CE382A

TRANSPORTATION ENGINEERING

Prof. Prabin Kumar Ashish

Aman

CE382A – Pavement Engineering Part

Taught using slides!!

Broad Course Content

- Basic properties of pavement materials
- Performance based evaluation of bituminous mix.
- Viscoelastic modelling
- Pavement Analysis and Design
- Geometric Design
- Pavement Distress and Maintenance

India – 2nd largest road network in the world.

Pavement Distress

- pothole · crushing
- depression · cracking
- deliminated layer

Why cracks?

Differential settlement

Broash – low level distress

thin surfacing, microsurfacing

Emulsion – colloid

Bitumen molecule + water (liq.)

Typical Pavement Composition

	Bituminous / Flexible pavement	Concrete / Rigid pavement
Material	Bitumen & Aggregate	Cement, Aggregate & Water
Cost	Less expensive	More expensive
Durability	Less durability	More durability
Maintenance	Require more freq. maintenance	Require less freq. maintenance

Crusher Plant – Why? – Batch Mix Plant – Compaction

Bituminous Pavement

Material →	Purpose →
· Subgrade	· Load transfer
· Subbase	· Minimize stress & subgrade
· Base course	· Good riding quality
· Bituminous	· Drainage.

Bitumen vs Aggregate quantity in bituminous mixture? (4–7%)

Generally, Bitumen → 4 to 7 %

Aggregate → 93 to 96 %

Design Life?

Generally 15 to 20 years.

Some may last upto 30 years.

Cement Concrete Pavement

Material →	Purpose →
· Subgrade	· Load transfer
· Base	· DLC provides strong support & avoids mud pumping
· Surface	· Good riding quality.
· Steel	

Design Life?

Generally, 20–30 years.

Typical Cost Comparison

- Bituminous pavement – lower initial construction cost.
  – more cost effective in short term.
  – require more maintenance in long term.
- Cement concrete pavement – higher initial construction cost.
  – more cost effective in long term
  – require less maintenance in long term.

Pavement Material Characterization

- Soil · Aggregate
- Bitumen · Cement

Why should we bother about these materials?

- Load bearing capacity
- Durability
- Performance , etc. . . .

Important Properties

- Strength & stability · Skid resistance · Void ratio
- Durability · Fatigue resistance · Bearing capacity
- Moisture susceptibility

How to evaluate those properties

Tests are there. . . .

Utility of those properties

These properties ensure that pavement perform well and as per intended design well.

Taught using slides!

Lec2—PKA – 2 Mar 2023

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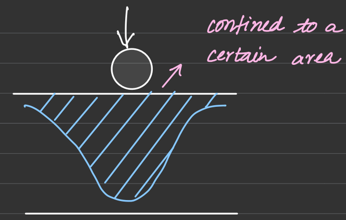
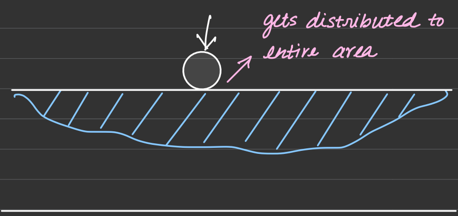


Bituminous Pavement
—due to slab action



Cement Concrete Pavement
—due to grain to grain contact

· Better riding quality? comfort level
· Effect of temp.

It has better riding quality as compared to bituminous pavement

Different types of Bituminous Material

· Tack coat — purpose —?
· Prime coat — Bonding.
— to control dust particles.
— to plug the surface voids.

Filter Layer. — Subcourse II
Drainage layer }
Filter layer }

· WBM — Water Bound Macadam
· WMM — Wet Mix Macadam.
· Quality control of WMM is better than WBM.
· Two main functions — 1. distribute load. — 2. drainage

Pavement Material characterization

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· Aggregate
· Bitumen
· Cement

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· Skid resistance
· Fatigue resistance
· Void ratio
· Bearing capacity

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Utility of those properties
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· Bounded and Unbounded Pavement Structures? — Based on plastic sheet.
• Dowel bar —
&
• Tie bar —
· Why plastic sheet for bitum.? — ?

L = W =

L = 1000 m B = 7m
GSB = 325 mm
WMM = 250 mm
DBM = 125 mm
BC = 50 mm

} → Calculate Volume.
↓
Multiply by individual rates
· GSB 2000/m³
· WMM 2500/m³

Cost Ratio??

Soil — What properties?
• Bearing Capacity (strain
• void ratio
· cement — cohesionless soil }
· lime — cohesive soil } typical subgrade strengthening measures.
· woven type?
· non-woven type?

Lecture 3 – PKA – 13 Mar 2023

Important properties for subgrade soil

Strength — Volumetric Stability — Long term strength

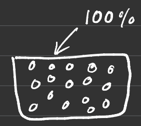
Drainage potential — Leaching potential — Ease of compaction

Performance under dynamic and static load

Tests on soil

Basic Test
- Atterberg limits
- Specific gravity
- Gradation
- Compaction
- Free swelling index
- pH
- Chemical analysis
  - ↳ Imp for durability: cavities, SO_3, carbonation

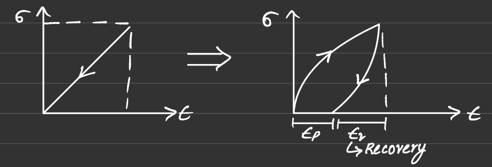
Mechanical properties based test
- CBR test
- UCS test
- Durability test
- Direct Shear test
- Permeability test
- Flexural Strength test
- Resilient modulus test



Field based tests
- DCPT
- LWD test
- Plate Load Test

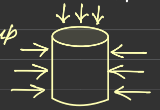
Resilient Modulus ✓

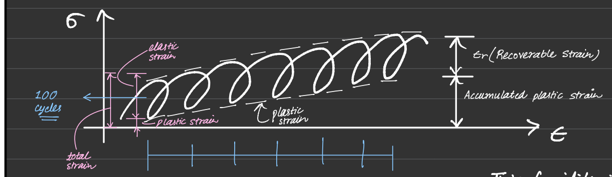
Resilient modulus is a measure of how well a material, such as soil or pavement, can resist deformation and recover its shape after being repeatedly loaded or stressed. It is an important property in predicting the long-term performance of pavements and other geotechnical structures. Think of it as a material's ability to "bounce back" after being pushed or loaded repeatedly.



soil's behaviour is notorious !!

Triaxial setup



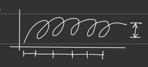


Effect of Temperature?

As temperature increases, the resilient modulus of road materials generally decreases. This is because higher temperatures cause the road materials to soften, making them more susceptible to deformation under load.

$$\text{Resilient Modulus} = M_R = \frac{\sigma_d}{\varepsilon_r}$$

This facility is not available everywhere so we relate it to CBR test



- $M_R = 10 \times CBR$; $CBR < 5\%$
- $M_R = 17.6 \times (CBR)^{0.64}$; $CBR > 5\%$

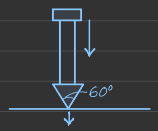
↳ MPa, CBR in %

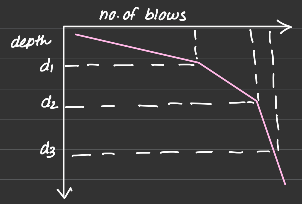
Field Test

Dynamic Cone Penetration Test (DCPT)

During a DCP T test, a metal cone with a weight is dropped onto the pavement surface, and the penetration depth is measured. This process is repeated at regular intervals along the pavement section to determine the strength and stiffness of the pavement layers.

- Rate of penetration ↓ ⇒ higher resistance
- " " " ↑ ⇒ lower resistance





d_3 – strongest

$$\log_{10}(CBR) = 2.465 - 1.12 \log_{10} N$$

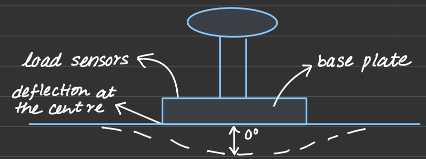
mm / no. of blows ✓
or
no. of blows / mm

log eqⁿ → ?? See somewhere the relⁿ

LWD test (Light Weight Deflectometer) test

An LWD test is a way to check how strong a road is without damaging it. A small plate is pushed down onto the road, and sensors m'easure how much the road bends. This tells engineers how strong the road is and if it can handle heavy traffic. The LWD test is quick, inexpensive, and doesn't require the road to be closed.

- Pavement response under impact loading.
- To measure stiffness of different layers.



$$E = \frac{a(1-\mu^2) r \times p}{\delta}$$

- E: modulus (MPa)
- δ: deflection below plate at centre
- p: contact pressure
- μ: poisson's ratio
- r: radius of plate
- a: shape factor – depends on soil & plate type

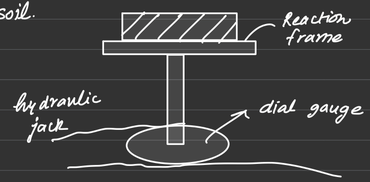
$$a = \begin{cases} 2 & \text{for rigid plate} \\ \frac{\pi}{2} & \text{for flexible plate} \end{cases}$$

Plate Load Test (PLT)

A plate load test is a way to check how strong a road is by applying a known weight onto a metal plate that is placed on the road surface. Engineers use a hydraulic jack or weights to push the plate down onto the road, and instruments measure how much the road deforms or bends. By measuring the deformation, engineers can determine the load-bearing capacity of the road and its suitability for heavy traffic. The plate load test is a simple, cost-effective way to check the strength of a road, but it can be time-consuming and may require the road to be temporarily closed during the test.

- Initially developed to estimate bearing capacity of soil.
- To measure the modulus of subgrade reaction (K)

$$K = \frac{p}{\delta\ (=1.25\,mm)}$$ → p: pressure



Effective Resilient Modulus

It takes into account the complex interactions between the material properties, loading conditions, and environmental factors, such as temperature and moisture.

Effective resilient modulus vs resilient modulus

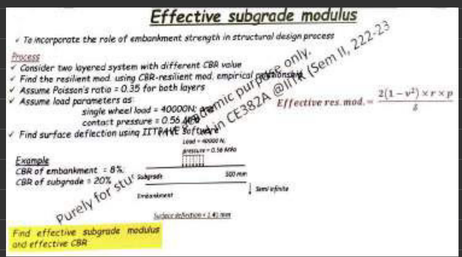
resilient modulus is a basic measure of material stiffness under laboratory conditions, while effective resilient modulus is a more realistic and comprehensive measure of material strength and stiffness under real-world conditions.

Effective resilient modulus

$$M_R = \frac{2(1-\mu^2)\, r \times p}{\delta}$$

- M_R: effective resilient modulus (psi or MPa)
- δ: deflection of pavement surface under loading (mm)
- μ: poisson's ratio (unitless)
- r: radius of circular loading plate (mm)
- p: pressure

→ effective CBR.



Effective subgrade modulus

- ✓ To incorporate the role of embankment strength in structural design process

Process
- ✓ Consider two layered system with different CBR value
- ✓ Find the resilient mod. using CBR-resilient mod. empirical relationship
- ✓ Assume Poisson's ratio = 0.35 for both layers
- ✓ Assume load parameters as
  - single wheel load = 40000N;
  - contact pressure = 0.56 MPa
- ✓ Find surface deflection using IITPAVE Software

Effective res. mod. = $\frac{2(1-\nu^2)\times r \times p}{\delta}$

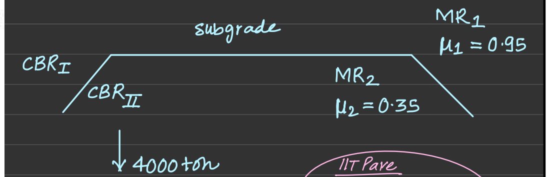
Example
CBR of embankment = 8%
CBR of subgrade = 20%

Load = 40000 N; pressure = 0.56 MPa
Subgrade 500 mm
Embankment Semi infinite
Surface deflection = 1.41 mm

Find effective subgrade modulus and effective CBR

Purely for academic purpose only. CE382A @IITK (Sem II, 222-23)

Prob :-

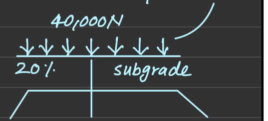


IIT Pave Software · Pavement Design

Resilient modulus $M_R = 17.6\ (\%CBR)^{0.64}$ for CBR > 5%

∴ For embankment $M_R = 17.6\,(8)^{0.64} = 66.6$

For subgrade $M_R = 17.6\,(20)^{0.64} = 119.7$



Deflection – Find using IIT Pave software or $\frac{1.5\,q\,a\,F_2}{E_2}$

$\mu = 0.35$, $p = 0.56\,MPa$

$r = 140.8\,mm$, $\delta = 1.41\,mm$

Eff. res. modulus $M_R = \frac{2(1-\mu^2)\, r \times p}{\delta}$ → Find CBR using relⁿ $M_R = 17.6\,(\%CBR)^{0.64}$

Lec 4 – PKA – 14 Mar 2023

Aggregate and Volumetrics

AGGREGATES

Role of Aggregates
- → interlocking — even load distribution on road
- → friction — surface texture – provide skid resistance
- → strength — distribute load over large area; avoid cracking

M30 — 1 : 0.75 : 1.5 (cement : sand : coarse aggregate)

When aggregate quality is poor?

- Skidding resistance is low → **Effect of water?** Water can also have a significant impact on skid resistance. If the pavement surface is wet, the presence of water can further reduce the friction between the tire and the pavement, increasing the risk of skidding or hydroplaning.
- Ravelling → Ravelling happens when the surface of the pavement wears away, causing loose rocks and aggregate particles to appear. This can create a rough, uneven surface that can be dangerous for vehicles and pedestrians.
- Stripping → Stripping is when the asphalt binder that holds the pavement together separates from the aggregate particles. This can cause the pavement to become weaker and more susceptible to other types of damage, like potholes and cracks.

Microtexture — less than 0.5mm in height – friction development – avoid skidding

Macrotexture — greater than 0.5mm in height

Macro and micro texture are two important factors that affect skid resistance. Macro texture refers to the larger features on the surface of the pavement, such as the size and depth of the aggregate particles. Micro texture refers to the smaller features, such as the surface roughness and the shape and distribution of the aggregate particles.

Types of natural aggregates

- Igneous — granite, basalt
- metamorphic — marble, schist, gneiss
- sedimentary — sandstone, limestone, chalk

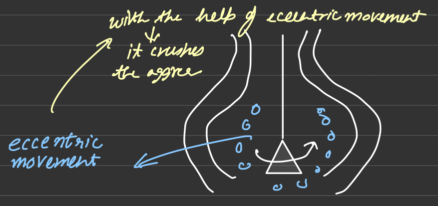
Chemical Nature :-

- Acidic — silica content is high than 50%
- Basic — silica content is less than 50%

water affinity :-

- hydrophobic — acidic aggregate — granite
- hydrophilic — basic aggregate — limestone

* crusher - jaw crusher — most common
* cone crusher
* vertical shaft
* horizontal shaft



shape properties

---

v.v.imp.

Shape Properties of Aggregates

- Angularity
- Texture
- Sphericity → can find the sphericity → Image Processing!!
- Flatness and Elongation

Water absorption — Why it is important?

If high water absorption — bitumen will get absorbed.
— strength of aggregate will be less.
— more fractures will be there (it will break down easily)

SPECIFIC GRAVITY — Mixed Design

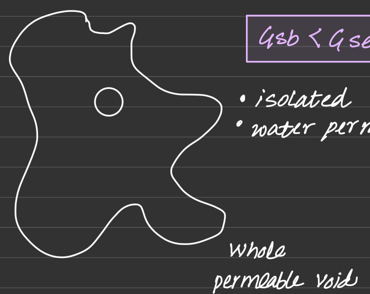
Bulk, Apparent, Effective — considers mass of given material

Bulk specific gravity — G_{sb} — including both impermeable and water permeable voids (all pores and voids included — whole volume)

Apparent specific gravity — G_{sa} — includes only isolated voids (impermeable voids)

Effective specific gravity — G_{se} — includes both impermeable and water permeable voids, not filled with absorbed asphalt

$G_{sb} < G_{se} < G_{sa}$



- isolated void (impermeable)
- water permeable voids

Well graded

one - sized.

- density is highest

Aggregate gradation example

Maximum theoretical density of a compacted bituminous mixture

$P_A f_A + P_B f_B + P_C f_C$ > Upper Limit
" " " < Lower Limit

{ P_A, P_B, P_C — % of coarse, fine, mineral agg.
f_A, f_B, f_C — bulk specific gravity corresp. }

Target grading

Sieve	A	B	C	Mid Pt.
19	100	100	100	100
13.2	63	100	100	78
4.75	19	100	100	48
2.36	8	93	100	36
0.3	0	55	100	25
0.15	0	36	97	17
0.075	0	3	88	8

Solver function in Excel

Lecture 5 – PKA – 16 Mar 2023

Aggregate ✓ Soil ✓ Flexible Pavement ✓

Bitumen → has notorious behaviour bcoz of viscoelastic nature

Marshall Mix Design — Volumetrics — Do on your own!!

A B C D
- Different grades of bitumen
- Choose based on softening point / viscosity.

softness ——→ softness ↓ hardness ↑

viscosity ——→ viscosity ↑es

- Components of Bitumen
- Chemistry
- Composition

- Bitumen → Maltene → Resins, Aromatics, Saturates
- Bitumen → Asphaltene
  - Highest Polarity
  - Responsible for Stiffness

- Mechanical Properties of Bitumen — Stiffness, Elasticity, Ductility, Cohesion, Fatigue resistance, Adhesion.
- Bitumen is a colloidal structure (small particles of asphalt in a mixture of oils and waxes)

Stability of Bitumen → Imp mechanical property

- [Colloidal Index = (Saturates + Asphaltene) / (Resins + Aromatics)] → ☆ Imp for exams!!
- Ability to resist deformations under traffic loads.
- More stable bitumen has less colloidal index.

- Asphaltene ↑ ⟹ Colloidal Index ↑
  - ↳ proportionally maltene content is ↓

Asphaltene	5–25%	→ Although less but it has bigger role to play.
Saturates	5–20%	
Aromatics	40–65%	→ Most of the bitumen is aromatics
Resins	10–20%	

Chemistry of Bitumen

C	82–88%
H	8–11%
Sulfur	0–6%
Oxygen	0–1.5%
Nitrogen	0–1.1%

What properties do we want out of bitumen?
- Affinity towards aggregate
- less temperature susceptible.
- Fine balance b/w stiffness and flexibility.
- Should be fluid enough to coat aggregate but shouldn't segregate during transportation.
- Aging Resistivity
  - → Short term aging — happen during production stage
  - → Long term aging — happen when placed in field & exposed to atmosphere.

Environmental loading }
Traffic loading }
unmodified bitumen is not good for use.

Bitumen Modification Process → (we have different kinds of modifiers)

↓ modifiers
- → polymers — SBS (Styrene Butadiene Styrene)
  - ↳ 3–5% by wt. of bitumen (more costly)
- → Crumb rubber — waste tyres and refine them to be used as modifiers
  - ↳ 5–20% by wt. of bitumen

S – B – S

surface layer
binder layer
⟩ Where should we place modifiers?
- polymer — we prefer using it in 'binder.' however it can be used in 'surface' as well
- crumb rubber — we put at 'surface' — noise canceller to reduce noise in locality.

Bitumen Grading

Penetration grading — 1990 — 30/40 60/70 80/100

↳ What's the problem? Why we changed to viscosity grading now?
- It doesn't reflect grading properties. It had several limitations.
- Take into account the temperature dependence of bitumen.

→ Shifted to viscosity grading — 2005 — VG10, VG20, VG30, VG40
- classify bitumen based on viscosity

2400–3600

3000 ± 20% poise

$3000 \times \frac{30}{1.5} = 600$

SHRP — Strategic Highway Research Program
↳ superpave performance grading 1992/1991

perf. grade (PG 76 (-22)) → This is (-22) i.e. minus 22

- 76: 7 day average max. pavement temperature 20 mm
- -22: lowest pavement temp. at the surface

PG 76 − 22 → Bitumen is suitable at max. temp upto 76°C and min. temp −22°C.

High temperature performance grade — Dynamic Shear Rheometer
Low temperature performance grade — Bending Beam Rheometer

Rheometer → 40–50 lacs → expensive → that's why not in use right now.

High Temperature Performance Grade
↳ Rutting Parameter

$$\frac{|G^*|}{\sin(\delta)}$$

- $|G^*|$ → comb. modulus
- $\sin(\delta)$ → phase angle

can do test on
- unaged sample >1 KPa
- short term aged sample ≥2.2 KPa ↓ Values of rutting parameter

Temp.	
52	—
58	—
64	— 60.3
70	—
75	—

can interpolate to find others.

60.3 → continuous grade: exact number where you're hitting

Stiffness
↳ S-value ≤ 300 MPS

Rate of change in stiffness, 60 sec of creep loading
↓
W-value ≥ 0.5

- PG 76−22
- PG 76−12
- PG 76−32

$$\text{ITPG} = \text{High temp. PG} - \frac{[\text{High temp PG} - \text{Low temp PG}]}{2} + 4$$

Intermediate Temp. PG → $G^* \times \sin\delta$
↳ Fatigue factor ≤ 5000 KPa — For long term sample.

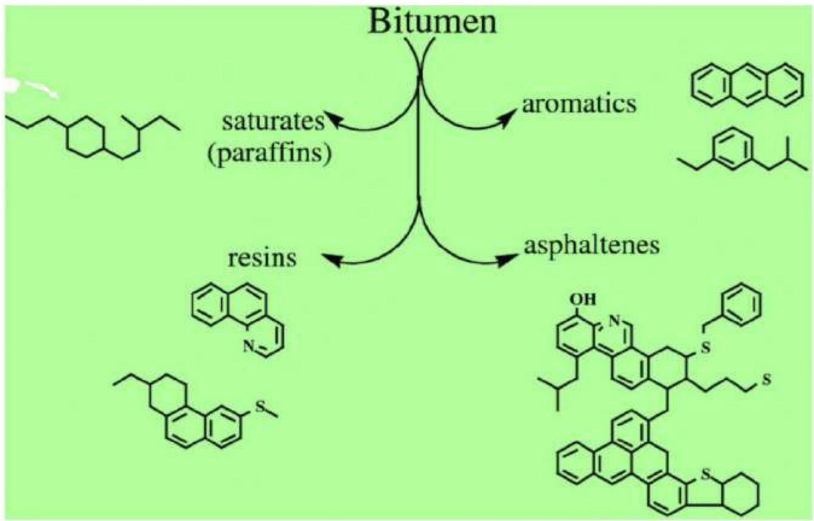


Fig.1

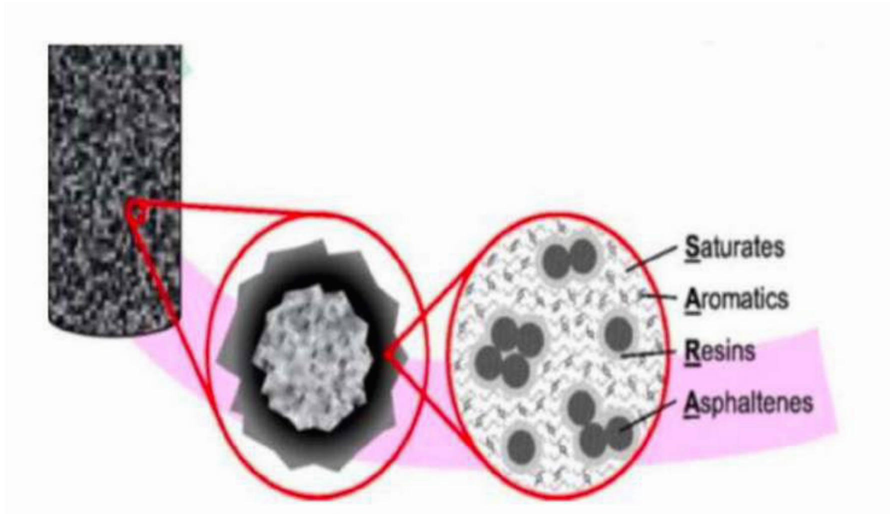


Fig.2

Table 1 Requirements for Paving Bitumen
(*Clause* 6.2)

Sl No.	Characteristics	Paving Grades VG10	VG20	VG30	VG40	Method of Test, Ref to
(1)	(2)	(3)	(4)	(5)	(6)	(7)
i)	Penetration at 25°C, 100 g, 5 s, 0.1 mm, *Min*	80	60	45	35	IS 1203
ii)	Absolute viscosity at 60°C, Poises	800-1 200	1 600-2400	2 400-3 600	3 200-4 800	IS 1206 (Part 2)
iii)	Kinematic viscosity at 135°C, cSt, *Min*	250	300	350	400	IS 1206 (Part 3)
iv)	Flash point (Cleveland open cup), °C, *Min*	220	220	220	220	IS 1448 [P : 69]
v)	Solubility in trichloroethylene, percent, *Min*	99.0	99.0	99.0	99.0	IS 1216
vi)	Softening point (R&B), °C, *Min*	40	45	47	50	IS 1205
vii)	Tests on residue from rolling thin film oven test:					
	a) Viscosity ratio at 60°C, *Max*	4.0	4.0	4.0	4.0	IS 1206 (Part 2)
	b) Ductility at 25°C, cm, *Min*	75	50	40	25	IS 1208

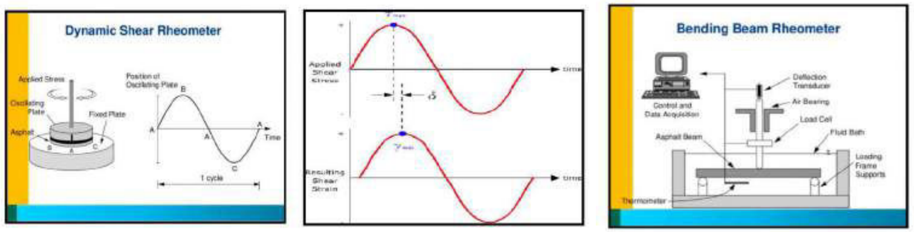


Fig.3

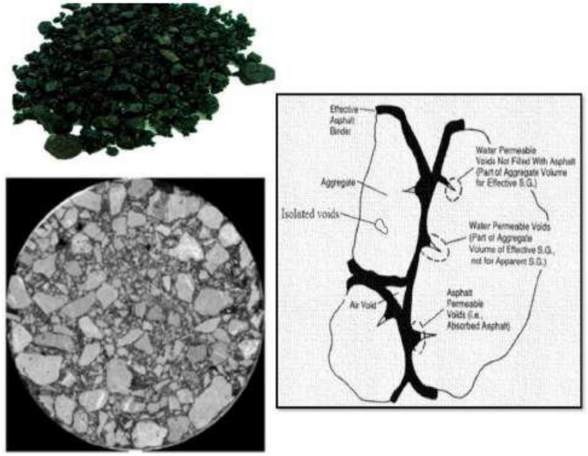


Fig.4

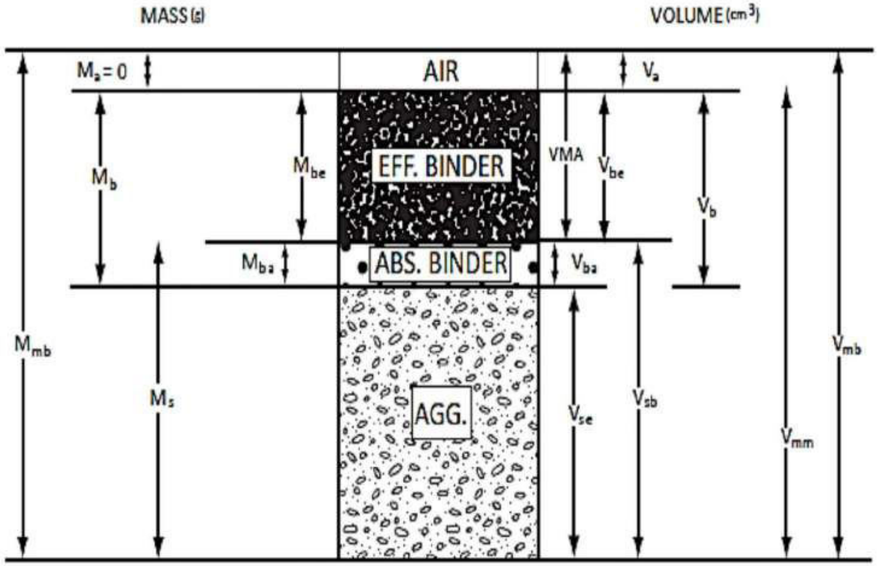


Fig.5

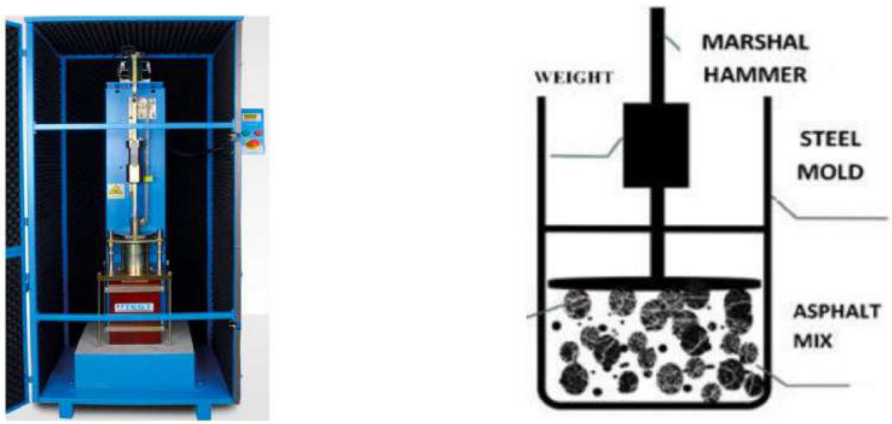


Fig.6

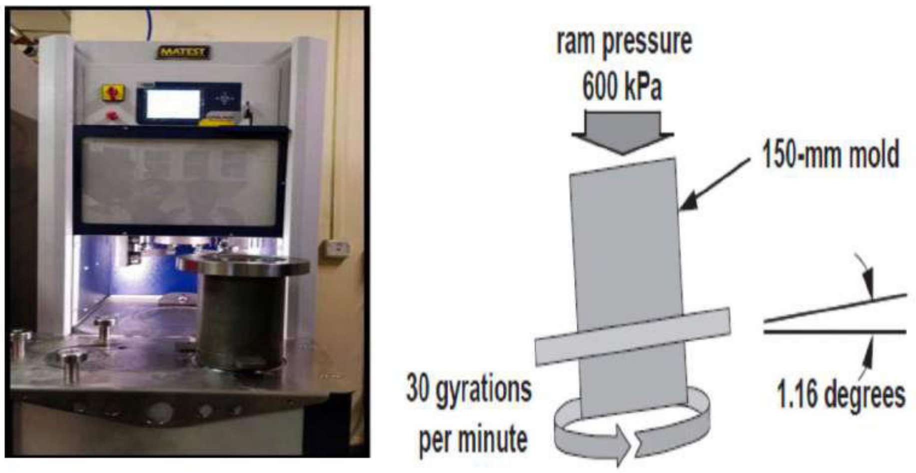


Fig.7

Lecture 6 – PKA – 17 Mar 2023

Corrections

Low temp PG → −10, −16, −22, −28, −34, −40

testing temp → −6, −12, −18, −24, −30

−6 −10 = −16
low temp PG

Ex

	S	m-value
−6	223	0.186
−12	473	0.258
−18	872	0.340

Grading for which S → 300, m → 0.3 } = ?

For S :-

$$\frac{300-223}{x-(-6)} = \frac{473-223}{-12-(-6)}$$

$x = -7.848$ → choose this one ✓

For m :- $x = -15.07$

Viscoelastic Modelling

viscoelastic → elastic + viscous

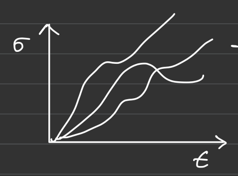
low temp.	intermediate temp.	high temp
elastic	elastic + viscous ←→ service temp. condition	viscous

Effect of Temp?

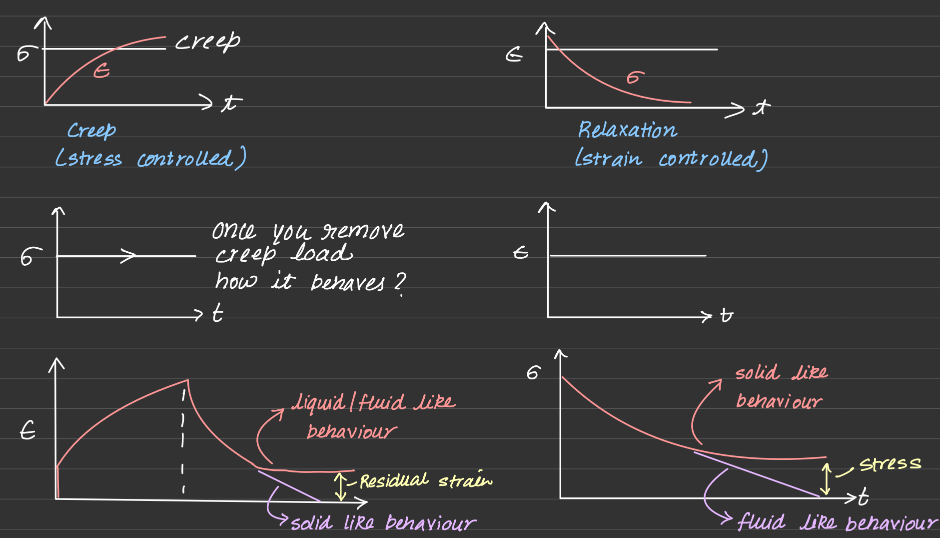
- Temp ↑↓ Stiffness ↓↑
- Loading freq. ↑↓ Stiffness ↑↓

Load → σ_t, ε_t → Linear viscoelastic range → Assumption: · scalar · superposition

→ Non-linear viscoelastic range → Boltzman superposition principle

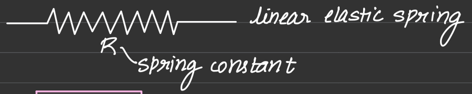


→ To model, we have to take some simple case.



Non-linear time dependent strain response.

Elastic Response



$$\sigma = R\epsilon$$

stress $\propto$ strain

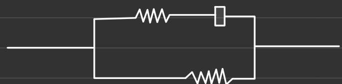
Viscous Response

$$\sigma = \eta \frac{d\epsilon}{dt}$$

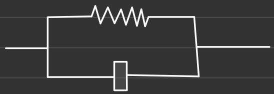
stress $\propto \frac{d\epsilon}{dt}$

Clubbing

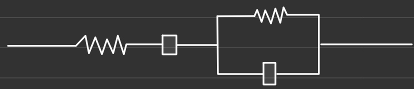
Maxwell Model



3 element model (Zener Model)

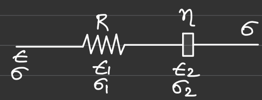


Kelvin-Voigt Model



4 element model (Burger's model)

Maxwell Model



$\sigma = \sigma_1 = \sigma_2$

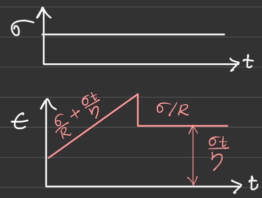
$\epsilon = \epsilon_1 + \epsilon_2 \Rightarrow \dot{\epsilon} = \dot{\epsilon}_1 + \dot{\epsilon}_2$

$$\dot{\epsilon} = \frac{\dot{\sigma}}{R} + \frac{\sigma}{\eta}$$

$\sigma = R\epsilon_1 \quad \sigma = \eta \dot{\epsilon}_2 = \eta \frac{d\epsilon_2}{dt}$

$\dot{\epsilon}_1 = \frac{\dot{\sigma}}{R} \quad \dot{\epsilon}_2 = \frac{\sigma}{\eta}$

$\dot{\epsilon} = \frac{\dot{\sigma}}{R} + \frac{\sigma}{\eta} \quad \sigma = \eta \frac{d\epsilon}{dt}$



constitutive eqn $\dot{\epsilon} = \frac{\dot{\sigma}}{R} + \frac{\sigma}{\eta}$

$\dot{\sigma} = 0$

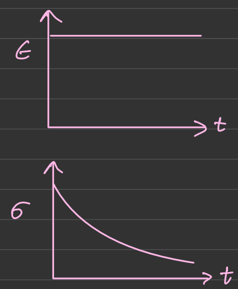
$\dot{\epsilon} = \frac{\sigma}{\eta} \Rightarrow \frac{d\epsilon}{dt} = \frac{\sigma}{\eta}$

$\int_{\sigma/R}^{\epsilon} d\epsilon = \frac{\sigma}{\eta} \int_0^t dt$

$\epsilon - \frac{\sigma}{R} = \frac{\sigma t}{\eta}$

$$\epsilon = \frac{\sigma}{R} + \frac{\sigma t}{\eta}$$

Relaxation Mode



$\dot{\epsilon} = \frac{\dot{\sigma}}{R} + \frac{\sigma}{\eta}$

$\dot{\epsilon} = 0 \Rightarrow 0 = \frac{\dot{\sigma}}{R} + \frac{\sigma}{\eta}$

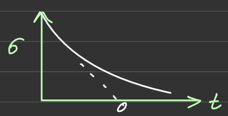
$\frac{d\sigma}{dt} = -\frac{\sigma R}{\eta}$

$\int_{\sigma_0}^{\sigma} \frac{d\sigma}{\sigma} = -\frac{R}{\eta} \int_0^t dt$

$\ln \sigma - \ln \sigma_0 = -\frac{Rt}{\eta}$

$\ln\left(\frac{\sigma}{\sigma_0}\right) = -\frac{Rt}{\eta}$

$$\sigma = \sigma_0 e^{-Rt/\eta}$$



$\sigma = \sigma_0 e^{-Rt/\eta}$

$\frac{d\sigma}{dt} = \sigma_0 \times \left(-\frac{R}{\eta}\right) \times e^{-Rt/\eta}$

At $t=0$

$\left(\frac{d\sigma}{dt}\right)_{t=0} = -\frac{\sigma_0 R}{\eta}$ → slope

$$\sigma = \sigma_0 - \frac{\sigma_0 Rt}{\eta}$$

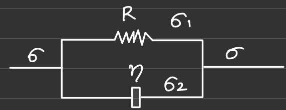
$0 = \sigma_0 - \frac{\sigma_0 Rt}{\eta} \Rightarrow \sigma_0 = \frac{\sigma_0 Rt}{\eta}$

$$t = \frac{\eta}{R}$$ $\frac{(Pa\text{-}sec)}{(Pa)}$

Relaxation Time

Similarity with viscoelastic model?

Kelvin Voigt Model



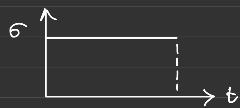
$\epsilon = \epsilon_1 = \epsilon_2$

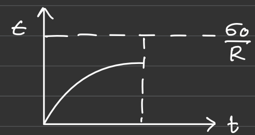
$\sigma = \sigma_1 + \sigma_2$

$\sigma_1 = R\epsilon$

$\sigma_2 = \eta \dot{\epsilon}$ $\Rightarrow$

$$\sigma = R\epsilon + \eta\dot{\epsilon}$$





How it behaves under creep recovery?

$\sigma_0 = R\epsilon$

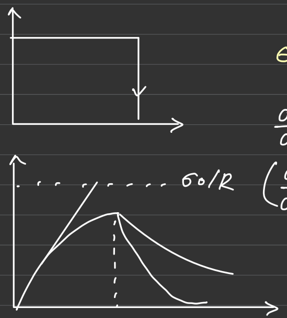
$\epsilon = \frac{\sigma_0}{R}$

$\sigma = R\epsilon + \eta\dot{\epsilon}$

$\sigma - R\epsilon = \eta \frac{d\epsilon}{dt}$

$\int_0^{\epsilon} \frac{d\epsilon}{(\sigma - R\epsilon)} = \frac{1}{\eta} \int_0^t dt$

$$\epsilon(t) = \frac{\sigma_0}{R}\left(1 - e^{Rt/\eta}\right)$$



$$\epsilon(t) = \frac{\sigma_0}{R}\left(1 - e^{-Rt/\eta}\right)$$

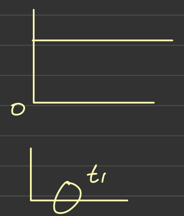
$$\frac{d\epsilon}{dt} = \frac{\sigma_0}{\eta} e^{-Rt/\eta}$$

$$\left(\frac{d\epsilon}{dt}\right)_{t=0} = \frac{\sigma_0}{\eta} \rightarrow \frac{\sigma_0 t}{\eta}$$

$$\frac{\sigma_0 t}{\eta} = \frac{\sigma_0}{R}$$

$$t = \frac{\eta}{R}$$

Retardation Time



$$\frac{\sigma_0}{R}\left(1 - e^{-Rt/\eta}\right) + \left(-\frac{\sigma_0}{R}\left(1 - e^{-R(t-t_1)/\eta}\right)\right)$$

$$\Downarrow$$

$$\epsilon(t) = \frac{\sigma_0}{R}\left(e^{-Rt/\eta}\right)\left(e^{\frac{-Rt_1}{\eta}} - 1\right)$$

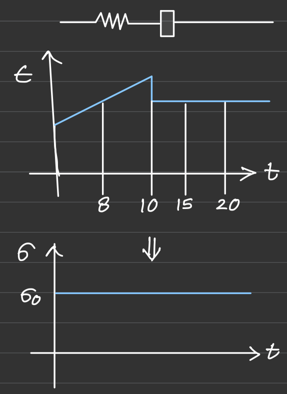
Applicable only for $t > t_1$

Limitation of Kelvin-Voigt Model
1. No relaxation test
2. No instantaneous strain

Lec 7 — PKA — 21 Mar 2023

Example 1:

Maxwell's Model for creep recovery test



- Modelled creep-recovery behaviour of bitumen using Maxwell's model
- Creep loading — 20 sec — unloading it
  $\sigma_0 \longrightarrow 2.5\sigma_0$
- What kind of change in strain at $t = 8$ sec, $t = 15$ sec, $t = 20$ sec.

$$\epsilon = \frac{\sigma}{R} + \frac{\sigma}{\eta} t$$

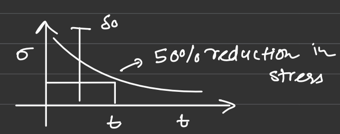
$$\dot{\epsilon} = \frac{\sigma}{\eta} \Rightarrow \dot{\epsilon} = \frac{(2.5\sigma_0)}{\eta}$$

→ stress rate ↑es by 2.5 times and it remains constt.

Relaxation Test using Maxwell's Model

$$\sigma = \sigma_0 \times e^{-\frac{Rt}{\eta}}$$

$R = 873$ MPa, $\eta = 148{,}750$ MPa·sec



Find time in reduction to 50% in stress.

$$\frac{\sigma_0}{2} = \sigma_0 \times e^{-\frac{Rt}{\eta}}$$

$$e^{-\frac{Rt}{\eta}} = \frac{1}{2}$$

$$t = -\frac{\eta}{R} \times \log_e\left(\frac{1}{2}\right) = 118.105 \approx 118 \text{ sec}$$

$$\sigma = \sigma_0 - \frac{\sigma_0 R t}{\eta}$$

$R \rightarrow 1.6R_1$, $\eta \rightarrow 1.4\eta_1$ } $\sigma_0 \rightarrow 0.2\sigma_0$ What time = ? 239 sec — How ??

$$0.2\sigma_0 = 0.2\,\sigma_0 \times \left(1 - \frac{1.6Rt}{1.4\eta}\right)$$

K-V Model

Creep test

$\sigma_0 = 200$ KPa
$R = 500$ MPa
$\eta = 34000$ MPa·sec

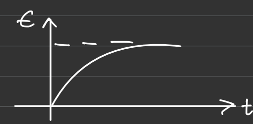
$\frac{\sigma_0}{R} = 4 \times 10^{-4}$

} strain response = ?

50 sec, 100 sec, 200 sec, 500 sec } & see whether strain value is converging or not?

$$\epsilon(t) = \frac{\sigma_0}{R}\left(1 - e^{-\frac{Rt}{\eta}}\right)$$

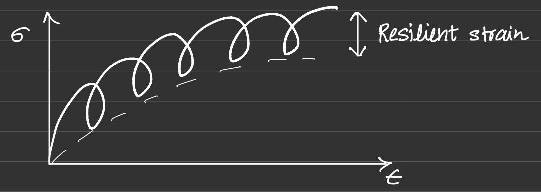
At $t = 50$ sec — $\epsilon(t) = 2.1 \times 10^{-4} = 208\mu$
At $t = 100$ sec — $\epsilon(t) = 308\mu$
At $t = 200$ sec — $\epsilon(t) = 380\mu$
At $t = 500$ sec — $\epsilon(t) = 400\mu$
At $t = 5000$ sec — $\epsilon(t) = 400\mu$



70% of max. strain value ⟶ How much time will it take?
$\epsilon \rightarrow 0.7\,\epsilon_{max}$, changing with initial rate of change in strain value.

Lecture 8 — PKA – 23 Mar 2023

Resilient Modulus of Bituminous Mixture



Resilient Modulus = $\frac{\sigma_d}{\epsilon_r}$

= $\frac{\text{deviator stress}}{\text{recoverable strain}}$

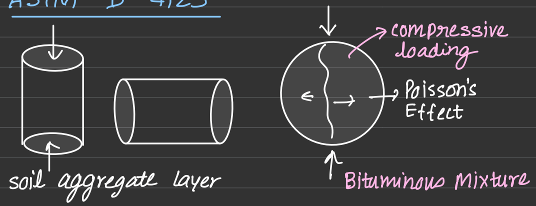
AAPT — Average Annual Pavement Temperature

35°C or 20°C
↳ snowbound area

Different at different plates.

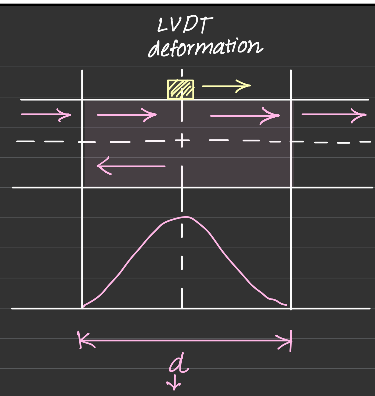
How to find out? → ASTM D 4123
→ ASTM D 7369

ASTM D 4123



- Loading – loading time – t_L (different on basis of vehicle speed)
- Unloading – t_R

Loading Time

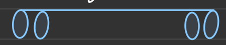


Linear Variable Differential Transformation (LVDT)
→ To measure deformations
→ even very small deformations can be measured

contact radius = a
= 12 x radius
speed 's'

Ex:- a = 150 mm
S = 64 Kmph
Loading duration, $d = \frac{12 \times a}{s} = 0.1 sec$

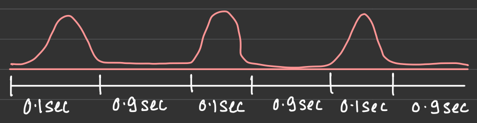
$d = \frac{12 \times a}{s}$
(duration of loading)



Standard axle – two tyre on both side
Simple axle – one tyre

Loading period ⇒ { ↑ with ↑ in depth ; ↓ with ↑ in speed }

{ Loading period 0.1 sec ; Unloading period 0.9 sec } 1 Hz frequency

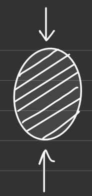


Recovery period ↓
Recoverable strain ↓
Resilient modulus ↑

- Preconditioning → 50 – 200 cycles
- Test temperature → 5°C – 40°C
- Loading frequency → 0.33, 0.5, 1 Hz → { loading = 0.1 sec ; unloading = 1 – 0.1 = 0.9 sec }

For this $t = \frac{1}{0.5} = 2$ sec

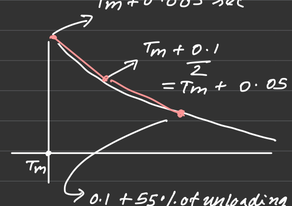
{ loading = 0.1 sec (remains same unless specified) ; unloading = 2 – 0.1 = 1.9 sec }



Bitumen

Strip Load → strength 'x' mpr – beyond this — can't go

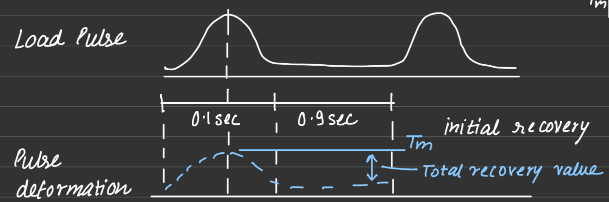
∴ Loading range should be within linear viscoelastic range
∴ 10 to 50% of x.



= 0.9 x 0.55 + 0.1
= 0.495 + 0.1
= 0.595 sec

Resilient Modulus

- Instantaneous Resilient Modulus
- Total Resilient Modulus



Resilient Modulus = $\frac{P(\mu + 0.27)}{t \times \delta}$

P: applied vertical pressure
μ: poisson's ratio
t: pavement thickness
δ: vertical strain/deformation

- ASTM 4123 – Assume 0.35 and doesn't change with temp.

Table 9.2 Indicative Values of Resilient Modulus (MPa) of Bituminous Mixes

Mix type	Average Annual Pavement Temperature °C				
	20	25	30	35	40
BC and DBM for VG10 bitumen	2300	2000	1450	1000	800
BC and DBM for VG30 bitumen	3500	3000	2500	2000	1250
BC and DBM for VG40 bitumen	6000	5000	4000	3000	2000
BC with Modified Bitumen (IRC:SP:53)	5700	3800	2400	1600	1300
BM with VG10 bitumen	500 MPa at 35°C				
BM with VG30 bitumen	700 MPa at 35°C				
RAP treated with 4 per cent bitumen emulsion/ foamed bitumen with 2-2.5 per cent residual bitumen and 1.0 per cent cementitious material.	800 MPa at 35°C				

Fig.1

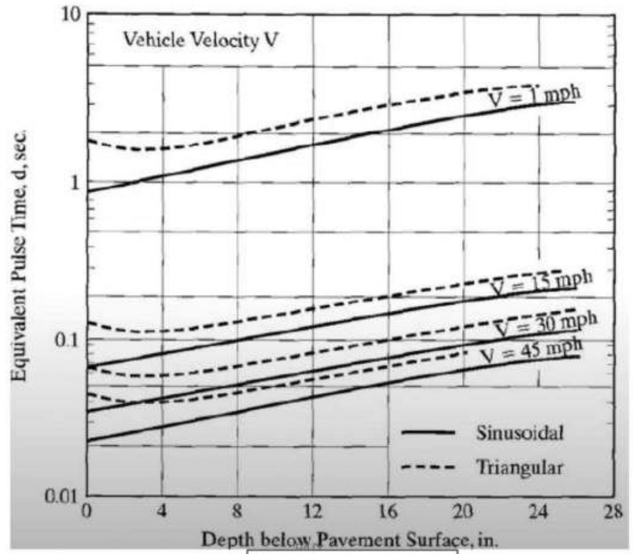
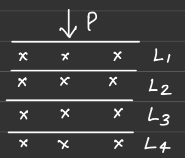


Fig.2

Lec 9 - PKA – 28 Apr 2023

Bituminous Pavement Analysis

- Prof. Huang – Pavement Analysis and Design — Chapter 2
- AAA Molennan – Lecture Notes – Design of Flex. pavement

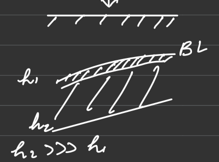


$h_2 > h_1$

Cost I > Cost II

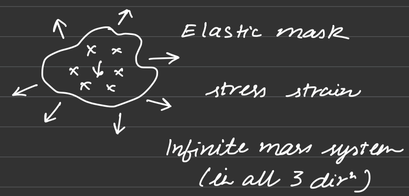
Introduction → one layer system → two layer system → Multi-layer pavement structure

↓ Historical Development



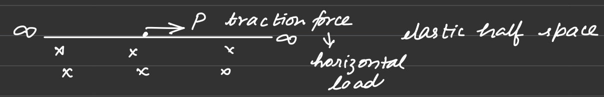
Historical Developments

- Kelvin Problem (1885)

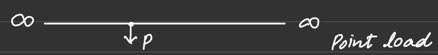


- Boussineq Problem (1885)

- cerruti's Problem



- Mindlin's Problem I



$\sigma_z = \frac{P}{2\pi} \frac{3z^2}{(r^2+z^2)^{5/2}}$

· Indeterminate at $z=0$, $\sigma_z = \infty$.

- Mindin's Problem II

∞ ————— $\cdot \rightarrow p$ ————— ∞

- For 1 layer system → Foster & Ahlvin → several charts (σ, ϵ, δ)
- Burmister → 2 layer system → 1943
  → 3 layer system → 1945
  — Several Charts — to reduce computation (motivation)
- Fox (1948) → Tables/Charts → 2 layer system
- Acum & fox → Tables

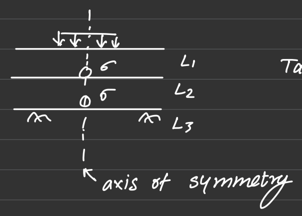


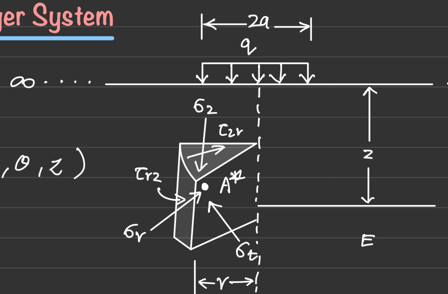
Table — to find 'σ' over layer(s)

- Jones (1962) → Table → σ at other than axis of symmetry

- Computer Program (1960s)
  — Chev (1963)
  — BISAR (1973)
  — DAMA (1979)
  — ILUPAVE (1986)
  — ELSYM5L (1986)
  — PDMAR (1986)
  — MICPAVE (1989)
  — PIPCOMAT (1995)
  — PENLAYER (2000)
  — IITPAVE → Prof. Animesh Das (faculty at IITK)

1 Layer System

(ϕ, θ, z)



elastic half space

Components of stresses under axisymmetric loading

$$\sigma_{ij} = \begin{bmatrix} - & \ominus & \ominus \\ \ominus & - & \ominus \\ \ominus & \ominus & - \end{bmatrix} \; 9 \quad \rightarrow \quad \sigma_{ij} = \sigma_{ji}$$

⇓

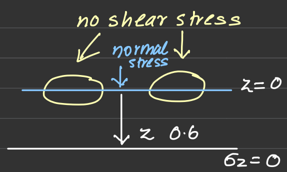
$$[\sigma] = [\quad] \; 6$$

axisymmetric ⟹ shear stresses w.r.t. tangential dir^n = 0
$\{\tau_{tz}, \tau_{rt}; \tau_{zt}, \tau_{tr}\} \rightarrow 0$

$\sigma_z, \sigma_t, \sigma_r, \tau_{rz}$ *

$\sigma_z, \sigma_t, \sigma_r, \tau_{rz}$

→ Stress-Strain Relationship — constitutive eq^n
→ Stress - Displacement Relationship
→ Equilibrium Equation
→ Boundary Condition



$$\sigma_r = \frac{\partial}{\partial z}\left(\mu^2 \nabla^2 \phi - \frac{\partial^2 \phi}{\partial r^2}\right)$$

$$\sigma_\theta = \frac{\partial}{\partial z}\left(\mu \nabla^2 \phi - \frac{1}{\mu}\frac{\partial \theta}{\partial \mu}\right)$$

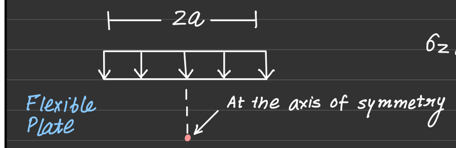
$$\sigma_z = \frac{\partial}{\partial z}\left((z-\mu)\nabla^2 \phi - \frac{\partial^2 \phi}{\partial z^2}\right)$$

$$\tau_{rz} = \frac{\partial}{\partial \mu}\left[(1-\mu)\nabla^2 \phi - \frac{\partial^2 \phi}{\partial z^2}\right]$$

∇^2 = laplace operator
ϕ = stress function

Airey Function

Stress-Strain – Boussinesq's – Solutions at the Axis of symmetry



$\sigma_z, \sigma_t, \sigma_r, \tau_{rz}$ → 0 at the axis of symmetry

- $\tau_{rz} = 0$
- $\sigma_r = \sigma_t$
- deflection, σ_z, σ_r
- σ_z, σ_r → principal stresses

The stresses & strains beneath the center of the plate can be obtained from :–

$$\sigma_z = q\left[1 - \frac{z^3}{(a^2+z^2)^{1.5}}\right]$$

σ_z → independent of E and μ.

$$\sigma_r = \frac{q}{2}\left[(1+2\mu) - \frac{2(1+\mu)z}{(a^2+z^2)^{0.5}} + \frac{z^3}{(a^2+z^2)^{1.5}}\right]$$

σ_r → independent of E

$$\epsilon_z = \frac{(1+\mu)q}{E}\left[(1-2\mu) + \frac{2\mu z}{(a^2+z^2)^{0.5}} - \frac{z^3}{(a^2+z^2)^{1.5}}\right]$$

$$\epsilon_r = \frac{(1+\mu)q}{2E}\left[(1-2\mu) - \frac{2(1-\mu)z}{(a^2+z^2)^{0.5}} + \frac{z^3}{(a^2+z^2)^{1.5}}\right]$$

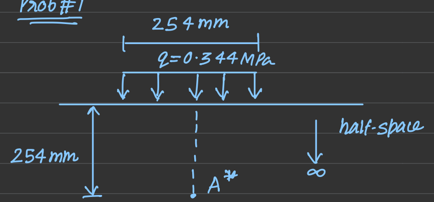
The vertical deflection w can be determined from :–

$$w = \frac{(1+\mu)qa}{E}\left\{\frac{a}{(a^2+z^2)^{0.5}} + \frac{(1-2\mu)}{a}\left[(a^2+z^2)^{0.5} - z\right]\right\}$$

For $\mu = 0.5$, $w = \frac{3qa^2}{2E(a^2+z^2)^{0.5}}$

Lecture 10 – PKA – 31 Mar 2023

Prob#1



$E = 68.9$ MPa $q = 0.344$ MPa

$\mu = 0.3$

Determine σ, ϵ, deflection (vertical) } = ? at A*

$(\sigma_z, \sigma_t = \sigma_r)$

Axisymmetric.

$z = 254$ mm

$q = 0.344$ MPa

Soln $2a = 254$ mm ⇒ $a = 127$ mm

$$\sigma_z = q\left[1 - \frac{z^3}{(a^2+z^2)^{1.5}}\right] = 0.344\left[1 - \frac{254^3}{(127^2+254^2)^{1.5}}\right] = 0.098 \text{ MPa}$$

$$\sigma_t = \sigma_r = \frac{q}{2}\left[(1+2\mu) - \frac{2(1+\mu)z}{(a^2+z^2)^{0.5}} + \frac{z^3}{(a^2+z^2)^{1.5}}\right] = (-0.001715 \text{ MPa}) = (-1.715 \text{ kPa})$$

$$w = \frac{(1+\mu)}{E}qa\left(\frac{a}{(a^2+z^2)^{0.5}} + \frac{(1-2\mu)}{a}\left[(a^2+z^2)^{0.5} - z\right]\right) =$$

$\sigma_r = -1.77 \times 10^{-3}$ MPa $= \sigma_t$

$\sigma_z = 0.098$ MPa

$\epsilon_z = 1.44 \times 10^{-3}$

$\epsilon_r = 4.44 \times 10^{-4}$

Relationship b/w Stress and Strain

After the stresses are obtained from the charts, the strains can be obtained from :–

$$\epsilon_z = \frac{1}{E}\left[\sigma_z - \mu(\sigma_r + \sigma_t)\right]$$

$$\epsilon_r = \frac{1}{E}\left[\sigma_r - \mu(\sigma_z + \sigma_t)\right]$$

$$\epsilon_t = \frac{1}{E}\left[\sigma_t - \mu(\sigma_r + \sigma_z)\right]$$

Prob#2

Linearly Elastic & Isotropic Material

Put values from prev. question and check whether this relationship holds true or not!!

↳ All values coming same and matches the prev. prob.

Foster and Ahlvin's Chart (1954)

- Valid for $\mu = 0.5$ only → later modified by Ahlvin and Ulery (1962)
- Charts — $\sigma_z, \sigma_r, \sigma_t, \tau_{rz}$
- What is the significance $\mu = 0.5$ (Poisson's ratio) ?

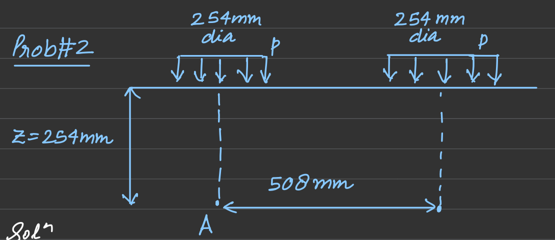
  It represents the limit condition for the chart

  Incompressible material

  Resilient modulus — Independent of confining pressure applied.

  $\sigma_z, \sigma_r, \sigma_t, \tau_{rz}$ found ⟹ $\varepsilon_z, \varepsilon_r, \varepsilon_t$, deflection can be calculated.

Prob#2



$p = 345$ kPa → Both → 0.345 MPa

$\mu = 0.5$

$E = 69$ MPa

σ_z, ε_z & vertical deflection at A

Sol^n

$2a = 254$, $a = 127$ mm, $q = 0.345$ MPa

$\frac{z}{a} = 2$

$\frac{r}{a} = \frac{508}{254} = 4$

For σ_z Left → $r/a = 0$ $\left[\frac{\sigma_z}{q} \times 100 = 28 \Rightarrow \sigma_{z_1} = 0.00966 \text{ MPa}\right]$ → Total $\sigma_{z,total} = \sigma_{z1} + \sigma_{z2} = 9.936 \times 10^{-2}$ MPa

Right → $r/a = 4$ $\left[\frac{\sigma_z}{q} \times 100 = 0.8 \Rightarrow \sigma_{z_2} = 2.76 \times 10^{-3} \text{ MPa}\right]$

For σ_r Left → $r/a = 0$ $\left[\frac{\sigma_r}{q} \times 100 = 1.7 \Rightarrow \sigma_{r_1} = 5.865 \times 10^{-3} \text{ MPa}\right]$ → $\sigma_{r,total} = \sigma_{r1} + \sigma_{r2} = 11.385 \times 10^{-3}$ MPa

Right → $r/a = 4$ $\left[\frac{\sigma_r}{q} \times 100 = 1.6 \Rightarrow \sigma_{r2} = 5.52 \times 10^{-3} \text{ MPa}\right]$

For σ_t Left → $r/a = 0$ $\left[\frac{\sigma_t}{q} \times 100 = 0.1 \Rightarrow \sigma_t = 0.345 \times 10^{-3} \text{ MPa}\right]$

Right → $r/a = 4$ $\left[\frac{\sigma_t}{q} \times 100 = (?)\right]$ — How to find? — No line for $\frac{r}{a} = 4$!

For τ_{rz} Left → $r/a = 0$ → At axisymmetric $\tau_{rz} = 0$ itself

Right → $r/a = 4$ $\left[\frac{\tau_{rz}}{q} \times 100 = 1.8 \Rightarrow \tau_{rz} = 6.21 \times 10^{-3} \text{ MPa}\right]$

⟹ $\tau_{rz} = 6.21$ kPa

For w (vertical deflection) $w = \frac{qa}{E} \times F$

Left → $r/a = 0$ → $F = 0.68$ → $w_1 = \frac{qa}{E} F = 0.4318$ mm

Right → $r/a = 4$ → $F = 0.22$ → $w_2 = \frac{qa}{E} F = 0.01397$ mm

$w_{total} = w_{left} + w_{right} = w_1 + w_2 = 0.4577$ mm

σ_z

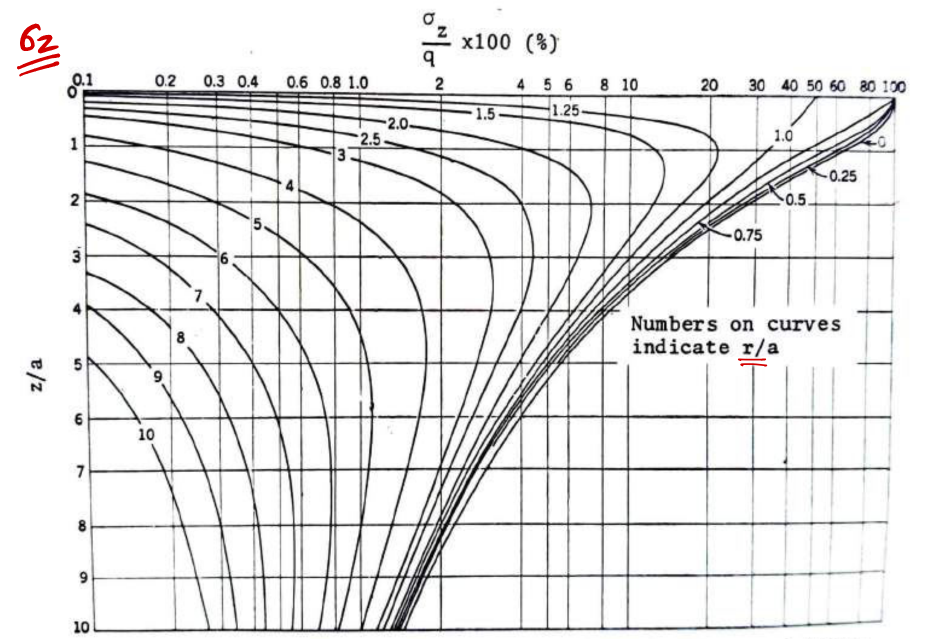


Figure 2.2 Vertical stresses due to circular loading. (After Foster and Ahlvin (1954).)

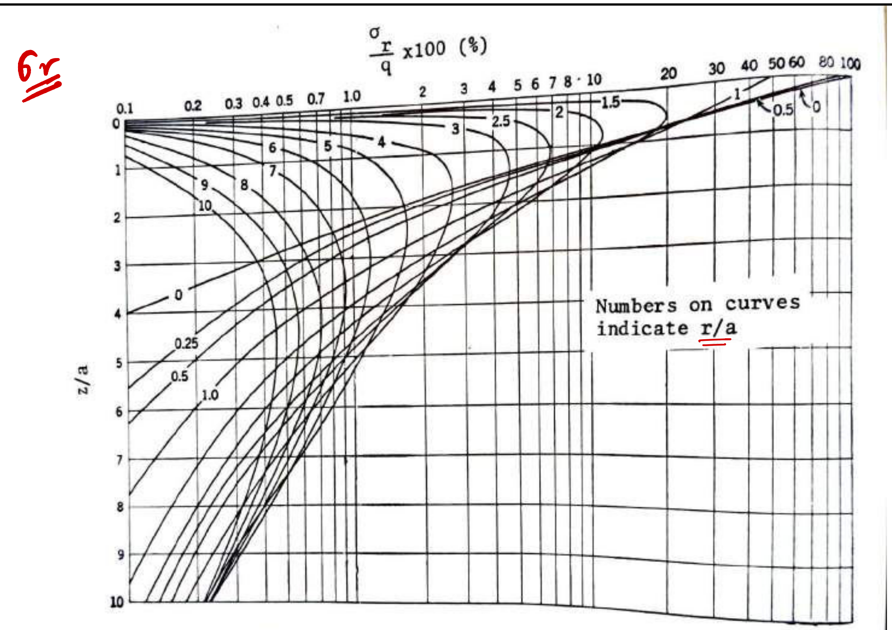


Figure 2.3 Radial stresses due to circular loading. (After Foster and Ahlvin, (1954).)

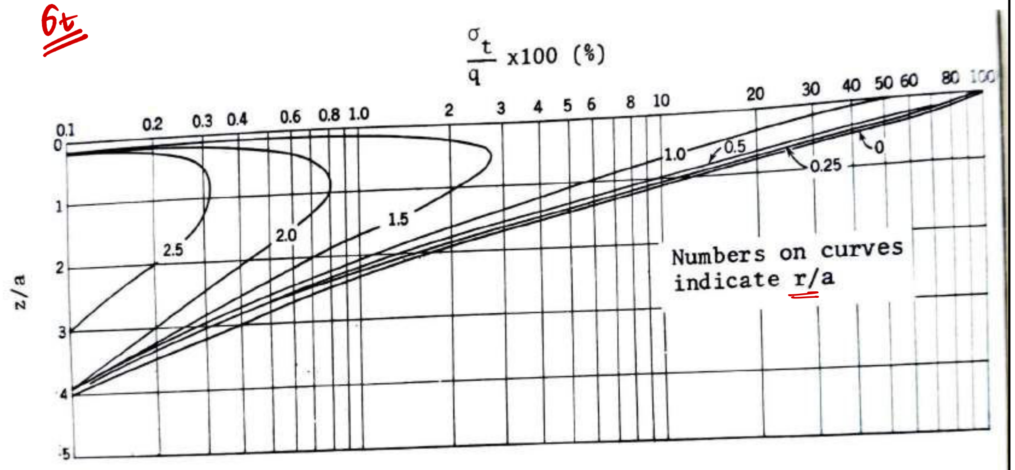


Figure 2.4 Tangential stresses due to circular loading. (After Foster and Ahlvin (1954).)

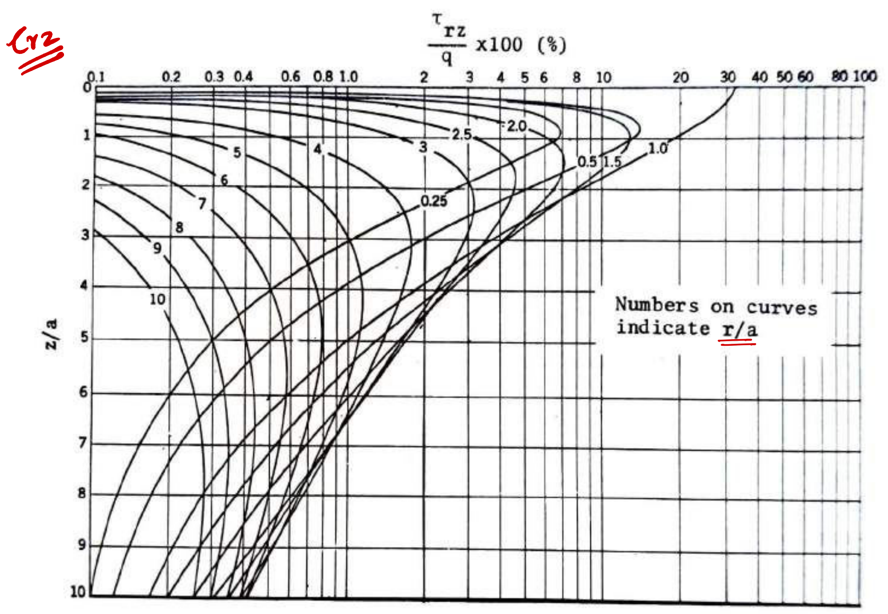


Figure 2.5 Shear stresses due to circular loading. (After Foster and Ahlvin (1954).)

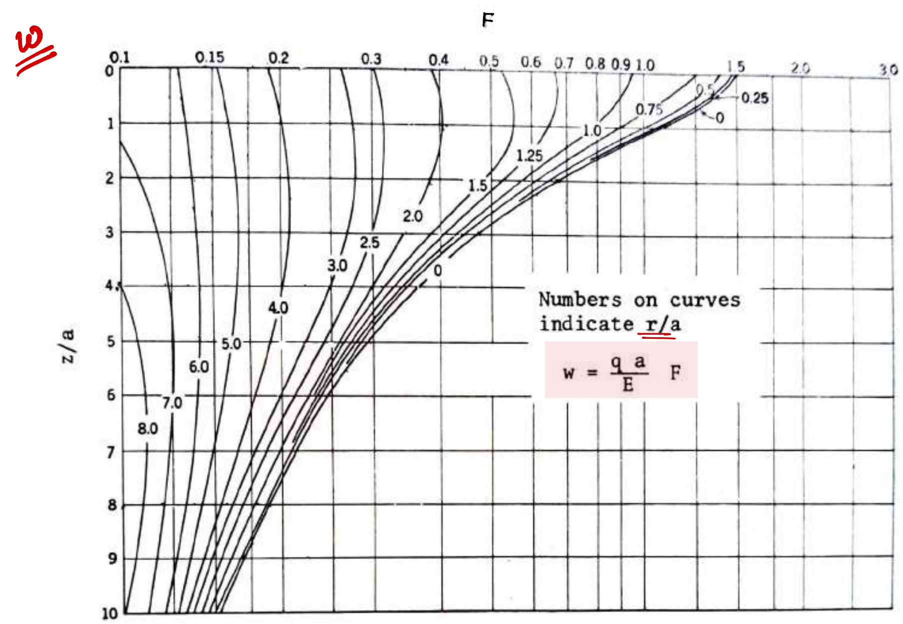
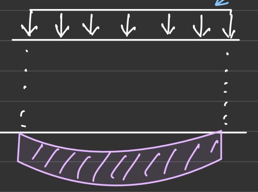


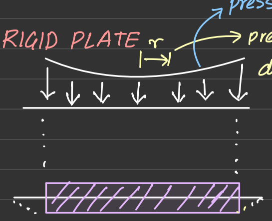
Figure 2.6 Vertical deflections due circular loading. (After Foster and Ahlvin (1954).)

Lecture 11 – PKA – 6 Apr 2023

FLEXIBLE PLATE



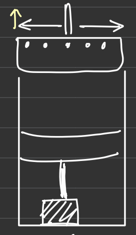
RIGID PLATE



$\left(\frac{P}{A}\right)$ average loading pressure ← $q(r) = \frac{q \times a}{2(a^2-r^2)^{0.5}}$ → dist. from center

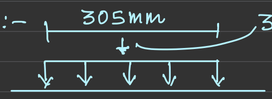
Deformation below center = $\delta = \frac{\pi}{2E}(1-\mu^2)\, q \times a$

Put $r = 0$, $q(r) = \frac{qa}{2a} = \frac{q}{2}$



mod. of surface reaction

Prob :–

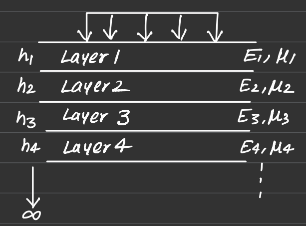


$\mu = 0.4$
$\delta = 2.54$ mm
E of subgrade = ?

Sol^n $q = \frac{35.6}{\pi r^2 \text{(in m)}} = 488$ kPa

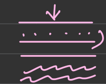
$\delta = \frac{\pi}{2E}(1-\mu^2)qa \Rightarrow E = \frac{\pi}{2\delta}(1-\mu^2)qa = \underline{\underline{38.66 \text{ MPa}}}$

Layered System



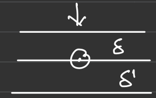
- $E_1 > E_2 > E_3 > \cdots$ usually.
- But maybe $E_1 < E_2 < E_3$ in some cases. Those are called composite pavements

Assumptions :–
- homogenous
- weightless
- isotropic
- elastic half-space
- compatibility b/w layers at interface



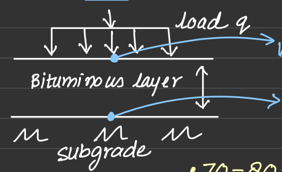
Bituminous layer — 3000 MPa
WMM — Replaced by cementitious material → 10,000 MPa
GSB
suspended...

compatibility b/w two layers :–
- vertical stress
- shear stress
- vertical displacement



- Charts – assume perfect bonding b/w two layers.

2 Layer System

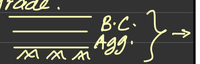


What's the max. deformation?

What's the vertical stress at the interface?

vertical strain

- 70–80% contribution to rutting comes from subgrade.



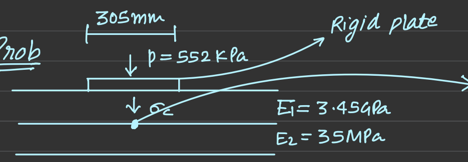
Vertical Stress (Figure 2.14)

z/a, σ_z/q, E_1/E_2 value

- What does E_1/E_2 ↑sing mean?
  It means upper layer has more stress
- strongest layer at top.
  stress ↓es as we go down
- Only applicable if top layer = radius of rutting area (Fig 2.14)
  i.e. $H_1 = a$ → 2a = top length
  top layer thickness

Figure 2.15
- a/h_1 → changing
- increase↑ the layer thickness → stress will decrease↓

Prob



→ allowable stress = σ_c = 55 kPa

Det. $h_1 = ?$

Sol^n $\frac{E_1}{E_2} = \frac{3.45 \times 10^3 \text{ MPa}}{35 \text{ MPa}} = 98.57 \approx \underline{\underline{100}}$

$\frac{\sigma_c}{q} = \frac{55 \text{ kPa}}{552 \text{ kPa}} = 0.0996 \approx \underline{\underline{0.1}}$

} → using chart (Huang)

$\frac{a}{h_1} = 1.1 \Rightarrow h_1 = \frac{a}{1.1}$

$h_1 = \frac{305}{2 \times 1.1} = \underline{\underline{138.64 \text{ mm}}}$ Ans

Now $E_1 = 173$ MPa → what change?

$\frac{E_1}{E_2} = \frac{173}{35} = 4.94 \approx \underline{\underline{5}}$

$\frac{\sigma_c}{q} = 0.1$ (same)

} → using chart (Huang)

$\frac{a}{h_1} = 0.4 \Rightarrow h_1 = \frac{305}{2 \times 0.4} = \underline{\underline{381.25 \text{ mm}}}$ Ans

Allowable No. of stress repititions to limit permanent deformation

$$N_d = 4.873\times10^{-5}\,\sigma_c^{-3.734}\,E_2^{3.583}$$

1 MPa = 145 psi

σ_c : vertical compressive stress on subgrade surface (in psi)
E_2 : elastic modulus of subgrade (in psi)
N_d : no. of load repititions

Prob:–

$\sigma_c = 55\,kPa = 55\times10^{-3}\times145\ psi = 8\ psi$
$E_2 = 35\,MPa = 35\times145\ psi = 5000\ psi$
No. of load repitions = ?

Soln: $N_d = 4.873\times10^{-5}\times(8)^{-3.734}\times(5000)^{3.583}$
$= 3.7\times10^{5}$

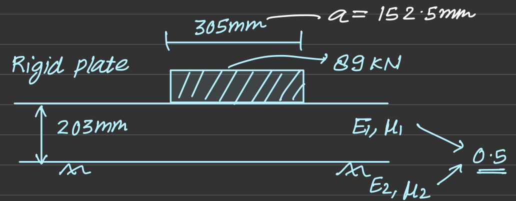
Vertical Surface Deflection (w_0)

For rigid plate, $w_0 = \dfrac{1.18\,q\,a}{E_2}F_2$

For flexible plate, $w_0 = \dfrac{1.5\,q\,a}{E_2}F_2$

W_0 = max deflection at the top of 1st layer
F_2 = deflection factor

Prob:-



$E_2 = 44.2\,MPa$
allowable deflection = 0.1mm
Det. $E_1 = ?$

Soln:- $w_0 = 0.1\,mm$
$w_0 = \dfrac{1.18\,q\,a\,F_2}{E_2}$

$q = \dfrac{89\,kN\times10^{-3}}{\pi a^2} = \dfrac{89\times10^{-3}}{\pi\times(152.5)^2\times10^{-6}} = 1.218 \approx 1.22\,MPa$

$F_2 = \dfrac{0.1\times44.2}{1.18\times1.22\times152.5} = 0.02$

But $F_2 = 0.51$

$\dfrac{h_1}{a} = \dfrac{203}{152.5} = 1.33$

Using Burmister chart find $\dfrac{E_1}{E_2} = ?$

$E_1 = 221\,MPa$

σ_z vertical stress

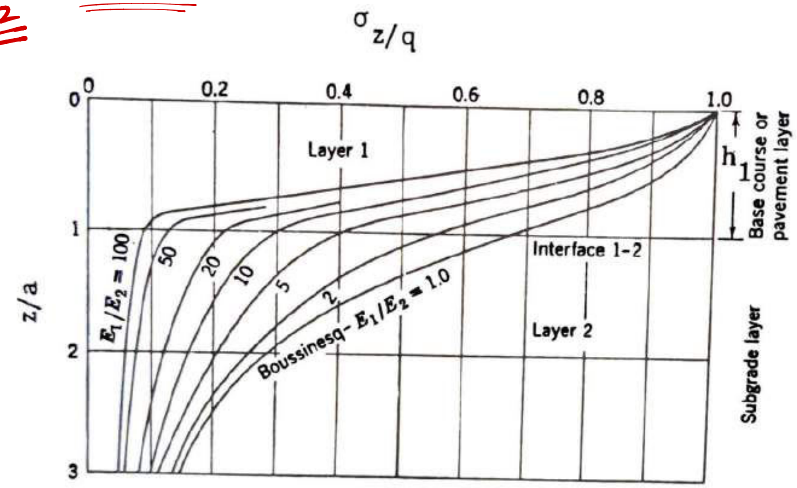


Figure 2.14 Vertical stress distribution in a two-layer system. (After Burmister (1958).)

σ_c vertical interface stress

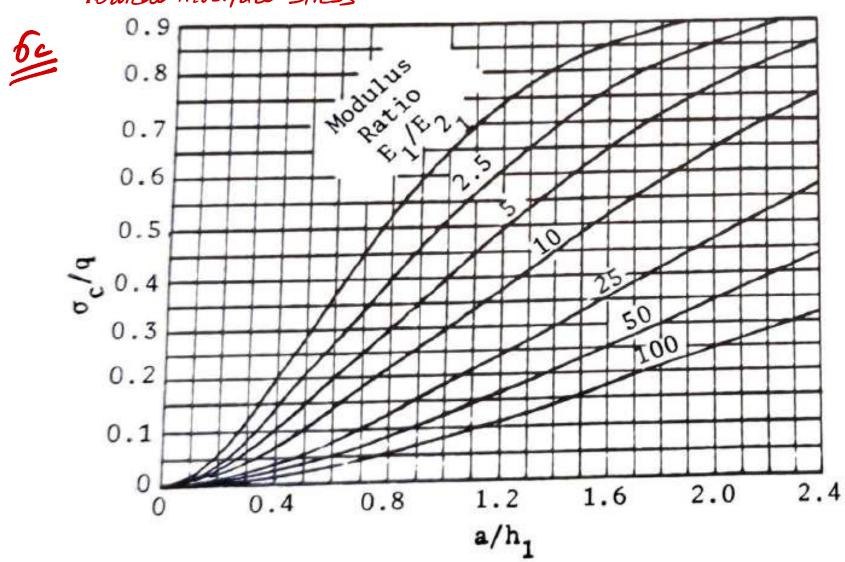


Figure 2.15 Vertical interface stresses for two-layer systems. (After Huang (1969b).)

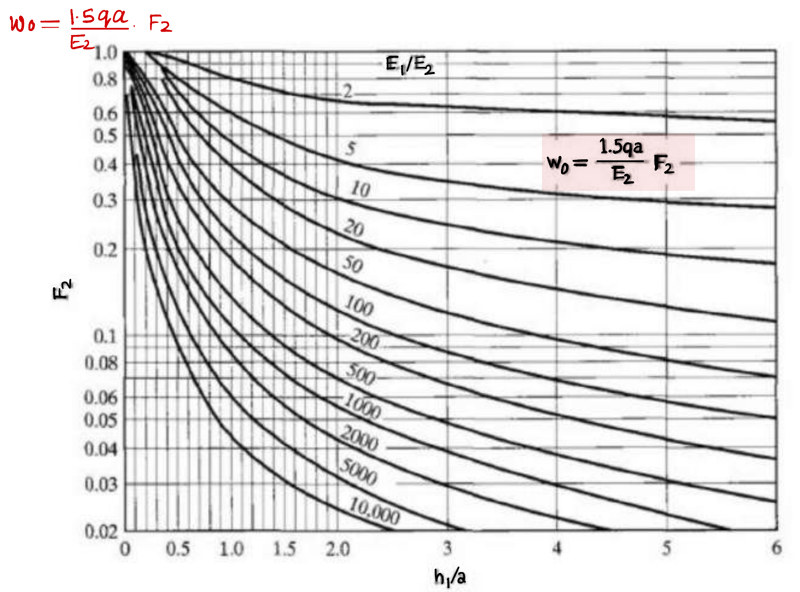


FIGURE 2.17

Vertical surface deflections for two-layer systems. (After Burmister (1943).)

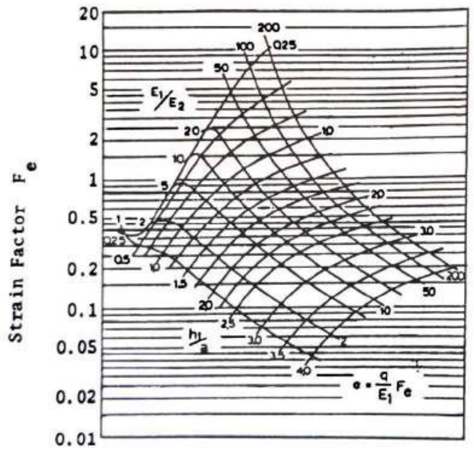


Figure 2.21 Strain factor for single wheel. (After Huang (1973a).)

Lecture12 – PKA – 8Apr 2023

Taught using Slides!!

Distress Transfer Functions (IRC 37-2018)

Subgrade Rutting Criteria

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

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

Subgrade Fatigue Criteria

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

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

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

IRC 37-2018

3.6.1 *Subgrade rutting criteria*

An average rut depth of 20 mm or more, measured along the wheel paths, is considered in these guidelines as critical or failure rutting condition. The equivalent number of standard axle load (80 kN) repetitions that can be served by the pavement, before the critical average rut depth of 20 mm or more occurs, is given by equations 3.1 and 3.2 respectively for 80 % and 90 % reliability levels. The rutting performance model developed initially based on the MoRTH R-6 Research Scheme[2] performance data was subsequently developed into two separate models for two different reliability levels based on the additional performance data collected for MoRTH R-56 Research Scheme[3].

$N_R = 4.1656 \times 10^{-08} [1/\varepsilon_v]^{4.5337}$ (for 80 % reliability) (3.1)

$N_R = 1.4100 \times 10^{-08} [1/\varepsilon_v]^{4.5337}$ (for 90 % reliability) (3.2)

Where,

N_R = subgrade rutting life (cumulative equivalent number of 80 kN standard axle loads that can be served by the pavement before the critical rut depth of 20 mm or more occurs)

ε_v = vertical compressive strain at the top of the subgrade calculated using linear elastic layered theory by applying standard axle load at the surface of the selected pavement system

3.6.2 *Fatigue cracking criteria for bituminous layer*

The occurrence of fatigue cracking (appearing as inter connected cracks), whose total area in the section of the road under consideration is 20 % or more than the paved surface area of the section, is considered to be the critical or failure condition. The equivalent number of standard axle (80 kN) load repetitions that can be served by the pavement, before the critical condition of the cracked surface area of 20 % or more occurs, is given by equations 3.3 and 3.4 respectively for 80 % and 90 % reliability levels. The fatigue performance models given by equations 3.3 and 3.4 were developed under MoRTH R-56 scheme[3] utilizing primarily the R-6 scheme (Benkelman Beam Studies) performance data[2] supplemented by the data available from R-19 (Pavement Performance Studies)[8] and R-56 schemes[3].

$N_f = 1.6064 \cdot C \cdot 10^{-04} [1/\varepsilon_t]^{3.89} \cdot [1/M_{Rm}]^{0.854}$ (for 80 % reliability) (3.3)

$N_f = 0.5161 \cdot C \cdot 10^{-04} [1/\varepsilon_t]^{3.89} \cdot [1/M_{Rm}]^{0.854}$ (for 90 % reliability) (3.4)

Where

$C = 10^M$, and $M = 4.84\left(\frac{V_{be}}{V_a + V_{be}} - 0.69\right)$

V_a = per cent volume of air void in the mix used in the bottom bituminous layer

V_{be} = per cent volume of effective bitumen in the mix used in the bottom bituminous layer

N_f = fatigue life of bituminous layer (cumulative equivalent number of 80 kN standard axle loads that can be served by the pavement before the critical cracked area of 20 % or more of paved surface area occurs)

ε_t = maximum horizontal tensile strain at the bottom of the bottom bituminous layer (DBM) calculated using linear elastic layered theory by applying standard axle load at the surface of the selected pavement system

M_{Rm} = resilient modulus (MPa) of the bituminous mix used in the bottom bituminous layer, selected as per the recommendations made in these guidelines.

The factor 'C' is an adjustment factor used to account for the effect of variation in the mix volumetric parameters (effective binder volume and air void content) on the fatigue life of bituminous mixes [9] and was incorporated in the fatigue models to integrate the mix design considerations into the fatigue performance model.

3.6.3 *Fatigue performance models for Cement Treated Base (CTB)*

3.6.3.1 In the case of pavements with CTB layer, fatigue performance check for the CTB layer should be carried out as per equation 3.5 (based on cumulative standard axle load repetitions estimated using vehicle damage factors), and as per equations 3.6 and 3.7 (cumulative fatigue damage analysis) using axle load spectrum data. It may be noted that 'cement treated' refers to stabilization by different types of cementitious materials such as cement, lime, fly-ash, or a combination thereof. The terms, 'cement treated' and 'cementitious', have been used interchangeably in these guidelines. Equation 3.5 is based on the Australian experience[11] whereas equation 3.6 is as per the recommendations of the Mechanistic-Empirical Pavement Design Guide[12]. Pavement analysis shall be carried out using IITPAVE with a contact stress of 0.8 MPa on the pavement surface to determine the tensile strain (εt) value at the bottom of the CTB layer. The number of standard axle loads derived from equation 3.5 by substituting the computed tensile strain value along with other inputs shall not be less than the design traffic.

$$N = RF\left[\frac{\left(\frac{113000}{E^{0.804}} + 191\right)}{\varepsilon_t}\right]^{12} \quad (3.5)$$

Where,

RF = reliability factor for cementitious materials for failure against fatigue

= 1 for Expressways, National Highways, Sate Highways and Urban Roads and for other categories of roads if the design traffic is more than 10 msa

= 2 for all other cases

N = number of standard axle load repetitions which the CTB can sustain

E = elastic modulus of CTB material (MPa)

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

3.6.3.2 *Cumulative fatigue damage analysis*

The CTB layer is subjected to cumulative fatigue damage by the application of axle loads of different categories and different magnitudes applied over the design life period. The fatigue life N_i of the CTB material when subjected to a specific number of applications (n_i) of axle load of class 'i' during the design period, is given by equation 3.6. Details of different types of axles, axle load spectrum, repetitions of each load group expected during the design life period, shall be obtained from the analysis of the axle load survey data.

For the purpose of analysis, each tandem axle repetition may be considered as two repetitions of a single axle carrying 50 % of the tandem axle weight as axles separated by a distance of 1.30 m or more do not have a significant overlapping of stresses. Similarly, one application of a tridem axle may be considered as three single axles, each weighing one third the weight of the tridem axle. For example, if a tridem axle carries a load of 45 tonnes, it may be taken to be equivalent to three passes of a 15 tonne single axle.

For analyzing the pavement for cumulative fatigue damage of the CTB layer, contact stress shall be taken as 0.80 MPa instead of 0.56 MPa.

$$\log_{0.8} N_i = \frac{0.972 - (\sigma_t / M_{Rup})}{0.0825} \quad (3.6)$$

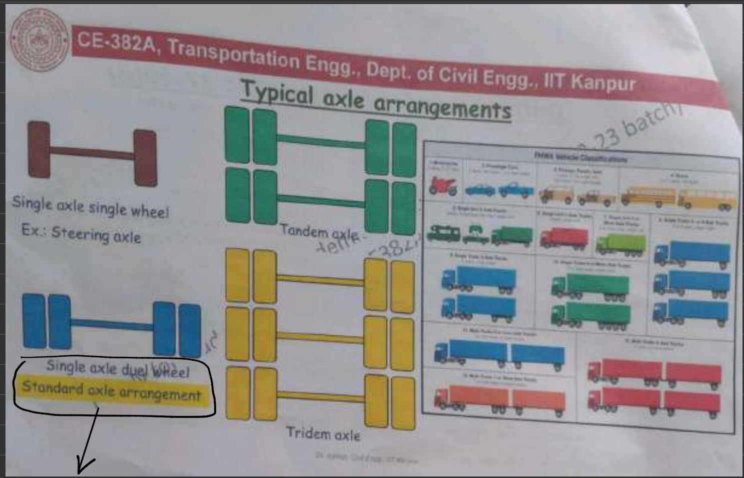
Where,

N_i = Fatigue life of CTB material which is the maximum repetitions of axle load class 'i' the CTB material can sustain

σ_t = tensile stress at the bottom of CTB layer for the given axle load class.

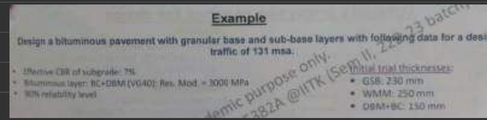
M_{Rup} = 28-day flexural strength of the cementitious base

σ_t/M_{Rup} = Stress Ratio



- All are converted to <u>single axle duel wheel</u> (standard axle arrangement)

IIT Pave – Pavement Design



3 layers

BL						
WMM	Base	L1	3000	0·35	150
CGB	subbase	L2	196	0·40	480
~ ~	subgrade	L3	61	0·45	

standard 8·1 ton axle load total → $\frac{8.1}{4}$ ton in Newton

Tyre pressure = 0·56 MPa
load = 20,000 N

Analysis point

Depth	Radial distance
150	0
150	155
630	0
630	155

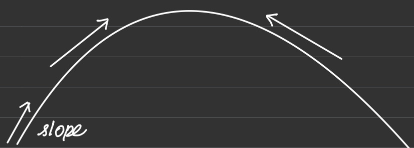
standard distance b/w those tires.

Fatigue N_f – 131×10⁶ ; V_{be} = 3%
Rutting N_R – ← ϵ_r ; V_a = 11·5%
} calculate N_f

Lecture 13 – PKA – 11 Apr 2023 — Taught using slides !!

Some Typical Observations

- Maximum speed you drive? Do you care about speed limit? Design speed?
- How fast you apply the break?
- How do you decide overtaking?
- Driving at curves: Horizontal curves ; vertical curves.



- Other important aspects: camber, widening of curves, driving in nights, traffic channelization, etc

How about understanding the driving behaviour of a driver?

camber

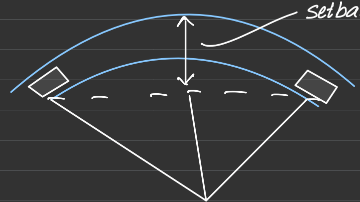
Why camber?
To ensure proper drainage of rainwater

Design of Horizontal & vertical curves and components.

Typical Terrain Types

IRC 73 : 2020
Classification of terrain based on slope.

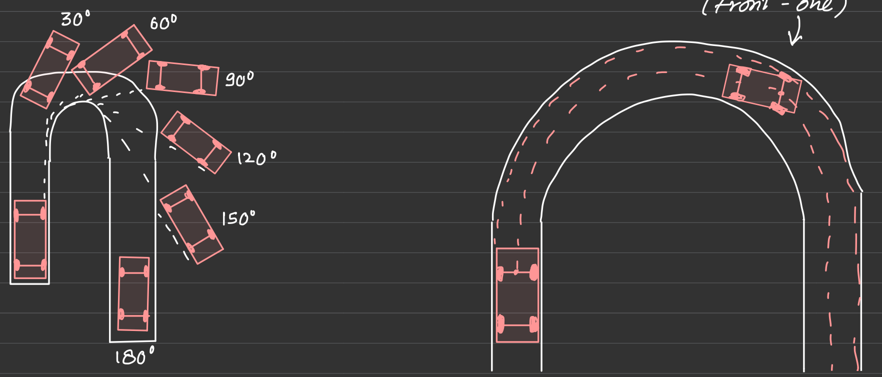
Horizontal Curves



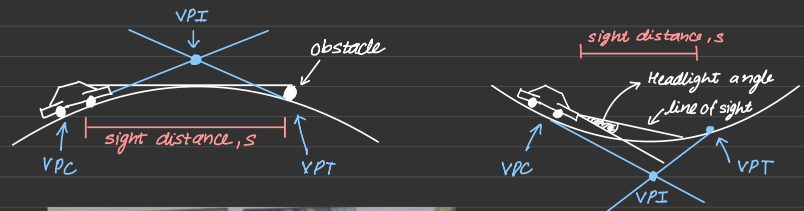
crash barriers
- to reduce the intensity of accident.
- prevent cars from leaving track.

Turning Radius and Turning Path

Geometric design especially for sharp turns based horizontal curves.
- Front wheel can only turn.
- Minimum and Maximum turning radius.
- Centre line turning radius.

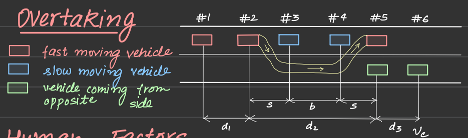


Vertical curves



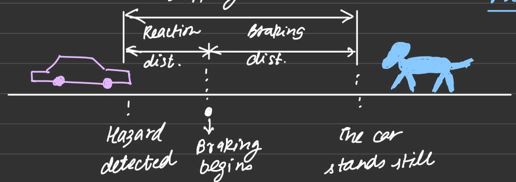
why parabola?
Transition should be smooth

Overtaking



Human Factors

Perception Reaction Process

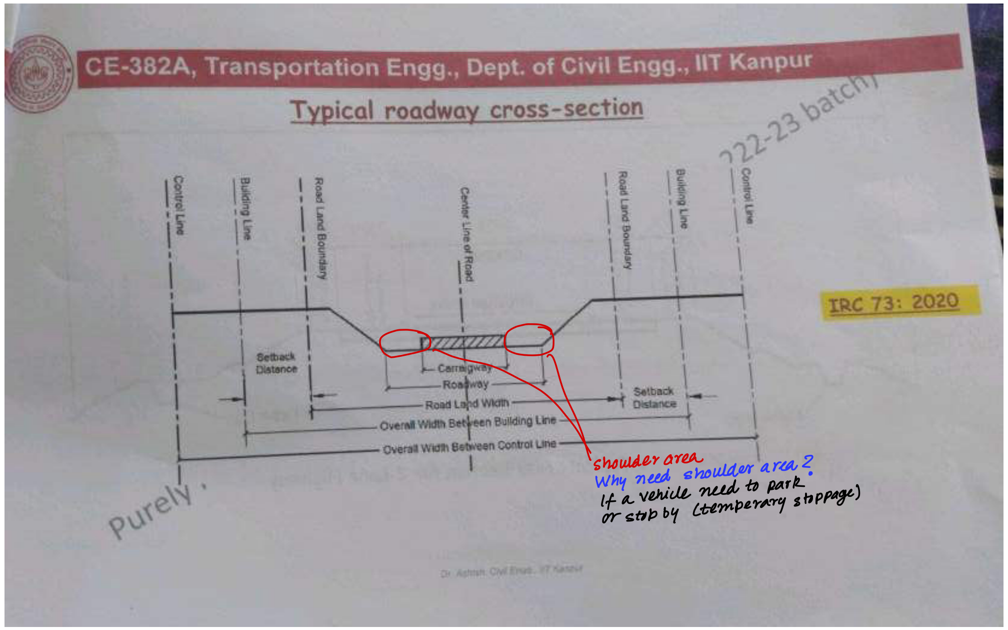


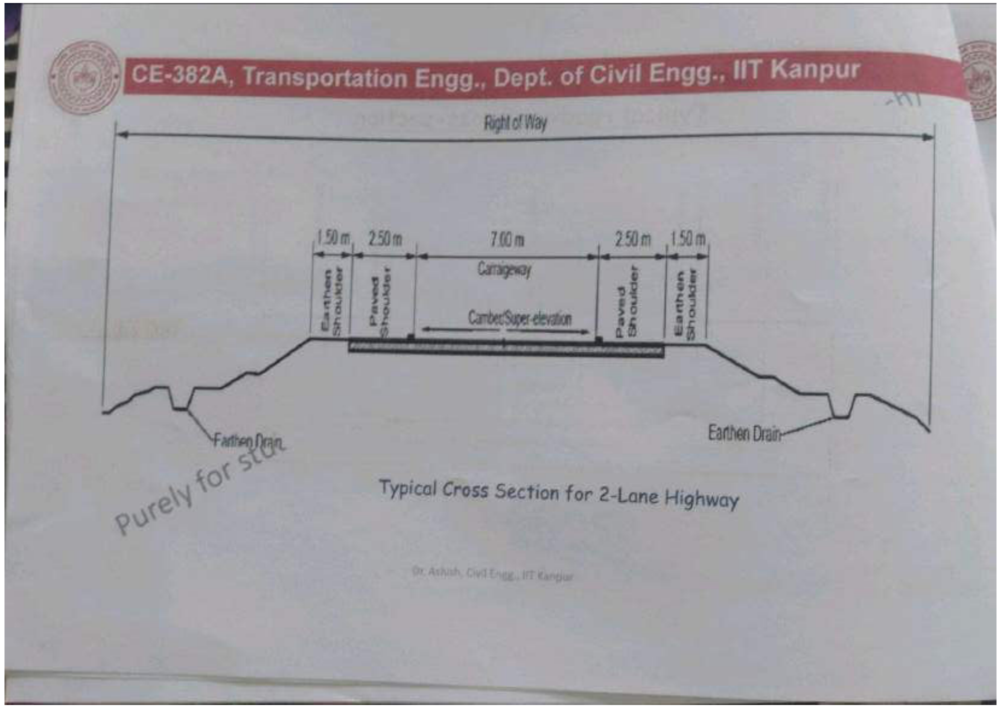
PIEV Theory

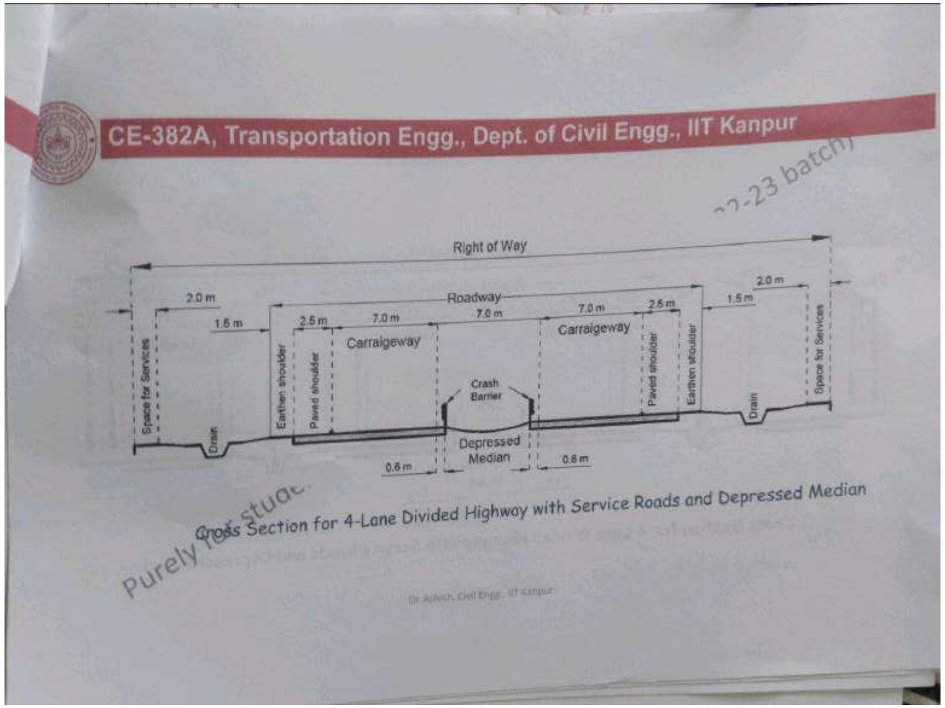
Influencing factors:-
- Age
- Intoxication level
- Fatigue level
- Distracted driving

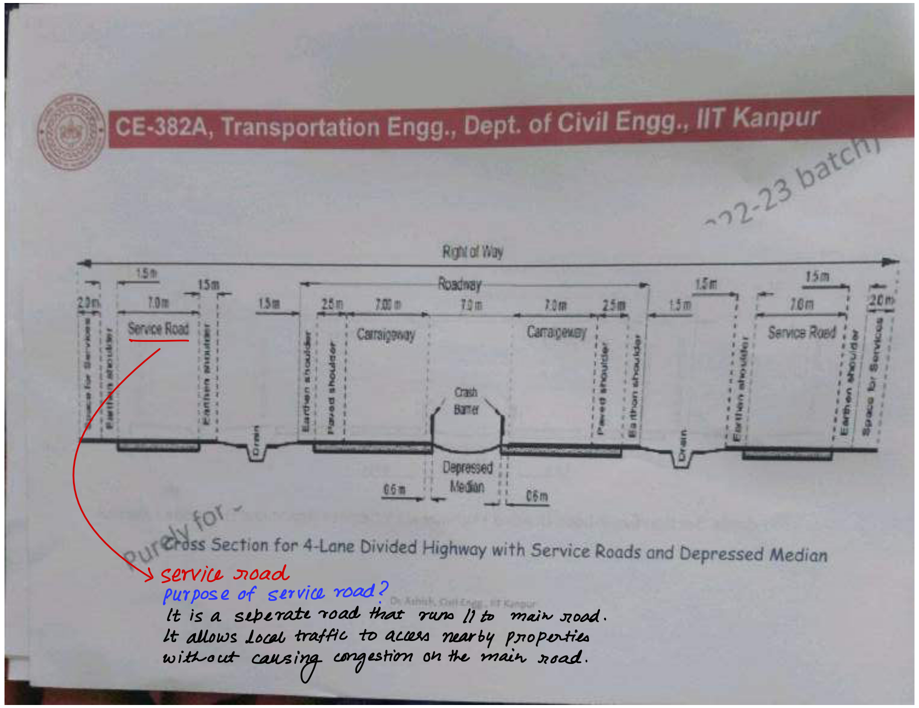
- 2.5 sec as per IRC:73 and AASHTO
- Mobile talking → ↑es by 200% → 5 sec.

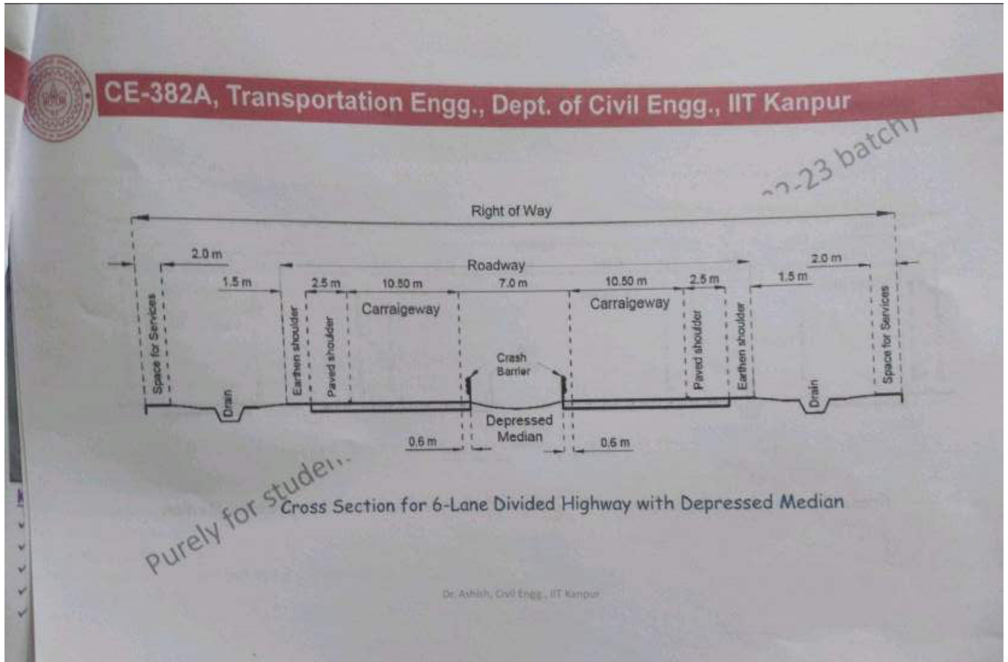
How to study driver's behaviour?
Using simulations
(Driving simulation based study)

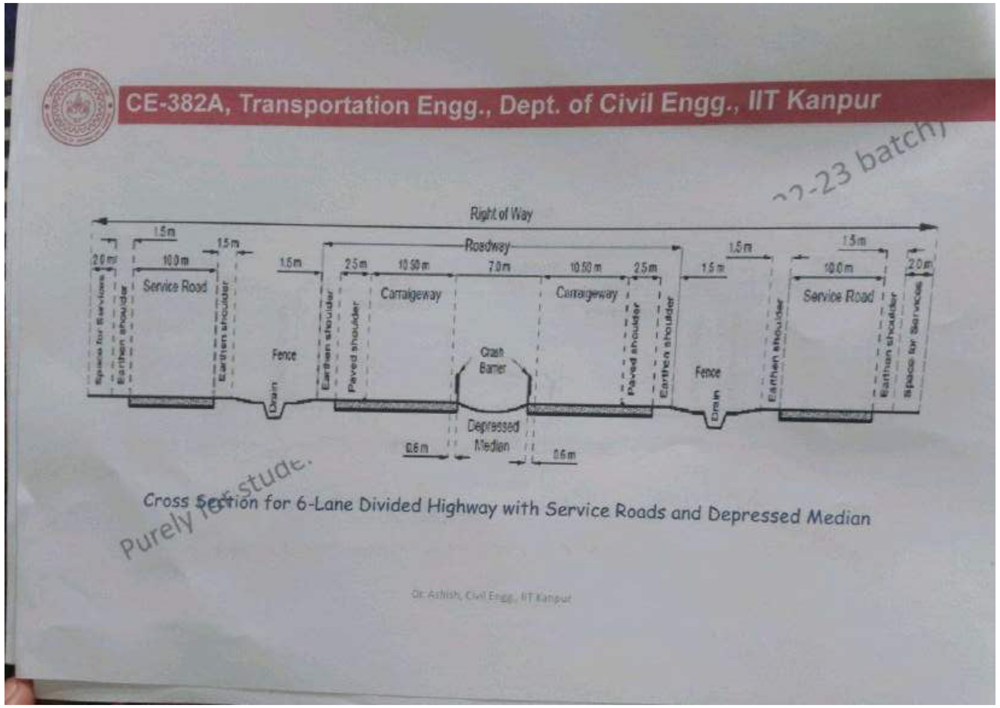



CE-382A, Transportation Engg., Dept. of Civil Engg., IIT Kanpur
Right of Way
1.50 m
2.50 m
7.00 m
2.50 m
1.50 m
Earthen Shoulder
Paved Shoulder
Carriageway
Camber/Super-elevation
Paved Shoulder
Earthen Shoulder
Earthen Drain
Earthen Drain
Purely for stu
Typical Cross Section for 2-Lane Highway
Dr. Ashish, Civil Engg., IIT Kanpur


CE-382A, Transportation Engg., Dept. of Civil Engg., IIT Kanpur
22-23 batch)
Right of Way
Roadway
2.0 m
1.5 m
2.5 m
7.0 m
7.0 m
7.0 m
2.5 m
1.5 m
2.0 m
Space for Services
Drain
Earthen shoulder
Paved shoulder
Carriageway
Crash Barrier
Carriageway
Paved shoulder
Earthen shoulder
Drain
Space for Services
Depressed Median
0.6 m
0.6 m
Purely for stud
Cross Section for 4-Lane Divided Highway with Service Roads and Depressed Median
Dr. Ashish, Civil Engg., IIT Kanpur


CE-382A, Transportation Engg., Dept. of Civil Engg., IIT Kanpur
22-23 batch)
Right of Way
Roadway
Space for Services
Earthen shoulder
Service Road
Earthen shoulder
Drain
Earthen shoulder
Paved shoulder
Carriageway
Crash Barrier
Carriageway
Paved shoulder
Earthen shoulder
Drain
Earthen shoulder
Service Road
Earthen shoulder
Space for Services
Depressed Median
0.6 m
0.6 m
Purely for
Cross Section for 4-Lane Divided Highway with Service Roads and Depressed Median
service road
purpose of service road?
It is a seperate road that runs || to main road.
It allows local traffic to access nearby properties
without causing congestion on the main road.

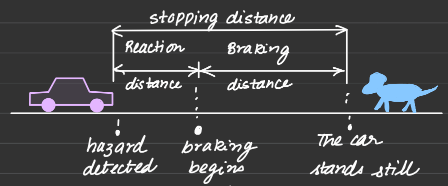

CE-382A, Transportation Engg., Dept. of Civil Engg., IIT Kanpur
22-23 batch)
Right of Way
Roadway
2.0 m
1.5 m
2.5 m
10.50 m
7.0 m
10.50 m
2.5 m
1.5 m
2.0 m
Space for Services
Drain
Earthen shoulder
Paved shoulder
Carriageway
Crash Barrier
Carriageway
Paved shoulder
Earthen shoulder
Drain
Space for Services
Depressed Median
0.6 m
0.6 m
Purely for studen
Cross Section for 6-Lane Divided Highway with Depressed Median
Dr. Ashish, Civil Engg., IIT Kanpur



Lecture 14 – PKA – 13 Apr 2023 | Taught using Slides!!

Stopping Sight Distance (SSD)

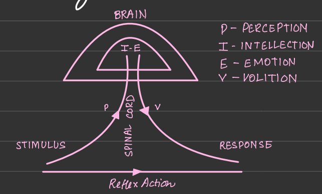
Stopping sight distance is the minimum distance required for a driver to see an obstacle ahead and stop their vehicle safely without colliding with the obstacle.



PIEV Theory

Perception + Intellection + Emotion + Volition

Perceiving → Inferring the situation → Action



- Height of the driver's eye is assumed to be 1.2 m.
- Height of the object is assumed to be at 0.15 m.

Major Influencing Factors

- Reaction time (typically 2.5 sec)
- Vehicle Speed
- Break Efficiency
- Friction b/w road and tyre (assumed to be 0.35 – 0.4 as per IRC 73)
- Gradient, if any

SSD = Reaction (or lag) distance + Breaking distance

superelevation vertical curves

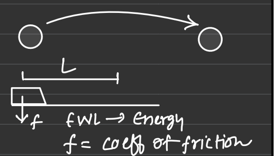
Stopping Distance on Level Road

Stopping sight Distance = Lag Distance + Braking Distance

Design speed = v , Reaction time = t

Reaction Distance (lag distance) = $v \times t$

For braking distance, equating work done and K.E.



$$\frac{1}{2}mv^2 - 0 = \frac{1}{2}\frac{W}{g}v^2$$

$$\frac{1}{2}\frac{W}{g}v^2 - 0 = fWL$$

$$\frac{v^2}{2g} = fL$$

$$L = \frac{v^2}{2gf}$$ (Braking distance)

Recommended coeff. of friction (f) values for SSD

Speed (Km/h)	< 30	40	50	60	65	> 80
f	0.40	0.38	0.37	0.36	0.36	0.35

$$SSD = vt + \frac{v^2}{2gf}$$

Stopping Distance on Slopes

Work done by friction = $fWL + W\sin\theta\, L = \frac{1}{2}\frac{W v^2}{g}$

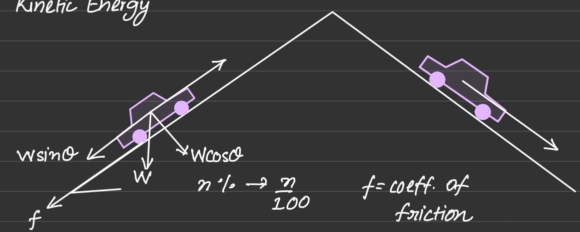
Equating work done and Kinetic Energy

$$L\left(fW + \frac{Wn}{100}\right) = \frac{Wv^2}{2g}$$

$$L\left(f + \frac{n}{100}\right) = \frac{v^2}{2g}$$

$$L = \frac{v^2}{2g\left(f + \frac{n}{100}\right)}$$

$$L = \frac{v^2}{2g\left(f \pm \frac{n}{100}\right)}$$



n = gradient (or slope) in %

+ → ascending gradient → upward

– → descending gradient → downward

$$SSD = \text{lag distance} + \text{break distance} = vt + \frac{v^2}{2g\left(f \pm \frac{n}{100}\right)}$$

Problems

Prob#1

SSD = ?

$f = 0.4$ $t = 2\,sec$

Soln

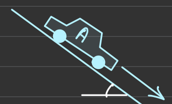
$n = 0$

lag distance $= vt = (90\times0.28)\times2 = 50.4\,m$

braking distance $= \frac{v^2}{2gf} = \frac{(90\times0.28)^2}{2\times10\times0.4} = 79.38\,m$

SSD = lag dist. + braking dist. $= 50.4 + 79.38 = 129.78\,m$

Prob#2



$n = 2\%$ RT = 2.5 sec SSD = ?

$v = 80\,kmph$ $f = 0.35$

Soln:- $n = 2\%$ → descending →−

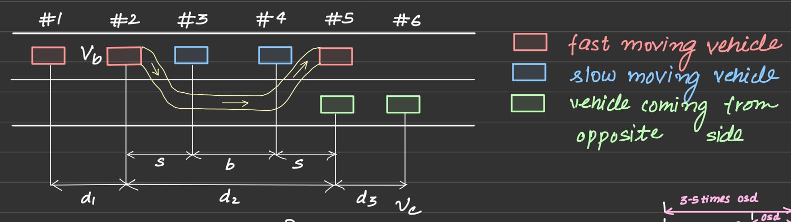
lag dist. $= vt = (80\times0.28)\times2.5 = 56\,m$

braking dist. $= \frac{v^2}{2g(f \pm \frac{n}{100})} = \frac{(80\times0.28)^2}{2\times10(0.35 - 2/100)} = 76\,m$

SSD = lag dist. + braking dist $= 56 + 76 = 132\,m$

Overtaking Sight Distance (SSD)

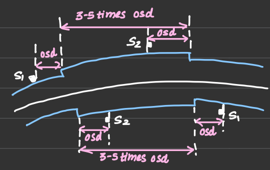
Overtaking sight distance is the minimum distance required for a driver to safely overtake another vehicle on a roadway.



Need to find:- d_1, d_2, d_3?

Major Influencing Factors

- Speed of all three vehicles
- Distance b/w overtaking & overtaken vehicle
- Reaction Time
- Rate of acceleration
- Gradient, if any.



S_1 – overtaking zone begin
S_2 – End of overtaking zone

Overtaking Zone

- Minimum overtaking specified length = 3×OSD
- Desirable overtaking specified length = 5×OSD

---

t_1 – Reaction time (IRC–2sec)

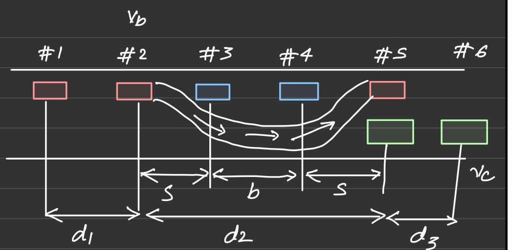
$d_1 = v_b \times t_1$ ——(1)

T – overtaking time

$d_2 = v_b T + \frac{1}{2}aT^2 = s+b+s = b+2s$ ——(2)

$s = (0.7 v_b + 6)$ (spacing b/w vehicles) ——(3)

$b = v_b T$ ——(4)



using (4) and (2), $v_b T + \frac{1}{2}aT^2 = b + 2s \Rightarrow \cancel{v_b T} + \frac{1}{2}aT^2 = \cancel{v_b T} + 2s$

$\frac{1}{2}aT^2 = 2s$ ——(5)

$T = \sqrt{\frac{4s}{a}} = 2\sqrt{\frac{s}{a}} \Rightarrow b = v_b T = 2v_b\sqrt{\frac{s}{a}}$

$d_2 = b + 2s = 2v_b\sqrt{\frac{s}{a}} + 2s$ ——(6)

$d_3 = v_c T$ ——(7)

$OSD = d_1 + d_2 + d_3$

$d_1 = v_b \times t$	$T = 2\sqrt{\frac{s}{a}}$
$d_2 = v_b \times T + 2s$	
$d_3 = v_c \times T$	$s = (0.7 v_b + 6)$ m/sec
$OSD = d_1 + d_2 + d_3$	

- $OSD = d_1 + d_2$ for one way roads
- $OSD = d_1 + d_2 + d_3$ for two way roads

Prob: $V_a = 70\,kmph$ — V_c – same in the beginning

$V_b = 40\,kmph$ one-way

$a = 0.99\,m/s^2$ $t = 2\,sec$ OSD = ?

In 1-way $d_3 = 0$

If median is there, then also $d_3 = 0$ and $OSD = d_1 + d_2$

Soln

$d_1 = v_b t = (40\times0.28)\times2 = 22.4\,m$

$S = 0.7V_b + 6 = 0.7\times(40\times0.28) + 6 = 13.84\,m$

$T = 2\sqrt{\frac{s}{a}} = 2\sqrt{\frac{13.84}{0.99}} = 7.48\,s$

$d_2 = b + 2s = V_bT + 2s = (40\times0.28)\times7.48 + 2\times13.84 = 111.46\,m$

$d_3 = V_cT = (70\times0.28)\times7.48 = 148.6\,m$

$OSD = d_1 + d_2 + d_3 = \underline{282.46\,m}$

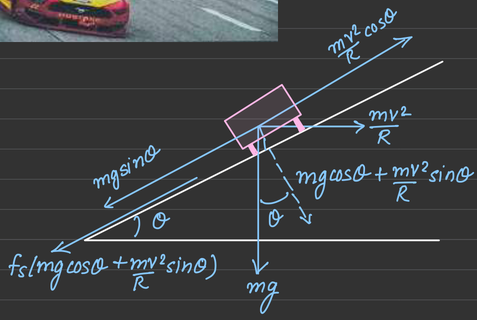
Superelevation

Superelevation is the banking or tilting of a road or highway's horizontal curve. It is designed to counteract the centrifugal force that pushes a vehicle outwards when it travels around a curve at high speeds. By angling the roadway slightly, superelevation helps keep the vehicle on the road, making it safer for drivers. In simpler terms, superelevation is the slope on a curve that helps you stay on the road when driving around a bend.

Frictional Coeff. Value
- Typical suggested value 0.15
- As per AASHTO code :
  - $= 0.19 - 0.0006V$; $30 < V < 80$ kmph
  - $= 0.24 - 0.0012V$; $V > 80$ kmph

Imp factors affecting friction
- Tyre condition
- Weather condition
- Road condition

Key Design Parameters
- Radius of horizontal curve
- Max/Min superelevation
- Negotiating speed
- How to introduce superelevation
- setback distance



$$mg\sin\theta + f\left(mg\cos\theta + \frac{mv^2}{R}\sin\theta\right) = \frac{mv^2}{R}\cos\theta$$

$$g\sin\theta + fg\cos\theta + \frac{fv^2}{R}\sin\theta = \frac{v^2}{R}\cos\theta$$

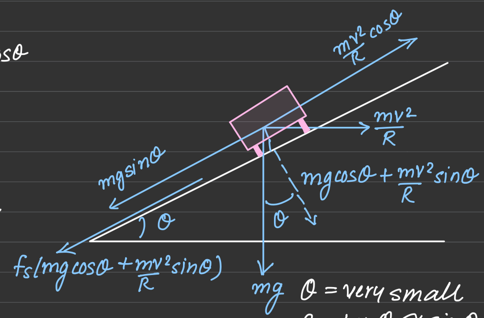
$$g\tan\theta + fg + \frac{fv^2}{R}\tan\theta = \frac{v^2}{R} \quad (\tan\theta \rightarrow = e)$$

$$ge + fg + \frac{fv^2}{R}e = \frac{v^2}{R}$$

$$\frac{v^2}{R}(1-fe) = g(e+f)$$

$$R = \frac{v^2(1-fe)}{g(e+f)} \approx \frac{v^2}{g(e+f)} \quad \{fe \rightarrow 0 \text{ (very small)}\}, \ fe \rightarrow 0$$

$$\therefore \ R = \frac{v^2}{g(e+f)}$$



θ = very small
$e = \tan\theta \approx \sin\theta$
$\sin\theta \approx \tan\theta$
$\cos\theta \approx 1$

Lecture 15 – PKA – 19 Apr 2023

Superelevation

$$mg\sin\theta + f\left(mg\cos\theta + \frac{mv^2}{R}\sin\theta\right) = \frac{mv^2}{R}\cos\theta$$

$$g\sin\theta + fg\cos\theta + \frac{fv^2}{R}\sin\theta = \frac{v^2}{R}\cos\theta$$

$$g\tan\theta + fg + \frac{fv^2}{R}\tan\theta = \frac{v^2}{R} \quad (\tan\theta \rightarrow = e)$$

$$ge + fg + \frac{fv^2}{R}e = \frac{v^2}{R}$$

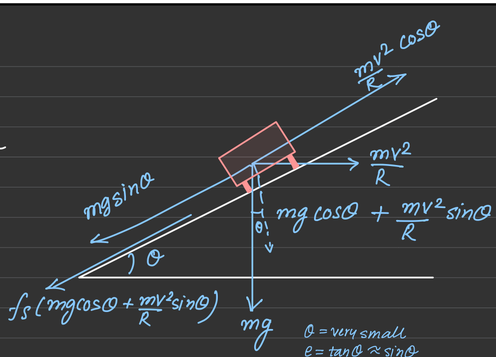
$$\frac{v^2}{R}(1-fe) = g(e+f)$$

$$R = \frac{v^2(1-fe)}{g(e+f)} \approx \frac{v^2}{g(e+f)} \quad \therefore \ R = \frac{v^2}{g(e+f)}$$

e: elevation $= \tan\theta$
f: coeff. of lateral fric.

$e+f = \frac{v^2}{gR}$ — v in m/sec

$e+f = \frac{V^2}{127R}$ — V in km/h



θ = very small
$e = \tan\theta \approx \sin\theta$
$\sin\theta \approx \tan\theta$, $\cos\theta \approx 1$ } for small θ

Suggested lateral frictional coefficient value
- Typical suggested value : 0.15
- As per AASHTO code $= 0.19 - 0.0006V$; $30 < V < 80$ Kmph
  $= 0.24 - 0.0012V$; $V > 80$ Kmph

Suggested superelevation values as per IRC 73
- For plain and rolling terrain : max 7%
- For hilly and steep slope terrain : max 10%
- Minimum value : camber of the road

Speed for superelevation design
- Max. superelevation may convenient for vehicle moving close to design speed but not for slow moving vehicle.
- As a compromise, and practical consideration, superelevation is aimed to counteract centrifugal force developed by 75%. of the design speed (by neglecting lateral friction)

$$e = \frac{(0.75V)^2}{127R} = \frac{V^2}{225R}$$

V is in Kmph

Steps for superelevation design

- Cal. 75% of the design speed.
- If $e_{cal} < e_{max}$; e_{cal} will be provided.
- If $e_{cal} > e_{max}$; keep $e_{max} = 0.07$ (say for plain and rolling terrain) and check for f value at full design speed

$$f = \frac{V^2}{127R} - 0.07$$

- If f from above step < 0.15 ; provided e is safe. If not, restriction on speed needs to be made as per:

$$e + f = 0.07 + 0.15 = 0.22 = \frac{V^2}{127R}$$

Prob: $R = 500\,m$, $V = 100\,kmph$; $e = ?$, $f = ?$

Soln: $e = \frac{V^2}{225R} = \frac{100^2}{225 \times 500} = 0.09$

$$f = \frac{V^2}{127R} - 0.07 = \frac{100^2}{127 \times 500} - 0.07 = 0.0875$$

Ruling and Minimum Radius

→ Question in exams → Maybe on this!

$$e + f = \frac{V^2}{127R}$$

$$R_{ruling} = \frac{V_{ruling}^2}{127(e+f)} \qquad R_{min} = \frac{V_{min}^2}{127(e+f)}$$

Table 4.8 Design Speeds on Rural Highways

Road classification	Design speed in kmph for various terrains							
	Plain		Rolling		Mountainous		Steep	
	Ruling	Min.	Ruling	Min.	Ruling	Min.	Ruling	Min.
National & State Highways	100	80	80	65	50	40	40	30
Major District Roads	80	65	65	50	40	30	30	20
Other District Roads	65	50	50	40	30	25	25	20
Village Roads	50	40	40	35	25	20	25	20

Table 4.10 Minimum radii of horizontal curves for different terrain conditions, m

Classification of roads	Plain terrain		Rolling terrain		Mountainous terrain				Steep terrain			
					Area not affected by snow		Snow bound areas		Area not affected by snow		Snow bound areas	
	Ruling Mini	Absolute Mini	Ruling Mini	Absolute Mini	Ruling Mini	Absolute Mini	Ruling Mini	Absolute Mini	Ruling Mini	Absolute Mini	Ruling Mini	Absolute Mini
NH & SH	360	230	230	155	80	50	90	60	50	30	60	33
MDR	230	155	155	90	50	30	60	33	30	14	33	15
ODR	155	90	90	60	30	20	33	23	20	14	23	15
VR	90	60	60	45	20	14	23	15	20	14	23	15

Note: The values of ruling minimum and absolute minimum radii correspond to the ruling and minimum design speed values given in Table 4.8.

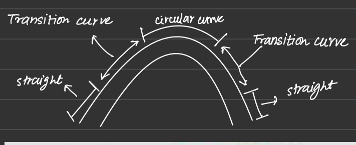
Khanna and Justo [Highway Engineering]

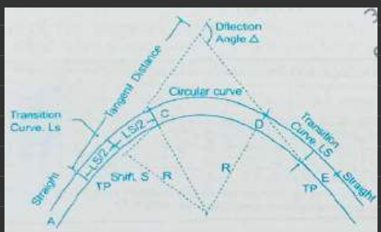
Dr. Ashish, Civil Engg., IIT Kanpur

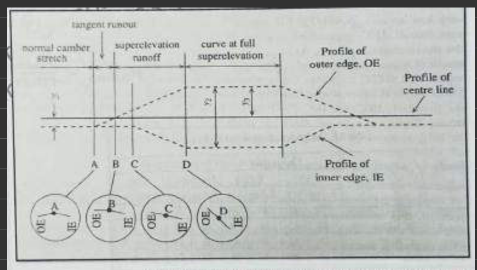
How to introduce superelevation at horizontal curve?

- With transition curve: Gradually introduced over the transition curve and remains constant over the circular curve.
- Without transition curve: 2/3rd e is provided at the beginning of circular curve and 1/3rd e is gradually attended till the half part of the circular curve.
- Natural path of driver: follow transition curve

Rotation about the outer edge
Rotation about the inside edge
Rotation about the central line







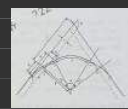
Chakroborty and Das [Principles of Transpiration Engineering]

Transition Curves

- Form: spiral: because of linear increases in its curvature (1/radius) with the length of transition curve
- Major controlling factor for designing transition curve: rate of change of acc: $0.5 - 0.8\ m/s^2$ a/c IRC 73

Rate of change of acc $= \frac{80}{75 + V}$; V is in kmph

- Acc at the start of transition curve $= 0$ & Acc. at the end of transition curve $= V^2/R$
- If 'J' is the rate of change of acc; length of transition curve 'L' then for moving vehicle at speed v



$$\text{Rate of change in acc.} = \frac{\frac{v^2}{R} - 0}{L/v} = \frac{v^3}{LR}$$

- If J^* is the permissible limit for the rate of change in acc, then

$$L_{min} = \frac{v^3}{RJ^*}$$

★ superelevation runoff needs to be provided on the transition curve; therefore, L should always be greater than superelevation runoff and L_{min}.

★ The length of transition curve can also be calculated based on rate of introducing superelevation.

Transition Curves

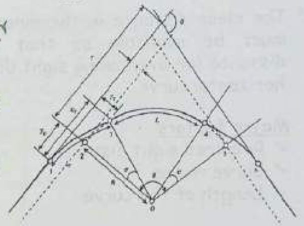
CE-382A, Transportation Engg., Dept. of Civil Engg., IIT Kanpur

Transition curves

- Form: Spiral: because of linear increase in its curvature (1/radius) with the length of transition curve
- Major controlling factor for designing transition curve: rate of change of acc.: 0.5-0.8 m/s³ a/c IRC 73.
  - Rate of change of acc. $= \frac{80}{75+V}$; V is in km/hr
- Acc. at the start of transition curve = 0 ; & Acc. at the end of transition curve = V^2/R
- If "J" is the rate of change in acc., length of transition curve as "L", then for vehicle moving at speed "v";
  - Rate of change in acc. $= \frac{\frac{v^2}{R} - 0}{L/v} = \frac{v^3}{LR}$
- If J* is the permissible limit for the rate of change in acc.: then $L_{min} = \frac{v^3}{RJ^*}$

*Superelevation runoff needs to be provided on the transition curve; therefore, L should always be greater than superelevation runoff and L_{min}

**The length of transition curve can also be calculated based on rate of introducing superelevation.



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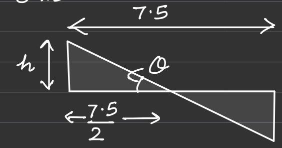
Prob:- S = 65 Kmph, R = 220 m. Pav. width = ? Allowable rate of introducing 'e' = 1 in 150. Rot. about central line.
a) Based on rate of change of acc.
b) e

Solⁿ:-

$$e = \frac{V^2}{225R} = \frac{65^2}{225 \times 220} = 0.08 \not> 0.07 \Rightarrow e = 0.07$$

$$e = \tan\theta = \frac{h}{(7.5/2)} = 0.07 \Rightarrow h = 0.26\ m$$



∵ For 1 m length, 150 m rise (given)

rise for ('h' = 0.26 m)
= 150 × 0.26
= 39 m
↳ total length of transition curve (pavement width)

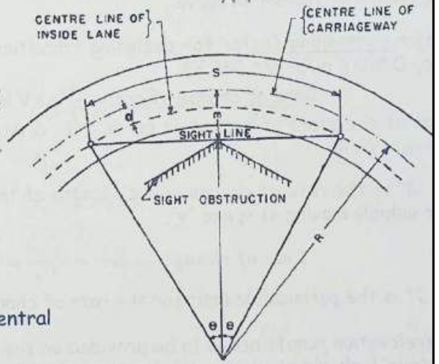
Setback Distance

Setback distance

- The clear distance in the inner side of the curve which must be available so that adequate stopping sight distance (or overtaking sight distance) is available on the horizontal curve.

Major factors
- Required sight distance
- Curve radius
- Length of the curve

Critical lanes for setback distance calculation
- For narrow roads:, sight distance is measured along the central line of the horizontal curve
- For wider roads, sight distance is measured along the inner lane of the horizontal curve.



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When sight distance is less than length of the curve

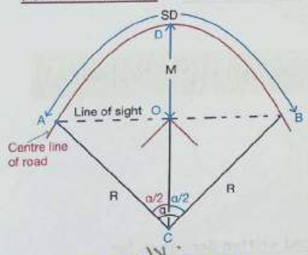
For narrow road
$m = R - R(\cos(\frac{\alpha}{2}))$

For wider road
$m = R - (R-d)(\cos(\frac{\theta}{2}))$

Setback distance

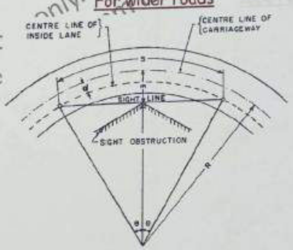
When sight distance is less than length of the curve

For narrow roads



$m = R - R(\cos(\alpha/2))$

For wider roads



$m = R - (R-d)(\cos(\theta/2))$

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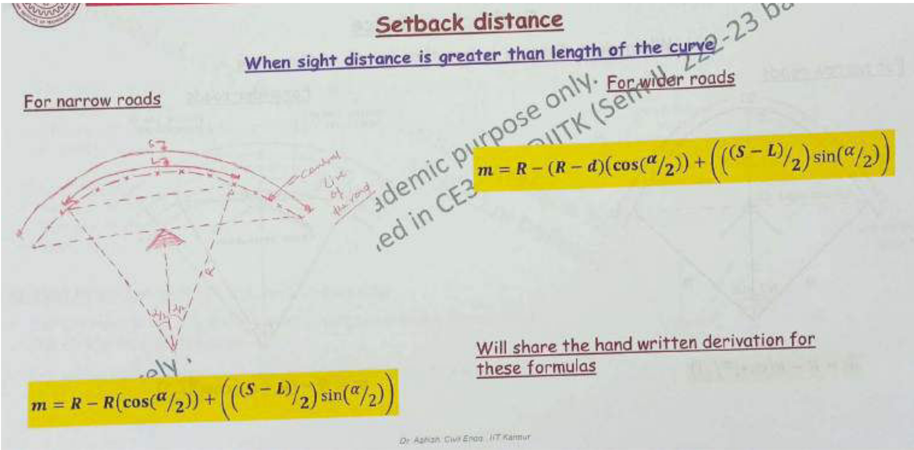
When sight distance is greater than length of the curve

For narrow road

$$m = R - R\left(\cos\left(\frac{\alpha}{2}\right)\right) + \left(\left(\frac{S-L}{2}\right)\sin(\alpha/2)\right)$$

For wider road

$$m = R - (R-d)\left(\cos\left(\frac{\alpha}{2}\right)\right) + \left(\left(\frac{S-L}{2}\right)\sin\left(\frac{\alpha}{2}\right)\right)$$

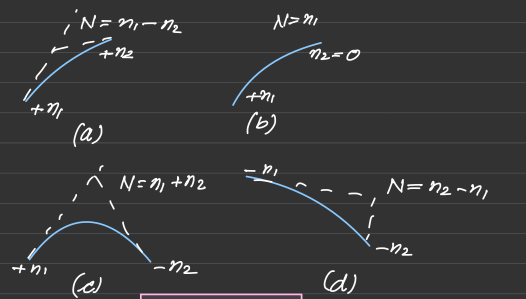


Lecture 16 – PKA – 12 Apr 2023 VERTICAL CURVES

Different types of vertical curves

- For summit curve, $N = n_1 - n_2$
- For valley curve, $N = n_2 - n_1$

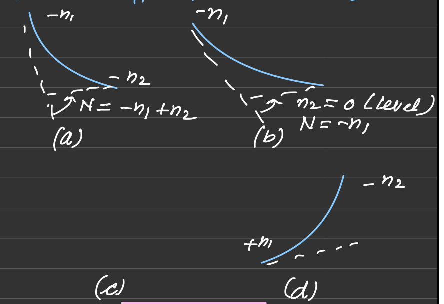
Different type of summit curves



$N = n_1 - n_2$

- No issue in terms of discomfort to the passengers as well as vehicle
- Major design criteria for summit curve: sight distance
- Shape: Parabola • small angle of deviation

Different type of vertical curves

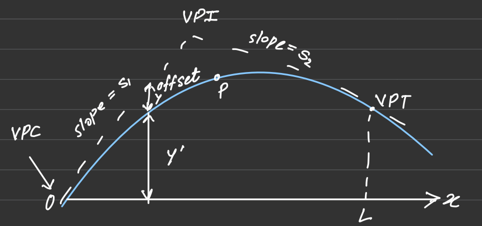


$N = n_2 - n_1$

- Discomfort to the passenger as well as to the vehicle
- Major design criteria for valley curve: night vision

Geometry of the vertical curve

↳ To know cutting/filling → need to know.



- Generic Mathematical formulation of vertical curves

$$y' = -\frac{N}{2L}x^2 + n_1 x$$

- Position of summit crest w.r.t. VPC

$$x = \frac{n_1 L}{N}$$

- VPI coordinate

$$(x, y) = (L/2,\ n_1 L/2)$$

- Radius of curvature

$$R = \frac{L}{N}$$

- Offset value for the summit curve

$$y = \frac{N}{2L} \times x^2$$

Length of summit curve

Based on SSD or OSD value

When length > sight distance

$$L = \frac{N \times SD^2}{2(\sqrt{H} + \sqrt{h})^2}$$

When length < sight distance

$$L = 2 \times SD - \frac{2(\sqrt{H} + \sqrt{h})^2}{N}$$

N = deviation angle

H = ht. of driver eye above road surface

h = ht. of subject above road surface

SD = sight distance

Prob: $n_1 = 3\%$, $n_2 = -5\%$, $t = 2.5\,sec$, $f = 0.35$, design speed = 80 kmph, ignore gradient effects for SSD. $H = 1.2$, $h = 0.15$, $L = ?$

Sol^n

$$SSD = vt + \frac{v^2}{2gf} = (80\times0.28)\times2.5 + \frac{(80\times0.28)^2}{20\times0.35} = 56 + 71.68 = 127.68\,m$$

$N = n_1 - n_2 = 0.03 - (-0.05) = 0.08$

length of summit curve

$$L = \frac{N\times SSD^2}{2(\sqrt{H}+\sqrt{h})^2} = \frac{0.08\times(127.68)^2}{2(\sqrt{1.2}+\sqrt{0.15})^2} = 296.6\,m \rightarrow \therefore \text{length} > 127.68\,m\ (SSD)$$

Prob: $n_1 = 1/100$, $n_2 = -1/120$, $OSD = 470\,m$, $H = 1$, $h = 2$, design speed = 80 kmph, $L = ?$

Sol^n $N = n_1 - n_2 = \frac{1}{100} - \left(-\frac{1}{120}\right) = 0.0183$

$$L = 2\times SD - \frac{2(\sqrt{H}+\sqrt{h})^2}{N} = 303\,m \rightarrow \text{length} < 470\,m\ (OSD)$$

Length of valley curve

- Case I: Allowable rate of change in acceleration: $0.6\,m/s^3$
- Case II: Headlight sight distance: Typically more than Case I.

Based on headlight sight distance

When length > sight distance $L = \frac{N\times SD^2}{2(h' + SD\times\tan\alpha)}$

When length < sight distance $L = 2S - \frac{2(h' + SD\times\tan\alpha)}{N}$

Based on comfort condition

$$L = 2\times\left(\frac{NV^3}{J}\right)^{1/2}$$

V is in m/sec

N = deviation angle

J = rate of change in acceleration (recommended as $0.6\,m/s^3$)

α = headlight beam angle

SD = sight distance

h' = ht. of the headlight

Prob: $n_1 = -1/25$, $n_2 = 1/30$, $f = 0.35$, $t = 2.5s$, $V = 80\,kmph$, $h' = 0.75$, $\alpha = 1^\circ$

a) comfort condition

b) headlight sight cond^n

ignore grad. effect for SSD.

Sol^n

$N = n_2 - n_1 = \frac{1}{30} - \left(-\frac{1}{25}\right) = 0.073$

a) $L = \left(\frac{NV^3}{J}\right)^{1/2}\times2 = 2\times\left(\frac{0.073\times(80\times0.28)^3}{0.6}\right)^{1/2} = 74.13\,m$

b) $SD = \frac{V^2}{2gf} + vt = 71.68 + 56 = 127.68$

$$L = \frac{0.073\times SD^2}{2(h' + SD\tan\alpha)} = 199.76\,m \approx 200\,m$$