MOST standards. These guidelines apply to new pavements.

Design criteria

The flexible pavements has been modeled as a three layer structure and stresses and strains at critical locations have been computed using the linear elastic model. To give proper consideration to the aspects of performance, the following three types of pavement distress resulting from repeated (cyclic) application of traffic loads are considered:

vertical compressive strain at the top of the sub-grade which can cause sub-grade deformation resulting in permanent deformation at the pavement surface.

horizontal tensile strain or stress at the bottom of the bituminous layer which can cause fracture of the bituminous layer.

pavement deformation within the bituminous layer.

While the permanent deformation within the bituminous layer can be controlled by meeting the mix design requirements, thickness of granular and bituminous layers are selected using the analytical design approach so that strains at the critical points are within the allowable limits. For calculating tensile strains at the bottom of the bituminous layer, the stiffness of dense bituminous macadam (DBM) layer with 60/70 bitumen has been used in the analysis.

Failure Criteria

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| \begin{figure}\centerline{\epsfig{file=../../../figeps/p23-flexible-pavement-critical-stress-locations,width=7cm}}\end{figure} |
| Figure: Critical Locations in Pavement |
| \begin{displaymath} N_f = 2.21\times10^{-4}\times\left(\frac{1}{\epsilon_t}\right)^{3.89}\times\left(\frac{1}{E}\right)^{0.854} \end{displaymath} | (1) |

in which,  is the allowable number of load repetitions to control fatigue cracking and  is the Elastic modulus of bituminous layer. The use of equation would result in fatigue cracking of 20%ofthetotalarea. RuttingCriteria
The allowable number of load repetitions to control permanent deformation can be expressed as

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| \begin{displaymath} N_r = 4.1656\times10^{-8}\times\left(\frac {1}{\epsilon_z}\right)^{4.5337} \end{displaymath} | (2) |

 is the number of cumulative standard axles to produce rutting of 20 mm.

**Design procedure**

Based on the performance of existing designs and using analytical approach, simple design charts and a catalogue of pavement designs are added in the code. The pavement designs are given for subgrade CBR values ranging from 2% to 10% and design traffic ranging from 1 msa to 150 msa for an average annual pavement temperature of 35 C. The later thicknesses obtained from the analysis have been slightly modified to adapt the designs to stage construction. Using the following simple input parameters, appropriate designs could be chosen for the given traffic and soil strength:

Design traffic in terms of cumulative number of standard axles; and

CBR value of subgrade.

Design traffic

The method considers traffic in terms of the cumulative number of standard axles (8160 kg) to be carried by the pavement during the design life. This requires the following information:

Initial traffic in terms of CVPD

Traffic growth rate during the design life

Design life in number of years

Vehicle damage factor (VDF)

Distribution of commercial traffic over the carriage way.

**Initial traffic**
Initial traffic is determined in terms of commercial vehicles per day (CVPD). For the structural design of the pavement only commercial vehicles are considered assuming laden weight of three tonnes or more and their axle loading will be considered. Estimate of the initial daily average traffic flow for any road should normally be based on 7-day 24-hour classified traffic counts (ADT). In case of new roads, traffic estimates can be made on the basis of potential land use and traffic on existing routes in the area.

**Traffic growth rate**

Traffic growth rates can be estimated (i) by studying the past trends of traffic growth, and (ii) by establishing econometric models. If adequate data is not available, it is recommended that an average annual growth rate of 7.5 percent may be adopted.

**Design life**
For the purpose of the pavement design, the design life is defined in terms of the cumulative number of standard axles that can be carried before strengthening of the pavement is necessary. It is recommended that pavements for arterial roads like NH, SH should be designed for a life of 15 years, EH and urban roads for 20 years and other categories of roads for 10 to 15 years.

**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 axle load equivalency factors are used to convert different axle load repetitions into equivalent standard axle load repetitions. For these equivalency factors refer IRC:37 2001. The exact VDF values are arrived after extensive field surveys.
 **Vehicle distribution**
A realistic assessment of distribution of commercial traffic by direction and by lane is necessary as it directly affects the total equivalent standard axle load application used in the design. Until reliable data is available, the following distribution may be assumed.

Single lane roads: Traffic tends to be more channelized on single roads than two lane roads and to allow for this concentration of wheel load repetitions, the design should be based on total number of commercial vehicles in both directions.

Two-lane single carriageway roads: The design should be based on 75 % of the commercial vehicles in both directions.

Four-lane single carriageway roads: The design should be based on 40 % of the total number of commercial vehicles in both directions.

Dual carriageway roads: For the design of dual two-lane carriageway roads should be based on 75 % of the number of commercial vehicles in each direction. For dual three-lane carriageway and dual four-lane carriageway the distribution factor will be 60 % and 45 % respectively.

**Pavement thickness design charts**

For the design of pavements to carry traffic in the range of 1 to 10 msa, use chart 1 and for traffic in the range 10 to 150 msa, use chart 2 of IRC:37 2001. The design curves relate pavement thickness to the cumulative number of standard axles to be carried over the design life for different sub-grade CBR values ranging from 2 % to 10 %. The design charts will give the total thickness of the pavement for the above inputs. The total thickness consists of granular sub-base, granular base and bituminous surfacing. The individual layers are designed based on the the recommendations given below and the subsequent tables.

**Pavement composition**

**Sub-base**
Sub-base materials comprise natural sand, gravel, laterite, brick metal, crushed stone or combinations thereof meeting the prescribed grading and physical requirements. The sub-base material should have a minimum CBR of 20 % and 30 % for traffic upto 2 msa and traffic exceeding 2 msa respectively. Sub-base usually consist of granular or WBM and the thickness should not be less than 150 mm for design traffic less than 10 msa and 200 mm for design traffic of 1:0 msa and above.
Base
The recommended designs are for unbounded granular bases which comprise conventional water bound macadam (WBM) or wet mix macadam (WMM) or equivalent confirming to MOST specifications. The materials should be of good quality with minimum thickness of 225 mm for traffic upto2msaan150mmfortrafficexceeding2msa.
**Bituminoussurfacing**
The surfacing consists of a wearing course or a binder course plus wearing course. The most commonly used wearing courses are surface dressing, open graded premix carpet, mix seal surfacing, semi-dense bituminous concrete and bituminous concrete. For binder course, MOST specifies, it is desirable to use bituminous macadam (BM) for traffic upto o 5 msa and dense bituminous macadam (DBM) for traffic more than 5 msa.

**Numerical example**

Design the pavement for construction of a new bypass with the following data:

Two lane carriage way

Initial traffic in the year of completion of construction = 400 CVPD (sum of both directions)

Traffic growth rate = 7.5 %

Design life = 15 years

Vehicle damage factor based on axle load survey = 2.5 standard axle per commercial vehicle

Design CBR of subgrade soil = 4%.

Solution

Distribution factor = 0.75

![\begin{eqnarray*} N&=&\frac{365\times{\left[(1+0.075)^{15}-1)\right]}}{0.075}\times{400}\times{0.75}\times{2.5}\\ &=&7200000\\ &=&7.2~msa \end{eqnarray*}]()

Total pavement thickness for CBR 4% and traffic 7.2 msa from IRC:37 2001 chart1 = 660 mm

Pavement composition can be obtained by interpolation from Pavement Design Catalogue (IRC:37 2001).

Bituminous surfacing = 25 mm SDBC + 70 mm DBM

Road-base = 250 mm WBM

sub-base = 315 mm granular material of CBR not less than 30 %

**Rigid pavement design**

**Overview**

As the name implies, rigid pavements are rigid i.e, they do not flex much under loading like flexible pavements. They are constructed using cement concrete. In this case, the load carrying capacity is mainly due to the rigidity ad high modulus of elasticity of the slab (slab action). H. M. Westergaard is considered the pioneer in providing the rational treatment of the rigid pavement analysis.

Modulus of sub-grade reaction

Westergaard considered the rigid pavement slab as a thin elastic plate resting on soil sub-grade, which is assumed as a dense liquid. The upward reaction is assumed to be proportional to the deflection. Base on this assumption, Westergaard defined a modulus of sub-grade reaction  in kg/cm given by  where  is the displacement level taken as 0.125 cm and  is the pressure sustained by the rigid plate of 75 cm diameter at a deflection of 0.125 cm.

Relative stiffness of slab to sub-grade

A certain degree of resistance to slab deflection is offered by the sub-grade. The sub-grade deformation is same as the slab deflection. Hence the slab deflection is direct measurement of the magnitude of the sub-grade pressure. This pressure deformation characteristics of rigid pavement lead Westergaard to the define the term radius of relative stiffness  in cm is given by the equation [1](http://nptel.ac.in/courses/105101087/29-Ltexhtml/p2/p.html#qeRadRelSti).

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| \begin{displaymath} l = \sqrt[4]{\frac{Eh^3}{12K(1-\mu^2)}} \end{displaymath} | (1) |

where E is the modulus of elasticity of cement concrete in kg/cm (3.010),  is the Poisson's ratio of concrete (0.15),  is the slab thickness in cm and  is the modulus of sub-grade reaction

Critical load positions

Since the pavement slab has finite length and width, either the character or the intensity of maximum stress induced by the application of a given traffic load is dependent on the location of the load on the pavement surface. There are three typical locations namely the interior, edge and corner, where differing conditions of slab continuity exist. These locations are termed as critical load positions.

Equivalent radius of resisting section

When the interior point is loaded, only a small area of the pavement is resisting the bending moment of the plate. Westergaard's gives a relation for equivalent radius of the resisting section in cm in the equation [1](http://nptel.ac.in/courses/105101087/29-Ltexhtml/p3/p.html#qeEquRadRes).

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| \begin{displaymath} b=\left\{\begin{array}{ll}\sqrt{1.6a^2+h^2}-0.675~h&\mathrm{if}~a<1.724~h\\ a&\mathrm{otherwise}\end{array}\right. \end{displaymath} | (1) |

where  is the radius of the wheel load distribution in cm and  is the slab thickness in cm.

Wheel load stresses - Westergaard's stress equation

The cement concrete slab is assumed to be homogeneous and to have uniform elastic properties with vertical sub-grade reaction being proportional to the deflection. Westergaard developed relationships for the stress at interior, edge and corner regions, denoted as  in kg/cm respectively and given by the equation [1](http://nptel.ac.in/courses/105101087/29-Ltexhtml/p4/p.html#qeWesStrI)-[3](http://nptel.ac.in/courses/105101087/29-Ltexhtml/p4/p.html#qeWesStrC).

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| \begin{displaymath} \sigma_i=\frac{0.316~P}{h^2}\left[4~\log_{10}\left(\frac{l}{b}\right)+1.069\right] \end{displaymath} | (1) |

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| \begin{displaymath} \sigma_e=\frac{0.572~P}{h^2}\left[4~\log_{10}\left(\frac{l}{b}\right)+0.359\right] \end{displaymath} | (2) |

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| \begin{displaymath} \sigma_c=\frac{3~P}{h^2}\left[1-\left(\frac{a\sqrt{2}}{l}\right)^{0.6}\right] \end{displaymath} | (3) |

where  is the slab thickness in cm,  is the wheel load in kg,  is the radius of the wheel load distribution in cm,  the radius of the relative stiffness in cm and  is the radius of the resisting section in cm

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| Figure 1: Critical stress locations |
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| Temperature stressesTemperature stresses are developed in cement concrete pavement due to variation in slab temperature. This is caused by (i) daily variation resulting in a temperature gradient across the thickness of the slab and (ii) seasonal variation resulting in overall change in the slab temperature. The former results in warping stresses and the later in frictional stresses.Warping stressThe warping stress at the interior, edge and corner regions, denoted as $\sigma_{t_i},~\sigma_{t_e},~\sigma_{t_c}$ in kg/cm$^2$respectively and given  by the equation [2](http://nptel.ac.in/courses/105101087/29-Ltexhtml/p5/p.html#qeWarStrI)-[3](http://nptel.ac.in/courses/105101087/29-Ltexhtml/p5/p.html#qeWarStrC).

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| \begin{displaymath} \sigma_{t_i} = \frac{E\epsilon t}{2} \left( \frac{C_x + \mu C_y}{1-\mu^2}\right) \end{displaymath} | (1) |

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| \begin{displaymath} \sigma_{t_e} = \mathrm{Max~}\left(\frac{C_x E \epsilon t}{2} , \frac{C_y E \epsilon t}{2} \right) \end{displaymath} | (2) |

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| \begin{displaymath} \sigma_{t_c} = \frac{E \epsilon t}{3(1-\mu)}{\sqrt{\frac{a}{l}}} \end{displaymath} | (3) |

where $E$ is the modulus of elasticity of concrete in kg/cm$^2$ (3$\times$10$^5$), $\epsilon$ is the thermal coefficient of concrete per $^o$C (1$\times$10$^{-7}$) $t$ is the temperature difference between the top and bottom of the slab, $C_x$ and $C_y$ are the coefficient based on $L_x/l$ in the desired direction and $L_y/l$ right angle to the desired direction, $\mu$ is the Poisson's ration (0.15), $a$ is the radius of the contact area and $l$ is the radius of the relative stiffness. |

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| ExampleA cement concrete pavement of thickness 18 cm, has two lanes of 7.2 m with a joint. Design the tie bars.     (Solution:)  Given h=18 cm, b=7.2/2=3.6m, $S_s=1700~kg/cm^2$ $W=2400~kg/cm^2$ $f=1.5$ $S_b=24.6~kg/cm^2$.     Step 1: diameter and spacing: Get $A_s$ from\begin{eqnarray*} A_s=\frac{3.6\times{}18\times{}2400\times{}1.5}{100\times{}1750}=1.33~cm^2/m \end{eqnarray*}Assume $\phi=1~cm,~\Rightarrow~A=0.785~cm^2$. Therefore spacing is $\frac{100\times{}0.785}{1.33}=59~cm$, say $55~cm$     Step 2: Length of the bar: Get $L_t$ from\begin{eqnarray*} L_t=\frac{1\times{}1750}{2~246}~=~36.0~cm \end{eqnarray*}[Ans] Use $1~cm~\phi$ tie bars of length of $36~cmi~@~55~cm~c/c$ |

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**Problems**

Design size and spacing of dowel bars at an expansion joint of concrete pavement of thickness 20 cm. Given the radius of relative stiffness of 90 cm. design wheel load 4000 kg. Load capacity of the dowel system is 40 percent of design wheel load. Joint width is 3.0 cm and the permissible stress in shear, bending and bearing stress in dowel bars are 1000,1500 and 100  respectively.

Design the length and spacing of tie bars given that the pavement thickness is 20cm and width of the road is 7m with one longitudinal joint. The unit weight of concrete is 2400 , the coefficient of friction is 1.5, allowable working tensile stress in steel is 1750 , and bond stress of deformed bars is 24.6