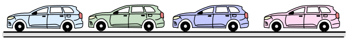
CE481A

TRANSPORTATION FACILITIES DESIGN

PART-1 PAVEMENT DESIGN

Dr. Prabin Kumar Ashish



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31 July

- Partha Chakraborty - Principles of transportation engineering Ch-12
  Animesh Das
- Ch 11, 12 } Yang H. Huang
  Ch 4 } Pavement Analysis & Design
- IRC 37:2018 — codal practice for design of flexural pavement
- IRC 58:2015 — codal practice for design of rigid pavement

- Pavement Design
- Traffic
- Geometric Design

Broad coverage from pavement part
- General Design Philosophy
- Design Input Parameters
- Design of pavement structures
  - Bituminous Pavement /Asphalt
  - Cement concrete Pavement
  - Overlay Design

IITPAVE — Bituminous pavement
IITRIGID — Cement Concrete pavement

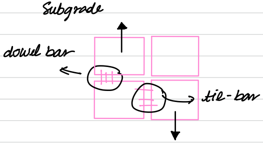
BITUMINOUS / Flexible Pavement

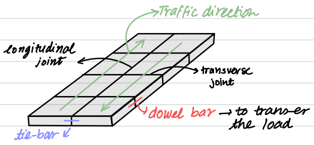
Bituminous layer < surface coarse, binder coarse
Base layer, Sub base } unbounded → Bounded layer using cementitious layer (cement/stabilizer) ↳ modulus of rigidity ↑es.
Sub base → for drainage purpose
Subgrade → embankment

usually, the stiffness ↓ from top to bottom.
Adding constituent layer increases the stiffness of base layer + subbase layer.

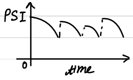
CONCRETE / Rigid Pavement

PQC layer — Pavement Quality Concrete → strongest
DLC layer — Dry lean Concrete → to have strong support from the bottom. else there'll be cracking in PQC.
Base layer
Subbase layer
Subgrade





Flexible pavement which lasts more than 15 years — Perpetual pavement.



Pavement Serviceability Index (PSI)

BITUMINOUS PAVEMENT

Design Methodology
1. Empirical Approach
2. Mechanistic Empirical Approach → Factor of safety (endurance limit)
3. Mechanistic Approach

Pavement Design — Structural design
— Functional Design → surface Characteristic

3 Aug

Structural Design → Analysis
- Fresh road construction
- Rehabilitation

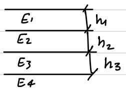
- Material properties < Temperature, Moisture
- Traffic loading + Design life →
  - Axle configuration
  - Axle repetition
  - Speed
  - Tyre conditions
  - Tyre pressure

DESIGN PARAMETERS
- Traffic loading
- Material properties
- Environmental factors
- Design life

TRAFFIC CHARACTERISTICS

Homogenous section
Average tyre load : 0.56 MPa
0.8 MPa (taking safety factor into account)
— cementitious layer.

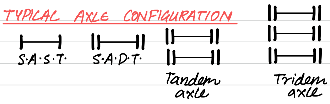
Assumption: Thickness of layer



Different axle load
Different ↓ damage

TRAFFIC
- Axle Configuration
- Load Repetition
- Tyre Pressure
- Speed
- Traffic Growth

TYPICAL AXLE CONFIGURATION



CVPD : commercial vehicles per day
commercial traffic on road (both dirⁿ)
(7 day, 24 hours) — survey [IRC:108]

AXLE LOAD

- legal load — max load allowed legally
- Standard load — ref. load used by engineers for designing
  (Standard load < Legal load)

How to measure legal load?
- Static way — pad to measure axle load
- WIM — Way in motion / motion way
  toll plaza, etc — measure the load

Load level
- gross weight of vehicles > 3 ton [IRC3-1983]
  (commercial vehicles only)

- Overloading — main cause of pavement failure in India.

TYRE CONTACT PRESSURE

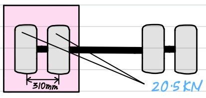
pressure exerted by tyre on the ground.
can be >, < or = to internal tyre pressure (assumed equal and uniform)
- 0.56 MPa
- CTB → 0.8 MPa

TYRE IMPRINT AREA

tyres — approximated as idealized shapes
- For bituminous pavement — circular contact area (bcoz of cylindrical coordinates)
- For concrete pavement — rectangular contact area (bcoz of cartesian coordinates)

WHEEL CONFIGURATION

Effect of various wheel configuration — taken into account by linear superposition.
A single wheel system — standard configuration.
Length of axle is long enough s.t. effect of wheels at one end not felt at other end.
- For practical purposes, only loading due to two wheels is considered.

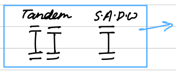


20.5 KN each (= 41 KN)
0.56 MPa tyre pressure

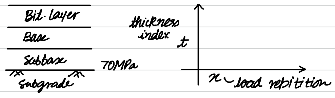
Example Find % increase in legal truck load?

S.A.S.W	6	7.5
S.A.D.W	10.2	11.5
Tandem	19	21
Tridem	24	27

$$\rightarrow \%\ \text{increase} = \left[\left(\frac{11.5-10.2}{10.2}\right)+\left(\frac{21-19}{19}\right)\right]\times 100 = 23.27\%$$

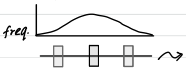


→ Truck



LATERAL DISTRIBUTION OF WHEEL PATH IN A LANE

maximum traversed path is distressed the highest. — critical distress line.
But other wheel paths also have contribution in distress along critical line.
Lateral Distribution Factor (LtDF) — conversion factor for equivalent repetitions along the critical line.



↝ various positions for left wheel

Fourth Power Damage Formula

N_1 no. of repetitions for axle weight w_1] — Both cause same amount
N_2 " " " " " " w_2] of damage

AASHO's study proposed
4th Power law

$$\boxed{\frac{N_1}{N_2} = \left(\frac{W_2}{W_1}\right)^4}$$

eg:- 18 Kips — 190000 Load repetitions to fail }
30 Kips — 25000 " " " " }
(Kilopounds)

$\frac{190\,000}{25000} \approx 7.6$, $\frac{30\text{ Kips}}{18\text{ Kips}} = 1.667$, $7.6 = (1.667)^n$

$\Rightarrow n = \log_{1.667} 7.6 = 3.97 \approx 4$

4 ⇒ conversion factor (axle damage factor)

- This equation helps to convert number of repetition of vehicles of various axle loads plying on the road to an equivalent standard load repetition. [termed as Equivalent Single Axle Load (ESAL)]
- Legal axle load is the maximum axle load permitted by legislation. In India 10.2 tonnes (Motor Vehicles Act)
- Standard axle load is the axle load based on which all the pavement design calculations are standardized by engineers. In India 8.16 tonnes (≈80KN) for S.A.D.W & 14.968 tonnes for tandem. Thus, all various axle repetitions need to be converted to ESAL rep.
  ↳ we use VDF to convert to standard axle load rep.

Note : ESAL = (total no. of commercial traffic) x VDF
↓ equivalent single axle load repetitions — multiplier

VEHICLE DAMAGE FACTOR (VDF)

(4.4, IRC37)

Defn: A typical factor representing the loads carried by commercial vehicles plying on the road converted to standard axle load.

- The weighted average of damages caused by the individual axle load group for the corresponding volume of traffic is VDF.

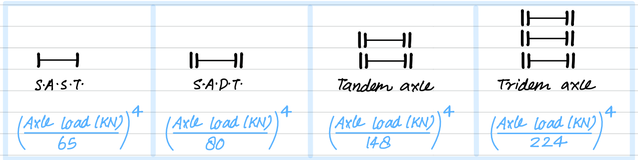
$$\boxed{VDF = \frac{A_1\left(\frac{w_1}{w_s}\right)^4 + A_2\left(\frac{w_2}{w_s}\right)^4 + \cdots}{V}}$$

A_i — no. of axles
w_i — median values of axle load
w_s — standard axle load
V — no. of vehicles surveyed

History of VDF — In 1950s — AASHO (American Association of State Highway & Transport Officials
↳ Design Guide (1961) → load ↑ damage rate ↑
load ↓ damage rate ↓

For converting one repitition of a particular type of axle carrying a specific axle load into equivalent repetitions of 80KN single axle with dual wheel, we use below eqns

axle damage factor for different type of axle configurations



$\left(\frac{\text{Axle load (KN)}}{65}\right)^4$ | $\left(\frac{\text{Axle load (KN)}}{80}\right)^4$ | $\left(\frac{\text{Axle load (KN)}}{148}\right)^4$ | $\left(\frac{\text{Axle load (KN)}}{224}\right)^4$

here, axle load is due to all the wheels in axle and this gives axle damage factor. (not VDF)

Example

Truck — If 500 trucks
VDF or standard axle per truck = ?

Soln $VDF_{truck} = \left(\frac{50}{65}\right)^4 + \left(\frac{195}{148}\right)^4 + \left(\frac{290}{224}\right)^4 = 6.17$

for 500 trucks,
$6.1 + 4.2 + 7.3 + \cdots\cdots$ 500 trucks $= 3000$
VDF or std. axle per truck $= \frac{3000}{500} = 6$

Aliter :- $VDF = \frac{500 \times \left[\left(\frac{50}{65}\right)^4 + \left(\frac{195}{148}\right)^4 + \left(\frac{290}{224}\right)^4\right]}{500} = 6.17$

how is that & this different?
How for 500 trucks — how?

VDF → can be for one truck or for whole road maybe.
legal load ↑ ⇒ VDF ↑

Table 4.1 Minimum Sample Size for Axle Load Survey

Commercial Traffic Volume (CVPD)	Min.% of Commercial Traffic to be Surveyed
< 3000	20 per cent
3000 to 6000	15 per cent (subject to a minimum of 600 cvpd)
> 6000	10 per cent (subject to a minimum of 900 cvpd)

Pt 4.4.4 & 4.4.6, IRC37:2018

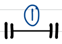
Table 4.2 Indicative VDF values

Initial (Two-Way) Traffic Volume in Terms of Commercial Vehicles Per Day	Terrain	
	Rolling/Plain	Hilly
0-150	1.7	0.6
150-1500	3.9	1.7
More than 1500	5.0	2.8

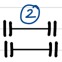
$VDF_{rolling} > VDF_{hilly}$?

Example

Total no. of trucks = 250
Find VDF = ?


① (291)

load	No. of axle
0-20	5
20-40	16
40-60	100
60-80	50
80-100	20
100-120	100


② (356)

load	No. of axle
0-40	0
40-80	6
80-120	50
120-160	150
160-200	120
200-240	30

Soln: ①

Average load	load equivalency factor	No. of axle	load equivalency factor = N X LEF
10	$(10/80)^4 = 0.0002$	5	$0.0002 \times 5 = 0.0012$
30	$(30/80)^4 = 0.0198$	16	$= 0.3164$
50	$(50/80)^4 = 0.1526$	100	$= 15.2588$
70	$(70/80)^4 = 0.5862$	50	$= 29.3091$
90	$(90/80)^4 = 1.6018$	20	$= 32.0361$
110	$(110/80)^4 = 3.5745$	100	$= 357.4463$

$x_1 = 434.3679$

②

Average load	load equivalency factor	No. of axle	load equivalency factor = N X LEF
20	0.0003	0	$0.0003 \times 0 = 0$
60	0.0270	6	0.1621
100	0.2084	50	10.4213
140	0.8007	150	120.1037
180	2.1880	120	262.5575
220	4.8825	30	146.4755

$x_2 = 539.7202$

Total no. of trucks = 250
Total load equivalency factor $= x_1 + x_2 = 974.0881$
$VDF = \left(\frac{x_1 + x_2}{\text{Total no. of trucks}}\right) = \underline{3.8964}$ ↳ This VDF is just for truck.

Example Find VDF of the traffic condition (mixed traffic)?

7 Aug

vehicle	no. of veh.	VDF
Bus	10	2.5
LCV	10	2.1
2A-truck	200	15.2
3A-truck	300	10.4
multi-axle	250	15

Soln: mixed traffic will have average VDF

$VDF = \frac{\sum n_i * VDF_i}{\sum n_i} = \frac{10 \times 2.5 + 10 \times 2.1 + \cdots + 250 \times 15}{10 + 10 + 200 + 300 + 250}$

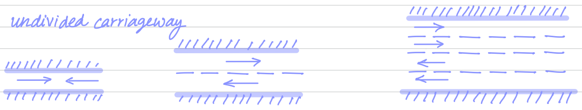
VDF = 12.93 (average vdf)

LANE DISTRIBUTION FACTOR (LDF)

(4.5, IRC37-2018)

For design purpose, we convert CVPD (both dirn) ⟶ traffic along single lane.
Traffic along single lane = CVPD X LDF

undivided carriageway



1 (100%) single lane | 0.5 (50%) two-lane two way | 0.4 (40%) four lane single carriageway

divided carriageway

0.75 (75%) dual two-lane | 0.6 (60%) dual three-lane | 0.45 (45%) dual four-lane

DESIGN TRAFFIC

4.6, IRC37:2018
Design traffic for full design life.

$$\boxed{N_{design} = A \times 365 \times \left[\frac{(1+r)^n - 1}{r}\right] \times VDF \times LDF}$$

Ndesign = cumulative no. of standard axles for design period of n years
A = initial traffic (cvpd)
n = design period (in years)
LDF = lane distribution factor (decimal)
VDF = vehicle damage factor
r = traffic growth rate (decimal)

$\boxed{A = P \times (1+r)^x}$
P : present traffic (cvpd)
x : no. of years for construction

Traffic Growth Rate

IRC 108:2015 talks about traffic growth rate

- Previous traffic growth rates (toll plaza, etc)
- Demand Elasticity w.r.t. GDP — macro economic parameters
- Demand expected due to specific developments and land use pattern
- Data from petrol pump, toll plaza, etc

Example 3 lane undivided carriageway
m^{th} total CVPD at opening year = 1450
A, D Ndesign = ?

VDF = 6·35
n = 20 yrs
r = 5·6%

Soln: – LDF = 0·6 A = 1450 VDF = 6·35 n = 20 r = 0·056

$$N_{design} = 1450 \times 365 \times \left[\frac{(1+0.056)^{20}-1}{0.056}\right] \times 6.35 \times 0.6 = 71064163.3928$$

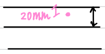
$N_{design} \approx 71064163$ or 71 msa (million std. axle)

ENVIRONMENTAL FACTORS

- Pavement temperature
- Subgrade Moisture
- Frost Action

Pavement Temperature

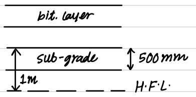
- The pavement temp. varies during day and also seasonally.
  For design purposes, we use Average Annual Pavement Temperature (AAPT)
  35°C in India & 20°C for low temp. regions.
  Some empirical relationship b/w AAPT and AAAT (Av. annual air temp.)
  eg:- jaipur 36°C 45·8°C max 0·7°C min } like this.
  vishakhapatnam 36·7°C 37·4°C max 13·2°C min
  need to change standards for AAPT.



60-30mm top layer – surface } Bituminous layer
bottom layer – binder

- Pavement Temperature at 20mm below pavement surface is taken.
- Pavement Temp. > Climate Temp. outside
- Pavement Temp. = $[T_{air} - 0.00618 \times lat^2 + 0.2289 \times lat + 42.2] * 0.9545 - 17.78$
  IS15462 — US formula – valid well for US lat but not India. ↳ need not rem!
- Pavement Temp. = $[-0.7147 + 1.3023 * A_t + 0.1103 * A_t]$ ↳ Air temp.
  IIT Madras Formula
- $M_p = M_a * 1.05 + 5$, M_p : monthly average pavement temp.
  M_a : " " air "
- Temp. differential induce thermal stress in concrete. Thermal stress/crack occur due to lower temp.

Moisture



- Moisture affects M_R (resilient modulus) of subgrade.
- Selection of bitumen + aggregate which are compatible.
- Unbonding happens due to presence of water.
- Water lead to formation of potholes.
  bonding unbonding – imp. from moisture pt. of view

H.F.L. Highest Flood Level
H.F.L. is 1m below subgrade

Frost Action

1. Freezing of soil water — heaving of road surface
2. Thawing of soil water — Softening of subgrade

PAVEMENT DESIGN PHILOSOPHIES

10 Aug

Design Methods

- Empirical
- Mechanistic Empirical

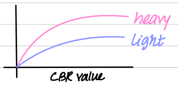
Empirical

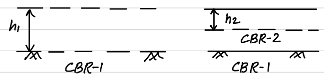
- CBR method [1928-29]*
- California (Hveem) method
- Bearing Capacity method
- Limiting depth criteria
- Regression method based on pavement performance

CBR Method

two loading condition
- light traffic — wheel load (3175 Kg)
- heavy traffic — wheel load (5443 Kg)

$$\boxed{T\,(cm) = \left[\frac{1.75 \times \overset{Kg}{P}}{\underset{\%}{CBR}} - \frac{\overset{cm^2}{A}}{\pi}\right]^{1/2}}$$; CBR < 12%





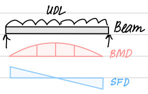
subbase thickness = $h_1 - h_2$

Mechanistic Empirical Method for Bituminous Pavement Design

mechanistic + empirical = mechanistic empirical approach

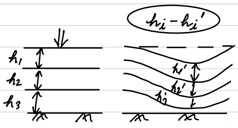
stress
strain
deflection

Relate with physical manifestation of distresses
↳ fatigue crack
↳ rutting
↳ thermal crack
↳ thermal fatigue crack
↳ moisture damage

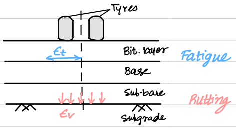


similar for pavement

ϵ_t, ϵ_v are critical strain in bituminous pavement



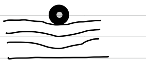
every layer's deflection get accumulated at the top.



ϵ_t horizontal tensile strain at the bottom of bituminous layer
ϵ_v vertical compressive strain on the top of subgrade

Why don't we have stress criteria instead of this strain criteria?
bcoz strain is dimensionless and we can apply it anywhere.

Fatigue test in lab — 4PBT / ITFT



testing condition
self healing

Mathematical model

$$N_f = K_1\left(\frac{1}{\epsilon_t}\right)^{K_2} \rightsquigarrow N_f = K_1\left(\frac{1}{\epsilon_t}\right)^{K_2}\left(\frac{1}{M_r}\right)^{K_3} \rightsquigarrow N_f = SF \times K_1 \times \left(\frac{1}{\epsilon_t}\right)^{K_2} \times \left(\frac{1}{M_r}\right)^{K_3}$$

refined
M_r ↓ resilient modulus of bit. mat. ↓ initial mod. value
shift factor & calibration
SF = shift factor value
high variation [10 – (600 or 700)]

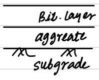
Fatigue cracking criteria for bituminous layer : fatigue area ≥ 20% paved surface area

Rutting test in lab
$N_r = K_1\left(\frac{1}{\epsilon_v}\right)^{K_2}$
- Hamberg wheel track test
- Flow no. test
- Flow time test

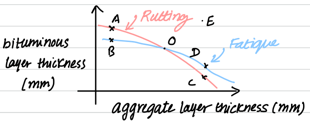
} for bit. mixture

subgrade rutting criteria : rut depth ≥ 20mm (critical/failure rutting condition)

Optimum Pavement Thickness of Layers



Pavement Design Curve

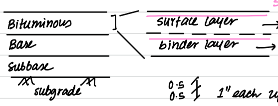


A oversafe from fatigue POV
B undersafe from rutting POV
C undersafe from fatigue POV
D oversafe from rutting POV
E oversafe from both rutting & fatigue POV
O optimum from both rutting & fatigue POV

- MEPDG – Mechanistic Empirical Pavement Design Guide
- Climate Data – Temperature and Moisture
- Resilient modulus – dynamic modulus – facilitates us to find temperature factor
- Granular layer — Rainfall data & Water table depth.
- MEPDG — "AASHTOWare" Software
  collect 6 different climate data (once in hour for 2 years – frequency of data collection)
  - Air temp.
  - Precipitation
  - Wind speed
  - Relative humidity
  - % sunshine
  - water table depth
- Enhanced Integrated Climate Model – develop/find pavement temperature
- CPREL frost freeze and thaw settlement model
- Infiltration and drainage model (applicable for aggregate & subgrade layer)

Sub-layering

14 Aug



surface layer → prone to rutting
binder layer → prone to fatigue

0·5 / 0·5 } 1" each upto 4 layers

Traffic

$$TT_{(l,i,j)} = (AADTT_l) \times (MDF_j) \times (HDF_i) \times (DDF) \times (LDF)$$

Truck traffic ⟶ cumulative fatigue damage analysis
AADTT : Average Annual Daily Truck Traffic

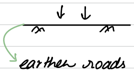
l =
i = year (1, 2, 3 ...)
j = month

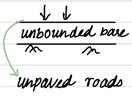
- Bituminous concrete rutting
- Total concrete rutting
- BUC (bottom up cracking)
- TDC (top down cracking)
- Thermal crack for low temp. regions
- Smoothness

Two Codes (IN)

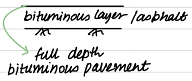
- IRC 37: 2018 — For Design Traffic > 2 msa (million standard axle) ← unit
- IRC : SP72 — For " " ≤ 2 msa

- Different Pavement Composition
- Different distress models
- Input parameters for design
- Important Features of Materials in different layers.

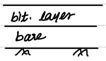

earthen roads

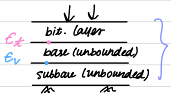


unpaved roads



full depth bituminous pavement

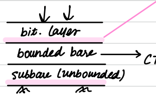




very common

IRC 37, cl 8·3 Crack Relief layer in CTB

"Crack Relief Layer" on the top of CTB base layer provided to protect the layer from reflection of crack from the CTB layer. It delays reflection of crack.



bounded base ⟶ CTB (cement treated base) ⟶ shrinkage cracks → cracks due to construction vehicles
↓
reflective cracking
these cracks may go up to above layers.

Aggregate interface ⟶ 100mm thickness
Stress absorbing membrane interface

Pavement Distress Models

- Rutting
- Fatigue ⟨ Asphalt / Bituminous layer
  CTB layer

Rutting model

$$N_R = 4.1656 \times 10^{-8} \times \left(\frac{1}{\epsilon_v}\right)^{4.5337} \quad 80\% \text{ realibility}$$

$$N_R = 1.41 \times 10^{-8} \times \left(\frac{1}{\epsilon_v}\right)^{4.5337} \quad 90\% \text{ realibility}$$

N_R : subgrade rutting life (cum. eq. no. of std. axle loads that can be served by the pavement before the critical rut depth of ⩾ 20mm occurs

ϵ_v : allowable compressive strain at the top of subgrade (ϵ_v)

Example $N_R = 125$ msa ⟶ Find ϵ_v for 80% and 90% realibility?

Soln $\frac{125 \times 10^6}{4.1656} \times 10^8 = \left(\frac{1}{\epsilon_v}\right)^{4.5337}$ for 80% ⤳ $\epsilon_v = 385\mu\epsilon$

$\frac{125 \times 10^6 \times 10^8}{1.41} = \left(\frac{1}{\epsilon_v}\right)^{4.5337}$ for 90% ⤳ $\epsilon_v = 303\mu\epsilon$

↑ realibility, ϵ_v ↓es

Fatigue distress model

$$N_f = 1.6064 \times C \times 10^{-4} \times \left(\frac{1}{\epsilon_t}\right)^{3.89} \times \left(\frac{1}{M_r}\right)^{0.854} \quad \text{for } 80\% \text{ realibility}$$

$$N_f = 0.5161 \times C \times 10^{-4} \times \left(\frac{1}{\epsilon_t}\right)^{3.89} \times \left(\frac{1}{M_r}\right)^{0.854} \quad \text{for } 90\% \text{ realibility}$$

M_r → MPa

$$C = 10^M \quad \text{where } M = 4.84\left[\frac{V_{be}}{V_a + V_{be}} - 0.69\right]$$

N_f : fatigue life of bit. layer (cum eq. no. of std. axle loads that can be served by the pavement before critical cracked area of ⩾ 20% paved surface area occurs

ϵ_t : allowable tensile strain at the bottom of bituminous layer (ϵ_t)

V_a = % vol. of air void

V_{be} = % vol. of effective bitumen binder

M_r = Resilient modulus (in MPa)

Example $N_f = 125$ msa (125×10^6) $V_a = 3.5\%$ $V_{be} = 11.5\%$ $M_r = 3000$ MPa Find ϵ_t = ?

Soln $M = 4.84\left(\frac{11.5}{11.5+3.5} - 0.69\right) =$ ______, $C = 10^M = 2.34$

for 80% $\epsilon_t = 188\ \mu\epsilon$
for 90% $\epsilon_t = 140\ \mu\epsilon$

For $V_a = 4.5\%$ $M_r = 3000$MPa $V_{be} = 10.5\%$ $N_f = 125$msa , ϵ_t = ?

Soln $\epsilon_t = 156\mu\epsilon$ for 80%
$\epsilon_t = 116\mu\epsilon$ for 90%

Fatigue models for Cement Treated Base (CTB) layer

$$N_f = R{\cdot}F \cdot \times \left[\frac{\frac{113000}{E^{0.804}} + 191}{\epsilon_t}\right]^{12}$$

RF = reliability factor = { 1 for ⩾ 10msa ; 2 for < 10msa

N_f = no. of std. axle rep. that CTB can sustain

E = elastic modulus of CTB (MPa)

ϵ_t = tensile strain at bottom of the CTB (microstrain)

Cumulative Fatigue damage analysis (AASHTO)

$$\log_{10}(N_{fi}) = \frac{0.972 - (\sigma_t / M_{Rup})}{0.0825}$$

N_{fi} : Fatigue life of CTB material i.e. max. rep. of axle load class 'i' the CTB material can sustain

σ_t : tensile stress at bottom of CTB layer for given axle load class

M_{Rup} : flexural strength of cementitious base (28 days)

σ_t / M_{Rup} = stress Ratio

Cumulative Fatigue Damage (CFD) caused by different rep. of axle loads of diff. categories and diff. magnitudes expected to be applied on pavement during its design period is

$$CFD = \Sigma\left(\frac{n_i}{N_{fi}}\right)$$

n_i = expected rep. of axle load of class 'i' (during the design life pd.)

N_{fi} = fatigue life / max. no. of load rep. CTB layer would sustain if only axle load of class 'i' were to be applied.

- If expected CFD < 1 , acceptable design
- If expected CFD > 1 , not acceptable design — need to revise pavement section.

Cumulative Fatigue Damage Analysis (CFD Analysis)

If at a strain level S_1, the sample is subjected to n_1 number of repetitions ,
" " " " S_2, " " " " " n_2 " " "
and so on . . . upto failure of the sample, then

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots + = 1 \quad \text{or} \quad \Sigma \frac{n_i}{N_i} = 1$$

where, $N_1, N_2, N_3 \ldots$ are number of repetitions for failure in respect of the individual failure load tests with strain levels $S_1, S_2, S_3 \ldots$ respectively.

In an in-service road, axle loads of various magnitudes (different axle loads) apply repetitive loading on the pavement. Thus, the above equation can be used in such cases where different axle loads can be considered to find cumulative fatigue damage.

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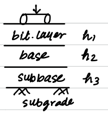
17 Aug

Input Parameters



- Traffic → million std. axle load repetitions (msa)
- Layers' properties → modulus value
  → poisson's ratio

Subgrade

- $M_r = 10 \times CBR$ for CBR ⩽ 5%
  $= 17.6 \times (CBR)^{0.64}$ for CBR > 5%
  M_r = res. mod. of subgrade (MPa)
  CBR (in %)
- 80% CBR considered for design traffic < 20msa
- 90% CBR considered for design traffic ⩾ 20msa
- Poisson's ratio, $\mu = 0.35$
- Effective modulus/CBR for design for equivalent combination of subgrade and embankment with different CBR values.
- Effective M_R approach
  1. Use IITPave to find 'δ' (max. surface deflection)
  2. Using δ, find $M_{RS} = \frac{2(1-\mu^2)pa}{\delta}$

p = contact pressure = 0.56MPa

a = radius of circular contact area ↓ using 40KN load & 0.56 p.

μ = poisson's ratio

Max. Effective M_R = 100MPa for design.

Subbase

- Drainage layer — for fast drainage of subsurface water percolating into pavement.
  — remove excess water
- Filter layer — provide capillary cutoff
  — prevent further rise of capillary water

- Criteria for GSB (granular sub base) thickness based on NMAS (Nominal Maximum Aggregate Size)
- $M_r = 0.2 \times (h)^{0.45} \times M_{r,subgrade}$ h = thickness of granular layer (mm) = $h_{base} + h_{subbase}$
- $\mu = 0.35$ M_r & $M_{r,subgrade}$ (in MPa)

Base layer

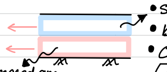
- $M_r = 0.2 \times (h)^{0.45} \times M_{r,subbase}$ ⤳ may be subgrade

aggregate layer on top of soil layer

- Aggregate layer {Base + Subbase} kept over top of subgrade
  ↳ stronger than subbase thoo.

Bituminous layer

- surface coarse (rutting resistant)
- binder coarse (fatigue resistant)



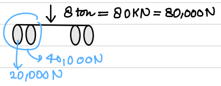
gap graded mixture

- stone matrix asphalt
- bituminous concrete
- CRMB (Crumb Rubber Modified Bitumen)
  → ground ture rubber
  → GRGB mixture ground graded rubberized bitumen.

Table 9.1, IRC — tells what mixture to use?

Table 9.2 — diff. values of Mr for diff. mixture at diff. temp.

IITPave Exercise Find effective CBR?



500mm subgrade — 20% CBR

embankment — 8% CBR

effective CBR value = ?

tyre pressure = 0.56MPa

max. subgrade M_r = 100MPa

$M_r = 17.6\,(CBR)^{0.64}$ for CBR > 5%

$$M_r = \frac{2(1-\mu^2)pa}{\delta}$$ p ~ pressure, a ~ rad.

Soln:-

Step-1 Find deflection (δ) from IITPAVE by giving parameters.

	Mr	μ	t
layer 1	119.72	0.35	500mm
layer 2	66.6	0.35	

From IIT pave, deflection = 1.41 mm = δ

wheel load = 40000 N wheel set = 1 (single)

tyre pressure = 0.56 MPa

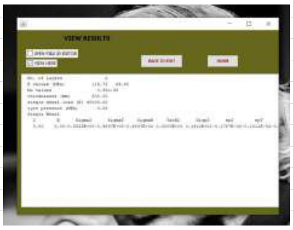
Analysis point: depth = 0 radial dist = 0

Find a = contact radius

$\frac{\text{load}}{\text{pressure}}$ = area ($= \pi a^2$)

load → 20,000N, pressure → 0.56×10^6 Pa

Found a = 105 mm



Now, need to find effective CBR value .

Step-2

Using formula, $M_r = \frac{2(1-\mu^2)pa}{\delta} = 105$ (μ ~ 0.35, p ~ 0.56MPa, a ~ 105mm, δ ~ 1.41mm)

$M_r = 105$ but we take max. possible $M_r = 100$.

Now, using formula, $M_r = 17.6\,(CBR)^{0.64}$ to find % CBR.

$100 = 17.6\,(CBR)^{0.64} \Rightarrow CBR = 15\%$

This is effective CBR value

$\boxed{\text{Eff. CBR} = 15\%}$

IITPave Exercise check safety/adequacy for design?

Check the adequacy of GSB thickness.
effective CBR = 5 %, thickness = ??

200 repitions for construction
↓
Compare whether this is more than 10,000 or not!

Sol^n Step 1 – Find ε_v induced & ε_v allowable
Step 2 – check ε_v induced < ε_v allowable, ok!

take some trial thickness, $h_{trial} = 150mm$
10,000 standard axle repititions.

$$N_R = 1.41\times10^{-8}\left(\frac{1}{\varepsilon_v}\right)^{4.5337}$$ for 90% realibility (Rutting)

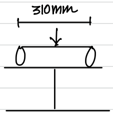
↳ Find $\varepsilon_r = ?$

Put $N_R = 10{,}000$ find $\varepsilon_r = \left(\frac{1}{N_R\times1.41\times10^{8}}\right)^{1/4.5337} = 0.00243258$ or $2432\,\mu\varepsilon$

From IITPave — find induced ε_v and compare to check whether $\varepsilon_{v,induced}$ < or > $\varepsilon_{v,calculated}$.

$$VDF = \left(\frac{\text{axle load}}{148}\right)^4 + \left(\frac{\text{axle load}}{65}\right)^4 = 9.2$$

From IIT pave, find induced ε_v and check whether $\varepsilon_{v,induced}$ < or > ε_v calculated.

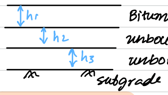


$$VDF = \left(\frac{\text{axle load}}{148}\right)^4 + \left(\frac{\text{axle load}}{65}\right)^4 = 9.2$$

Using IIT Pave
$Mr_{subbase} = 0.2\times h^{0.45}\times Mr_{subgrade}$ ← $Mr = 50MPa$
$= 95.33\,MPa$

analysis points: 150mm 0
150 mm 155L → L indicate top of subgrade

wheel load = 20,000N
↳ Found induced ε_v i.e. maximum of the two analysis points.
$\varepsilon_{v,induced} = 4324\,\mu\varepsilon = 4324\times10^{-6}$

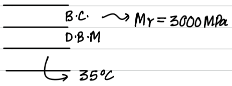


21 Aug

IITPave Exercise Design check?

rem., have to take half for 'A' value (∵ both ways)

4 lane divided carriageway
initial traffic in the year of completion of construction = 5000 CVPD (both ways)
design life = 20 years
VDF = 5.2 % (same for both dir^n)
Effective CBR = 7%
Effective bitumen content in bituminous material = 11.5% = V_{be}
Air void = 3% = V_a
traffic growth rate = 6%



Sol^n
for 4 lane divided carriageway
LDF = 0.75 or 75%.
We have to first find million standard axle repitition.

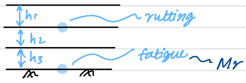
Step (i) $N_{design} = A\times365\times\left[\frac{(1+r)^n-1}{r}\right]\times VDF\times LDF = 1309107.227$
$A = \frac{5000}{2} = 2500$, $r = 0.06$, $VDF = 0.052$, $LDF = 0.75$

$N_{design} \approx 131\,msa$ or $131\times10^6\,sa$

Using IITPave — Base 250mm, Subbase 200mm, Bit. layer 175mm (60 mm B.C, 115mm DBM)
→ $Mr = 0.2\times h^{0.45}\times Mr_{subgrade} = 191MPa$, $h = 200+250 = 450mm$

$Mr_{subgrade} = 17.6\,(CBR)^{0.64} = 61MPa$, CBR = 7%

Allowable strain values at the critical locations.



for fatique, 90% realibility

$$N_f = 0.5161\times C\times10^{-4}\times\left(\frac{1}{\varepsilon_t}\right)^{3.89}\times\left(\frac{1}{M_r}\right)^{0.854}$$

$N_f = 131\times10^6$, $M_r = 3000MPa$
$C = 10^M = 3.16$
$M = 4.84\left(\frac{V_{be}}{V_a+V_{be}} - 0.69\right) =$

→ Find $\varepsilon_t = 150\,\mu\varepsilon$ or 150×10^{-6}

for rutting 90% real. $N_R = 1.41\times10^{-8}\times\left(\frac{1}{\varepsilon_r}\right)^{4.5337}$
↳ 131×10^6
→ Find $\varepsilon_r = 300\,\mu\varepsilon$ or 0.0003005

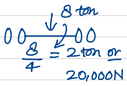
Now, finding the induced strain values from IIT pave for comparison.

Step (ii) IIT Pave:

	Mr	μ	t
layer 1	3000	0.35	175
layer 2	191	0.35	450
layer 3	61	0.35	

450 → Base + subbase = 200+250

wheel load = 20,000N → standard value for dual wheel
tyre pressure = 0.56MPa



$\frac{8}{4} = 2$ ton or 20,000N

allowable ε_t (fatigue) = 150με
induced ε_t (") = 158με
allowable ε_v (rutting) = 300με
induced ε_v (") = 284με

Not safe need to alter thickness.

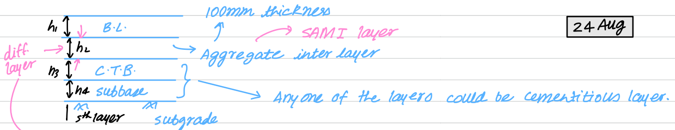
changing thickness of layers
Base 250 mm
subbase 225mm
Bit. layer 200mm
→ $Mr = 0.2\times(475)^{0.45}\times61 = 195MPa$

allowable ε_t (fatigue) = 150 με
induced ε_t (") = 139 με
allowable ε_v (rutting) = 300 με
induced ε_v (") = 237 με

ε_t = tangential tensile strain
ε_r = radial tensile strain
ε_v = comp. strain at top of subgrade

project PPT — after midsem but before midsem recess
– Have to make ppt only
– No report submission.

Project Group 7 → Aman, Chandan, Archana, Apoorva, Chandramani.
Types of distresses in bituminous pavement structure
(field identification, causes, countermeasures, mechanism, etc....)
→ process ↳ how it formed
→ let's go scan the campus roads today ☺



24 Aug

have to consider this aggregate inter layer a different one
For SAMI layer, have to consider just 4 layers

cemented subbase
UCS → 1.5 – 3 MPa traffic level > 10 msa → E 600MPa
0.75 – 1.5MPa < 10 msa but > 2msa → E 400MPa
↳ 7th day cured strength

$\boxed{E = 1000\times UCS}$ (E → modulus value) → AUSTROADS

Shrinkage cracks

lab strength should be at least 1.5 times of the field strength
E = 600 or 400MPa
μ = 0.25 (poisson's ratio) {poisson's ratio 0.15 for cement-concrete}

CTB (Cement Treated Base)
minimum UCS = 4.5 to 7 MPa → 7th day or 28th day cured strength

$\boxed{E = 1000\times UCS}$ (E → modulus value)

E value → 6000 MPa
for construction, just use 5000 MPa

Durability criteria
12 repeated wet and dry cycle
↳ loss of weight ≯ 14 %
E = 5000MPa, μ = 0.25

Aggregate Inter layer
Thickness = 100mm (standard value) This is normal WMM
E = modulus value = 450MPa
μ = poisson's ratio = 0.35

$$N_f = R.F.\left[\frac{\frac{113000}{E^{0.804}} + 191}{\varepsilon_t}\right]^{12}$$

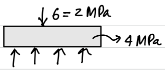
$$\log_{10}(N_{fi}) = \frac{0.972 - (\sigma_t/M_{rup})}{0.0825}$$ → cummulative fatigue damage analysis for CTB.

- 200,000 load cycle it can sustain under this shear ratio.

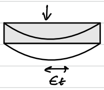
But in real case, it is having only 50,000 load cycle.

$$\text{ratio} = \frac{50{,}000}{200{,}000} = 0.25 \text{ or } 25\% \text{ of total fatigue life (capacity)}$$

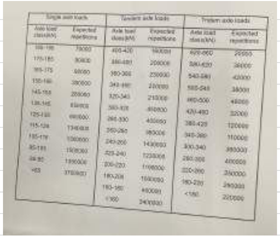
↳ consumed fatigue life.



$$\text{stress ratio} = \frac{2}{4} = 0.5$$



$$CFD = \left(\Sigma \frac{n_i}{N_{fi}}\right) < 1$$



IITPave Exercise

Design check? 100 msa

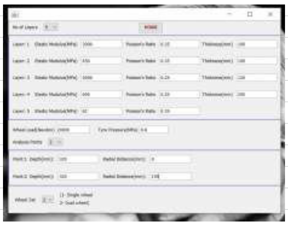
tyre pressure = 0.8 MPa

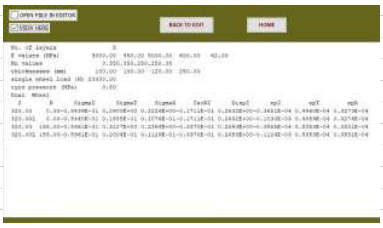
	thickness	E	μ
B.L.	100 mm	3000 MPa	0.35
Agg Interface	100 mm	450 MPa	0.35
CTB	120 mm	5000 MPa	0.25
CTSB	250 mm	600 MPa	0.25
		62 MPa	

62 MPa → analysis pt.

$$N_f = \underset{=1}{R.F.}\left[\frac{\overset{\to 5000}{\frac{113000}{E^{0.804}}} + 191}{\epsilon_t}\right]^{12} = 100\,msa$$

→ ϵ_t = ? → allowable strain = 67 $\mu\epsilon$





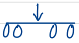
Allowable ϵ_t (calculated) = 67 $\mu\epsilon$ Induced ϵ_t (IITPave) = 50 $\mu\epsilon$

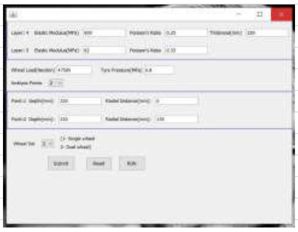
$$\log_{10}(N_{fi}) = \frac{0.972 - (\sigma_t/M_{rup})}{0.0825} = \frac{0.972 - S.R}{0.0825}$$

↳ wheel load = 47.5 KN = 47500 N

↳ 70,000 load cycle.

190 KN





sigmaT	sigmaR
0.7 $\mu\epsilon$	0.5 $\mu\epsilon$

For single axle loads

Maximum allowable Rept. = 526,000

But in reality = 70,000

} ratio = 0.13 or 13%.

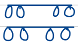
similar for tridem / tandem

Tandem axle

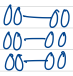
400 – 420 KN → 160,000 rebititions → actual load repitions = 160,000 × 2 = 320,000

↳ bcoz two axles.

↳ 410 KN ↳ $\frac{410}{8}$ = 51.25 KN (8 wheels)



Tridem axle



620 – 660 → 20000

↳ 640 KN → actual axle load = $\frac{610}{12}$ = 53.33

↳ 12 wheels.

actual repitions = 20,000 × 3 = 60,000

↳ 3 axle

all whole calculations — for diff. loads.

		CFD
single axle	→	0.474
tandem axle	→	2.03 → >1 inapt. composition
tridem axle	→	0.56

sum. = 3.064 > 1 → unsafe — need to change composition

Iteration continues until you get the clubbed value less than 1 for safe design.

CEMENT CONCRETE PAVEMENT

28 Aug

In India, 95% — bituminous pavement, 5% — cement concrete pavement were there.

Why we have more bit. vis-a-vis cement conc. pavement?

- quality control
- affordability
- better skid resistance
- riding quality

Bituminous pavement less stronger than cement concrete pavement.

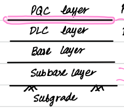
But now, we're slowly shifting to cement concrete pavement, why? — low maintenance — heavy traffic loads

(Bituminous)	(Cement concrete)
Low load bearing capacity	High load bearing capacity
Low construction cost	High construction cost
High maintenance requirements	low maintenance requirements
Less lifespan	More lifespan
Flexible — Grain to grain load transfer	Rigid — bending) slab action load transfer

Topics in cement concrete pavement

- Analysis of Cement Concrete Pavement Structure
- Structural thickness Design
- Design of Reinforcement Parts

Cross section of cement concrete pavement (Clause 4.1, IRC58)



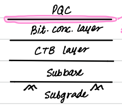
PQC layer — Pavement Quality Concrete

DLC layer — Dry Lean Concrete

Subbase layer → drainage layer → seperation layer

plastic sheet → Debonding layer (125 μm)

- If this sheet is not there then there will be lot of stresses in the layers due to change in temperature.
- Summer — compressive stress }
- winter — tensile stress }
- Advantages: reduced cracking & moisture barrier.
- 125 microns thick plastic sheet
- Avoid black color plastic sheet (traps more heat)
- Recommended to use white Plastic sheet.



30 – 40 mm → white washing of bit. conc. top surface → Debonding layer (so that it traps less heat)

(CFD Analysis — stress ratio – mod. of rupture diff. approach for analysis)

Design Life

- Bituminous pavement — 15 to 20 years
- Cement concrete pavement — ≥ 30 years

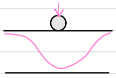
Stiffness

- ↑ with temperature
- more in cement conc. pav.

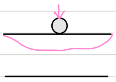
Loading frequency

Load distribution

- Rigidity — resistance to deformation — more in cement conc. pav.
- Flexibility — more in bit. pav.

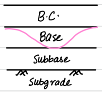


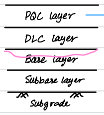
Flexible Pavement



Rigid Pavement

confined to a certain area	get distributed to entire area.
due to grain to grain contact	due to bending / slab action
Bituminous pavement (Flexible)	Cement Concrete pavement (Rigid)





PQC layer → M30

DLC layer → M15, M20

flexural strength = $0.7\sqrt{f_{ck}}$

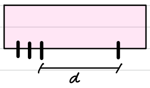
$E = 5000\sqrt{f_{ck}}$

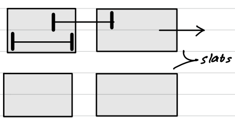
$\mu = 0.15$

coeff. of thermal expansion : $10^{-5}/°C$

Traffic Characteristics

- Axle load repitition
- Axle load
- Wheel base configuration → axle

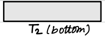




axle configuration

Temperature Considerations

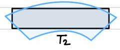
warping stress : When there is variation in slab temperature, stresses are developed.



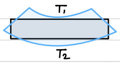
$T_1 \neq T_2$

$\boxed{T_1 = T_2}$ → no bending, same degree of contraction

During day time	During night time
higher temperature at top layer	lower temperature at top layer



$T_1 > T_2$



$T_1 < T_2$

$T_1 > T_2$

convex

$T_1 < T_2$

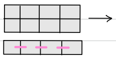
concave

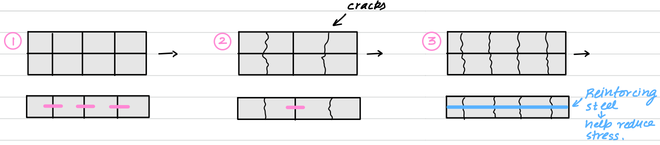
Top face = compression	Top face = tension
Bottom face = tension	Bottom face = compression
In daytime – Non-linear (downward curling)	In night time – linear (upward curling)

Three different types of cement concrete pavement

- Jointed plane concrete pavement (JPCP)
- Jointed reinforced concrete pavement (JRCP)
- Continuously reinforced concrete pavement (CRCP)

} Taught using slides.





4th kind → in IITK → Kargil heights circular area → & shoulder area
dowel bar – used in higher traffic only. Otherwise not needed.

Different type of joints

- Transverse joints — contraction joint / construction joint / expansion joint } Taught using slides
- Longitudinal joints

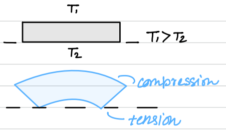
shrinkage cracks – due to tension.

IRC 15 — filings

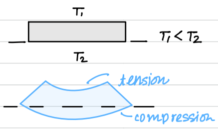
31 Aug

stresses → Traffic loading
→ Temperature → warping stresses or curling
→ ~~Moisture variation~~ ×× often neglected during design

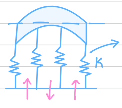
During day time



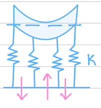
During night time



restraints contributing to this stress due to temp. variation.
↳ spring Westergaard (1926)



→ winkler foundation
liquid foundation



Downward curling

Upward curling

Determination of warping / curling stress

Infinite plates / slabs → integrated with temperature differential.
↓
correction factor to convert it from infinite to finite slab.

For infinite slab condition — Determination of warping / curling stress

- $\epsilon_x = \frac{\sigma_x}{E} - \mu\frac{\sigma_y}{E}$

strain due to stress in x-direction. | strain in x-direction due to stress in y-direction.

- $\epsilon_y = \frac{\sigma_y}{E} - \mu\frac{\sigma_x}{E}$
- $\epsilon_y = 0 \Rightarrow 0 = \frac{\sigma_y}{E} - \mu\frac{\sigma_x}{E} \Rightarrow \boxed{\sigma_y = \mu\sigma_x}$ → $\epsilon_y = 0$, bcoz we are not allowing curling in y-direction.

$\epsilon_x = \frac{\sigma_x}{E} - \mu\frac{\sigma_y}{E}$ → $\mu\sigma_x$

$\epsilon_x = \frac{\sigma_x}{E} - \mu\frac{(\mu\sigma_x)}{E} \Rightarrow \epsilon_x = \frac{\sigma_x}{E}(1-\mu^2)$

$\Rightarrow \boxed{\sigma_x = \frac{\epsilon_x E}{1-\mu^2}}$ Ideal situation when only 1D curling. For real life ↓ superposition.

- $\epsilon_x = 0 \Rightarrow 0 = \frac{\sigma_x}{E} - \frac{\mu\sigma_y}{E} \Rightarrow \boxed{\sigma_x = \mu\sigma_y}$ → $\epsilon_x = 0$, not allowing curling in x-direction.

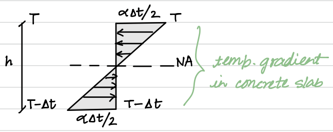
$\epsilon_y = \frac{\sigma_y}{E} - \frac{\mu(\mu\sigma_y)}{E} \Rightarrow \epsilon_y = \frac{\sigma_y}{E}(1-\mu^2)$

$\Rightarrow \boxed{\sigma_y = \frac{\epsilon_y E}{1-\mu^2}}$

- Total stress in x-direction

$$\sigma_x = \frac{E\sigma_x}{1-\mu^2} + \mu\sigma_y = \frac{E}{1-\mu^2}[\epsilon_x + \mu\epsilon_y]$$

σ_y → $\frac{E\sigma_y}{1-\mu^2}$



temp. gradient in concrete slab

α – coeff. of thermal expansion (linear – y-dirⁿ)
Δt – temp. diff
$\Delta = l\alpha\Delta t$
$\epsilon = \alpha\Delta t$
↳ ϵ_x, ϵ_y.

At N.A., average temp. of both extreme fibres $= \frac{T + (T-\Delta t)}{2} = T - \frac{\Delta t}{2}$

Δt (N.A., extreme fibres) $= T - \left(T - \frac{\Delta t}{2}\right) = \frac{\Delta t}{2}$

$\epsilon_x = \epsilon_y = \frac{\alpha\Delta t}{2}$

$$\sigma_x = \frac{E\sigma_x}{1-\mu^2} + \mu\sigma_y = \frac{E}{1-\mu^2}[\epsilon_x + \mu\epsilon_y]$$

σ_y → $\frac{E\sigma_y}{1-\mu^2}$ ↳ Put ϵ_x, ϵ_y.

$\alpha = 10^{-5}/^\circ C$

$$= \frac{E}{1-\mu^2}\left(\frac{\alpha\Delta t}{2}\right)(1+\mu)$$

$\boxed{\sigma_x = \frac{E}{1-\mu^2}\cdot\frac{\alpha\Delta t}{2}}$ But this was for infinite slab, for finite slab we have correction factors to convert from ∞ to finite.

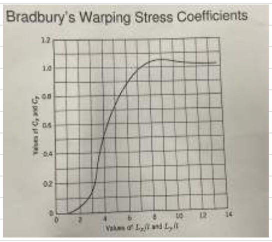
- Curling stresses in finite slab

$\boxed{\sigma_x = C_x\frac{E\alpha\Delta t}{2(1-\mu^2)} + C_y\frac{\mu E\alpha\Delta t}{2(1-\mu^2)}}$, Similarly, $\boxed{\sigma_y = \frac{E\alpha\Delta t}{2(1-\mu^2)}(C_y + \mu C_x)}$

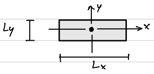
↳ (x) ↳ (y)

Bradbury coefficients
(correction factors to convert from ∞ to finite) – given by bradbury (1938)

Bradbury developed a simple chart to determine C_x and C_y.



C_x, C_y – correction factors
L_x, L_y – length dimension of slab



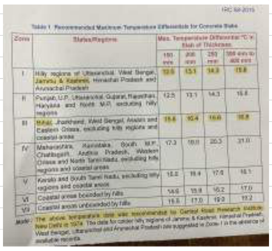
l – radius of Relative Stiffness ↳ by Westergaard.

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

where E = mod. of elasticity of concrete (3×10^5 kg/cm²)
μ = poisson's ratio (0.15)
h = slab thickness (m)
K = mod. of subgrade reaction (kg/cm³)
$K = \frac{P_a}{\Delta}$ ~ pressure sustained / ~ deflection
unit: kg/cm³ → imp. → can ask in exams like IES.

l (m) h (m)
E (MPa) K (MPa/m)

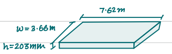
IRC 58 — diff. values for diff. regions



We usually assume for concrete μ = 0.15 E = 4 × 10⁶ psi (27.6 GPa)

Example

$\mu = 0.15$ ↗ always unless stated



thickness, h = 203 mm
L = 7.62 m K = 54.2 MN/m³
W = 3.66 m $\alpha = 9\times10^{-6}/^\circ C$ $E = 2.75\times10^4$ MPa
Δt = 20° F Find max. curling stress in interior and edge of slab? i.e. σ_x = ?

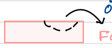
Solⁿ
step-1 Find $l = \frac{Eh^3}{12(1-\mu^2)K} = 0.77\,m \approx 775\,mm$

$C_x \approx 1.07$, $C_y \simeq 0.63$ } → Using bradbury's chart

max. curling stress (interior / midspan)
$\sigma_{x_i} = \frac{E\alpha\Delta t}{2(1-\mu^2)}(C_x + \mu C_y) = 1.63$

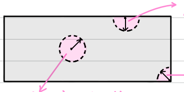
σ_x will be max. at midspan and min at edge.

max. curling stress (edges)
$\sigma_{x_e} = \frac{E\alpha\Delta t}{2(1-\mu^2)}(C_x + \mu C_y) = \frac{E\alpha\Delta t\,C_x}{2} = 1.46$
($\mu \to 0$)



For edges, put μ = 0 in σ_x formula → $\sigma_x^{edge} = \frac{C_x E\alpha\Delta t}{2}$

Critical load positions



edge loading compression – top / tension – bottom
corner loading tension – top / compression – bottom
interior loading compression – top / tension – bottom

note this deformation is due to loading and not temperature.

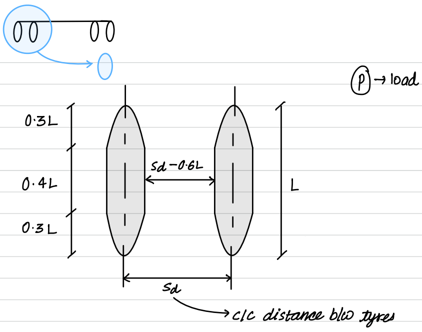
- The intensity of maximum stress induced due to application of traffic load is dependent on the location of the load on pavement surface.
- Edge stress is critical.

Wheel load stresses — Westergaard's stress equations ↝ IRC recommends these

- Edge – loading $\sigma_e = \frac{0.529P}{h^2}(1+0.54\mu)\left[4\log_{10}\left(\frac{l}{b}\right) + \log_{10}b - 0.4048\right]$
- Corner – loading $\sigma_c = \frac{3P}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{l}\right)^{1.2}\right]$
- Interior – loading $\sigma_i = \frac{0.316P}{h^2}\left[4\log_{10}\left(\frac{l}{b}\right) + 1.069\right]$

where, h = slab thickness (in cm) a = rad. of wheel distr. (in cm)
P = wheel load (in kg) – Not axle load l = rad. of rel. stiffness (in cm)
b = rad. of resisting section (in cm) $= \begin{cases} a & ;\ a \geq 1.724h \\ \sqrt{1.6a^2 + h^2} - 0.675h & ;\ a \leq 1.724h \end{cases}$

- no need to rem. these formulas !



(p) → load (q) → pressure

IRC 58

$\frac{P_d}{q}$ load per unit pressure

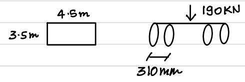
$$= \pi(0.3L)^2 + (0.4L \times 0.6L) = 0.5227L^2$$

$$L = \sqrt{\frac{P_a}{0.5227q}}$$

Area of eq. circle

$$\pi a^2 = 2 \times 0.5227L^2 + (S_d - 0.6L) \times L$$

Example



thickness $h = 300mm$
$K = 80\ MPa/m$
M40, $E = 30{,}000\ MPa$
$\mu = 0.15$, $p = 0.80MPa$

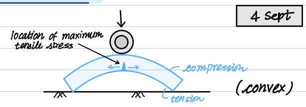
Find edge stress, interior stress & corner stress?

DESIGN OF SLAB THICKNESS

(IRC58, 6, Pg 14..)

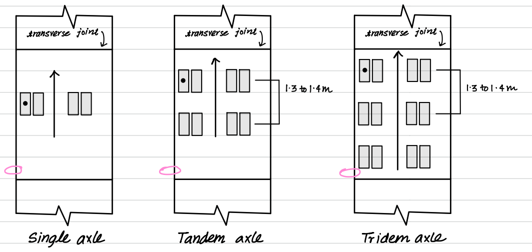
4 Sept

Critical Stress Condition

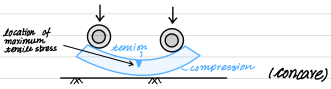


① Day Condition

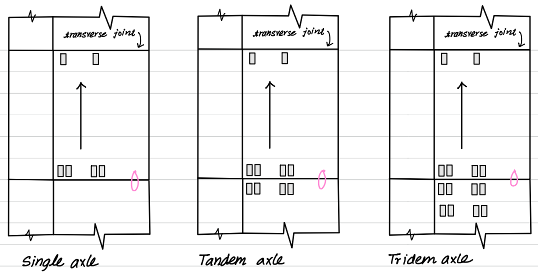
- The flexural stress at bottom layer of concrete slab is maximum during the daytime when the axle loads act midway on the pavement slab while there is +ve temperature gradient.
- This condition likely produce Bottom-Up Cracking (BUC).
- Placement of axles for maximum edge flexural stress at bottom of the slab (without shoulders) is shown in diagram.
- Single axle cause highest stress followed by tandem and tridem resp.
- Δt keep on ↓sing as day progresses to night. (Δt → temb. gradient)
- 10AM to 4 PM for BUC calculations.
- consider only single + tandem case, ignore tridem for BUC calculations.
- Tie bar provides restraint.



② Night Condition



- The flexural stress at top layer of concrete slab is maximum during the night when the axle loads act close to transverse joints while there is -ve temperature gradient.
- This condition leads to Top-Down Cracking (TDC).
- complete analysis including single, tandem and tridem for TDC calculations.
- 12 AM to 6AM for TDC calculations.
- Dowel bar provides restraint.



Calculation of Flexural stress

Cumulative Fatigue Damage Analysis (CFD Analysis)

$$CFD(BUC) = \sum_i^j \frac{n_i}{N_i}\ (10AM\ to\ 4PM) \quad ; \quad CFD(TDC) = \sum_i^j \frac{n_i}{N_i}\ (12AM\ to\ 6AM)$$

where n_i — allowable no. of load rep. for i^{th} load group during specified 6hrs
N_i — predicted no. of load rep. " " " " " " "
j — total no. of load groups

Design Criteria for Rigid Pavements

$\boxed{CFD(BUC) + CFD(TDC) \leq 1}$ → pavement is safe from large scale cracking.

If the sum of cumulative fatigue damages (i) due to wheel load and curling stresses at the bottom and (ii) wheel load and curling stresses at the top is less than 1, the pavement is safe.

Relation b/w fatigue life and stress ratio

N = infinite for $SR < 0.45$
$N = \left(\frac{4.2577}{SR - 0.4325}\right)$ for $0.45 \leq SR \leq 0.55$
$N = \left(\frac{0.9718 - SR}{0.0828}\right)$ for $SR > 0.55$

N = fatigue life
SR = stress ratio

- IRC 58 recommends to take 25% of the total commercial traffic as design traffic for designing. Actually it is just 2 to 3% in real field.

- Dowel bar — 60% } ⤳ taken as 50% } in IRC code for
Tie bar — 50% } ⤳ taken as 40% } conservative estimate
β-factor – to account for stress analysis.

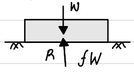
- Δt = -ve = temp. diff. ______ less → beneficial for BUC but not TDC.
______ more
permanent stress −5°C eq. stress

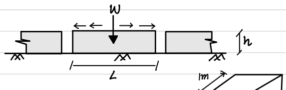
- Frictional Related Stress
- Joint Opening width
- Tie bar
- Dowel bar

11 Sept

FRICTIONAL RELATED STRESS

Frictional Related Stress

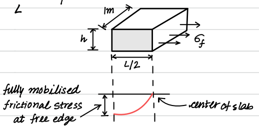




- Frictional force per unit width of slab

$$= \gamma \times h \times 1 \times \frac{L}{2} \times f = \frac{\gamma h L f}{2}$$

where γ – density of cement concrete (KN/m³)
h – slab thickness (m), L – slab length (m)



Variation of frictional stress
0 at centre
highest at edge

- Tensile force in slab at the middle

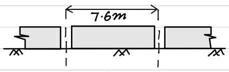
$$= \sigma_c \times A = \sigma_c \times h \times 1 = \sigma_c h$$

- Equating the two,

$$\sigma_c h = \frac{\gamma h L f}{2} \Rightarrow \boxed{\sigma_c = \frac{f \gamma L}{2}}$$ independent of slab thickness h

$\gamma = 23.6\ KN/m^3$
$f = 1.5$ ~ field survey (0.9 to 1.8) ~ doubtful (why not < 1)

Example



$f_a = 1.5$
$\gamma = 23.6\ KN/m^3$

Find $\sigma_c = ?$

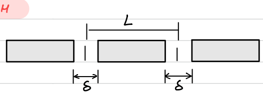
$$\sigma_c = \frac{f \gamma L}{2} = \frac{1.5 \times 23.6\ KN/m^3 \times 7.6m}{2} = 134.52\ KN/m^2 \text{ or } 134.52\ KPa$$

In exam → frictional stress has most critical effect when?

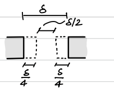
JOINT OPENING WIDTH

Joint Opening Width (δ)

- The spacing of joints depends on
  - temperature
  - shrinkage



$\boxed{\delta = CL(\alpha \Delta T + \varepsilon_s)}$



C = adjustment factor due to slab subsurface thickness
ε_t = strain due to temperature = $\alpha \Delta T$
ε_s = strain due to shrinkage
α = coeff. of thermal expansion
ΔT = temperature variation ⤳ seasonal
L = joint spacing

δ/2 – kept free
δ/2 – for strain

Example

Find allowable joint spacing of dowelled and undowelled contraction joints?

allowable joint opening $\delta = 1.3mm$ for undowelled joints

$= 6.4mm$ for dowelled joints

$\Delta T = 33°C$ $\quad \varepsilon = 100\mu\varepsilon = 10^{-4}$

$\alpha = 10^{-5}/°C$ $\quad C = 0.65$

Solⁿ:- $L = \frac{\delta}{C(\alpha\Delta T + \varepsilon)} = 4651.2\ mm = 4.6\ m$ without dowel bar

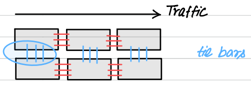
$= 22898\ mm = 22.9\ m$ with dowel bar

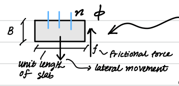
Why we need to ↑ joint opening δ with dowel bar in joints? → Think

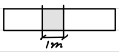
TIE BARS

Tie bars

- Diameter of tie bars
- Spacing b/w tie bars } — related
- Number of tie bars







n – no. of tie bars

ϕ – diameter of tie bars

slab movement in lateral direction need tie bars to keep them intact also for proper load transfer through transverse joints.

Equating the force in steel to frictional force

$A_{st} f_s = \gamma f_a (B h \times 1)$

$$\Rightarrow \boxed{A_{st} = \frac{\gamma B h f_a}{f_s}}$$

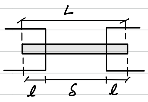
$f_a = 1.5$ $\quad B$ = lane width

A_{st} – amount of steel required per unit length of slab

f_s – allowable tensile stress in steel

- Length of tie bar

$L = \delta + 2\ell \Rightarrow$ $\ell = \frac{L-\delta}{2}$



$$f_s \frac{\pi}{4}\phi^2 = \tau \pi \phi \left(\frac{L-\delta}{2}\right)$$ → ℓ

$$\ell = \frac{f_s \pi \phi^2}{4\tau\pi\phi} = \frac{f_s\phi}{4\tau} \Rightarrow \boxed{\ell = \frac{f_s\phi}{4\tau}}$$

↝ Not full length of tie bar.
Full length $L = \delta + 2\ell$

τ = allowable bond stress

f_s = allowable tensile stress in steel

ϕ = diameter of steel bars

- What kind of reinforcement we need for tie bars? Plain or Deformed?

Deformed ⟷ more bond stress (τ) ⟶ amount of reinforcement decreases (ℓ)

that's why we use deformed rather than plain.

Example $\quad h = 0.33mm$ $\quad f_a = 1.5$ $\quad \phi = 12mm$

$B = 3.5\ m$ $\quad \gamma = 24\ KN/m^3$ $\quad$ Find $A_{st} = ?$

f_s = allowable tensile stress $= 125MPa$ $\quad L = ?$

τ = allowable bond stress $= 1.75MPa$ $\quad$ Spacing = ?

Solⁿ

amount of steel req. per unit length of slab

$A_{st} = \frac{\gamma B h f_a}{f_s} = 332.64\ mm^2$

c/s area of tie bar $A = \frac{\pi}{4} \times \phi^2 = 113\ mm^2$

perimeter of tie bar $P = \pi\phi = 37.7\ mm$

length of tie bar required

$\ell = \frac{f_s\phi}{4\tau} = 857.2mm$ ↝ assume $\delta = 0$ ⟶ $L = 2\ell =$

no. of bars required

$n = \frac{A_{st}}{A} \approx 3$ thus 3# of bars to be used.

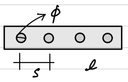
Example – Tie bar
Appendix 9, IRC58

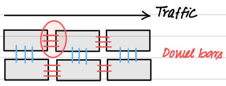
DOWEL BARS

14 Sept

Dowel bars

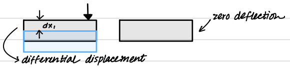
- Diameter φ
- Spacing b/w dowel bars
- length of dowel bars



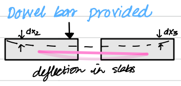


- Mild steel round dowel bars provide load transfer to relieve part of the load stresses in edge & corner regions of pavement slab at transverse joints.
- Mechanism of load transfer by dowel bars.

Dowel bar not provided



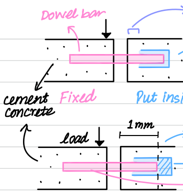
Dowel bar provided



In absence of dowel bar, there'll be differential settlement due to load acting on it.
$dx_1 > dx_2, dx_3$
high stress in loaded area.

In presence of dowel bar, load transfer from loaded slab to adjacent slab takes place and adjacent slab also deflect.
theoretically $dx_2 = dx_2$
evenly distribute stress due to load in slabs.

for load transfer — [dowel bar / aggregate interlocking



small spacing on next slab towards end — to compensate expansion due to temperature variation

expansion cab (plastic cabing)
allows free expansion of the concrete slabs

Put inside an expansion cap

→ length of plastic cab

→ Some combressive material

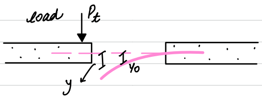
→ bearing stress (some allowable value)

plane/deformed bars ??

- induced bearing stress ≯ allowable bearing stress of dowel bar
- Concrete ⇒ we should put plane bars and more diameter bars.
  To combat crushing, plane dowel bars should be provided.
- Dowel bars allow opening and closing of joint, thus maintaining the slab edges at same level.
  expand (hot) contract (cold)
- Only the Bearing stress in concrete is responsible for performance of dowel bars at the expansion joints.
- Bearing stress depends on material property [cement concrete / diameter of dowel bar
- High concrete bearing stress —— fracture concrete surrounding dowel bars.
  —— leading to looseness of dowel bar + detoriation of load transfer system.
- Larger diameter bars ⇒ provide better performance

Deflection

$$y_0 = \frac{80(2+\beta z)}{4\beta^3 E_d I_d}$$



Bearing stress $= K y_0 = F_{b,max}$

Max Bearing stress (F_{bmax}) b/w concrete and dowel bar

$$\boxed{F_{bmax} = \frac{K P_t (2+\beta z)}{4\beta^3 E_d I_d}}$$

$$\beta = \sqrt[4]{\frac{K d}{4 E_d I_d}}$$

β = relative stiffness of bar embedded in concrete (mm⁻¹)

K = modulus of dowel support (MPa/m)

P_t = load transferred by dowel bar

E_d = young's modulus of elasticity of dowel bar (MPa)

I_d = moment of inertia of dowel bar (mm⁴)

d = dowel bar's diameter

Allowable Bearing stress (F_b) on concrete

$$\boxed{F_b = \frac{(101.6 - d)}{95.25} f_{ck}}$$

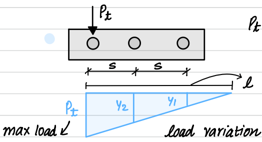
F_b = allowable bearing stress (MPa)

d = dowel diameter (mm)

f_{ck} = characteristic compressive stress (MPa)

f_{ck} = 40MPa for M20 concrete

- Dowel bars — provided at expansion joints. For traffic > 450cvpd provided at contraction joints.
  └ Reason: Aggregate interlocking can't be relied upon to effect load transfer across the joint to prevent faulting due to repeated loading of heavy axles.



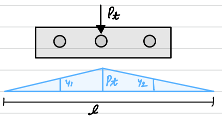
$P_t \neq$ axle load, but the load transferred to dowel bar $= (LTE) \times$ axle load
↳ Load transfer efficiency (0–1) or %

load variation (linear in nature)

here, ℓ = radius of relative stiffness

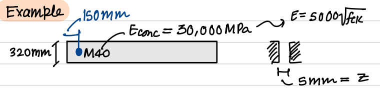
$$\ell = \left(\frac{Eh}{12(1-\mu^2)K_s}\right)^{1/4}$$

↳ modulus of subgrade reaction



load variation

Example



eff. modulus of subgrade reaction = 300MPa/m

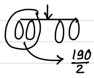
Mod. of dowel bar support, $K = 415000\ MPa/m$

Max. single axle load = 190 KN $\quad \mu = 0.15$

$E_d = 200,000\ MPa$

load transfer to shoulder = 30%

load transfer efficiency = 100% ⇒ it means 50% — one slab and 50% — other slab.



$\frac{190}{2} = 95kN$ = axle load
but $\neq P_t$

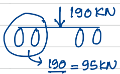
Solⁿ: [Assume $d = 38mm$ $\quad s = 300mm$
$\ell_d = 500mm$ $\quad$ load at 550 mm from edge]

Design check:
induced bearing stress < all. bearing stress

steb-1 allowable bearing stress $= \left(\frac{101.6 - d}{95.25}\right) f_{ck} = \underline{\underline{26.73\ MPa}}$ (d → 38mm)

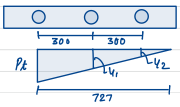
steb-2 radius of relative stiffness $\ell = \left[\frac{Eh^3}{12K_s(1-\mu^2)}\right]^{0.15} = \underline{\underline{727mm}}$ (E → 30,000MPa, h → 320mm; K_s ↳ this is of subgrade (3000MPa/m))

steb-3 total load $= 9.5 \times \underline{\underline{0.7}} \times \underline{\underline{0.5}} = 3.325kN$



$\frac{190}{2} = 95kN$

steb-4 load variation



similar Δ property

$\frac{y_2}{127} = \frac{y_1}{427} = \frac{P_t}{727}$ ⇒ $y_1 = 0.58P_t$, $y_2 = 0.17P_t$

Total load by dowel support $= P_t + y_1 + y_2 = 1.76P_t$

steb-5 equate $1.76P_t = 3.325\,kN$ (total load)

$P_t = \underline{\underline{18.87\,kN}}$

steb-6 bearing stress $= \dfrac{\overset{\nearrow 18.87}{P_t}\,K(2+\beta z)}{4\underset{\swarrow}{\beta^3} E_d I_d} = \underline{\underline{22\,MPa}}$

$$\beta = \left(\frac{415000\,\frac{MPa}{m} \times 38 \times 10^{-3}\,mm}{4 \times 200000\,MPa \times 1637661.985\,mm^4}\right)^{1/4} = 0.0209\,mm^{-1}$$

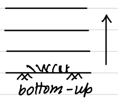
* $I_d = \left[\frac{\pi}{64} d^4\right] = 1637661.985\ mm^4$

induced bearing stress (22MPa) < allowable bearing stress (26.73MPa) ⇒ OKAY

DESIGN IS SAFE!

Example - Dowel bar
Appendix 8, IRC58

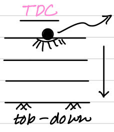
BUC



cracks propagate bottom to up

- cause:- subgrade issue due to fatigue

TDC



elastic deformation
└ not pull itself back
— cracks

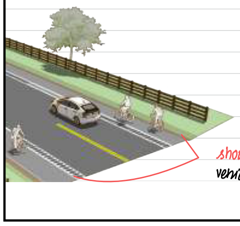
cracks propagate top to down

- cause :- surface distress

stresses due to

	temperature	load
corner	↓	↑
edge		
interior		

arrow points in ↑sing direction



shoulder area don't take traffic load.
vehicle can be parked for pending repair, etc.