Combination of Stresses

The following conditions are found to be critical combinations

- *During Summer* the critical combinations at interior and edge regions occurs when the slab tends to warp downward.

- The maximum tensile stress is developed at bottom fiber due to loading and warping, however the frictional stress is compressive

- *Critical combination of stresses = (*load stress + warping stress – frictional stress), at edge *region*

Combination of stresses

- *During winter* the critical combination of stress at interior and edge regions occur at bottom fiber when the slab contracts and slab warps downward during the mid day

- Critical stress combination = (load stress+ warping stress+ frictional stress), *at edge region*

- Since the differential temperature is higher in summer than in winter the combination of stress in summer is critical

- At corner regions there are no frictional stresses, the critical combination occurs at top fiber of slab during mid nights

  critical stress combination = (load stress + warping stress), at *corner region*

Design of Slab Thickness

Critical Stress condition

- The factors commonly considered for design of pavement thickness are flexural stress due to traffic loads and temperature differential between the top and bottom fibers of concrete slab

- The loads applied by single as well as tandem axles causes maximum flexural stresses when the tyre imprint touches the longitudinal edge

- Considering the total combined stress for the three regions for which the load stress decreases in that order while the temperature stress increases, the critical stress condition is reached in the edge region

Design Parameters

- **Traffic Parameters**

  1. Axle Load Spectrum

- **Environmental Factors**

  1. Temperature Differential
  2. Mean Temperature Cycles

Design Parameters

- **Foundation Strength and Surface Characteristics**
  1. Strength
  2. Foundation Surface Characteristics

- **Concrete Characteristics**
  1. Design Strength
  2. Modulus of Elasticity and Poisson's Ratio
  3. Coefficient of Thermal Expansion

Traffic Parameters

Axle Load Spectrum

- This should be obtained from axle load spectrum
- 98^{th} percentile axle load should be used for checking for the worst combination of stresses
- The fatigue consumption of the slab should be checked as per the axle load spectrum and design life
- In addition to axle load, tyre pressure and shape of the contact areas of the commercial vehicles also govern load stresses
- The tyre pressure ranges from about 0.7 to 1.0 Mpa however a tyre pressure of 0.8 Mpa is adopted for design

Traffic Parameters

- Data on axle load distribution of the commercial vehicles is required to compute the number of repetitions of single and tandem axles of different weights expected during design period

- An axle load survey should be conducted for a day covering a minimum sample size of 10 percent in both the directions

- For Computation of stresses in the pavements, the magnitude of axle loads should be multiplied by Load Safety Factor (LSF)

Traffic Intensity

- Repetitive loading of pavement reduces the fatigue strength of the concrete.
- Traffic intensity is a growing phenomenon, the heaviest will occur at the end of deign life of a pavement
- As the fatigue analysis is carried out for critical edge stress, only the axles that ply very close to the edge are to be considered. Conservatively it can be assumed that about one-third of axles ply close to the edge.
- The cumulative number of repetitions of axles during the design period on design lane may be computed from the following formula

$$C = \frac{365 \times A\{(1+r)^n - 1\}}{r} \times L \times D \times 0.33$$

C = Cumulative number of axles during the design period

A = Initial number of axles per day in the year when the road is operational

r = Annual rate of growth of commercial traffic

n = Design period in years

L = lane distribution factor

D = Directional distribution factor

Environmental Parameters

- **Temperature Differential**

  Function of

  - solar radiation received by pavement surface
  - Losses due to wind velocity
  - Thermal diffusivity of concrete

  Thus temperature differential is affected by geographical location of the pavement

- Mean Temperature Cycles

  Affect the maximum spacing of contraction and expansion joints in the pavement

Foundation strength and surface characteristics

- **Strength**

  Expressed in terms of modulus of subgrade reaction, k, which is defined as pressure per unit deflection of the foundation as determined from the plate bearing test

- **Surface characteristics**

  Determine the extent of resistance to slab movement during expansion and contraction on account of foundation restraint and affect spacing of joints.

Approximate k-value Corresponding to CBR values for Homogeneous Soil Subgrade

Soaked CBR value %	2	3	4	5	7	10	15	20	50	100
k-value ($kg/cm^2/cm$)	2.1	2.8	3.5	4.2	4.8	5.5	6.2	6.9	14.0	22.2

K-values over Granular and Cement treated Sub-bases

K-value of Subgrade, (kg/cm²/cm)	Effective k over untreated granular layer sub-base of thickness in cm			Effective k over cement treated sub-base of thickness in cm		
	15	22.5	30	10	15	20
2.8	3.9	4.4	5.3	7.6	10.8	14.1
5.6	6.3	7.5	8.8	12.7	17.3	22.5
8.4	9.2	10.2	11.9	----	----	----

K-values over Dry Lean Concrete Sub-base

K-value of Subgrade kg/cm^2/cm	2.1	2.8	4.2	4.8	5.5	6.2
Effective k over 100 mm DLC, kg/cm^2/cm	5.6	9.7	16.6	20.8	27.8	38.9
Effective k over 150 mm DLC, kg/cm^2/cm	9.7	13.8	20.8	27.7	41.7	----

Concrete Characteristics

- ## Design strength

As stresses induced in concrete pavements are due either to bending or its prevention, their design is necessarily based on flexural strength of concrete

- ## Modulus of Elasticity

. Modulus of Elasticity, is useful for determining the relative stiffness of the slab. Modulus of Elasticity, E, of concrete increases with its strength however for design purposes it is taken as $E = 3*10^5$ kg/cm^2 for concrete having flexural strength in the range of 38-42 kg/cm^2

- ## Poisson's ratio

This property of concrete is used for determination of stresses in concrete slabs. Its value is determined by static and dynamic methods the former value is around 0.15 and the latter around 0.24

Concrete Characteristics

- Coefficient of thermal expansion

  The coefficient of thermal expansion,α, of concrete of the same mix varies with the type of aggregate however for design purposes a value of

  $\alpha = 10*10^{-6}/^{o}c$ may be adopted

- Fatigue behavior of concrete

  Due to repeated application of flexural stresses by traffic loads, a progressive fatigue damage takes place in concrete slab in the form of gradual development of micro-cracks especially when applied stress in terms of flexural strength of concrete is high

- The ratio between the flexural stress due to load and the flexural strength due to concrete is termed as the stress Ratio (SR)

Stress Ratio and Fatigue analysis

- For a given slab thickness and other design parameters, the flexural stress at the edge due to the application of a single or tandem axle loads may be determined by approximate stress chart
- This stress value is divided by the flexural strength of the cement concrete, to obtain the stress ratio in the pavement
- If the stress ratio is less than 0.45, the allowable number of repetitions of the axle load is infinity
- Cumulative fatigue damage is determined for different axle loads and the value of the damage should be equal to or less than one

Distress Model

The relation between fatigue life and Stress Ratio (SR) is given as

N = unlimited for SR < 0.45

$$N = \left[\frac{4.2577}{SR - 0.4325}\right]^{3.268}$$ When 0.45≤SR ≤0.55

$$\log_{10} N = \frac{0.9718 - SR}{0.0828}$$ When SR > 0.55

Stress Ratio and Allowable Repetitions in Cement Concrete

Stress Ratio	Allowable Repetitions	Stress Ratio	Allowable Repetitions
0.45	6.279×10^7	0.66	5.83×10^3
0.46	1.4335×10^7	0.67	4.41×10^3
0.47	5.2×10^6	0.68	3.34×10^3
0.48	2.4×10^6	0.69	2531
0.49	1.287×10^6	0.70	1970
0.50	7.62×10^5	0.71	1451
0.51	4.85×10^5	0.72	1099
0.52	3.26×10^5	0.73	832
0.53	2.29×10^5	0.74	630
0.54	1.66×10^5	0.75	477
0.55	1.24×10^5	0.76	361
0.56	9.41×10^4	0.77	274
0.57	7.12×10^4	0.78	207
0.58	5.4×10^4	0.79	157
0.59	4.08×10^4	0.80	119
0.60	3.09×10^4	0.81	90
0.61	2.34×10^4	0.82	68
0.62	1.77×10^4	0.83	52
0.63	1.34×10^4	0.84	39
0.64	1.02×10^4	0.85	30
0.65	7.7×10^3		

Recommended Design Procedure

- Stipulate design values for the various parameters
- Decide types and spacing between joints
- Select a trial design and thickness of pavement slab
- Compute the repetitions of axle loads of different magnitudes during the design period
- Calculate the stresses due to single, Tandem and Tridem axle loads and determine the cumulative fatigue damage (CFD)

Recommended Design Procedure contd..

- If the CFD is greater than 1.0, select a higher thickness and repeat the above steps

- Compute the temperature stress at the edge and if the sum of the temperature stress and the flexural stress due to highest wheel load is greater than the modulus of rupture, select a higher thickness and repeat the above steps

- Design the pavement thickness on basis of corner tress if no dowel bars are provided

Example of Rigid Pavement Design

- Refer Excel Sheet

Check for Temperature Stresses

- Edge warping stress = $\frac{CE\alpha t}{2}$ = 1.59 MPa
- L = 4 m
- B = 3.5 m
- l = 0.875
- L/l = 4.572
- C = 0.60 (from the chart)
- Temperature Differential = 18ºC
- Sum of warping stress and highest axle load stress = 2.43 + 1.59 = 4.020 MPa
- Since 4.020 MPa < 4.5 MPa (flexural strength of Concrete)
- Pavement thickness of 325 mm is safe under the combined of wheel load and temperature

Check for Corner Stress

- Corner stress can be calculated from the following formula
- $$S_c = \frac{3P}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{l}\right)^{1.2}\right]$$
- The 98th percentile axle load is 24 tonnes. The wheel load, therefore, is 12 tonnes.
- Radius of relative stiffness, l = $l = \sqrt[4]{\frac{Eh^3}{12(1-\mu)^2 K}}$
- E = 2.943*10^4 MPa
- h = 325 mm
- μ = 0.15
- k = 147 MN/m^3
- Radius of relative stiffness *l* = $\sqrt[4]{\frac{3\times10^5\times33^3}{12(1-0.15^2)8}}$ = 0.875 m
- a = radius of area of contact of equivalent single wheel

Check for Corner Stress

- a = $\left[0.8521 \times \frac{P}{q \times \Pi} + \frac{S}{\Pi}\left(\frac{P}{0.5227 \times q}\right)^{0.5}\right]^{0.5}$
- Where
- P = Load
- S = C/c distance between two tyres = 31 cm
- q = tyre pressure
- = $\left[0.8521 \times \frac{12000}{8 \times \Pi} + \frac{31}{\Pi}\left(\frac{12000}{0.5227 \times 8}\right)^{0.5}\right]^{0.5}$

= 30.59 cm

Substituting these values in equation of corner stress

- Corner Stress = 19.45 kg/cm^2 (<45 kg/cm^2)