Pavement Analysis and Design

TE-503

Lecture-1
02-09-2019

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DTEM

Course Outline

Focusing on the empirical as well as mechanistic design procedures both for highway and airfield pavement systems. Introduction to multi-layered elastic and slab theories, properties of pavement materials and methods of characterization, stochastic treatment of design variables, economic principles of design alternates and the effect of environment upon pavement performance. Review of design methods including AASHTO, AI, PCA and USACE.

Books and Design Aids

- **Pavement Analysis and Design (*Second Edition)***

By

Yang H . Huang

- **Pavement Design and Materials**

By

A.T. Papagiannakis and E. A. Masad

- **Principles of Pavement Design**

By

Yoder and Witczak

- **AASHTO Design Guides**

Pavement Analysis and Design

- **Road Note-31**

Historical Developements

- **Although pavement design has gradually evolved from art to science, empiricism still plays an important role even up to the present day.**

- **Prior to the early 1920s, the thickness of pavement was based purely on experience. The same thickness was used for a section of highway even though widely different soils were encountered.**

- **As experience was gained throughout the years, various methods were developed by different agencies for determining the thickness of pavement required.**

Flexible Pavement

Flexible pavements are constructed of bituminous and granular materials.

The first asphalt roadway in the United States was constructed in 1870 at Newark, New Jersey.

Design Methods of Flexible Pavement Design

Five categories:

- **Empirical method**
- **Limiting shear failure method**
- **Limiting deflection method**
- **Regression method based on pavement performance or road test**
- **Mechanistic-empirical method**

Design Methods of Flexible Pavement Design

Empirical method

The use of the empirical method without a strength test dates back to the development of the Public Roads (PR) soil classification system in which the subgrade was classified as uniform from A-1 to A-8 and non-uniform from B-1 to B-3.

The PR system was later modified by the Highway Research Board (HRB), in which soils were grouped from A-1 to A-8 and a group index was added to differentiate the soil within each group.

Steele (1945) discussed the application of HRB classification and group index in estimating the sub-base and total pavement thickness without a strength test.

Design Methods of Flexible Pavement Design

Empirical method (Contd.)

The empirical method with a strength test was first used by the California Highway Department in 1929.

The thickness of pavements was related to the California Bearing Ratio (CBR), defined as the penetration resistance of a subgrade soil relative to a standard crushed rock.

The CBR method of design was studied extensively by the U.S. Corps of Engineers during World War II and became a very popular method after the war.

Design Methods of Flexible Pavement Design

Limiting Shear Failure Methods

The limiting shear failure method is used to determine the thickness of pavements so that shear failures will not occur.

The major properties of pavement components and subgrade soils to be considered are their cohesion and angle of internal friction.

Barber (1946) applied Terzaghi's bearing capacity formula (1943) to determine pavement thickness.

With the ever increasing speed and volume of traffic, pavements should be designed for riding comfort rather than for barely preventing shear failures.

Design Methods of Flexible Pavement Design

Limiting Deflection Methods

The limiting deflection method is used to determine the thickness of pavements so that the vertical deflection will not exceed the allowable limit.

The Kansas State Highway Commission (1947) modified Boussinesq's equation (Boussinesq, 1885) and limited the deflection of subgrade to 0.1 in.

The U.S. Navy (1953) applied Burmister's two-layer theory (Burmister, 1943) and limited the surface deflection to 0.25 in.

Design Methods of Flexible Pavement Design

Limiting Deflection Methods (Contd.)

The use of deflection as a design criterion has the apparent advantage that it can be easily measured in the field.

Unfortunately, pavement failures are caused by excessive stresses and strains instead of deflections.

Design Methods of Flexible Pavement Design

Regression Methods Based on Pavement Performance or Road Tests

A good example of the use of regression equations for pavement design is the AASHTO method based on the results of road tests.

The disadvantage of the method is that the design equations can be applied only to the conditions at the road test site.

For conditions other than those under which the equations were developed, extensive modifications based on theory or experience are needed.

Although these equations can illustrate the effect of various factors on pavement performance, their usefulness in pavement design is limited because of the many uncertainties involved.

Design Methods of Flexible Pavement Design

Mechanistic-Empirical Methods

The mechanistic-empirical method of design is based on the mechanics of materials that relates an input, such as a wheel load, to an output or pavement response, such as stress or strain.

The response values are used to predict distress from laboratory-test and field-performance data.

Dependence on observed performance is necessary because theory alone has not proven sufficient to design pavements realistically.

Design Methods of Flexible Pavement Design

Mechanistic-Empirical Methods (Contd.)

The use of the above concepts for pavement design was first presented in the United States by Dormon and Metcalf (1965).

The advantages of mechanistic methods are the improvement in the reliability of a design, the ability to predict the types of distress, and the feasibility to extrapolate from limited field and laboratory data.

Rigid Pavements

Rigid pavements are constructed of Portland cement concrete.

The first concrete pavement was built in Bellefontaine, Ohio in 1893.

Design Methods of Rigid Pavements

The development of design methods for rigid pavements is not as dramatic as that of flexible pavements, because the flexural stress in concrete has long been considered as a major, or even the only, design factor.

Two categories of solutions:

-Analytical Solutions

-Numerical Solutions

Design Methods of Rigid Pavements

Analytical Solutions

Analytical solutions ranging from simple closed-form formulas to complex derivations are available for determining the stresses and deflections in concrete pavements.

-Westergaard's Analysis

Design Methods of Rigid Pavements

Numerical Solutions

All the analytical solutions mentioned above were based on the assumption that the slab and the subgrade are in full contact.

It is well known that, due to pumping, temperature curling, and moisture warping, the slab and subgrade are usually not in contact.

With the advent of computers and numerical methods, some analyses based on partial contact were developed.

-*Finite-Element Methods*

Pavement Types

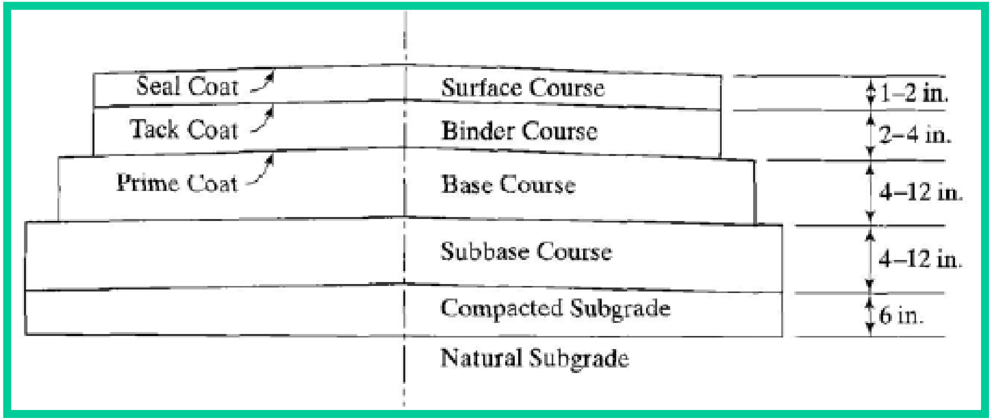
Three major types:

1. **Flexible pavements**
2. **Rigid pavements**
3. **Composite pavements**

Conventional Flexible Pavement

Seal Coat

Seal coat is a thin asphalt surface treatment used to waterproof the surface or to provide skid resistance where the aggregates in the surface course could be polished by traffic and become slippery. Depending on the purpose, seal coats might or might not be covered with aggregate.



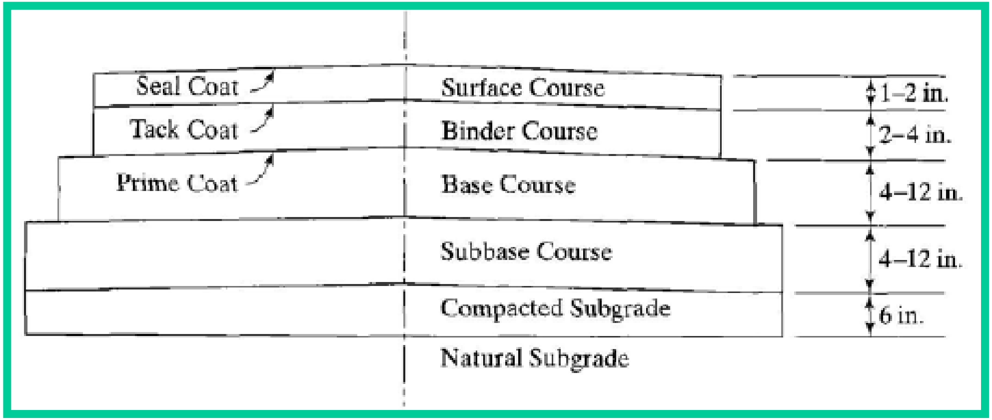
Pavement Analysis and Design

Conventional Flexible Pavement

Tack Coat

A tack coat is a very light application of asphalt, usually asphalt emulsion diluted with water, used to ensure a bond between the surface being paved and the overlying course. It is important that each layer in an asphalt pavement be bonded to the layer below. Tack coats are also used to bond the asphalt layer to a PCC base or an old asphalt pavement.

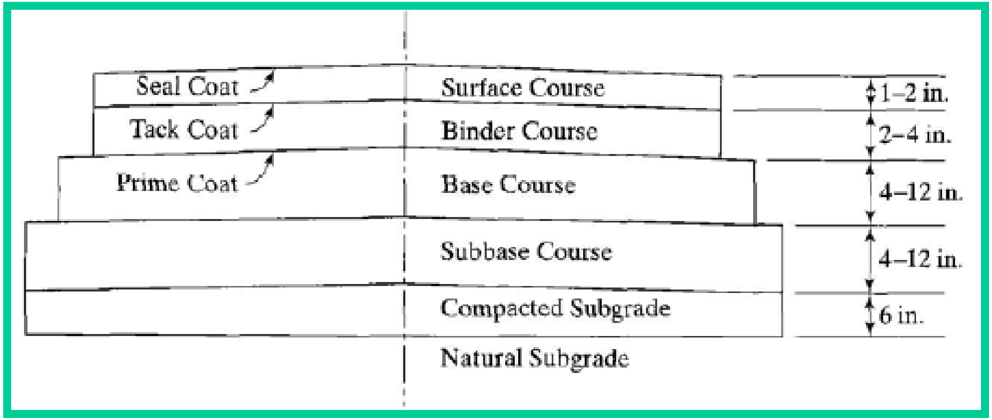
The three essential requirements of a tack coat are that it must be very thin, it must uniformly cover the entire surface to be paved, and it must be allowed to break or cure before the HMA is laid.



Conventional Flexible Pavement

Prime Coat

A prime coat is an application of low-viscosity cutback asphalt to an absorbent surface, such as an untreated granular base on which an asphalt layer will be placed. Its purpose is to bind the granular base to the asphalt layer.



The difference between a tack coat and a prime coat is that a tack coat does not require the penetration of asphalt into the underlying layer, whereas a prime coat penetrates into the underlying layer, plugs the voids, and forms a watertight surface. Although the type and quantity of asphalt used are quite different, both are spray applications.

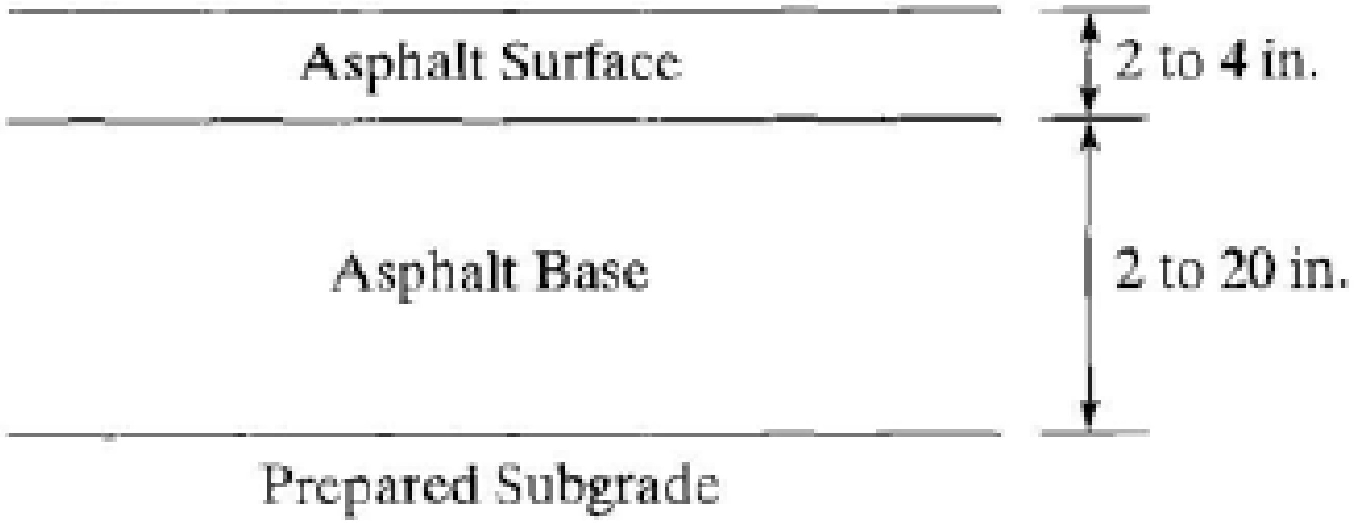
Conventional Flexible Pavement

Conventional flexible pavements are layered systems with better materials on top where the intensity of stress is high and inferior materials at the bottom where the intensity is low.

Adherence to this design principle makes possible the use of local materials and usually results in a most economical design.

This is particularly true in regions where high-quality materials are expensive but local materials of inferior quality are readily available .

Full Depth Asphalt Pavement



Full Depth Asphalt Pavement

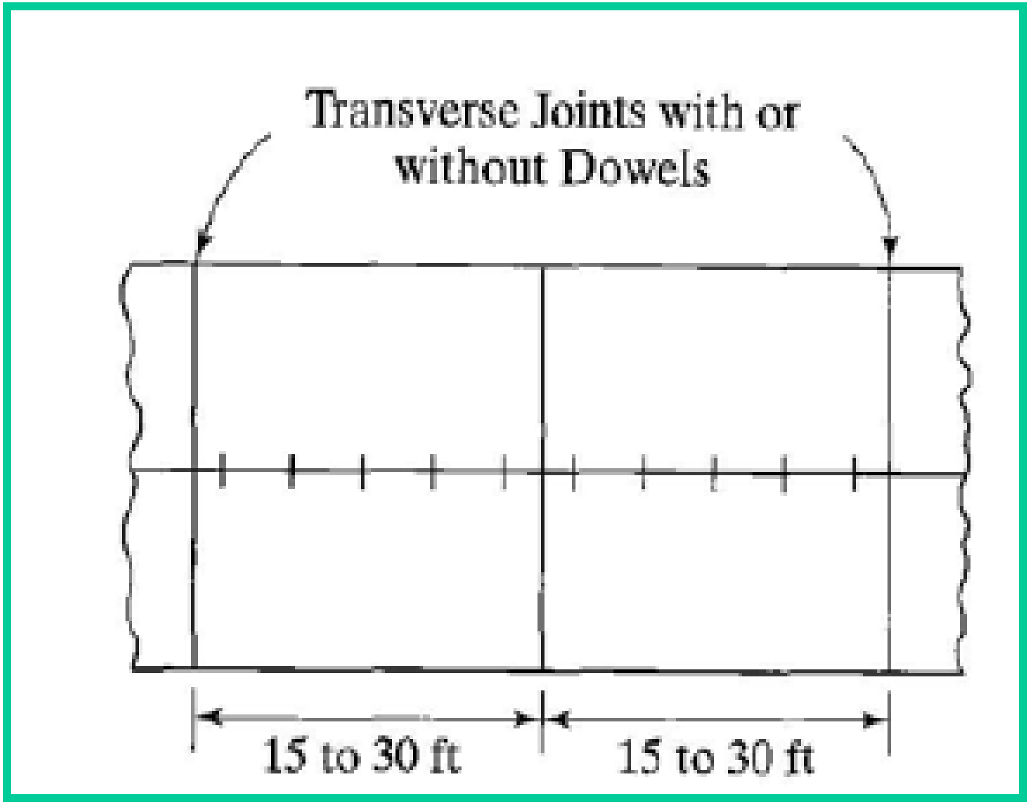
Full-depth asphalt pavements are constructed by placing one or more layers of HMA directly on the subgrade or improved subgrade.

This concept was conceived by the Asphalt Institute in 1960 and is generally considered the most cost-effective and dependable type of asphalt pavement for heavy traffic.

This type of construction is quite popular in areas where local materials are not available.

It is more convenient to purchase only one material, i.e., HMA, rather than several materials from different sources, thus minimizing the administration and equipment costs.

Rigid Pavements:Jointed Plain Concrete Pavements (JPCP)



Rigid Pavements:Jointed Plain Concrete Pavements (JPCP)

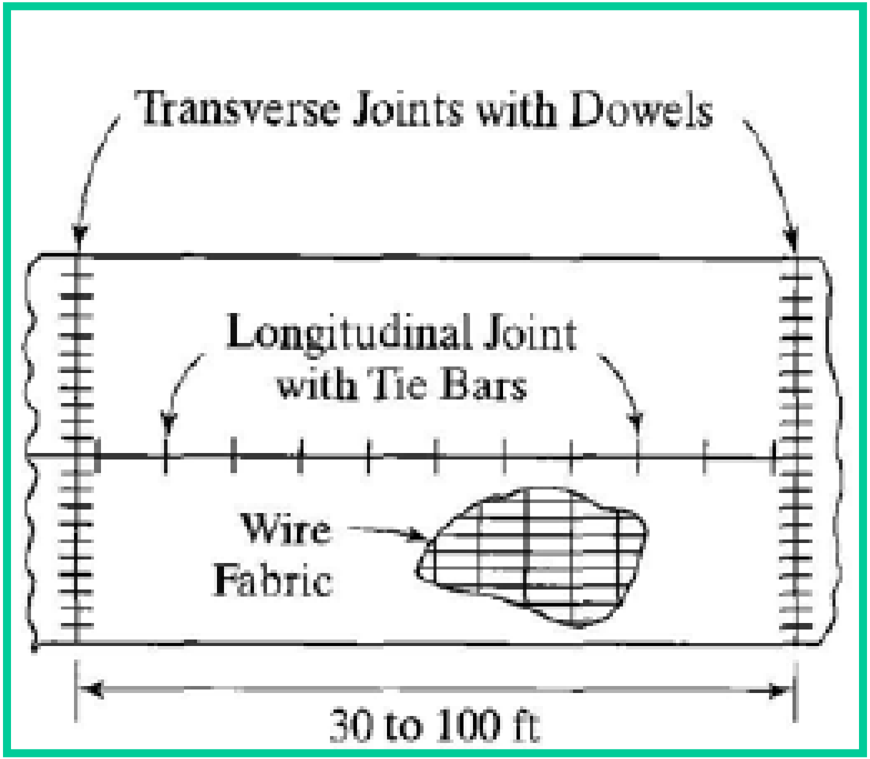
All plain concrete pavements should be constructed with closely spaced contraction joints.

Dowels or aggregate interlocks may be used for load transfer across the joints.

Depending on the type of aggregate, climate, and prior experience, joint spacings between 15 and 30 ft have been used.

However, as the joint spacing increases, the aggregate interlock decreases, and there is also an increased risk of cracking.

Jointed Reinforced Concrete Pavements (JRCP)



Rigid Pavements:Jointed Reinforced Concrete Pavements (JRCP)

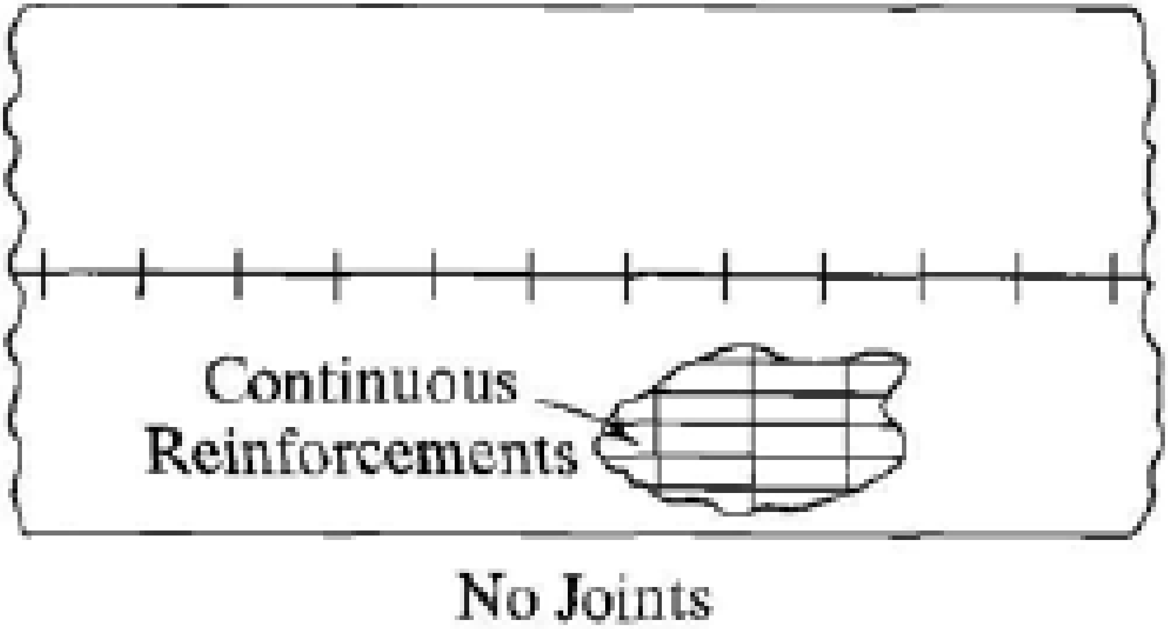
Steel reinforcements in the form of wire mesh or deformed bars do not increase the structural capacity of pavements but allow the use of longer joint spacings. Joint spacings vary from 30 to 100 ft.

Because of the longer panel length, dowels are required for load transfer across the joints .

The amount of distributed steel in JRCP increases with the increase in joint spacing and is designed to hold the slab together after cracking.

However, the number of joints and dowel costs decrease with the increase in joint spacing.

Rigid Pavements:Continuous Reinforced Concrete Pavements (CRCP)



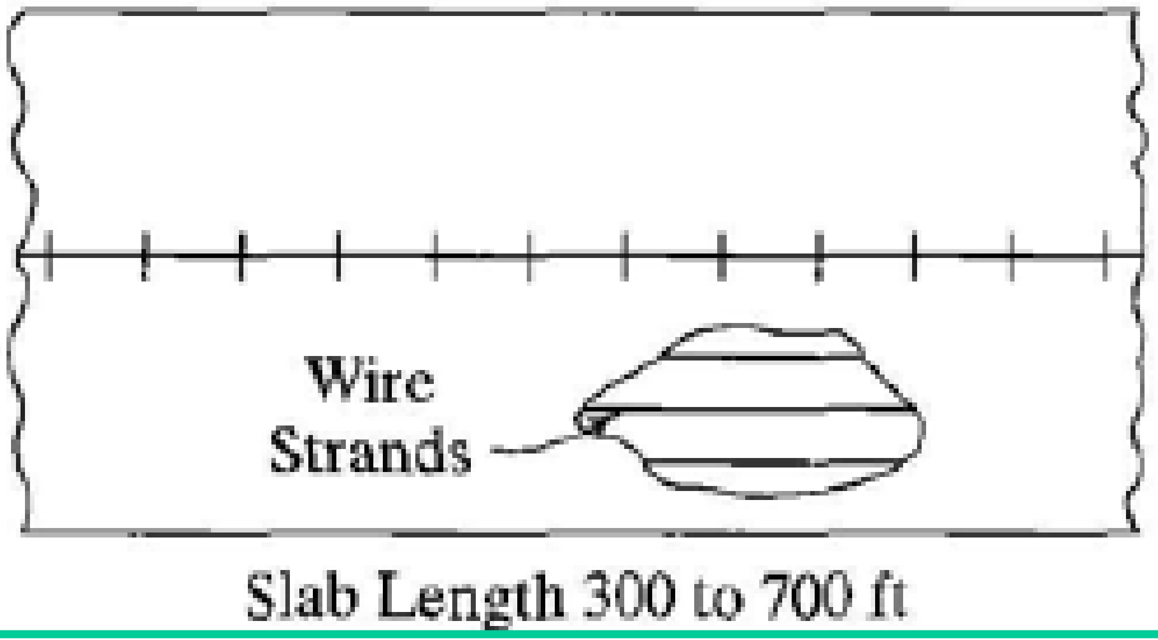
Rigid Pavements:Continuous Reinforced Concrete Pavements (CRCP)

The advantages of the joint-free design were widely accepted.

It was originally reasoned that joints were the weak spots in rigid pavements and that the elimination of joints would decrease the thickness of pavement required.

As a result, the thickness of CRCP has been empirically reduced by 1 to 2 in. or arbitrarily taken as 70 to 80% of the conventional pavement .

Rigid Pavements:Pre-stressed Concrete Pavements (PCP)



Rigid Pavements:Pre-stressed Concrete Pavements (PCP)

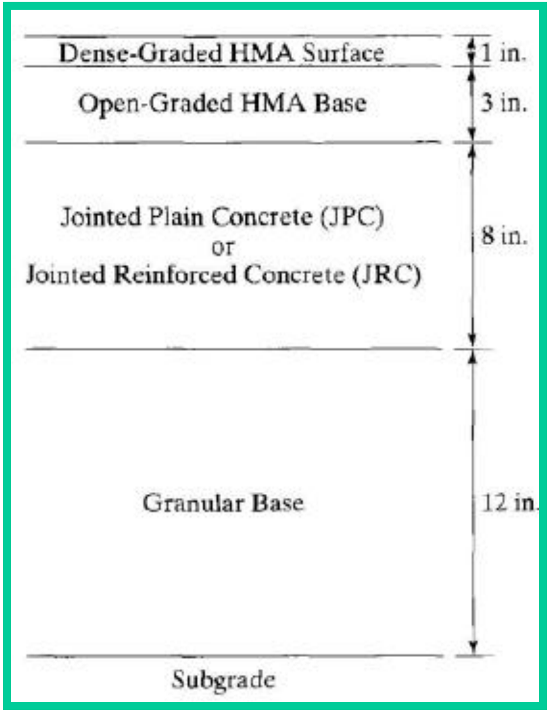
Concrete is weak in tension but strong in compression.

The thickness of concrete pavement required is governed by its modulus of rupture, which varies with the tensile strength of the concrete.

The pre-application of a compressive stress to the concrete greatly reduces the tensile stress caused by the traffic loads and thus decreases the thickness of concrete required.

The prestressed concrete pavements have less probability of cracking and fewer transverse joints and therefore result in less maintenance and longer pavement life.

Composite Pavements



Composite Pavements

A composite pavement is composed of both HMA and PCC. The use of PCC as a bottom layer and HMA as a top layer results in an ideal pavement with the most desirable characteristics.

The PCC provides a strong base and the HMA provides a smooth and non-reflective surface.

However, this type of pavement is very expensive and is rarely used as a new construction, rather employed as rehabilitation of concrete pavements using asphalt overlays .

Road Tests

Because the observed performance under actual conditions is the final criterion to judge the adequacy of a design method, three major road tests under controlled conditions were conducted by the Highway Research Board from the mid-1940s to the early 1960s.

- **Maryland Road Test**
- **WASHO Road Test**
- **AASHO Road Test**

Road Tests

AASHO Road Test

The objective of this project was to determine any significant relationship between the number of repetitions of specified axle loads of different magnitudes and arrangements and the performance of different thicknesses of flexible and rigid pavements (HRB, 1962).

The test facility was constructed along the alignment of Interstate 80 near Ottawa, Illinois, about 80 miles (128 km) southwest of Chicago.

Road Tests

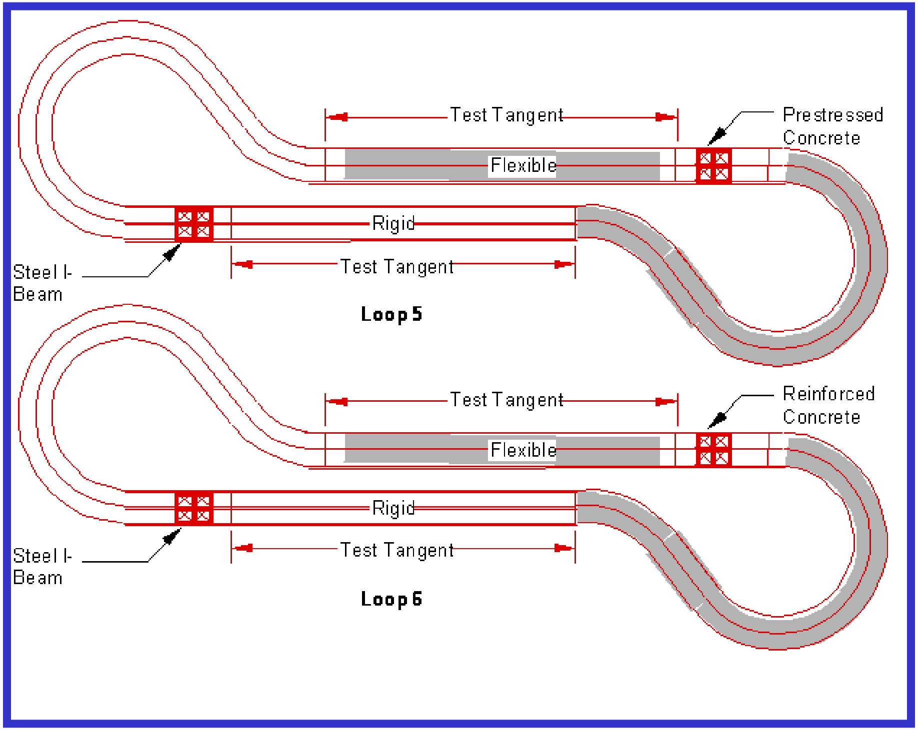
AASHO Road Test-General Layout

The test consisted of four large loops, numbered 3 through 6, and two smaller loops, 1 and 2. Each loop was a segment of a four-lane divided highway whose parallel roadways, or tangents, were connected by a turnaround at each end. Tangent lengths were 6800 ft (2070 m) in loops 3 through 6, 4400 ft (1340 m) in loop 2, and 2000 ft (610 m) in loop 1.

In all loops, the north tangents were surfaced with HMA and south tangents with PCC. Centerlines divided the pavements into inner and outer lanes, called lane 1 and lane 2. Each tangent was constructed as a succession of pavement sections called structural sections.

Road Tests

AASHO Road Test-General Layout



Road Tests

AASHO Road Test-General Layout

Pavement designs varied from section to section. The minimum length of a section was 100 ft (30.5 m) in loops 2 through 6 and 15 ft (4.6 m) in loop 1. The axle loads on each loop and lane are shown in Table 1.1.

Construction began in August 1956, and test traffic was inaugurated on October 15, 1958. Test traffic was operated until November 30, 1960, at which time 1,114,000 axle loads had been applied. The total cost of the project was $27 million.

Road Tests

AASHO Road Test-Axle loads on various lanes

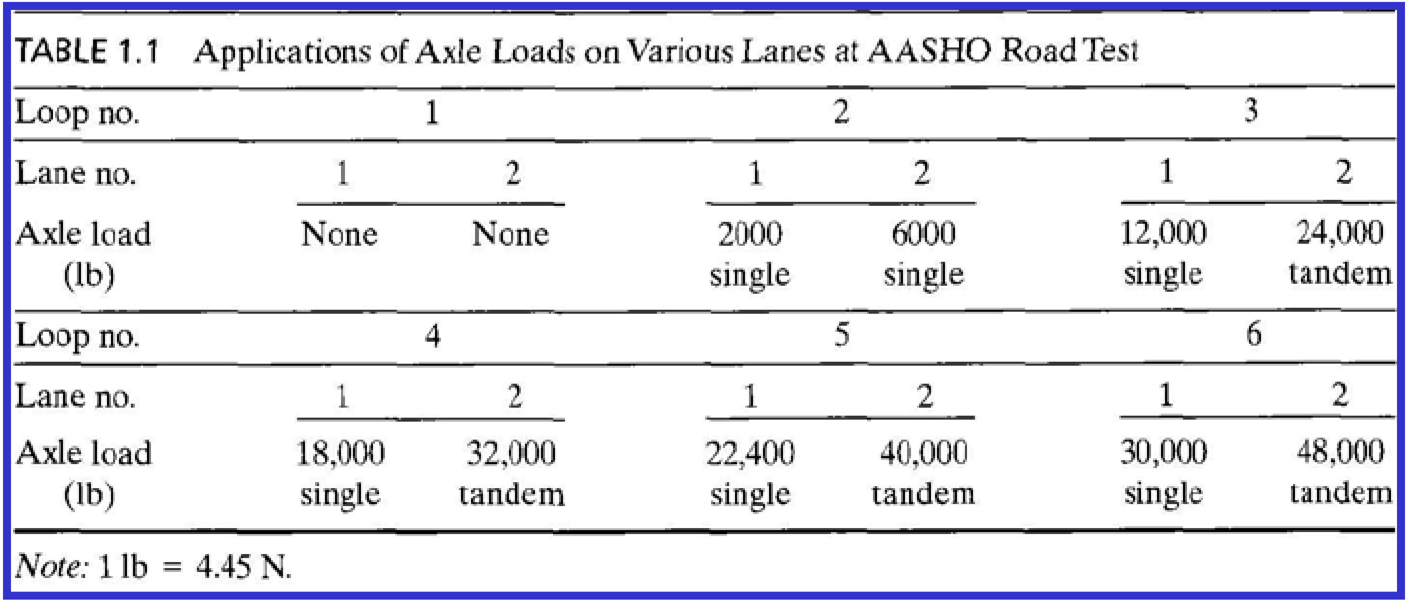


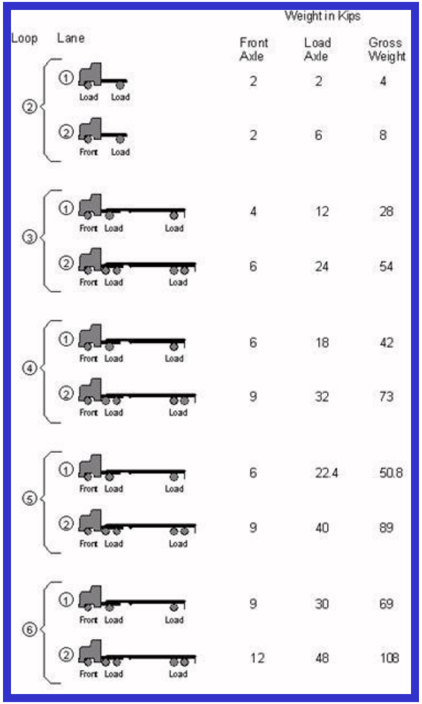
TABLE 1.1 Applications of Axle Loads on Various Lanes at AASHO Road Test

Loop no.	1		2		3	
Lane no.	1	2	1	2	1	2
Axle load (lb)	None	None	2000 single	6000 single	12,000 single	24,000 tandem
Loop no.	**4**		**5**		**6**	
Lane no.	1	2	1	2	1	2
Axle load (lb)	18,000 single	32,000 tandem	22,400 single	40,000 tandem	30,000 single	48,000 tandem

Note: 1 lb = 4.45 N.

Road Tests

AASHO Road Test-Axle loads on various lanes



Loop	Lane	Weight in Kips		
		Front Axle	Load Axle	Gross Weight
②	① Load Load	2	2	4
	② Front Load	2	6	8
③	① Front Load Load	4	12	28
	② Front Load Load	6	24	54
④	① Front Load Load	6	18	42
	② Front Load Load	9	32	73
⑤	① Front Load Load	6	22.4	50.8
	② Front Load Load	9	40	89
⑥	① Front Load Load	9	30	69
	② Front Load Load	12	48	108

AASHO Road Test-Major Findings

One important contribution of the AASHO Road Test was the development of the pavement serviceability concept, together with the equations relating serviceability, load and thickness design of both flexible and rigid pavements.

Flexible Pavements

1. The superiority of the four types of base under study fell in the following order: bituminous treated, cement treated, crushed stone and gravel. Most of the sections containing the gravel base failed very early in the test and their performance was definitely inferior to that of the sections with crushed-stone base.

Road Tests

AASHO Road Test-Major Findings -*Flexible Pavements*

2. The pavement needed to maintain a certain serviceability at a given number of axle-load applications would be considerably thinner in the inner than in the outer wheelpath.

3. Rutting of the pavement was due principally to decrease in thickness of the component layers. About 91% of the rutting occurred in the pavement itself: 32% in the surface, 14% in the base and 45% in the subbase. Thus, only 9% of a surface rut could be accounted for by rutting of the embankment. Data also showed that changes in thickness of the component layers were caused not by the increase in density, but primarily by lateral movements of the materials.

Road Tests

AASHO Road Test-Major Findings-*Flexible Pavements*

4. More surface cracking occurred during periods when the pavement was in a relatively cold state than during periods of warm weather. Generally, cracking was more prevalent in sections having deeper ruts than in sections with shallower ruts.

5. The deflection occurring within the pavement structure (surface, base, and subbase), as well as that at the top of the embankment soil, was greater in the spring than during the succeeding summer months. This effect was due to the higher moisture contents of the base, subbase, and embankment soil that existed in the spring.

Road Tests

AASHO Road Test-Major Findings-*Flexible Pavements*

6. A high degree of correlation was found between the deflection at the top of the embankment and the total surface deflection and one between deflection and rutting.

7.A pronounced reduction in deflection accompanied an increase in vehicle speed. Increasing the speed from 2 to 35 mph (3.2 to 56 km/h) reduced the total deflection 38% and the embankment deflection 35%.

Road Tests

AASHO Road Test-Major Findings-*Rigid Pavements*

1.Of the three design variables, viz ., reinforcement or panel length, subbase thickness and slab thickness, only slab thickness has an appreciable effect on measured strains.

2. Inspections of the pavements were made weekly and after each rain. Faulting occasionally occurred at cracks, never at the transverse joints, because all joints were doweled. No part of the cracking in the traffic loops was attributed solely to environmental changes, because no cracks appeared in the nontraffic loop, or loop 1.

Road Tests

AASHO Road Test-Major Findings-*Rigid Pavements*

3. Pumping of subbase material, including the coarser fractions, was the major factor causing failures of sections with subbase. The amount of materials pumped through joints and cracks was negligible when compared with the amount ejected along the edge.

4. Twenty-four-hour studies of the effect of fluctuating air temperature showed that the deflection of panel corners under vehicles traveling near the pavement edge might increase several fold from afternoon to early morning. Edge strains and deflections were affected to a lesser extent.

Road Tests

AASHO Road Test-Major Findings-*Rigid Pavements*

5. Corner deflections of a 40-ft (12.2-m) reinforced panel usually exceeded those of a 15-ft (4.6-m) non-reinforced panel, if all other conditions were the same. Edge deflections and strains were not affected significantly by panel length or reinforcement.

6. An increase in vehicle speed from 2 to 60 mph (3.2 to 96 km/h) resulted in a decrease in strain or deflection of about 29%.

Design Factors

Design factors can be divided into four broad categories:

- **Traffic and loading**
- **Environment**
- **Materials**
- **Failure criteria**

Design Factors

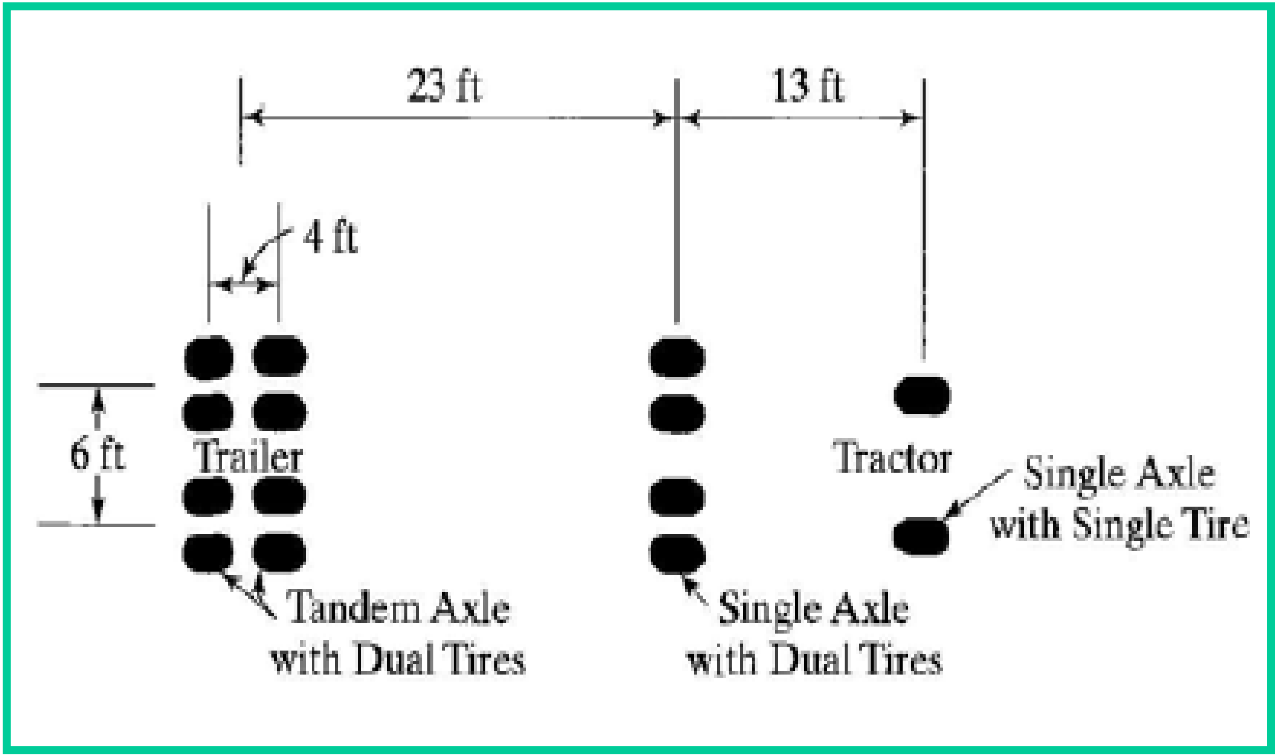
Traffic and loading

Under traffic and loading following factors are considered:

- Axle loads
- The number of load repetitions
- Tyre-contact areas
- Vehicle speeds

Design Factors

Traffic and loading-Axle loads



Design Factors

Traffic and loading-Axle loads

Figure shows the wheel spacing for a typical semitrailer consisting of single axle with single tyres, single axle with dual tyres and tandem axles with dual tyres.

For special heavy-duty haul trucks, tridem axles consisting of a set of three axles, each spaced at 48 to 54 in. apart, also exist.

The spacings of 23 and 13 ft shown in figure should have no effect on pavement design because the wheels are so far apart that their effect on stresses and strains should be considered independently.

Design Factors

Traffic and loading-Axle loads

Unless an equivalent single-axle load is used, the consideration of multiple axles is not a simple matter.

The design may be unsafe if the tandem and tridem axles are treated as a group and considered as one repetition.

The design is too conservative if each axle is treated independently and considered as one repetition.

Design Factors

Traffic and loading-Number of repetitions

With the use of a high-speed computer, it is no problem to consider the number of load repetitions for each axle load and evaluate its damage.

The method of dividing axle loads into a number of groups has been used frequently for the design of rigid pavements.

Design Factors

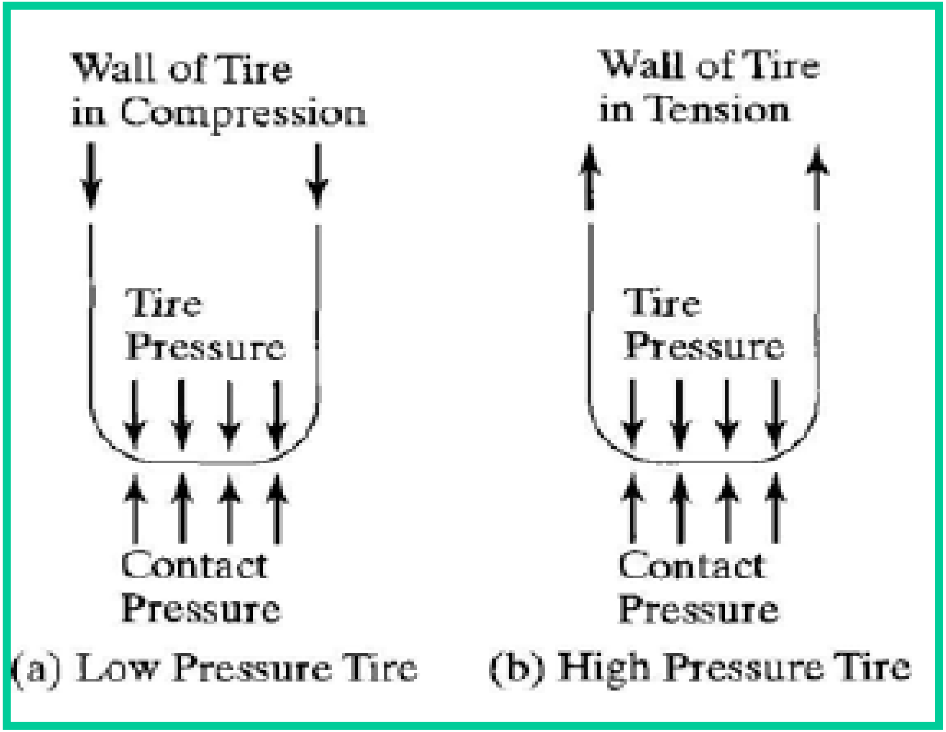
Traffic and loading-Number of repetitions

However, its application to flexible pavements is not widespread, because of the empirical nature of the design and of the large amount of computer time required.

Instead of analyzing the stresses and strains due to each axle-load group, a simplified and widely accepted procedure is to develop equivalent factors and convert each load group into an equivalent 18-kip (80-kN) single-axle load.

Design Factors

Traffic and loading-Contact area



Traffic and loading-Contact area

In the mechanistic method of design, it is necessary to know the contact area between tyre and pavement, so the axle load can be assumed to be uniformly distributed over the contact area.

The size of contact area depends on the contact pressure.

As indicated by Figure, the contact pressure is greater than the tyre pressure for low-pressure tyres, because the wall of tyre is in compression and the sum of vertical forces due to wall and tyre pressure must be equal to the force due to contact pressure.

Design Factors

Traffic and loading-Contact area

The contact pressure is smaller than the tyre pressure for high-pressure tyres, because the wall of tyre is in tension.

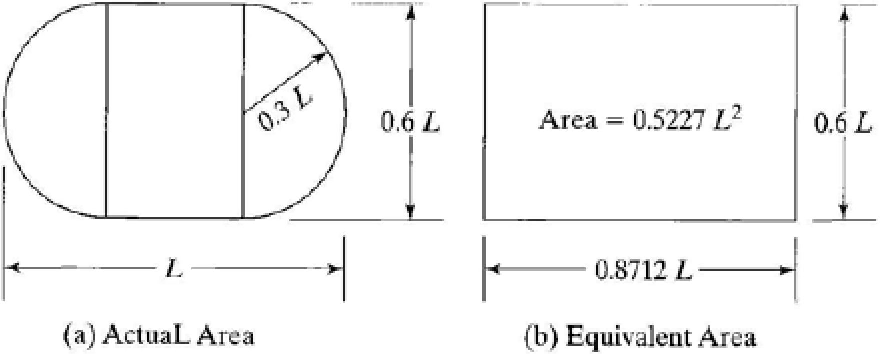
However, in pavement design, the contact pressure is generally assumed to be equal to the tyre pressure.

Because heavier axle loads have higher tyre pressures and more destructive effects on pavements, the use of tyre pressure as the contact pressure is therefore on the safe side.

Design Factors

Traffic and loading-Contact area

Heavier axle loads are always applied on dual tyres. Figure shows the approximate shape of contact area for each tyre, which is composed of a rectangle and two semicircles.



Design Factors

Traffic and loading-Contact area

By assuming length L and width 0.6L, the area of contact

$$A_c = \pi(0.3L)^2 + (0.4L)(0.6L) = 0.5227L^2, \text{ or}$$

$$L = \sqrt{\frac{A_c}{0.5227}}$$

in which A_c = contact area, which can be obtained by dividing the load on each tyre by the tyre pressure.

Design Factors

Traffic and loading-Contact area

The contact area shown in Figure (a) was used previously by PCA (1966) for the design of rigid pavements.

The current PCA (1984) method is based on the finite element procedure, and a rectangular area is assumed with length 0.8712L and width 0.6L, which has the same area of $0.5227L^2$, as shown in Figure (b).

Design Factors

Traffic and loading-Vehicle speed

Another factor related to traffic is the speed of travelling vehicles. If the viscoelastic theory is used, speed is directly related to the duration of loading.

If the elastic theory is used, the resilient modulus of each paving material should be properly selected corresponding with the vehicle speed.

Generally, the greater the speed, the larger the modulus, and the smaller the strains in the pavement.

Design Factors

Environment

The environmental factors that influence pavement design include temperature and precipitation, both affecting the elastic moduli of the various layers.

In the mechanistic-empirical method of design, each year can be divided into a number of periods, each having a different set of layer moduli.

The damage during each period is evaluated and summed throughout the year to determine the design life.

Design Factors

Materials

In the mechanistic-empirical methods of design, the properties of materials must be specified, so that the responses of the pavement, such as stresses, strains, and displacements in the critical components can be determined.

These responses are then used with the failure criteria to predict whether failures will occur.

Design Factors

Materials

The following general material properties should be specified for both flexible and rigid pavements:

1. When pavements are considered as linear elastic, the elastic moduli and Poisson ratios of the subgrade and each component layer must be specified.

2. If the elastic modulus of a material varies with the time of loading, the resilient modulus, which is the elastic modulus under repeated loads, must be selected in accordance with a load duration corresponding to the vehicle speed.

Design Factors

Failure Criteria

In the mechanistic-empirical methods of pavement design, a number of failure criteria, each directed to a specific type of distress, must be established.

This is in contrast to the AASHTO method, which uses the present serviceability index (PSI) to indicate the general pavement conditions.

Design Factors

Failure Criteria

Flexible Pavements

Fatigue cracking and rutting are the principal types of distress to be considered for flexible pavement design. These criteria are briefly described below.

Fatigue Cracking

The fatigue cracking of flexible pavements is based on the horizontal tensile strain at the bottom of HMA.

Rutting

Rutting occurs only on flexible pavements, as indicated by the permanent deformation or rut depth along the wheelpaths.

Design Factors

Failure Criteria

Rigid Pavements

Fatigue Cracking

Fatigue cracking is most likely caused by the edge stress at the midslab.

Pumping or Erosion

Although permanent deformation are not considered in rigid pavement design, the resilient deformation under repeated wheel loads will cause pumping of the slabs.

Assignment No. 1

Pavement Analysis and Design by Yang H. Huang

Chapter-1

Problems and Questions (Pages 43-44)

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Evaluation

- **Quiz 1**
- **Mid Term**
- **Quiz 2**
- **End Term**
- **Semester Project**
- **Assignments/Analysis and Design problems**