G PULLAIAH COLLEGE OF ENGINEERING AND TECHNOLOGY

Department of Civil Engineering

Transportation Engineering – I

Lecture notes on

Pavement Design

Introduction to pavement design

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.

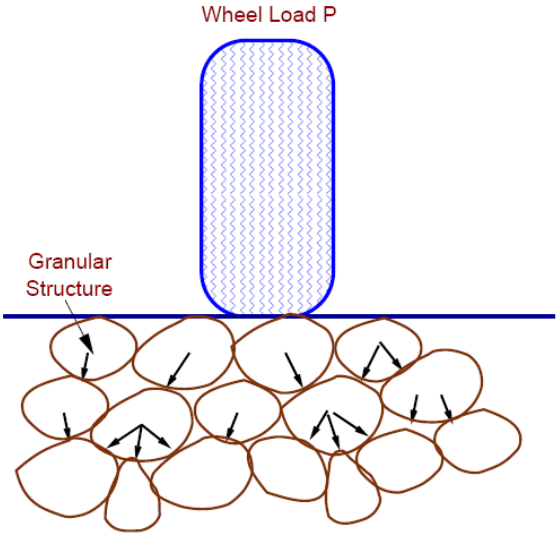
Requirements of a pavement

An ideal pavement should meet the following requirements:

- ✓ _Sufficient thickness to distribute the wheel load stresses to a safe value on the sub-grade soil,
- ✓ Structurally strong to withstand all types of stresses imposed upon it,
- ✓ Adequate coefficient of friction to prevent skidding of vehicles,
- ✓ Smooth surface to provide comfort to road users even at high speed,
- ✓ Produce least noise from moving vehicles,
- ✓ Dust proof surface so that traffic safety is not impaired by reducing visibility,
- ✓ Impervious surface, so that sub-grade soil is well protected, and
- ✓ Long design life with low maintenance cost.

Types of pavements

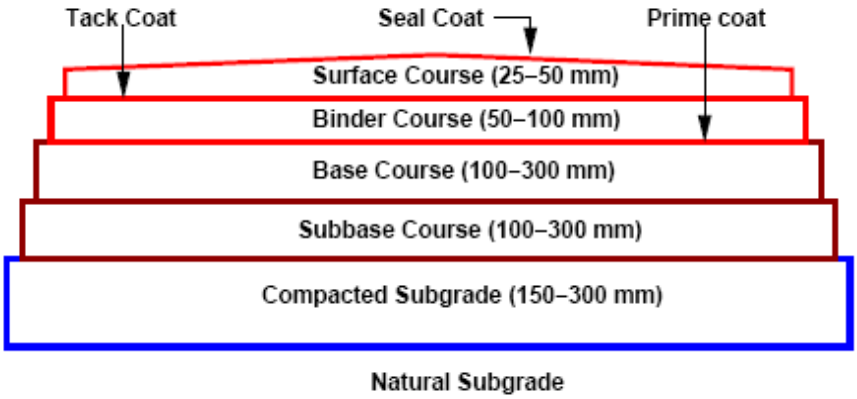
The pavements can be classified based on the structural performance into two, flexible pavements and rigid pavements. In flexible pavements, wheel loads are transferred by grain-to-grain contact of the aggregate through the granular structure. The flexible pavement, having less flexural strength, acts 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.

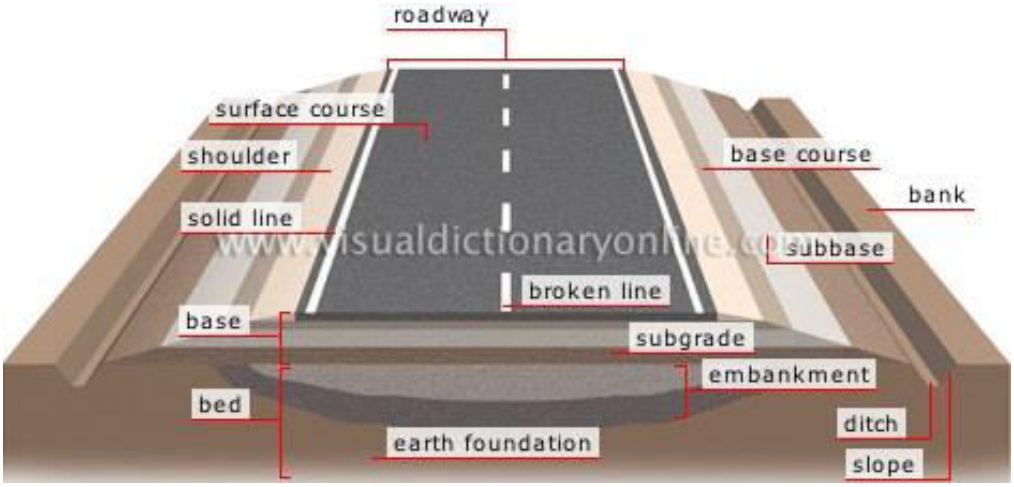


Load transfer in granular structure

Flexible pavements:

Flexible pavements will transmit wheel load stresses to the lower layers by grain-to-grain transfer through the points of contact in the granular structure (see Figure 19:1). The wheel load acting on the pavement will be distributed to a wider area, and the stress decreases with the depth. Taking advantage of these stress distribution characteristic, flexible pavements normally has many layers. Hence, the design of flexible pavement uses the concept of layered system. Based on this, flexible pavement may be constructed in a number of layers and the top layer has to be of best quality to sustain maximum compressive stress, in addition to wear and tear. The lower layers will experience lesser magnitude of stress and low quality material can be used. Flexible pavements are constructed using bituminous materials. These can be either in the form of surface treatments (such as bituminous surface treatments generally found on low volume roads) or, asphalt concrete surface courses (generally used on high volume roads such as national highways). Flexible pavement layers reflect the deformation of the lower layers on to the surface layer (e.g., if there is any undulation in sub-grade then it will be transferred to the surface layer). In the case of flexible pavement, the design is based on overall performance of flexible pavement, and the stresses produced should be kept well below the allowable stresses of each pavement layer.





Typical cross section of a exible pavement

Types of Flexible Pavements

The following types of construction have been used in flexible pavement:

- ✓ Conventional layered flexible pavement,
- ✓ Full - depth asphalt pavement, and

- ✓ Contained rock asphalt mat (CRAM).

Conventional flexible pavements are layered systems with high quality expensive materials are placed in the top where stresses are high, and low quality cheap materials are placed in lower layers.

Full - depth asphalt pavements are constructed by placing bituminous layers directly on the soil sub grade. This is more suitable when there is high traffic and local materials are not available.

Contained rock asphalt mats are constructed by placing dense/open graded aggregate layers in between two asphalt layers. Modified dense graded asphalt concrete is placed above the sub-grade will significantly reduce the vertical compressive strain on soil sub-grade and protect from surface water.

Typical layers of a flexible pavement

Typical layers of a conventional flexible pavement includes seal coat, surface course, tack coat, binder course, prime coat, base course, sub-base course, compacted sub-grade, and natural sub-grade (Figure 19:2).

Seal Coat: Seal coat is a thin surface treatment used to water-proof the surface and to provide skid resistance.

Tack Coat: Tack coat is a very light application of asphalt, usually asphalt emulsion diluted with water.

It provides proper bonding between two layer of binder course and must be thin, uniformly cover the entire surface, and set very fast.

Prime Coat: Prime coat is an application of low viscous cutback bitumen to an absorbent surface like granular bases on which binder layer is placed. It provides bonding between two layers. Unlike tack coat, prime coat penetrates into the layer below, plugs the voids, and forms a water tight surface.

Surface course

Surface course is the layer directly in contact with traffic loads and generally contains superior quality materials. They are usually constructed with dense graded asphalt concrete (AC). The functions and requirements of this layer are:

- ✓ It provides characteristics such as friction, smoothness, drainage, etc. Also it will prevent the entrance of excessive quantities of surface water into the underlying base, sub-base and sub-grade,
- ✓ It must be tough to resist the distortion under traffic and provide a smooth and skid- resistant riding surface,
- ✓ It must be water proof to protect the entire base and sub-grade from the weakening effect of water.

Binder course

This layer provides the bulk of the asphalt concrete structure. It's chief purpose is to distribute load to the base course The binder course generally consists of aggregates having less asphalt and doesn't require quality as high as the surface course, so replacing a part of the surface course by the binder course results in more economical design.

Base course

The base course is the layer of material immediately beneath the surface of binder course and it provides additional load distribution and contributes to the sub-surface drainage It may be composed of crushed stone, crushed slag, and other untreated or stabilized materials.

Sub-Base course

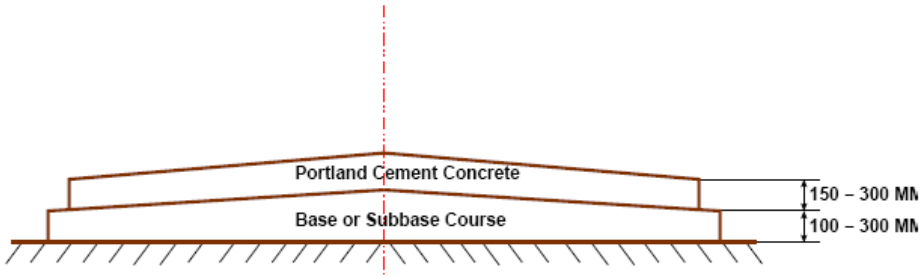
The sub-base course is the layer of material beneath the base course and the primary functions are to provide structural support, improve drainage, and reduce the intrusion of fines from the sub-grade in the pavement structure If the base course is open graded, then the sub-base course with more fines can serve as a filler between sub-grade and the base course A sub-base course is not always needed or used. For example, a pavement constructed over a high quality, sti_ sub-grade may not need the additional features offered by a sub-base course. In such situations, sub-base course may not be provided.

Sub-grade

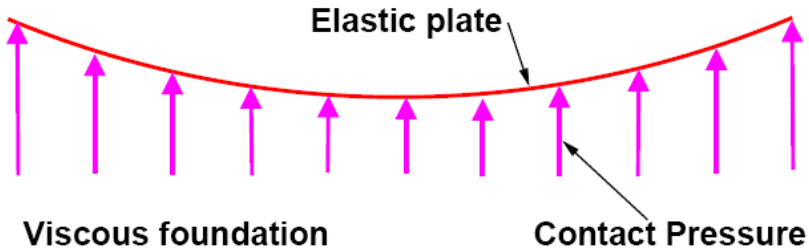
The top soil or sub-grade is a layer of natural soil prepared to receive the stresses from the layers above. It is essential that at no time soil sub-grade is overstressed. It should be compacted to the desirable density, near the optimum moisture content.

Failure of flexible pavements

The major flexible pavement failures are fatigue cracking, rutting, and thermal cracking. The fatigue cracking of flexible pavement is due to horizontal tensile strain at the bottom of the asphaltic concrete. The failure criterion relates allowable number of load repetitions to tensile strain and this relation can be determined in the laboratory fatigue test on asphaltic concrete specimens. Rutting occurs only on flexible pavements as indicated by permanent deformation or rut depth along wheel load path. Two design methods have been used to control rutting: one to limit the vertical compressive strain on the top of sub grade and other to limit rutting to a tolerable amount (12 mm normally). Thermal cracking includes both low-temperature cracking and thermal fatigue cracking.



Typical Cross section of Rigid pavement



Elastic plate resting on viscous foundation

Rigid pavements:

Rigid pavements have sufficient flexural strength to transmit the wheel load stresses to a wider area below.

A typical cross section of the rigid pavement is shown in Figure 19:3. Compared to flexible pavement, rigid pavements are placed either directly on the prepared sub-grade or on a single layer of granular or stabilized material. Since there is only one layer of material between the concrete and the sub-grade, this layer can be called as base or sub-base course.

In rigid pavement, load is distributed by the slab action, and the pavement behaves like an elastic plate resting on a viscous medium (Figure 19:4). Rigid pavements are constructed by Portland cement concrete (PCC) and should be analyzed by plate theory instead of layer theory, assuming an elastic plate resting on viscous foundation. Plate theory is a simplified version of layer theory that assumes the concrete slab as a medium thick plate which is plane before loading and to remain plane after loading. Bending of the slab due to wheel load and temperature variation and the resulting tensile and flexural stress.

Types of Rigid Pavements

Rigid pavements can be classified into four types:

- ✓ Jointed plain concrete pavement (JPCP),
- ✓ Jointed reinforced concrete pavement (JRCP),
- ✓ Continuous reinforced concrete pavement (CRCP), and
- ✓ Pre-stressed concrete pavement (PCP).

Jointed Plain Concrete Pavement are plain cement concrete pavements constructed with closely spaced contraction joints. Dowel bars or aggregate interlocks are normally used for load transfer across joints. They normally have a joint spacing of 5 to 10m.

Jointed Reinforced Concrete Pavement: Although reinforcements do not improve the structural capacity significantly, they can drastically increase the joint spacing to 10 to 30m. Dowel bars are required for load transfer. Reinforcement's help to keep the slab together even after cracks.

Continuous Reinforced Concrete Pavement: Complete elimination of joints are achieved by reinforcement.

Failure criteria of rigid pavements

Traditionally fatigue cracking has been considered as the major or only criterion for rigid pavement design.

The allowable number of load repetitions to cause fatigue cracking depends on the stress ratio between flexural tensile stress and concrete modulus of rupture. Of late, pumping is identified as an important failure criterion.

Pumping is the ejection of soil slurry through the joints and cracks of cement concrete pavement, caused during the downward movement of slab under the heavy wheel loads. Other major types of distress in rigid pavements include faulting, spalling, and deterioration.

Factors affecting pavement design:

In the previous chapter we had discussed about the types of pavements and their failure criteria. There are many factors that affect pavement design which can be classified into four categories as traffic and loading, structural models, material characterization, environment. They will be discussed in detail in this chapter.

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 determines 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 sub grade soil is not failed. Wheel configuration affects the stress distribution and deflection with in a pavement. 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 depends 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).

Structural models

The structural models are various analysis approaches to determine the pavement responses (stresses, strains, and deflections) at various locations in a pavement due to the application of wheel load. The most common structural models are layered elastic model and visco-elastic models.

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, the material properties are same at every point in a given layer and the layer will rebound to its original form once the load is removed. The layered elastic approach works with relatively simple mathematical models that relates stress, strain, and deformation with wheel loading and material properties like modulus of elasticity and poissons ratio.

Material characterization

The following material properties are important for both flexible and rigid pavements.

- ✓ When pavements are considered as linear elastic, the elastic moduli and poisson ratio of sub grade and each component layer must be specified.
- ✓ If the elastic modulus of a material varies with the time of loading, then the resilient modulus, which is elastic modulus under repeated loads, must be selected in accordance with a load duration corresponding to the vehicle speed.
- ✓ When a material is considered non-linear elastic, the constitutive equation relating the resilient modulus to the state of the stress must be provided.

However, many of these material properties are used in visco-elastic models which are very complex and in the development stage. This book covers the layered elastic model which requires the modulus of elasticity and poisson ratio only.

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 sub grade is a saturated condition.

Precipitation

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

Pavement materials: Aggregates

Aggregate is a collective term for the mineral materials such as sand, gravel, and crushed stone that are used with a binding medium (such as water, bitumen, Portland cement, lime, etc.) to form compound materials (such as bituminous concrete and Portland cement concrete). By volume, aggregate generally accounts for 92 to 96 percent of Bituminous concrete and about 70 to 80 percent of Portland cement concrete. Aggregate is also used for base and sub-base courses for both flexible and rigid pavements. Aggregates can either be natural or manufactured. Natural aggregates are generally extracted from larger rock formations through an open excavation (quarry). Extracted rock is typically reduced to usable sizes by mechanical crushing. Manufactured aggregate is often a bye product of other manufacturing industries.

Desirable properties:

Strength

The aggregates used in top layers are subjected to

(i) Stress action due to traffic wheel load,
(ii) Wear and tear,
(iii) Crushing.

For a high quality pavement, the aggregates should posse's high resistance to crushing, and to withstand the stresses due to traffic wheel load.

Hardness

The aggregates used in the surface course are subjected to constant rubbing or abrasion due to moving traffic. The aggregates should be hard enough to resist the abrasive action caused by the movements of traffic. The abrasive action is severe when steel tyred vehicles moves over the aggregates exposed at the top surface.

Toughness

Resistance of the aggregates to impact is termed as toughness. Aggregates used in the pavement should be able to resist the effect caused by the jumping of the steel tyred wheels from one particle to another at different levels cause severe impact on the aggregates.

Shape of aggregates

Aggregates which happen to fall in a particular size range may have rounded cubical, angular, flaky or elongated particles. It is evident that the flaky and elongated particles will have less strength and durability when compared with cubical, angular or rounded particles of the same aggregate. Hence too flaky and too much elongated aggregates should be avoided as far as possible.

Adhesion with bitumen

The aggregates used in bituminous pavements should have less affinity with water when compared with bituminous materials; otherwise the bituminous coating on the aggregate will be stripped off in presence of water.

Durability

The property of aggregates to withstand adverse action of weather is called soundness. The aggregates are subjected to the physical and chemical action of rain and bottom water, impurities there-in and that of atmosphere, hence it is desirable that the road aggregates used in the construction should be sound enough to withstand the weathering action.

Freedom from deleterious particles

Specifications for aggregates used in bituminous mixes usually require the aggregates to be clean, tough and durable in nature and free from excess amount of at or elongated pieces, dust, clay balls and other objectionable material. Similarly aggregates used in Portland cement concrete mixes must be clean and free from deleterious substances such as clay lumps, chert, silt and other organic impurities.

Aggregate tests

In order to decide the suitability of the aggregate for use in pavement construction, following tests are carried out:

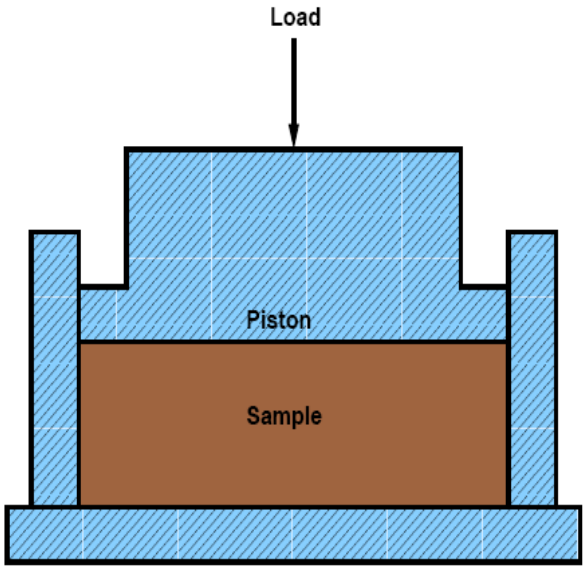
- ✓ Crushing test
- ✓ Abrasion test
- ✓ Impact test
- ✓ Soundness test
- ✓ Shape test
- ✓ Specific gravity and water absorption test
- ✓ Bitumen adhesion test

Crushing test

One of the model in which pavement material can fail is by crushing under compressive stress. A test is standardized by IS: 2386 part-IV and used to determine the crushing strength of aggregates. The aggregate crushing value provides a relative measure of resistance to crushing under gradually applied crushing load. The test consists of subjecting the specimen of aggregate in standard mould to a compression test under standard load conditions (Figure 22:1). Dry aggregates passing through 12.5 mm sieves and retained 10 mm sieves are filled in a cylindrical measure of 11.5 mm diameter and 18 cm height in three layers. Each layer is tampered 25 times with at standard tamping rod. The test sample is weighed and placed in the test cylinder in three layers each layer being tampered again. The specimen is subjected to a compressive load of 40 tones gradually applied at the rate of 4 tons per minute. Then crushed aggregates are then sieved through 2.36 mm sieve and weight of passing material (W2) is expressed as percentage of the weight of the total sample (W1) which is the aggregate crushing value.

$$\text{Aggregate crushing value} = (W_1/W2) \times 100$$

A value less than 10 signifies an exceptionally strong aggregate while above 35 would normally be regarded as weak aggregates.



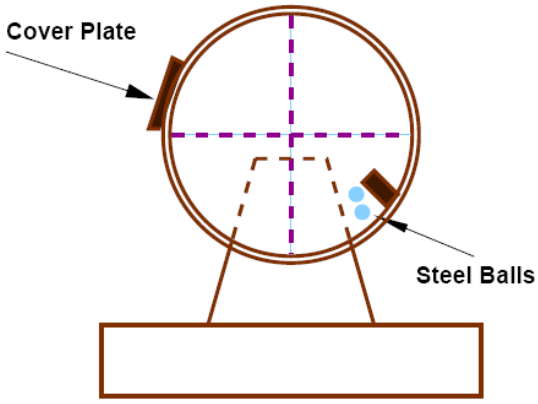
Crushing test setup

Abrasion test:

Abrasion test is carried out to test the hardness property of aggregates and to decide whether they are suitable for different pavement construction works. Los Angeles abrasion test is a preferred one for carrying out the hardness property and has been standardized in India (IS: 2386 part-IV). The principle of Los Angeles abrasion test is to find the percentage wear due to relative rubbing action between the aggregate and steel balls used as abrasive charge.

Los Angeles machine consists of circular drum of internal diameter 700 mm and length 520 mm mounted on horizontal axis enabling it to be rotated (see Figure 22:2). An abrasive charge consisting of cast iron

spherical balls of 48 mm diameters and weight 340-445 g is placed in the cylinder along with the aggregates. The number of the abrasive spheres varies according to the grading of the sample. The quantity of aggregates to be used depends upon the gradation and usually ranges from 5-10 kg. The cylinder is then locked and rotated at the speed of 30-33 rpm for a total of 500 -1000 revolutions depending upon the gradation of aggregates. After specified revolutions, the material is sieved through 1.7 mm sieve and passed fraction is expressed as percentage total weight of the sample. This value is called Los Angeles abrasion value.
A maximum value of 40 percent is allowed for WBM base course in Indian conditions. For bituminous concrete, a maximum value of 35 is specified.



Los Angeles abrasion test setup

Impact test

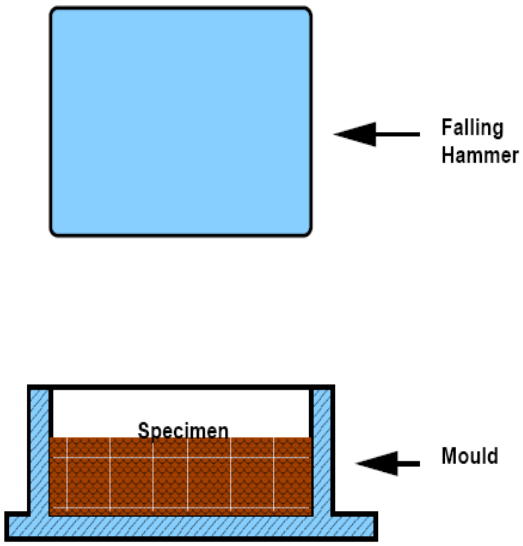
The aggregate impact test is carried out to evaluate the resistance to impact of aggregates. Aggregates passing 12.5 mm sieve and retained on 10 mm sieve is filled in a cylindrical steel cup of internal dia 10.2 mm and depth 5 cm which is attached to a metal base of impact testing machine. The material is filled in 3 layers where each layer is tamped for 25 numbers of blows. Metal hammer of weight 13.5 to 14 Kg is arranged to drop with a free fall of 38.0 cm by vertical guides and the test specimen is subjected to 15 numbers of blows. The crushed aggregate is allowed to pass through 2.36 mm IS sieve. And the impact value is measured as percentage of aggregates passing sieve (W2) to the total weight of the sample (W1).

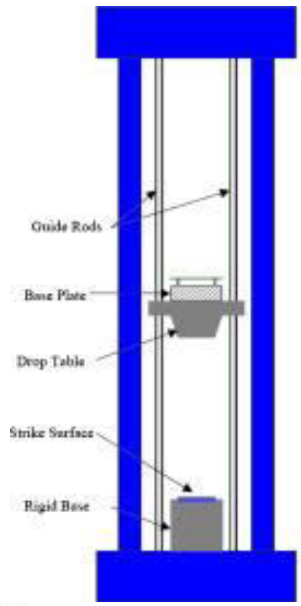
$$\text{Aggregate impact value} = (W_1/W2) \times 100$$

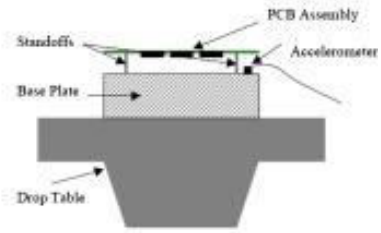
Aggregates to be used for wearing course, the impact value shouldn't exceed 30 percent. For bituminous macadam the maximum permissible value is 35 percent. For Water bound macadam base courses the maximum permissible value defined by IRC is 40 percent.

Soundness test

Soundness test is intended to study the resistance of aggregates to weathering action, by conducting accelerated weathering test cycles. The Porous aggregates subjected to freezing and thawing is likely to disintegrate prematurely. To ascertain the durability of such aggregates, they are subjected to an accelerated soundness test as specified in IS: 2386 part-V. Aggregates of specified size are subjected to cycles of alternate wetting in a saturated solution of either sodium sulphate or magnesium sulphate for 16 - 18 hours and then dried in oven at 105 - 110°C to a constant weight. After five cycles, the loss in weight of aggregates is determined by sieving out all undersized particles and weighing. And the loss in weight should not exceed 12 percent when tested with sodium sulphate and 18 percent with magnesium sulphate solution.







Shape tests

The particle shape of the aggregate mass is determined by the percentage of flaky and elongated particles in it. Aggregates which are flaky or elongated are detrimental to higher workability and stability of mixes. The flakiness index is defined as the percentage by weight of aggregate particles whose least dimension is less than 0.6 times their mean size. Test procedure had been standardized in India (IS: 2386 part-I)

The elongation index of an aggregate is defined as the percentage by weight of particles whose greatest dimension (length) is 1.8 times their mean dimension. This test is applicable to aggregates larger than 6.3 mm. This test is also specified in (IS: 2386 Part-I). However there are no recognized limits for the elongation index.

Specific Gravity and water absorption:

The specific gravity and water absorption of aggregates are important properties that are required for the design of concrete and bituminous mixes. The specific gravity of a solid is the ratio of its mass to that of an equal volume of distilled water at a specified temperature. Because the aggregates may contain water-permeable voids, so two measures of specific gravity of aggregates are used: apparent specific gravity and bulk specific gravity.

- ✓ Apparent Specific Gravity, Gap, is computed on the basis of the net volume of aggregates i.e the volume excluding water-permeable voids. Thus

$$G_{app} = \frac{M_D/V_N}{W}$$

Where, M_D is the dry mass of the aggregate, V_N is the net volume of the aggregates excluding the volume of the absorbed matter, W is the density of water.

- ✓ **Bulk Specific Gravity**, G_{bulk}, is computed on the basis of the total volume of aggregates including water permeable voids. Thus

$$G_{bulk} = \frac{M_D/V_B}{W}$$

Where, V_B is the total volume of the aggregates including the volume of absorbed water.

- ✓ **Water absorption**, the difference between the apparent and bulk specific gravities is nothing but the water permeable voids of the aggregates. We can measure the volume of such voids by weighing the aggregates dry and in a saturated, surface dry condition, with all permeable voids filled with water. The difference of the above two is M_W. M_W is the weight of dry aggregates minus weight of aggregates saturated surface dry condition. Thus

$$\text{Water absorption} = M_W / M_D \times 100$$

The specific gravity of aggregates normally used in road construction ranges from about 2.5 to 2.9. Water absorption values ranges from 0.1 to about 2.0 percent for aggregates normally used in road surfacing.

Bitumen adhesion test:

Bitumen adheres well to all normal types of road aggregates provided they are dry and free from dust. In the absence of water there is practically no adhesion problem of bituminous construction. Adhesion problem occurs when the aggregate is wet and cold. This problem can be dealt with by removing moisture from the aggregate by drying and increasing the mixing temperature. Further, the presence of water causes stripping of binder from the coated aggregates. These problems occur when bitumen mixture is permeable to water. Several laboratory tests are conducted to arbitrarily determine the adhesion of bitumen binder to an aggregate in the presence of water. Static immersion test is one specified by IRC and is quite simple. The principle of

the test is by immersing aggregate fully coated with binder in water maintained at 400C temperature for 24 hours. IRC has specified maximum stripping value of aggregates should not exceed 5%.

Property of aggregate	Type of Test	Test Method
Crushing strength	Crushing test	IS : 2386 (part 4) -1963
Hardness	Los Angeles abrasion test	IS : 2386 (Part 5)-1963
Toughness	Aggregate impact test	IS : 2386 (Part 4)-1963
Durability	Soundness test- accelerated durability test	IS : 2386 (Part 5)-1963
Shape factors	Shape test	IS : 2386 (Part 1)-1963
Specific gravity and porosity	Specific gravity test and water absorption test	IS : 2386 (Part 3)-1963
Adhesion to bitumen	Stripping value of aggregate	IS : 6241-1971

Tests for Aggregates with IS codes

Pavement materials: Bitumen

Bituminous materials or asphalts are extensively used for roadway construction, primarily because of their excellent binding characteristics and water proofing properties and relatively low cost. Bituminous materials consists of bitumen which is a black or dark colored solid or viscous cementations substances consists chiefly high molecular weight hydrocarbons derived from distillation of petroleum or natural asphalt, has adhesive properties, and is soluble in carbon disulphide. Tars are residues from the destructive distillation of organic substances such as coal, wood, or petroleum and are temperature sensitive than bitumen. Bitumen will be dissolved in petroleum oils where unlike tar.

Production of Bitumen

Bitumen is the residue or by-product when the crude petroleum is refined. A wide variety of refinery processes, such as the straight distillation process, solvent extraction process etc. may be used to produce bitumen of different consistency and other desirable properties. Depending on the sources and characteristics of the crude oils and on the properties of bitumen required, more than one processing method may be employed.

Vacuum steam distillation of petroleum oils

In the vacuum-steam distillation process the crude oil is heated and is introduced into a large cylindrical still. Steam is introduced into the still to aid in the vaporization of the more volatile constituents of the petroleum and to minimize decomposition of the distillates and residues. The volatile constituents are collected, condensed, and the various fractions stored for further refining, if needed. The residues from this distillation are then fed into a vacuum distillation unit, where residue pressure and steam will further separate out heavier gas oils. The bottom fraction from this unit is the vacuum-steam-refined asphalt cement. The consistency of asphalt cement from this process can be controlled by the amount of heavy gas oil removed. Normally, asphalt produced by this process is softer. As the asphalt cools down to room temperature, it becomes a semi solid viscous material.

Different forms of bitumen:

1. **Cutback bitumen**

Normal practice is to heat bitumen to reduce its viscosity. In some situations preference is given to use liquid binders such as cutback bitumen. In cutback bitumen suitable solvent is used to lower the viscosity of the bitumen. From the environmental point of view also cutback bitumen is preferred. The solvent from the bituminous material will evaporate and the bitumen will bind the aggregate. Cutback bitumen is used for cold weather bituminous road construction and maintenance. The distillates used for preparation of cutback bitumen are naphtha, kerosene, diesel oil, and furnace oil. There are different types of cutback bitumen like rapid curing (RC), medium curing (MC), and slow curing (SC). RC is recommended for surface dressing and

patchwork. MC is recommended for premix with less quantity of fine aggregates. SC is used for premix with appreciable quantity of fine aggregates.

Bitumen Emulsion:

Bitumen emulsion is a liquid product in which bitumen is suspended in a finely divided condition in an aqueous medium and stabilized by suitable material. Normally cationic type emulsions are used in India. The bitumen content in the emulsion is around 60% and the remaining is water. When the emulsion is applied on the road it breaks down resulting in release of water and the mix starts to set. The time of setting depends upon the grade of bitumen. The viscosity of bituminous emulsions can be measured as per IS: 8887-1995. Three types of bituminous emulsions are available, which are Rapid setting (RS), Medium setting (MS), and Slow setting (SC). Bitumen emulsions are ideal binders for hill road construction. Where heating of bitumen or aggregates are difficult. Rapid setting emulsions are used for surface dressing work. Medium setting emulsions are preferred for premix jobs and patch repairs work. Slow setting emulsions are preferred in rainy season.

Bituminous primers

In bituminous primer the distillate is absorbed by the road surface on which it is spread. The absorption therefore depends on the porosity of the surface. Bitumen primers are useful on the stabilized surfaces and water bound macadam base courses. Bituminous primers are generally prepared on road sites by mixing penetration bitumen with petroleum distillate.

Modified Bitumen

Certain additives or blend of additives called as bitumen midfielders can improve properties of Bitumen and bituminous mixes. Bitumen treated with these midfielders is known as modified bitumen. Polymer modified bitumen (PMB)/ crumb rubber modified bitumen (CRMB) should be used only in wearing course depending upon the requirements of extreme climatic variations. The detailed specifications for modified bitumen have been issued by IRC: SP: 53-1999. It must be noted that the performance of PMB and CRMB is dependent on strict control on temperature during construction. The advantages of using modified bitumen are as follows

- ✓ Lower susceptibility to daily and seasonal temperature variations
- ✓ Higher resistance to deformation at high pavement temperature
- ✓ Better age resistance properties
- ✓ Higher fatigue life for mixes
- ✓ Better adhesion between aggregates and binder
- ✓ Prevention of cracking and reflective cracking

Requirements of Bitumen

The desirable properties of bitumen depend on the mix type and construction. In general, Bitumen should posses following desirable properties.

- ✓ The bitumen should not be highly temperature susceptible: during the hottest weather the mix should not become too soft or unstable, and during cold weather the mix should not become too brittle causing cracks.
- ✓ The viscosity of the bitumen at the time of mixing and compaction should be adequate. This can be achieved by use of cutbacks or emulsions of suitable grades or by heating the bitumen and aggregates prior to mixing.
- ✓ There should be adequate affinity and adhesion between the bitumen and aggregates used in the mix.

Tests on bitumen:

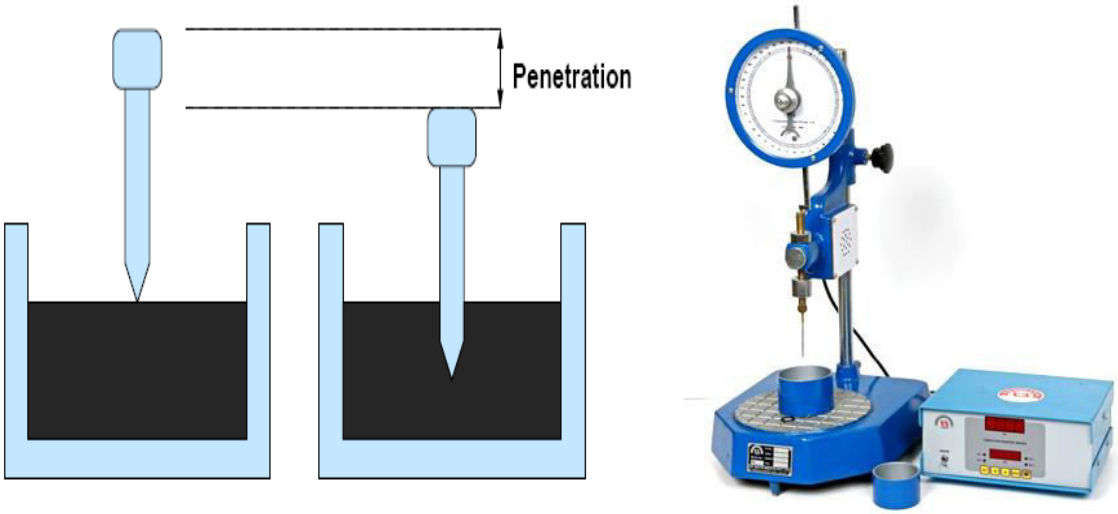
There are a number of tests to assess the properties of bituminous materials. The following tests are usually conducted to evaluate different properties of bituminous materials.

1. Penetration test
2. Ductility test
3. Softening point test

4. Specific gravity test
5. Viscosity test
6. Flash and Fire point test
7. Float test
8. Water content test
9. Loss on heating test

Penetration test

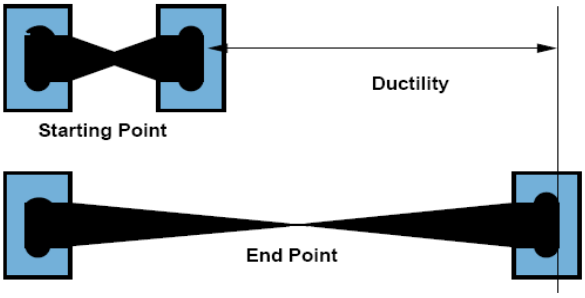
It measures the hardness or softness of bitumen by measuring the depth in tenths of a millimeter to which a standard loaded needle will penetrate vertically in 5 seconds. BIS had standardized the equipment and test procedure. The penetrometer consists of a needle assembly with a total weight of 100g and a device for releasing and locking in any position. The bitumen is softened to a pouring consistency, stirred thoroughly and poured into containers at a depth at least 15 mm in excess of the expected penetration. The test should be conducted at a specified temperature of 25o C. It may be noted that penetration value is largely influenced by any inaccuracy with regards to pouring temperature, size of the needle, weight placed on the needle and the test temperature. A grade of 40/50 bitumen means the penetration value is in the range 40 to 50 at standard test conditions. In hot climates, a lower penetration grade is preferred. The Figure 23.4.1 shows a schematic Penetration Test setup.



Penetration Test Setup

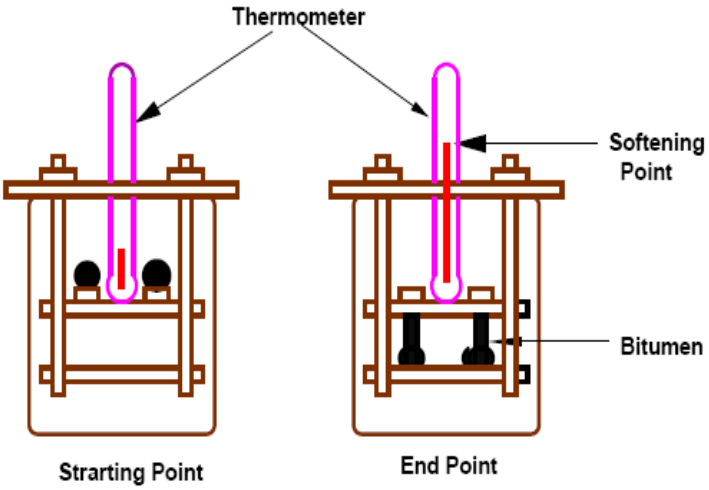
Ductility test

Ductility is the property of bitumen that permits it to undergo great deformation or elongation. Ductility is defined as the distance in cm, to which a standard sample or briquette of the material will be elongated without breaking. Dimension of the briquette thus formed is exactly 1 cm square. The bitumen sample is heated and poured in the mould assembly placed on a plate. These samples with moulds are cooled in the air and then in water bath at 27o C temperature. The excess bitumen is cut and the surface is leveled using a hot knife. Then the mould with assembly containing sample is kept in water bath of the ductility machine for about 90 minutes. The sides of the moulds are removed, the clips are hooked on the machine and the machine is operated. The distance up to the point of breaking of thread is the ductility value which is reported in cm. The ductility value gets affected by factors such as pouring temperature, test temperature, rate of pulling etc. A minimum ductility value of 75 cm has been specified by the BIS. Figure 23.4.2 shows ductility moulds to be filled with bitumen.



Softening point test:

Softening point denotes the temperature at which the bitumen attains a particular degree of softening under the specifications of test. The test is conducted by using Ring and Ball apparatus. A brass ring containing test sample of bitumen is suspended in liquid like water or glycerin at a given temperature. A steel ball is placed upon the bitumen sample and the liquid medium is heated at a rate of 5o C per minute. Temperature is noted when the softened bitumen touches the metal plate which is at a specified distance below. Generally, higher softening point indicates lower temperature susceptibility and is preferred in hot climates. Figure 23.4.3 shows Softening Point test setup.



Specific gravity test:

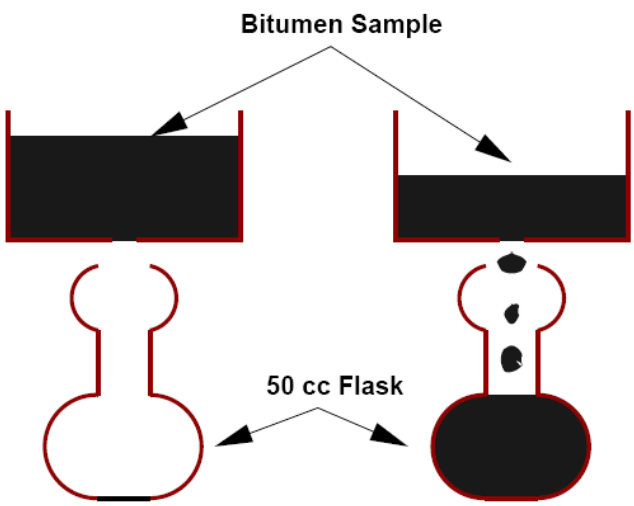
In paving jobs, to classify a binder, density property is of great use. In most cases bitumen is weighed, but when used with aggregates, the bitumen is converted to volume using density values. The density of bitumen is greatly influenced by its chemical composition. Increase in aromatic type mineral impurities cause an increase in specific gravity. The specific gravity of bitumen is defined as the ratio of mass of given volume of bitumen of known content to the mass of equal volume of water at 27° C. The specific gravity can be measured using either pycnometer or preparing a cube specimen of bitumen in semi solid or solid state. The specific gravity of bitumen varies from 0.97 to 1.02.

Viscosity test

Viscosity denotes the fluid property of bituminous material and it is a measure of resistance to flow. At the application temperature, this characteristic greatly influences the strength of resulting paving mixes. Low or high viscosity during compaction or mixing has been observed to result in lower stability values. At high viscosity, it resists the comp active effort and thereby resulting mix is heterogeneous, hence low stability values. And at low viscosity instead of providing a uniform film over aggregates, it will lubricate the aggregate particles. Orifice type viscometers are used to indirectly find the viscosity of liquid binders like cutbacks and emulsions. The viscosity expressed in seconds is the time taken by the 50 ml bitumen material to pass through the orifice of a cup, under standard test conditions and specified temperature. Viscosity of a cutback can be measured with either 4.0 mm orifice at 25o C or 10 mm orifice at 25 or 40° C.

Flash and fire point test

At high temperatures depending upon the grades of bitumen materials leave out volatiles. And this volatile catches fire which is very hazardous and therefore it is essential to qualify this temperature for each bitumen grade. BIS defined the ash point as the temperature at which the vapour of bitumen momentarily catches fire in the form of ash under specified test conditions. The fire point is defined as the lowest temperature under specified test conditions at which the bituminous material gets ignited and burns.



Float test

Normally the consistency of bituminous material can be measured either by penetration test or viscosity test. But for certain range of consistencies, these tests are not applicable and Float test is used. The apparatus consists of an aluminum oat and a brass collar filled with bitumen to be tested. The specimen in the mould is cooled to a temperature of 5oC and screwed in to oat. The total test assembly is floated in the water bath at 50oC and the time required for water to pass its way through the specimen plug is noted in seconds and is expressed as the oat value.

Water content test

It is desirable that the bitumen contains minimum water content to prevent foaming of the bitumen when it is heated above the boiling point of water. The water in bitumen is determined by mixing known weight of specimen in a pure petroleum distillate free from water, heating and distilling of the water. The weight of the water condensed and collected is expressed as percentage by weight of the original sample. The allowable maximum water content should not be more than 0.2% by weight.

Loss on heating test

When the bitumen is heated it loses the volatility and gets hardened. About 50gm of the sample is weighed and heated to a temperature of 1630C for 5hours in a specified oven designed for this test. The sample specimen is weighed again after the heating period and loss in weight is expressed as percentage by weight of the original sample. Bitumen used in pavement mixes should not indicate more than 1% loss in weight, but for bitumen having penetration values 150-200 up to 2% loss in weight is allowed.

Type of test	Test Method
Penetration Test	IS: 1203-1978
Ductility test	IS: 1208-1978
Softening Point test	IS: 1205-1978
Specific gravity test	IS: 1202-1978
Viscosity test	IS: 1206-1978
Flash and Fire Point test	IS: 1209-1978
Float Test	IS: 1210-1978
Determination of water content	IS: 1211-1978
Determination of Loss on heating	IS:1212-1978

Tests for Bitumen with IS codes

Requirements of bitumen as a binding material and its different forms were discussed. Various tests are conducted on bitumen to assess its consistency, gradation, viscosity, temperature susceptibility, and safety.

Bituminous mix design

The bituminous mix design aims to determine the proportion of bitumen, filler, fine aggregates, and coarse aggregates to produce a mix which is workable, strong, durable and economical. The requirements of the mix design and the two major stages of the mix design, i.e. dry mix design and wet mix design will be discussed.

Evolution of road surface

- ✓ Unsurfaced earthen roads, or cart-track
- ✓ Unsurfaced earthen roads upgrades with natural soil from borrow pits and attention to drainage, and compaction is by traffic
- ✓ Dry aggregate and sand-clays mix, in which the former act as wear resistant and the latter as natural binder
- ✓ Water-bound macadam, the above constituents, mixed together (pre-mix or in-situ) with water and compacted to improve the strength
- ✓ Oiled roads, introduced to reduce dust by bitumen stabilized soils
- ✓ Seal coat: the base course is protected from traffic and moisture by sealing the surface with a thin _lm of bitumen aggregate mix, which is structurally strong surface for pneumatic-tyred traffic. This is provided on firm and smooth base course after a tack coat using cutback bitumen or bitumen emulsions with a penetration of 5 mm.
- ✓ Asphaltic concrete: Traffic and the axle configuration are increasing very much which raises demand for the new type of pavement which can meet the above requirements. The asphaltic concrete is one

which is the high dense graded premix and it is termed as the highest quality pavement surface course.

- ✓ Bitumen mix or asphalt mix overlays of minimum 20 - 40 mm to as high as 300 - 500 mm or even more.

Objectives of mix design

The objective of the mix design is to produce a bituminous mix by proportionate various components so as to have:

1. Sufficient bitumen to ensure a durable pavement,
2. Sufficient strength to resist shear deformation under traffic at higher temperature,
3. Sufficient air voids in the compacted bitumen to allow for additional compaction by traffic,
4. Sufficient workability to permit easy placement without segregation,
5. Sufficient flexibility to avoid premature cracking due to repeated bending by traffic, and
6. Sufficient flexibility at low temperature to prevent shrinkage cracks.

Constituents of a mix

- ✓ Coarse aggregates: Offer compressive and shear strength and shows good interlocking properties. E.g. Granite
- ✓ Fine aggregates: Fills the voids in the coarse aggregate and stiffens the binder. E.g. Sand, Rock dust
- ✓ Filler: Fills the voids, stiffens the binder and offers permeability. E.g. Rock dust, cement, lime
- ✓ Binder: Fills the voids, cause particle adhesion and gluing and offers impermeability. E.g. Bitumen, Asphalt, Tar

Types of mix

- ✓ Well-graded mix:- Dense mix, bituminous concrete has good proportion of all constituents and are called dense bituminous macadam, offers good compressive strength and some tensile strength
- ✓ Gap-graded mix:- Some large coarse aggregates are missing and has good fatigue and tensile strength.
- ✓ Open-graded mix:- Fine aggregate and filler are missing, it is porous and offers good friction, low strength and for high speed.
- ✓ Unbounded:- Binder is absent and behaves under loads as if its components were not linked together though good interlocking exists. Very low tensile strength and needs kerb protection.

Different layers in a pavement

- ✓ Bituminous base course Consist of mineral aggregate such as stone, gravel, or sand bonded together by a bituminous material and used as a foundation upon which to place a binder or surface course.
- ✓ Bituminous binder course A bituminous-aggregate mixture used as an intermediate coarse between the base and surface courses or as the first bituminous layer in a two-layer bituminous resurfacing. It is sometimes called a leveling course.
- ✓ Asphaltic/Bituminous concrete Bituminous concrete consists of a mixture of aggregates continuously graded from maximum size , typically less than 25 mm, through fine filler that is smaller than 0.075 mm. Sufficient bitumen is added to the mix so that the compacted mix is effectively impervious and will have acceptable dissipative and elastic properties.

Table 24:1: Aggregate gradation for BC

Sieve size		Passing (%)
26.5	mm	- 100
19.	mm	90 - 100
9.5	mm	56 - 80
4.75	mm	35 - 65
2.36	mm	23 - 49
300	micron	5 - 19
75	micron	2 - 8

Requirements of Bituminous mixes:

Stability:

Stability is defined as the resistance of the paving mix to deformation under traffic load. Two examples of failure are

(i) Shoving - a transverse rigid deformation which occurs at areas subject to severe acceleration and

(ii) Grooving - longitudinal ridging due to channelization of traffic. Stability depends on the inter-particle friction, primarily of the aggregates and the cohesion offered by the bitumen. Sufficient binder must be available to coat all the particles at the same time should offer enough liquid friction. However, the stability decreases when the binder content is high and when the particles are kept apart.

Durability

Durability is defined as the resistance of the mix against weathering and abrasive actions. Weathering causes hardening due to loss of volatiles in the bitumen. Abrasion is due to wheel loads which causes tensile strains. Typical examples of failure are

(i) pot-holes, - deterioration of pavements locally and

(ii) Stripping lost of binder from the aggregates and aggregates are exposed. Disintegration is minimized by high binder content since they cause the mix to be air and waterproof and the bitumen film is more resistant to hardening.

Flexibility

Flexibility is a measure of the level of bending strength needed to counteract traffic load and prevent cracking of surface. Fracture is the cracks formed on the surface (hairline-cracks, alligator cracks), main reasons are shrinkage and brittleness of the binder. Shrinkage cracks are due to volume change in the binder due to aging. Brittleness is due to repeated bending of the surface due to traffic loads. Higher bitumen content will give better flexibility and less fracture.

Skid resistance

It is the resistance of the finished pavement against skidding which depends on the surface texture and bitumen content. It is an important factor in high speed traffic. Normally, an open graded coarse surface texture is desirable.

Workability

Workability is the ease with which the mix can be laid and compacted, and formed to the required condition and shape. This depends on the gradation of aggregates, their shape and texture, bitumen content and its type. Angular, flaky, and elongated aggregates workability on the other hand, rounded aggregates improve workability.

Desirable properties

From the above discussion, the desirable properties of a bituminous mix can be summarized as follows:

- ✓ Stability to meet traffic demand

- ✓ Bitumen content to ensure proper binding and water proofing
- ✓ Voids to accommodate compaction due to traffic
- ✓ Flexibility to meet traffic loads, esp. in cold season
- ✓ Sufficient workability for construction
- ✓ Economical mix

Bituminous mixes should be stable, durable, flexible, and workable and should offer sufficient skid resistance. The mix consists of course and fine aggregates, filler and binder. It may be well graded, open graded, gap graded or unbounded as per the requirements. As far as possible, it should be economical also.

Dry Mix Design

The objective of dry mix design is to determine the amount of various sizes of mineral aggregates to use to get a mix of maximum density. The dry mix design involves three important steps, viz. selection of aggregates, aggregates gradation, and proportion of aggregates, which are discussed below.

Selection of aggregates

The desirable qualities of a bituminous paving mixture are dependent to a considerable degree on the nature of the aggregates used. Aggregates are classified as coarse, _ne, and filler. The function of the coarse aggregates in contributing to the stability of a bituminous paving mixture is largely due to interlocking and frictional resistance of adjacent particles. Similarly, fines or sand contributes to stability failure function in filling the voids between coarse aggregates. Mineral filler is largely visualized as a void filling agent. Crushed aggregates and sharp sands produce higher stability of the mix when compared with gravel and rounded sands.

Aggregate gradation

The properties of the bituminous mix including the density and stability are very much dependent on the aggregates and their grain size distribution. Gradation has a profound effect on mix performance. It might be reasonable to believe that the best gradation is one that produces maximum density. This would involve a particle arrangement where smaller particles are packed between larger particles, thus reducing the void space between particles. This creates more particle-to-particle contact, which in bituminous pavements would increase stability and reduce water infiltration. However, some minimum amount of void space is necessary to:

- ✓ Provide adequate volume for the binder to occupy,
- ✓ Promote rapid drainage, and
- ✓ Provide resistance to frost action for base and sub base courses.

A dense mixture may be obtained when this particle size distribution follows Fuller law which is expressed as:

$$p = 100\left(\frac{d}{D}\right)^n$$

Where, p is the percent by weight of the total mixture passing any given sieve sized, D is the size of the largest particle in that mixture, and n is the parameter depending on the shape of the aggregate (0.5 for perfectly rounded particles). Based on this law Fuller-Thompson gradation charts were developed by adjusting the parameter n for fineness or coarseness of aggregates. Practical considerations like construction, layer thickness, workability, etc, are also considered. For example Table 25:1 provides a typical gradation for bituminous concrete for a thickness of 40 mm.

Specified gradation of aggregates for BC surface course of 40 mm

Sieve size (mm)	Wt passing (%) Grade 1	Wt passing (%) Grade 2
20	-	100
12.5	100	80-100
10.0	80 - 100	70 - 90
4.75	55 - 75	50 - 70
2.36	35 - 50	35 - 50
0.60	18 - 29	18 - 29
0.30	13 - 23	13 - 23
0.15	8 - 16	8 - 16
0.075	4 - 10	4 - 10
Binder*	5 - 7.5	5 - 7.5

Bitumen content in percent by weight of the mix

Proportioning of aggregates

After selecting the aggregates and their gradation, proportioning of aggregates has to be done and following are the common methods of proportioning of aggregates:

- ✓ Trial and error procedure: Vary the proportion of materials until the required aggregate gradation is achieved.
- ✓ Graphical Methods: Two graphical methods in common use for proportioning of aggregates are, Triangular chart method and Roch's method. The former is used when only three materials are to be mixed.
- ✓ Analytical Method: In this method a system of equations are developed based on the gradation of each aggregates, required gradation, and solved by numerical methods. With the advent of computer, this method is becoming popular and is discussed below. The resulting solution gives the proportion of each type of material required for the given aggregate gradation.

Example 1

The gradation required for a typical mix is given in Table 25:2 in column 1 and 2. The gradation of available for three types of aggregate A, B, and C are given in column 3, 4, and 5. Determine the proportions of A,B and C if mixed will get the required gradation in column 2.

Gradation

Sieve size (mm) (1)	Required Gradation Range (2)	Filler (A) (3)	Fine Aggr. (B) (4)	Coarse Aggr. (C) (5)
25.4	100.0	100.0	100.0	100.0
12.7	90-100	100.0	100.0	94.0
4.76	60-75	100.0	100.0	54.0
1.18	40-55	100.0	66.4	31.3
0.3	20-35	100.0	26.0	22.8
0.15	12-22	73.6	17.6	9.0
0.075	5-10	40.1	5.0	3.1

The solution is obtained by constructing a set of equations considering the lower and upper limits of the required gradation as well as the percentage passing of each type of aggregate. The decision need to take is the proportion of aggregate A, B, C need to be blended to get the gradation of column 2. Let x1, x2, x3 represent the proportion of A, B, and C respectively. Equation of the form ax1 +bx2 +cx3 $\leq p_l$ or $\geq p_v$ can be written for each sieve size, where a, b, c is the proportion of aggregates A, B, and C passing for that sieve size and p_l and p_v are the required gradation for that sieve size. This will lead to the following system of equations:

$$
\begin{array}{rrrcl}
x_1+ & x_2+ & x_3 & = & 1 \\
x_1+ & x_2+ & 0.94x_3 & \geq & 0.90 \\
x_1+ & x_2+ & 0.94x_3 & \leq & 1.0 \\
x_1+ & x_2+ & 0.54x_3 & \geq & 0.6 \\
x_1+ & x_2+ & 0.54x_3 & \leq & 0.75 \\
x_1+ & 0.664x_2+ & 0.313x_3 & \geq & 0.4 \\
x_1+ & 0.664x_2+ & 0.313x_3 & \leq & 0.55 \\
x_1+ & 0.260x_2+ & 0.228x_3 & \geq & 0.2 \\
x_1+ & 0.260x_2+ & 0.228x_3 & \leq & 0.35 \\
0.736x_1+ & 0.176x_2+ & 0.09x_3 & \geq & 0.12 \\
0.736x_1+ & 0.176x_2+ & 0.09x_3 & \leq & 0.22 \\
0.401x_1+ & 0.050x_2+ & 0.031x_3 & \geq & 0.05 \\
0.401x_1+ & 0.050x_2+ & 0.031x_3 & \leq & 0.10
\end{array}
$$

Solving the above system of equations manually is extremely difficult. Good computer programs are required to solve this. Software like solver in Excel and Matlab can be used. Solving this set of equations is outside the scope of this book. Suppose the solution to this problem is x1 = 0:05, x2 = 0:3, x3 = 0:65. Then Table shows how when these proportions of aggregates A, B, and C are combined, produces the required gradation.

Sieve size (mm) (1)	Filler (A) (2)	Fine Aggr. (B) (3)	Coarse Aggr. (C) (4)	Combined Gradation Obtained (5)	Required Gradation Range (6)
25.4	100x0.05=5.0	100x0.3=30.0	100x.65=65	100	100
12.7	100x0.05=5.0	100x0.3=30.0	94x0.65=61	96	90-100
4.76	100x0.05=5.0	100x0.3=30.0	54x0.65=35.1	70.1	60-75
1.18	100x0.05=5.0	66.4x0.3=19.8	31.3x0.65=20.4	45.2	40-55
0.3	100x0.05=5.0	26.3x0.3=07.8	22.8x.65=14.8	27.6	20-35
0.15	73.6x0.05=3.7	17.6x0.3=05.3	9x0.65=5.9	14.9	12-22
0.75	40.1x0.05=2.0	5x0.3=01.5	3.1x0.65=2.0	5.5	5-10

Various steps involved in the dry mix design were discussed. Gradation aims at reducing the void space, thus improving the performance of the mix. Proportioning is done by trial and error and graphical methods.

Marshall Mix Design

The mix design (wet mix) determines the optimum bitumen content. This is preceded by the dry mix design discussed in the previous chapter. There are many methods available for mix design which varies in the size of the test specimen, compaction, and other test specifications. Marshall method of mix design is the most popular one and is discussed below.

Marshall Mix design

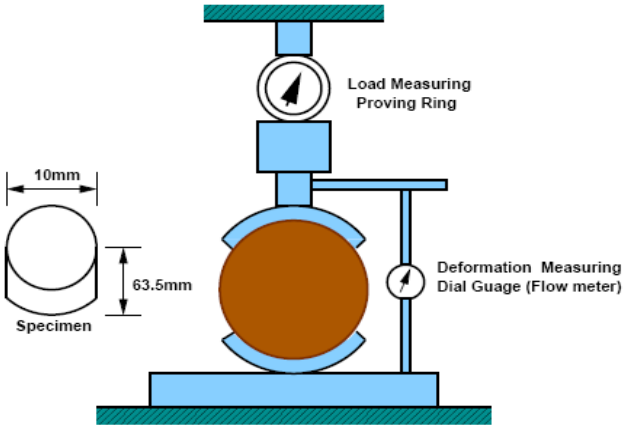
The Marshall Stability and flow test provides the performance prediction measure for the Marshall Mix design method. The stability portion of the test measures the maximum load supported by the test specimen at a loading rate of 50.8 mm/minute. Load is applied to the specimen till failure, and the maximum load is designated as stability. During the loading, an attached dial gauge measures the specimen's plastic flow (deformation) due to the loading. The flow value is recorded in 0.25 mm (0.01 inch) increments at the same time when the maximum load is recorded. The important steps involved in marshal mix design are summarized next.

Specimen preparation

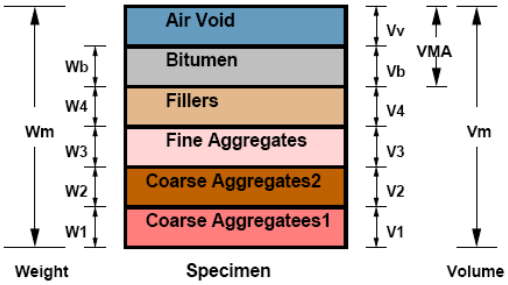
Approximately 1200gm of aggregates and filler is heated to a temperature of 17 - 190°C. Bitumen is heated to a temperature of 121□125oC with the first trial percentage of bitumen (say 3.5 or 4% by weight of the mineral aggregates). The heated aggregates and bitumen are thoroughly mixed at a temperature of 154 - 160°C. The mix is placed in a preheated mould and compacted by a rammer with 50 blows on either side at temperature of 138oC to 149oC. The weight of mixed aggregates taken for the preparation of the specimen may be suitably altered to obtain a compacted thickness of 63.5+/-3 mm. Vary the bitumen content in the next trial by +0:5% and repeat the above procedure. Number of trials is predetermined. The prepared mould is loaded in the Marshall Test setup as shown in the figure.

Properties of the mix

The properties that are of interest include the theoretical specific gravity G_t, the bulk specific gravity of the mix Gm, percent air voids Vv, percent volume of bitumen V_b, percent void in mixed aggregate VMA and percent voids filled with bitumen VFB. These calculations are discussed next. To understand this calculation a phase diagram is given in Figure.



Marshall Test setup



Phase diagram of a bituminous mix

Theoretical specific gravity of the mix G_t

Theoretical specific gravity G_t is the specific gravity without considering air voids, and is given by:

$$|G_t = \frac{W_1 + W_2 + W_3 + W_b}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_b}{G_b}}$$

Where, W1 is the weight of coarse aggregate in the total mix, W2 is the weight of _ne aggregate in the total mix, W3 is the weight of filler in the total mix, W_b is the weight of bitumen in the total mix, G_1 is the apparent specific gravity of coarse aggregate, G2 is the apparent specific gravity of _ne aggregate, G_3 is the apparent specific gravity of filler and G_b is the apparent specific gravity of bitumen.

Bulk specific gravity of mix G_m

The bulk specific gravity or the actual specific gravity of the mix Gm is the specific gravity considering air voids and is found out by:

$$G_m = \frac{W_m}{W_m - W_w}$$

Where, Wm is the weight of mix in air, W_w is the weight of mix in water, Note that W_m - W_w gives the volume of the mix. Sometimes to get accurate bulk specific gravity, the specimen is coated with thin _lm of paraffin wax, when weight is taken in the water. This however requires considering the weight and volume of wax in the calculations.

Air voids percent V_v

Air voids V_v is the percent of air voids by volume in the specimen and is given by:

$$V_v = \frac{(G_t - G_m)100}{G_t}$$

Where G_t is the theoretical specific gravity of the mix, given by equation theoretical specific gravity of the mix. And Gm is the bulk or actual specific gravity of the mix given by equation Percent volume of bitumen V_b .

Percent volume of bitumen V_b :

The volume of bitumen V_b is the percent of volume of bitumen to the total volume and given by: where, W1 is the weight of coarse aggregate in the total mix, W2 is the weight of fine aggregate in the total mix, W3 is the weight of filler in the total mix, W_b is the weight of bitumen in the total mix, G_b is the apparent specific gravity of bitumen, and Gm is the bulk specific gravity of mix given by equation bulk specific gravity of mix.

$$V_b = \frac{\frac{W_b}{G_b}}{\frac{W_1+W_2+W_3+W_b}{G_m}}$$

Voids in mineral aggregate VMA

Voids in mineral aggregate VMA is the volume of voids in the aggregates, and is the sum of air voids and volume of bitumen, and is calculated from

$$VMA = V_v + V_b$$

Where, Vv is the percent air voids in the mix, given by equation of Air voids percent. And V_b is percent bitumen content in the mix, given by equation of Percent volume of bitumen.

Voids filled with bitumen V FB

Voids filled with bitumen V FB is the voids in the mineral aggregate frame work filled with the bitumen, and is calculated as:

$$VFB = \frac{V_b \times 100}{VMA}$$

Where, V_b is percent bitumen content in the mix, given by equation of Percent volume of bitumen. And VMA is the percent voids in the mineral aggregate, given by equation of voids in mineral aggregate.

Determine Marshall Stability and Flow

Marshall Stability of a test specimen is the maximum load required to produce failure when the specimen is Preheated to a prescribed temperature placed in a special test head and the load is applied at a constant strain (5 cm per minute). While the stability test is in progress dial gauge is used to measure the vertical deformation of the specimen. The deformation at the failure point expressed in units of 0.25 mm is called the Marshall Flow value of the specimen.

Apply stability correction

It is possible while making the specimen the thickness slightly vary from the standard specification of 63.5 mm. Therefore, measured stability values need to be corrected to those which would have been obtained if the specimens had been exactly 63.5 mm. This is done by multiplying each measured stability value by an appropriated correlation factors as given in Table below.

Volume of specimen (cm^3)	Thickness of specimen (mm)	Correction Factor
457 - 470	57.1	1.19
471 - 482	68.7	1.14
483 - 495	60.3	1.09
496 - 508	61.9	1.04
509 - 522	63.5	1.00
523 - 535	65.1	0.96
536 - 546	66.7	0.93
547 - 559	68.3	0.89
560 - 573	69.9	0.86

Correction factors for Marshall Stability values

Prepare graphical plots

The average value of the above properties is determined for each mix with different bitumen content and the following graphical plots are prepared:

1. Binder content versus corrected Marshall Stability
2. Binder content versus Marshall Flow
3. Binder content versus percentage of void (V_v) in the total mix
4. Binder content versus voids filled with bitumen (V FB)
5. Binder content versus unit weight or bulk specific gravity (G_m)

Determine optimum bitumen content

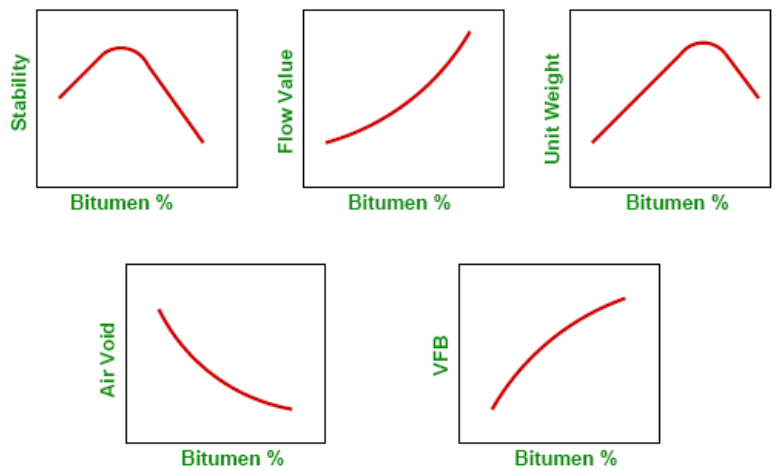
Determine the optimum binder content for the mix design by taking average value of the following three bitumen contents found form the graphs obtained in the previous step.

1. Binder content corresponding to maximum stability
2. Binder content corresponding to maximum bulk specific gravity (Gm)
3. Binder content corresponding to the median of designed limits of percent air voids (Vv) in the total mix (i.e. 4%)

The stability value, flow value, and V FB are checked with Marshall mix design specification chart given in Table below. Mixes with very high stability value and low flow value are not desirable as the pavements constructed with such mixes are likely to develop cracks due to heavy moving loads.

Marshall mix design specification

Test Property	Specified Value
Marshall stability, kg	340 (minimum)
Flow value, 0.25 mm units	8 - 17
Percent air voids in the mix $V_v\%$	3 - 5
Voids filled with bitumen $VFB\%$	75 - 85



Marshal graphical plots

Numerical example - 1

The specific gravities and weight proportions for aggregate and bitumen are as under for the preparation of Marshall mix design. The volume and weight of one Marshall specimen was found to be 475 cc and 1100 gm. Assuming absorption of bitumen in aggregate is zero, find V_v, V_b, VMA and V FB;

Item	A_1	A_2	A_3	A_4	B
Wt (gm)	825	1200	325	150	100
Sp. Gr	2.63	2.51	2.46	2.43	1.05

Solution:

$$
\begin{aligned}
G_t &= \frac{825+1200+325+150+100}{\frac{825}{2.63}+\frac{1200}{2.51}+\frac{325}{2.46}+\frac{150}{2.43}+\frac{100}{1.05}} \\
&= \frac{2600}{1080.86} \\
&= 2.406 \\
G_m &= \frac{1100}{475} \\
&= 2.316 \\
V_v &= \frac{2.406-2.316}{2.406} \times 100 \\
&= 3.741\ \% \\
V_b &= \frac{100}{1.05} \times \frac{2.316}{1100} \\
&= 20.052\ \% \\
VMA &= (3.741+20.05) \\
&= 23.793\ \% \\
VFB &= \frac{20.052}{23.793} \times 100 \\
&= 84.277\ \%
\end{aligned}
$$

Numerical example - 2

The results of Marshall Test for five specimens are given below. Find the optimum bitumen content of the mix.

Bitumen content	Stability (kg)	Flow (units)	V_v (%)	VFB (%)	G_m
3	499.4	9.0	12.5	34	2.17
4	717.3	9.6	7.2	65	2.21
5	812.7	12.0	3.9	84	2.26
6	767.3	14.8	2.4	91	2.23
7	662.8	19.5	1.9	93	2.18

Solution Plot the graphs and find bitumen content corresponding to

1. Max stability = 5 percent bitumen content.
2. Max Gm = 5 percent bitumen content.
3. 4% percent air void = 3 percent bitumen content.

The optimum bitumen extent is the average of above = 4.33 percent.

Marshal stability test is the performance prediction measure conducted on the bituminous nix. The procedure consists of determination of properties of mix, Marshal Stability and flow analysis and finally determination of optimum bitumen content. The concept of phase diagram is used for the calculations.

Flexible pavement design

Flexible pavements are so named because the total pavement structure defects, or exes, 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 sub grade. 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 sub grade. 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 without 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 loads 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 within 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 45o; and soil medium is elastic, homogeneous, and isotropic half space.

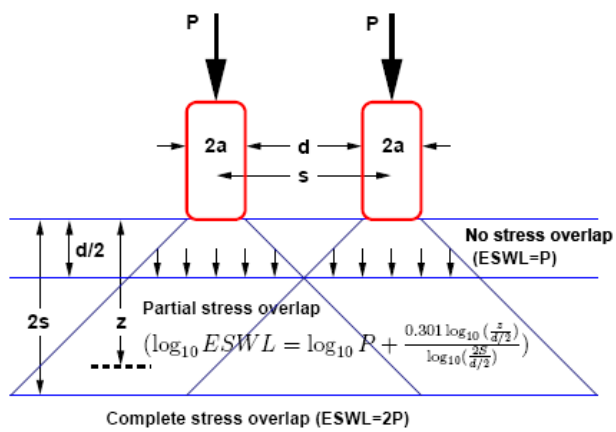
The ESWL is given by:

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

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.



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

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 exible 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 loads 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 W1 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 ith 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 rutting. The fatigue cracking model has the following form:

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

Where, N_f is the number of load repetition for a certain percentage of cracking, E_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:

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

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,

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

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

$$N_d = f_4 (\epsilon_c)^{-f_5}$$

Where N_d is the permissible design rut depth (say 20mm), ϵ_c is the compressive strain at the top of the sub grade, and f4; f5 are constants. Once we have the EALF, then we can get the ESAL as given below.

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

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: The ESAL is given as $\Sigma F_i n_i = 3225$ kN

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 $N_r = f_4 \epsilon_c^{-f5}$ c where f_4 =4.2 and f_5 =4.5.

Solution Refer the Table the ESAL is given as $\Sigma F_i n_i$ = 8904.94 kN

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

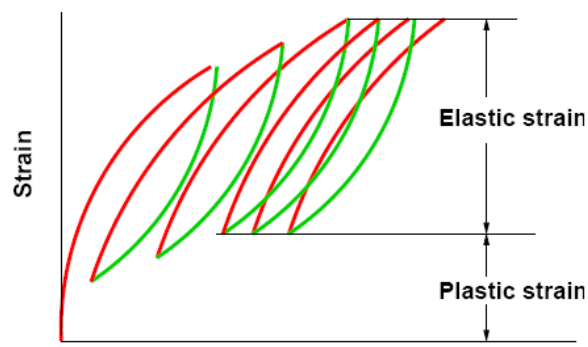
Material characterization

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 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. 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 for in the figure.

Resilient modulus of soil

The elastic modulus based on the recoverable strain under repeated loads is called the resilient modulus MR, 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



Recoverable strain under repeated loads

test or the axial stress in excess of the confining pressure in a tri-axial 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 have sine 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.

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 have sine loading. The test setup is similar to resilient 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.

Correlations with other tests

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

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.

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

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 sub grade) 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 (v),
- ✓ 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(p_a)
- ✓ 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 sub grade.

IRC method of design of flexible pavements

Indian roads congress has specified the design procedures for flexible pavements based on CBR values. The Pavement designs given in the previous edition IRC:37-1984 were applicable to design traffic up to 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 in IRC:37-2002.

Scope:

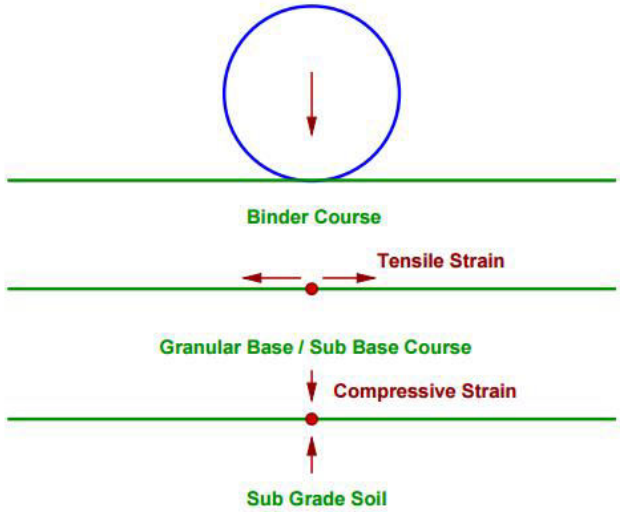
These guidelines will apply to design of flexible pavements for Expressway, National Highways, State Highways, Major District Roads, and other categories of roads. Flexible pavements are considered to include the pavements which have bituminous surfacing and granular base and sub-base courses conforming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

A and B are the critical locations for tensile strains (ϵ_t). Maximum value of the strain is adopted for design. C is the critical location for the vertical subgrade strain (ϵ_z) since the maximum value of the (ϵ_z) occurs mostly at C.

Fatigue Criteria:

Bituminous surfacing of pavements display flexural fatigue cracking if the tensile strain at the bottom of the bituminous layer is beyond certain limit. The relation between the fatigue life of the pavement and the tensile strain in the bottom of the bituminous layer was obtained as

$$N_f = 2.21 \times 10^{-4} \times \left(\frac{1}{\epsilon_t}\right)^{3.89} \times \left(\frac{1}{E}\right)^{0.854}$$

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

$$N_r = 4.1656 \times 10^{-8} \times \left(\frac{1}{\epsilon_z}\right)^{4.5337}$$

Nr 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 sub grade.

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:

1. Initial traffic in terms of CVPD
2. Traffic growth rate during the design life,
3. Design life in number of years
4. Vehicle damage factor (VDF)
5. 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 tones 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 2002. 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: Traffi nc 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 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 up to 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 up to 2 msa an 150 mm for traffic exceeding 2 msa.

Bituminous surfacing

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 tra_c 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:

1. Two lane carriage way
2. Initial traffic in the year of completion of construction = 400 CVPD (sum of both directions)
3. Traffic growth rate = 7.5 %
4. Design life = 15 years
5. Vehicle damage factor based on axle load survey = 2.5 standard axle per commercial vehicle
6. Design CBR of sub grade soil = 4%.

Solution

1. Distribution factor = 0.75
2.

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

3. Total pavement thickness for CBR 4% and traffic 7.2 msa from IRC:37 2002 chart1 = 660 mm
4. Pavement composition can be obtained by interpolation from Pavement Design Catalogue (IRC:37 2001).
   (a) Bituminous surfacing = 25 mm SDBC + 70 mm DBM
   (b) Road-base = 250 mm WBM
   (c) Sub-base = 315 mm granular material of CBR not less than 30 %

The design procedure given by IRC makes use of the CBR value, million standard axle concept, and vehicle damage factor. Traffic distribution along the lanes is taken into account. The design is meant for design traffic which is arrived at using a growth rate.

Problem

1. Design the pavement for construction of a new two lane carriageway for design life 15 years using IRC method. The initial traffic in the year of completion in each direction is 150 CVPD and growth rate is 5%. Vehicle damage factor based on axle load survey = 2.5 std axle per commercial vehicle. Design CBR of sub grade soil=4%.

1. Distribution factor = 0.75
2.

$$\begin{aligned} N &= \frac{365 \times [(1+0.05)^{15}-1)]}{0.05} \times 300 \times 0.75 \times 2.5 \\ &= 4430348.837 \\ &= 4.4\ msa \end{aligned}$$

3. Total pavement thickness for CBR 4% and traffic 4.4 msa from IRC:37 2001 chart1 = 580 mm

Pavement composition can be obtained by interpolation from Pavement Design Catalogue (IRC: 37- 2002).

(a) Bituminous surfacing = 20 mm PC + 50 mm BM
(b) Road-base = 250 mm Granular base
(c) Sub-base = 280 mm granular material

Rigid pavement design

As the name implies, rigid pavements are rigid i.e, they do not ex 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 K in kg/cm3 given by K = p/Δ where Δ is the displacement level taken as 0.125 cm and p 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. These pressure deformation characteristics of rigid pavement lead Westergaard to the define the term radius of relative stiffness l in cm is given by the equation

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

Where E is the modulus of elasticity of cement concrete in kg/cm2 (3.0_105), _ is the Poisson's ratio of concrete (0.15), h is the slab thickness in cm and K 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

$$b = \begin{cases} \sqrt{1.6a^2 + h^2} - 0.675\ h & \text{if a} < 1.724\ \text{h} \\ a & \text{otherwise} \end{cases}$$

Where a is the radius of the wheel load distribution in cm and h is the slab thickness in cm.

Wheel load stresses - Westergaard's stress equation

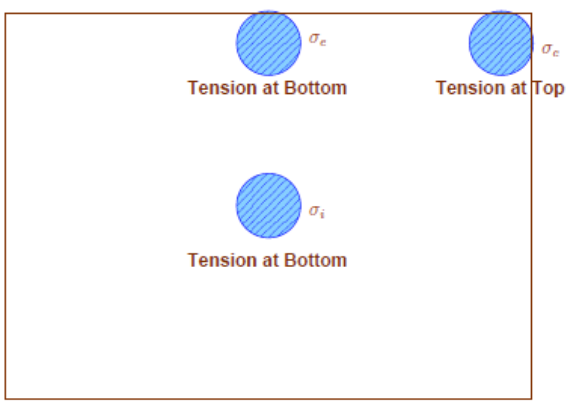
The cement concrete slab is assumed to be homogeneous and to have uniform elastic properties with vertical sub-grade reaction being proportional to the deection. Westergaard developed relationships for the stress at interior, edge and corner regions, denoted as _i; _e; _c in kg/cm2 respectively and given by the equation

$$\sigma_i = \frac{0.316\ P}{h^2}\left[4\ \log_{10}\left(\frac{l}{b}\right) + 1.069\right]$$

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

$$\sigma_c = \frac{3\ P}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{l}\right)^{0.6}\right]$$

where h is the slab thickness in cm, P is the wheel load in kg, a is the radius of the wheel load distribution in cm, l the radius of the relative stiffness in cm and b is the radius of the resisting section in cm



Critical stress locations

Temperature stresses:

Temperature 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 stress

The warping stress at the interior, edge and corner regions, denoted as $\sigma t_i\ \sigma t_e\ \sigma t_c$ in kg/cm2 respectively and given by the equation

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

$$\sigma_{t_e} = \text{Max}\left(\frac{\text{C}_\text{x}\text{E}\epsilon\text{t}}{2}, \frac{\text{C}_\text{y}\text{E}\epsilon\text{t}}{2}\right)$$

$$\sigma_{t_c} = \frac{E\epsilon t}{3(1-\mu)}\sqrt{\frac{a}{l}}$$

Where E is the modulus of elasticity of concrete in kg/cm2 (3_105), _ is the thermal coefficient of concrete per ^{o}C (1X10^{7}) t is the temperature difference between the top and bottom of the slab, C_x and C_y are the coefficient based on Lx=l in the desired direction and Ly=l right angle to the desired direction, μ is the Poisson's ration (0.15), a is the radius of the contact area and l is the radius of the relative stiffness.

Frictional stresses

The frictional stress σ_f in kg/cm2 is given by the equation

$$\sigma_f = \frac{WLf}{2 \times 10^4}$$

where W is the unit weight of concrete in kg/cm2 (2400), f is the coefficient of sub grade friction (1.5) and L is the length of the slab in meters.

Combination of stresses

The cumulative effect of the different stress give rise to the following thee critical cases

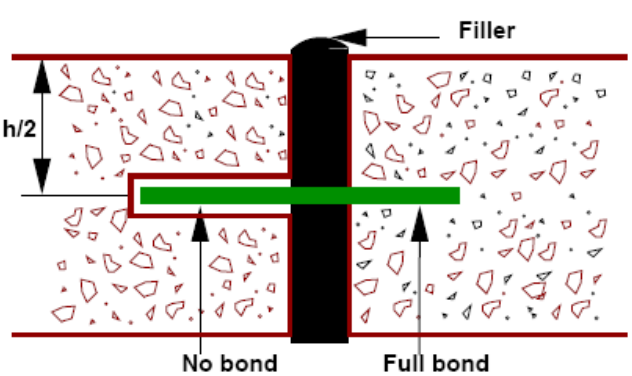
- ✓ Summer, mid-day: The critical stress is for edge region given by critical = $\sigma_e + \sigma t_e - \sigma_f$
- ✓ Winter, mid-day: The critical combination of stress is for the edge region given by $\sigma_{critical} = \sigma_e + \sigma t_e - \sigma_f$
- ✓ Mid-nights: The critical combination of stress is for the corner region given by $\sigma_{critical} = \sigma_c + \sigma_{tc}$

Design of joints:

Expansion joints

The purpose of the expansion joint is to allow the expansion of the pavement due to rise in temperature with respect to construction temperature. The design considerations are:

- ✓ Provided along the longitudinal direction,
- ✓ Design involves finding the joint spacing for a given expansion joint thickness (say 2.5 cm specified by IRC) subjected to some maximum spacing (say 140 as per IRC)



Expansion joint

Contraction joints

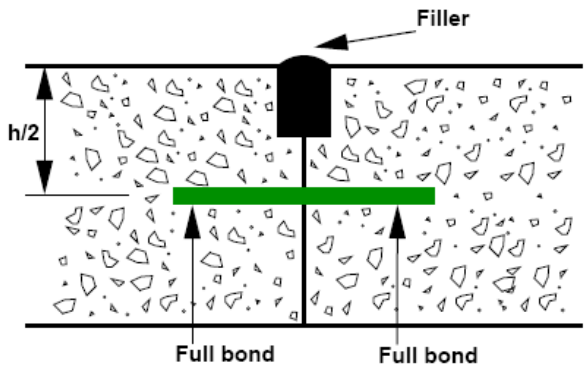
The purpose of the contraction joint is to allow the contraction of the slab due to fall in slab temperature below the construction temperature. The design considerations are:

- ✓ The movement is restricted by the sub-grade friction
- ✓ Design involves the length of the slab given by:

$$L_c = \frac{2 \times 10^4 S_c}{W.f}$$

Where, Sc is the allowable stress in tension in cement concrete and is taken as 0.8 kg/cm2, W is the unit weight of the concrete which can be taken as 2400 kg/cm3 and f is the coefficient of sub-grade friction which can be taken as 1.5.

Steel reinforcements can be use, however with a maximum spacing of 4.5 m as per IRC.



Contraction joint

Dowel bars

The purpose of the dowel bar is to effectively transfer the load between two concrete slabs and to keep the two slabs in same height. The dowel bars are provided in the direction of the traffic (longitudinal). The design considerations are:

- ✓ Mild steel rounded bars,
- ✓ bonded on one side and free on other side

Bradbury's analysis

Bradbury's analysis gives load transfer capacity of single dowel bar in shear, bending and bearing as follows:

$$P_s = 0.785\ d^2\ F_s$$

$$P_f = \frac{2\ d^3\ F_f}{L_d + 8.8\delta}$$

$$P_b = \frac{F_b\ L_d^2\ d}{12.5\ (L_d + 1.5\delta)}$$

where, P is the load transfer capacity of a single dowel bar in shear s, bending f and bearing b, d is the diameter of the bar in cm, Ld is the length of the embedment of dowel bar in cm, δ is the joint width in cm, F_s; F_f; F_b are the permissible stress in shear, bending and bearing for the dowel bar in kg/cm2.

Design procedure

Step 1 Find the length of the dowel bar embedded in slab L_d by

$$L_d = 5d\sqrt{\frac{F_f}{F_b}\frac{(L_d + 1.5\delta)}{(L_d + 8.8\delta)}}$$

Step 2 Find the load transfer capacities P_s, P_f , and P_b of single dowel bar with the Ld
Step 3 Assume load capacity of dowel bar is 40 percent wheel load, find the load capacity factor f as

$$\max\left\{\frac{0.4P}{P_s},\ \frac{0.4P}{P_f},\ \frac{0.4P}{P_b}\right\}$$

Step 4 Spacing of the dowel bars.

- ✓ Effective distance up to which effective load transfer take place is given by 1:8 l, where l is the radius of relative stiffness.
- ✓ Assume a linear variation of capacity factor of 1.0 under load to 0 at 1:8 l.
- ✓ Assume dowel spacing and find the capacity factor of the above spacing.
- ✓ Actual capacity factor should be greater than the required capacity factor.
- ✓ If not, do one more iteration with new spacing.

Example

Design size and spacing of dowel bars at an expansion joint of concrete pavement of thickness 25 cm. Given the radius of relative stiffness of 80 cm design wheel load 5000 kg Load capacity of the dowel system is 40 percent of design wheel load. Joint width is 2.0 cm and the permissible stress in shear, bending and bearing stress in dowel bars are 1000,1400 and 100 kg=cm^2 respectively.

Solution: Given, $P = 5000\ kg$, $l = 80\ cm$, $h = 25\ cm$, $\delta = 2\ cm$, $F_s = 1000\ kg/cm^2$, $F_f = 1400\ kg/cm^2$ and $F_b = 100\ kg/cm^2$; and assume $d = 2.5\ cm$ diameter.

Step-1: length of the dowel bar L_d

$$\begin{aligned} L_d &= 5 \times 2.5 \sqrt{\frac{1400}{100}\frac{(L_d + 1.5 \times 2)}{(L_d + 8.8 \times 2)}} \\ &\models 12.5 \times \sqrt{14\ \frac{(L_d + 3)}{(L_d + 17.6)}} \end{aligned}$$

Solve for L_d by trial and error:

put $L_d = 45.00 \Rightarrow L_d = 40.95$

put $L_d = 45.95 \Rightarrow L_d = 40.50$

put $L_d = 45.50 \Rightarrow L_d = 40.50$

Minimum length of the dowel bar is $L_d + \delta = 40.5 + 2.0 = 42.5\ cm$, So, provide 45 cm long and 2.5 $cm\ \phi$.

Therefore $L_d = 45 - 2 = 43\ cm$.

Step 2: Find the load transfer capacity of single dowel bar

$$\begin{aligned} P_s &= 0.785 \times 2.5^2 \times 1000 &&= 4906\ kg \\ P_f &= \tfrac{2\times 2.5^3 \times 1400}{43.0+8.8\times 2} &&= 722\ kg \\ P_b &= \tfrac{100\times 2.5\times 43.0^2}{12.5\ (43.0+1.5\times 2)} &&= 804\ kg \end{aligned}$$

Therefore, the required load transfer capacity

$$\max\left\{\frac{0.4\times 5000}{4906},\ \frac{0.4\times 5000}{722},\ \frac{0.4\times 5000}{804}\right\}$$
$$\max\{0.41, 2.77, 2.487\} = 2.77$$

Step-3 : Find the required spacing: Effective distance of load transfer $= 1.8\,l\ =\ 1.8\times 80\ =\ 144\ cm$. Assuming 35 cm spacing,

Actual capacity is

$$1+\frac{144-35}{144}+\frac{144-70}{144}+\frac{144-105}{144}+\frac{144-140}{144}$$
$$= 2.57\ <\ 2.77 \quad \text{(the required capacity)}$$

Therefore assume 30 cm spacing and now the actual capacity is

$$1+\frac{144-30}{144}+\frac{144-60}{144}+\frac{144-90}{144}+\frac{144-120}{144}$$
$$= 2.92\ >\ 2.77 \quad \text{(the required capacity)}$$

Therefore provide 2.5 cm ϕ mild steel dowel bars of length 45 cm @ 30 cm center to center.

Tie bars

In contrast to dowel bars, tie bars are not load transfer devices, but serve as a means to tie two slabs. Hence tie bars must be deformed or hooked and must be firmly anchored into the concrete to function properly. They are smaller than dowel bars and placed at large intervals. They are provided across longitudinal joints.

Step 1

Diameter and spacing: The diameter and the spacing is first found out by equating the total sub-grade friction tot he total tensile stress for a unit length (one meter). Hence the area of steel per one meter in cm2 is given by:

$$A_s \times S_s = b \times h \times W \times f$$
$$A_s = \frac{bhWf}{100S_s}$$

where, b is the width of the pavement panel in m, h is the depth of the pavement in cm, W is the unit weight of the concrete (assume 2400 kg=cm2), f is the coefficient of friction (assume 1:5), and Ss is the allowable working tensile stress in steel (assume 1750 kg=cm2). Assume 0:8 to 1:5 cm ø bars for the design.

Step 2

Length of the tie bar: Length of the tie bar is twice the length needed to develop bond stress equal to the working tensile stress and is given by:

$$L_t = \frac{d\ S_s}{2\ S_b}$$

where, d is the diameter of the bar, Ss is the allowable tensile stress in kg=cm^2, and S_b is the allowable bond stress and can be assumed for plain and deformed bars respectively as 17:5 and 24:6 kg=cm^2.

Example

A 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

$$A_s = \frac{3.6 \times 18 \times 2400 \times 1.5}{100 \times 1750} = 1.33\ cm^2/m$$

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

$$L_t = \frac{1 \times 1750}{2\ 246} = 36.0\ cm$$

[Ans] Use 1 cm ϕ tie bars of length of 36 cmi @ 55 cm c/c

Design of rigid pavements is based on Westergaard's analysis, where modulus of subgrade reaction, radius of relative stiffness, radius of wheel load distribution is used. For critical design, a combination of load stress, frictional stress and warping stress is considered. Different types of joints are required like expansion and contraction joints. Their design is also dealt with.

Problem:

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 kg=cm2 respectively.

1. Given, $P = 4000\ kg$, $l = 90\ cm$, $h = 20\ cm$, $\delta = 3\ cm$, $F_s = 1000\ kg/cm^2$, $F_f = 1500\ kg/cm^2$ and $F_b = 100\ kg/cm^2$; and assume $d = 2.5\ cm$ diameter.

   Step-1: length of the dowel bar L_d,

$$\begin{aligned} L_d &= 5 \times 2.5 \sqrt{\frac{1500}{100} \frac{(L_d + 1.5 \times 3)}{(L_d + 8.8 \times 3)}} \\ &= 12.5 \times \sqrt{15 \frac{(L_d + 4.5)}{(L_d + 26.4)}} \end{aligned}$$

   Solving for L_d by trial and error, it is =39.5cm Minimum length of the dowel bar is $L_d + \delta = 39.5 + 3.0 = 42.5\ cm$, So, provide 45 cm long and 2.5 cm ϕ. Therefore $L_d = 45 - 3 = 42\ cm$.

   Step 2: Find the load transfer capacity of single dowel bar

$$\begin{aligned} P_s &= 0.785 \times 2.5^2 \times 1000 &= 4906.25\ kg \\ P_f &= \tfrac{2 \times 2.5^3 \times 1500}{42.0 + 8.8 \times 3} &= 685.307\ kg \\ P_b &= \tfrac{100 \times 2.5 \times 42.0^2}{12.5\ (42.0 + 1.5 \times 3)} &= 758.71\ kg \end{aligned}$$

   Therefore, the required load transfer capacity (refer equation)

$$\max\left\{\frac{0.4 \times 4000}{4906.25}, \frac{0.4 \times 4000}{685.307}, \frac{0.4 \times 4000}{758.71}\right\}$$
$$\max\{0.326, 2.335, 2.10\} = 2.335$$

   Step-3 : Find the required spacing: Effective distance of load transfer $= 1.8 \times l = 1.8 \times 90 = 162\ cm$. Assuming 35 cm spacing,

   Actual capacity is

$$1 + \frac{162 - 35}{162} + \frac{162 - 70}{162} + \frac{162 - 105}{162} + \frac{162 - 140}{162} = 2.83$$

Assuming 40cm spacing, capacity is,

$$1 + \frac{162 - 40}{162} + \frac{162 - 80}{162} + \frac{162 - 120}{162} + \frac{162 - 160}{162} = 2.52$$

So we should consider 2.52>2.335 as it is greater and more near to other value. Therefore provide 2:5 cm ø mild steel dowel bars of length 45 cm @ 40 cm center to center.

Problem - 2

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 kg=m^3, the coefficient of friction is 1.5, allowable working tensile stress in steel is 1750 kg=cm^2, and bond stress of deformed bars is 24.6 kg=cm^2.

2.Given h=20 cm, b=7/2=3.5m, $S_s = 1750\ kg/cm^2$ $W = 2400\ kg/cm^2$ $f = 1.5$ $S_b = 24.6\ kg/cm^2$.

Step 1: diameter and spacing:

$$A_s = \frac{3.5 \times 20 \times 2400 \times 1.5}{100 \times 1750} = 1.44\ cm^2/m$$

Assume $\phi = 1\ cm$, $\Rightarrow$ $A = 0.785\ cm^2$. Therefore spacing is $\frac{100 \times 0.785}{1.44} = 54.57\ cm$, say 55 cm

Step 2: Length of the bar:

$$L_t = \frac{1 \times 1750}{2 \times 24.6} = 36.0\ cm$$

[Ans] Use 1 cm ϕ tie bars of length of 36 cm @ 55 cm c/c