National Examinations – May 2018

16-Civ-A6, Highway Design, Construction, and Maintenance

3 Hour Duration

NOTES

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper a clear statement of any assumptions made.

2. Any data, not given but required, can be assumed.

3. This is a **"CLOSED BOOK"** examination. Candidates may use one of two calculators, the Casio or Sharp approved models.

4. A total of **five** solutions is required. Only the first five as they appear in your answer book will be marked.

5. All questions are of equal value.

6. For non-numerical questions, clarity and organization of the answer are important.

Marking Scheme

1. (a) 14 marks; (b) 6 marks
2. (a) 8 marks; (b) 12 marks
3. (a) 8 marks; (b) 4 marks; (c) 8 marks
4. (a) 10 marks; (b) 10 marks
5. 20 marks
6. (a) 10 marks; (b) 10 marks
7. (a) 8 marks; (b) 4 marks; (c) 8 marks

Question 1:

A vehicle was traveling at 90 km/h on a parabolic crest vertical curve section on a rural highway. A stalled vehicle was spotted on the same curve section and the drive immediately took action to stop the vehicle. Unfortunately the driver struck the stalled vehicle at a speed of 10 km/h. An after-accident investigation reveals that the curve connects a +2% grade to the -3% grade, and has a length of 300 m. The design speed of this highway is 80km/h. The vehicle has an eye height of 1.08 m and the stalled vehicle has a height of 1.10 m. A series of test runs show that the coefficient of friction is 0.36.

a) The driver later claimed that there was not enough sight distance available at this section. Would you agree with him?
b) What could be the other factors that had contributed to the accident?

Question 2:

The first year AADT on a 6-lane freeway located in an urban area is expected to be 21,000 veh/day. The growth rate of the two-axle, 4-tire, single unit trucks is expected to be 5% per annum during the five years of the pavement life and will increase to 6% per annum for the remaining life of the pavement. The growth rate for all other categories of vehicles is expected to be 4% per annum throughout the life of the pavement. The design life of the pavement is 20 years and the projected vehicle mix during the first year is:

- Passenger cars = 83%
- Single-unit trucks, two-axle, four-tire = 10%
- Single-unit trucks, two-axle, six-tire = 5%
- Single-unit trucks, six-axle or more = 2%

a) Determine the design ESAL for the service life of the pavement.
b) Design the flexible pavement to carry this design ESAL based on the following information:

The following information is also available:

- The effective resilient modulus of the subgrade Mr = 15,000 psi.
- The subbase layer is an untreated silty sand with a resilient modulus (ESB) of 20,000 psi.
- The base layer is an untreated granular material with a resilient modulus (EB) of 27,000 psi.
- The elastic modulus of the asphalt concrete at 20°C (EAC) is 450,000 psi.
- The pavement structure will be exposed to moisture levels approaching saturation 20% of the time and it would take about 1 week to drain the water.
- The highway is in a busy area and traffic detours are difficult and expensive. The subgrade soil and the building materials used in the project were tested in the laboratory and the traffic information is accurate.
- The use of modern pavers allow the achieving of high level of initial serviceability values after the construction (p0 = 4.5) and the lowest acceptable value of the serviceability index is pt = 2.5.

Assume reasonably any missing information and justify you assumptions.

Question 3:

A 1.5 km curved section of an urban expressway in an urban area is characterized by a radius of 595 m (to the centreline of the road). According to the MTO study on provincial highway volumes in 2010, the estimated AADT of this section is 92,200 vehicles/day. The highway is a four-lane divided highway with a posted speed of 100 km/h and a lane width of 3.75m. This section is mainly in a cut area with a slope of 3:1 in the clear zone.

a) Would you consider that this curve is safe (The radius is sufficient)?
b) What should be the recommended clear zone distance for this section of the highway?
c) What length of the spiral curve between the tangent sections and the circular curve would you recommend? (For the calculation of the spiral length, consider a relative slope of 0.004 at 120 km/h)

Question 4:

Figure 1 shows two identical exit ramps on an urban highway in Southern Ontario. Several commuters have alerted the traffic department that some trees are very close to the edge of the road and impact the visibility of the drivers. The posted speed in the two exit ramps is 30 km/h and the radius of the horizontal curves is approximately 45m to the centreline of the exit ramp. Answer the following questions assuming a constant uphill grade of 8% in the exit ramp and that the trees are situated at 5 meters from the centreline of the inner lane in ramps #1 and at 4.3 metres from the centreline of the inner lane in ramps #2.

Figure 1: Sky view of the two exit ramps

a) Would you consider that this exit ramp is fully safe at the posted speed of 30 km/h?
b) What changes would you suggest to be done in order to make these exits fully safe at a design speed of 45 km/h?

Question 5:

You are in charge of the pavement design for a 4-lane rural highway in Northern Ontario. You have conducted the pavement design using the Asphalt Institute Method, using the charts corresponding to MAAT = 7°C, and found that the required asphalt thickness for a Full-Depth Pavement is 225 mm. Your supervisor wrote back to you and raised some concerns and recommendations that are summarized in the following bullet points:

- Good job so far! I agree with you using a resilient modulus of the subgrade of 70 MPa even if it's a bit conservative.
- Your ESAL estimation is good!
- You seem to neglect a major information. The frost depth in the area is 1.2 m and the thickness of the pavement structure should be at least 70% of the frost depth.
- I would recommend the final design to be a three-layer system (Figure 2). We need however to minimize the thickness of the asphalt concrete layer as the closest asphalt plant is 70 kms away from the jobsite and the good aggregates in that area are scarce and expensive.
- I suggest using a Cold Mix Asphalt in the Base Course. We can use a mobile plant to produce the cold mix in the jobsite using the local silty-sand that will be generated from the excavation.
- The Unbound Granular Base is necessary but we don't want it to be too thick as good aggregates are scarce. Please minimize the thickness of this layer with respect to frost protection.

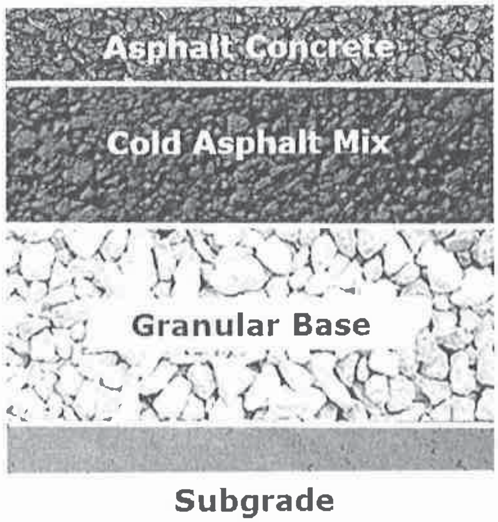

Figure 2: Pavement structure for question #5

Based on the information provided by your manager, modify your initial design and propose a new pavement design using the Asphalt Institute Method.

Question 6:

A plate bearing test using a 12-in. (300 mm) diameter rigid plate is made on a subgrade as shown in Figure 3-a. The total load required to cause a settlement of 0.2 in. (5 mm) is 9,600 lb. (42.7 kN). After that, 6 in. (150 mm) of gravel base course is placed on the subgrade and another plate bearing test is made on the top of the base course as shown in Figure 3-b. The total load required to cause a settlement of 0.2 in. (5 mm.) is 16,000 lb. (71.2 kN).

Assuming a Poisson ratio of 0.5, determine the thickness of the base course required to sustain the load of a tire exerting a contact pressure of 100 psi over a circular area with a radius of 5 in. as shown in Figure 3-c, yet maintain a deflection of no more than 0.1 in. (2.5 mm).

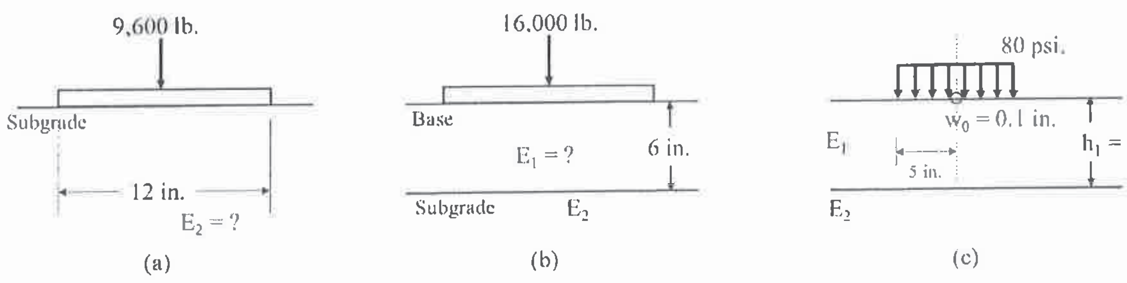

***Figure 3**: illustration of the three cases of question #6.*

Question 7:

For the pavement design of a major highway in an urban area, the design engineer would like to compare two options. The first option is a flexible pavement designed as a perpetual pavement (Option A) and the second is a rigid pavement (Option B). The two tables below show the maintenance and rehabilitation planning during the analysis period and the cost associated to each intervention. It also shows the initial construction cost and the salvage value of the pavement at the end of the 50-year analysis period. Assuming a discount rate of 5%:

a) Determine which of these two alternatives would be more cost effective.
b) Explain briefly how these two options would be compared if the analysis periods were different.
c) Explain briefly the difference in the mechanism and the pattern of the following three modes of flexible pavement deteriorations modes: Fatigue cracking, Rutting and Low Temperature Cracking.

LIFE CYCLE COST ANALYSIS: Option A -Flexible Pavement Design		
Initial Construction Cost		$ 71,050,000
Salvage Value at the end of the analysis period (50 years)		$ 12,000,000
Scheduled Maint/Rehab Year	Maintenance/Rehabilitation Treatment	Cost
3	Rout and Seal Cracks	$ 93,000
9	Mill 40mm & Patch 40mm	$ 1,406,063
15	Mill 40mm & Patch 40mm	$ 1,533,000
19	Rout and Seal Cracks	$ 123,900
21	Resurface with 50mm SMA 12.5	$ 1,267,500
24	Rout and Seal Cracks	$ 298,350
31	Rout and Seal Cracks	$ 274,500
35	Mill 50mm existing asphalt	$ 1,980,000
41	Mill 50mm existing asphalt	$ 2,145,000
44	Rout and Seal Cracks	$ 331,500

LIFE CYCLE COST ANALYSIS: Option B - Rigid Pavement Design		
Initial Construction Cost		$ 79,504,000
Salvage Value at the end of the analysis period (50 years)		$ 25,000,000
Scheduled Maint/Rehab Year	Maintenance/Rehabilitation Treatment	Cost
12	Reseal Joints (50% trans., 25% long.)	$ 680,000
18	Full-Depth PCC Patching	$ 1,120,000
26	Reseal Joints (100% trans., 50% long.)	$ 1,360,000
28	Diamond Grinding	$ 3,150,000
34	Reseal Joints	$ 1,380,000
38	Resurface with 40mm SMA 12.5	$ 5,696,000
44	30% Trans, 50% Long Crack Seal (Composite)	$ 260,000

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APPENDIX

AASTO Flexible pavement Design

TABLE IV-5 DISTRIBUTION OF TRUCK FACTORS (TF) FOR DIFFERENT CLASSES OF HIGHWAYS AND VEHICLES—UNITED STATES*

Vehicle Type	Truck Factors: Rural Systems: Interstate	Rural: Other Principal	Rural: Minor Arterial	Rural: Collectors Major	Rural: Collectors Minor	Rural: Range	Urban Systems: Interstate	Urban: Other Freeways	Urban: Other Principal	Urban: Minor Arterial	Urban: Collectors	Urban: Range
Single-unit trucks												
2-axle, 4-tire	0.003	0.003	0.003	0.017	0.003	0.003-0.017***	0.002	0.015	0.002	0.006	...	0.006-0.015***
2-axle, 6-tire	0.21	0.25	0.28	0.41	0.19	0.19-0.41	0.17	0.13	0.24	0.23	0.13	0.13-0.24
3-axle or more	0.61	0.86	1.06	1.26	0.45	0.45-1.26	0.61	0.74	1.02	0.76	0.72	0.61-1.02
All single-units	0.06	0.08	0.08	0.12	0.03	0.03-0.12	0.05	0.06	0.09	0.04	0.16	0.04-0.16***
Tractor semi-trailers												
4-axle or less	0.62	0.92	0.62	0.37	0.91	0.37-0.91	0.98	0.48	0.71	0.46	0.40	0.40-0.98
5-axle**	1.09	1.25	1.05	1.67	1.11	1.05-1.67	1.07	1.17	0.97	0.77	0.63	0.63-1.17
6-axle or more**	1.23	1.54	1.04	2.21	1.35	1.04-2.21	1.05	1.19	0.90	0.64	...	0.64-1.19
All multiple units	1.04	1.21	0.97	1.52	1.08	0.97-1.52	1.05	0.96	0.91	0.67	0.53	0.53-1.05
All trucks	0.52	0.38	0.21	0.30	0.12	0.12-0.52	0.39	0.23	0.21	0.07	0.24	0.07-0.39

**Compiled from data supplied by the Highway Statistics Division, U.S. Federal Highway Administration.*
***Including full-trailer combinations in some states.*
****See Article 4.05 for values to be used when the number of heavy trucks is low.*

$$ESAL = AADT \times HVP \times DF \times TF \times TDY$$

$$Cumulative\ ESALs = Initial\ year\ ESAL_{(Design\ Lane)} \times \frac{[(1+g)^t - 1]}{g}$$

$$\Delta PSI = p_o - p_t \qquad u_f = 1.18 \times 10^8 M_R^{-2.32}$$

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 + \cdots + a_i D_i m_i$$

$$\log_{10}(W_{18}) = Z_R \times S_o + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07$$

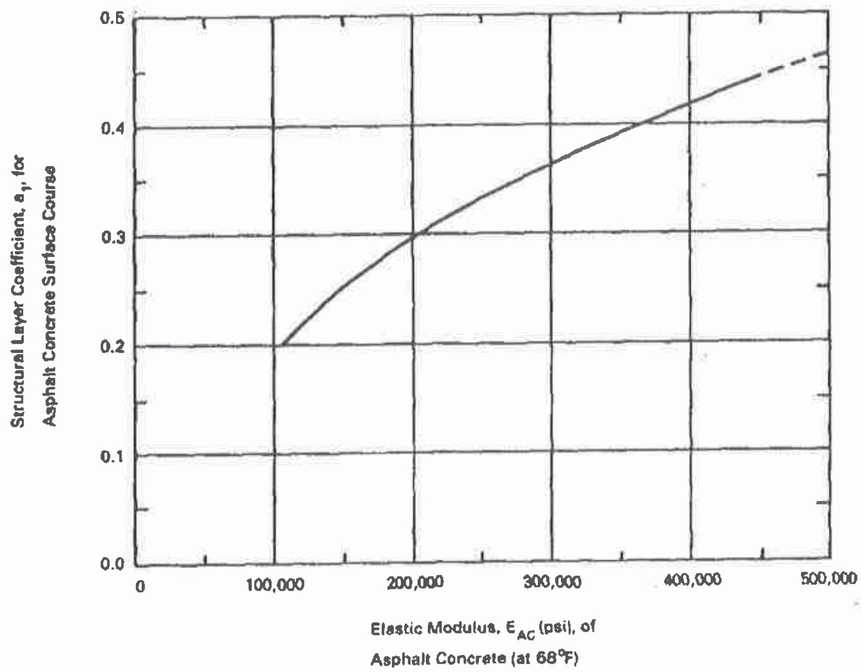
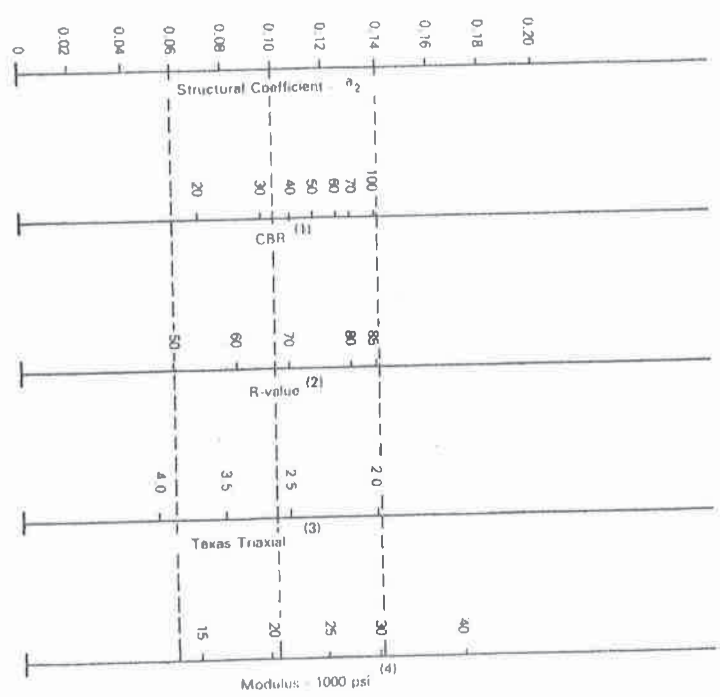
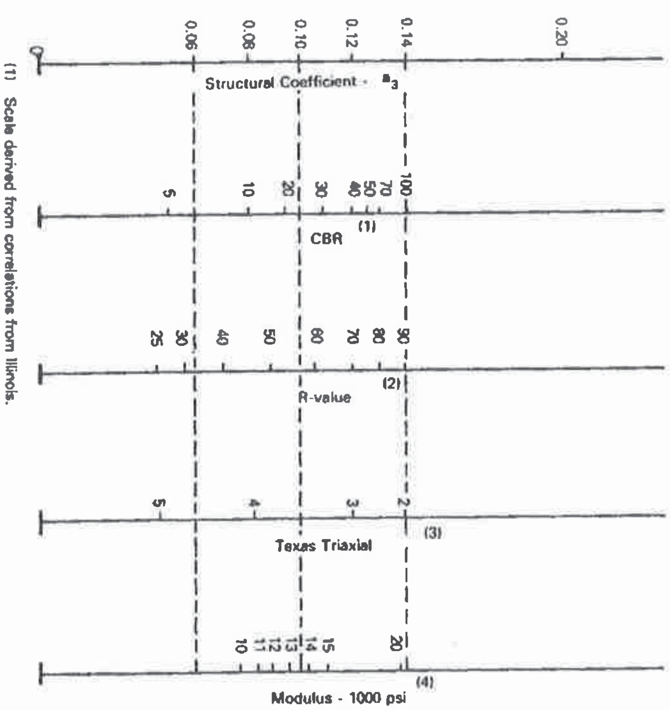


Figure 2.5. Chart for Estimating Structural Layer Coefficient of Dense-Graded Asphalt Concrete Based on the Elastic (Resilient) Modulus (3)



(1) Scale derived by averaging correlations obtained from Illinois.
(2) Scale derived by averaging correlations obtained from California, New Mexico and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas.
(4) Scale derived on NCHRP project (3).

Figure 2.6. Variation in Granular Base Layer Coefficient (a_2) with Various Base Strength Parameters (3)



(1) Scale derived from correlations from Illinois.
(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming.
(3) Scale derived from correlations obtained from Texas.
(4) Scale derived on NCHRP project (3).

Figure 2.7. Variation in Granular Subbase Layer Coefficient (a_3) with Various Subbase Strength Parameters (3)

Traffic, ESAL's	Minimum Thickness (Inches) Asphalt Concrete	Aggregate Base
Less than 50,000	1.0 (or surface treatment)	4
50,001–150,000	2.0	4
150,001–500,000	2.5	4
500,001–2,000,000	3.0	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4.0	6

Table 20.16 Suggested Levels of Reliability for Various Functional Classifications

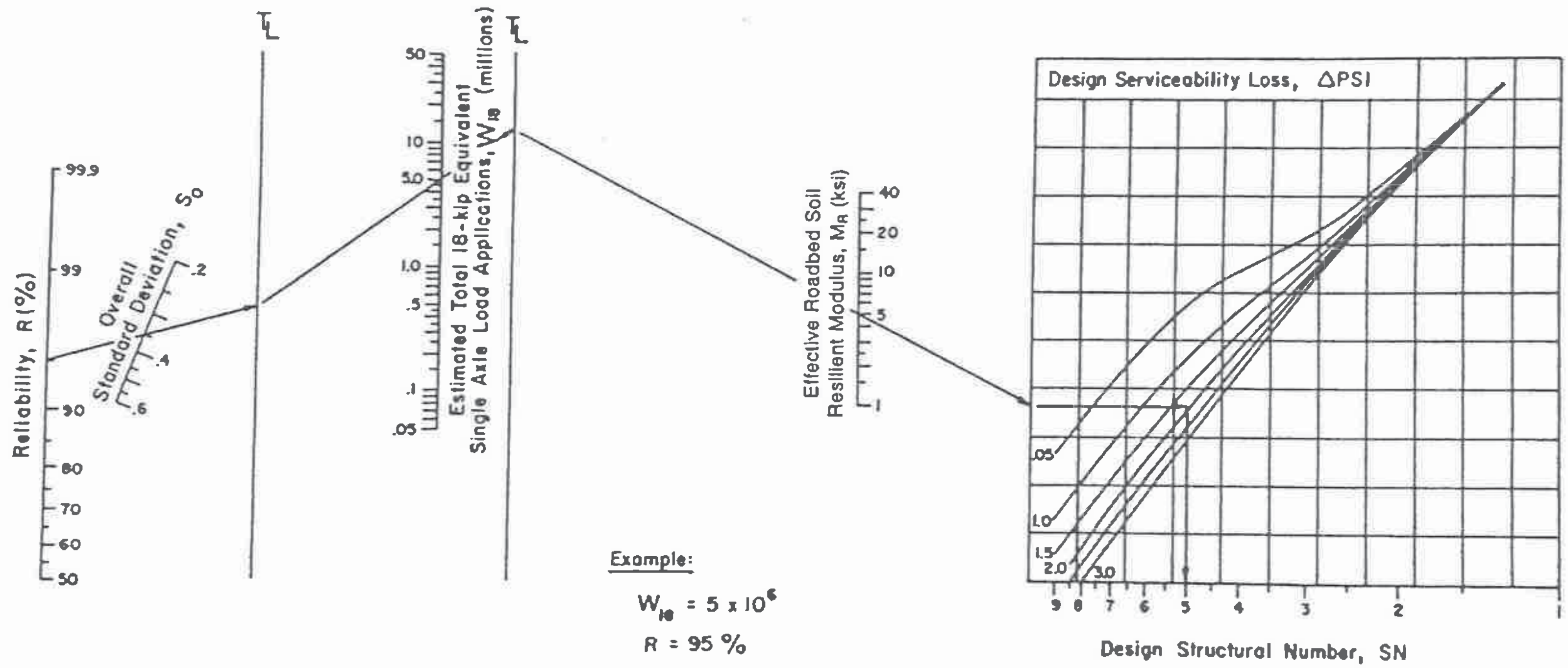
	Recommended Level of Reliability	
Functional Classification	*Urban*	*Rural*
Interstate and other freeways	85–99.9	80–99.9
Other principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

Table 2.4. Recommended m_i Values for Modifying Structural Layer Coefficients of Untreated Base and Subbase Materials in Flexible Pavements

	Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
Quality of Drainage	Less Than 1%	1–5%	5–25%	Greater Than 25%
Excellent	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	1.05–0.95	0.95–0.75	0.75–0.40	0.40

NOMOGRAPH SOLVES:

$$\log_{10} W_{18} = Z_R{*}S_o + 9.36{*}\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32{*}\log_{10}M_R - 8.07$$



Example:

$W_{18} = 5 \times 10^6$

$R = 95\ \%$

$S_o = 0.35$

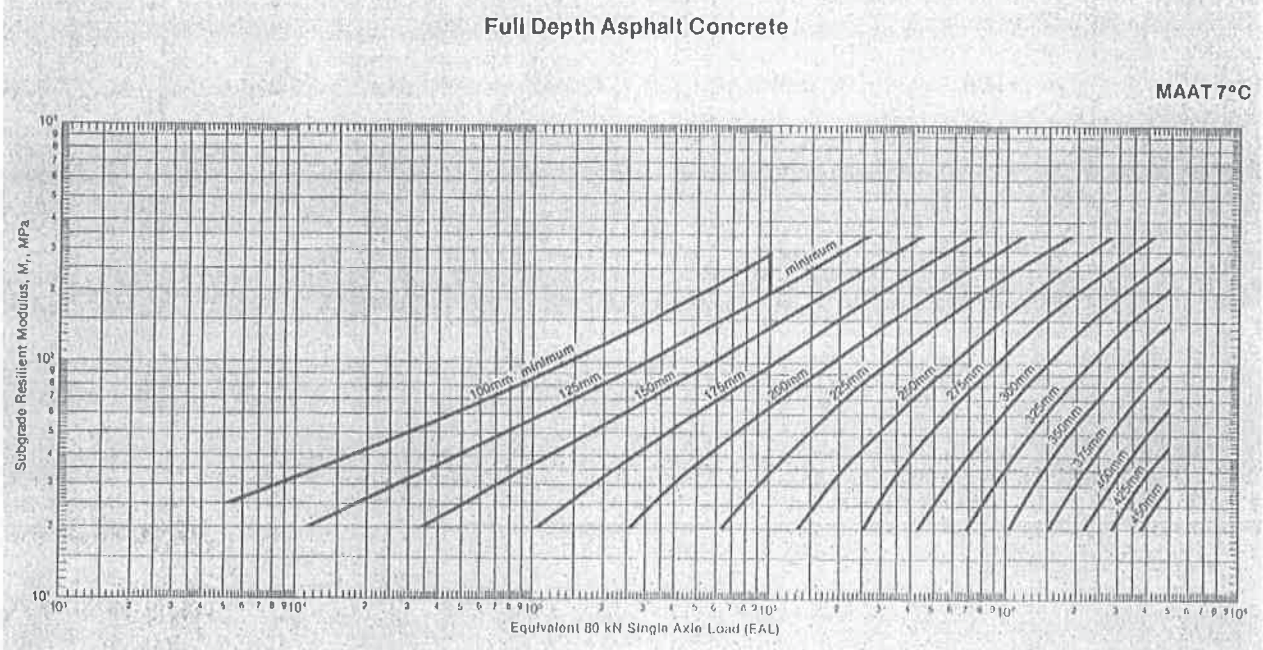
$M_R = 5000$ psi

$\Delta PSI = 1.9$

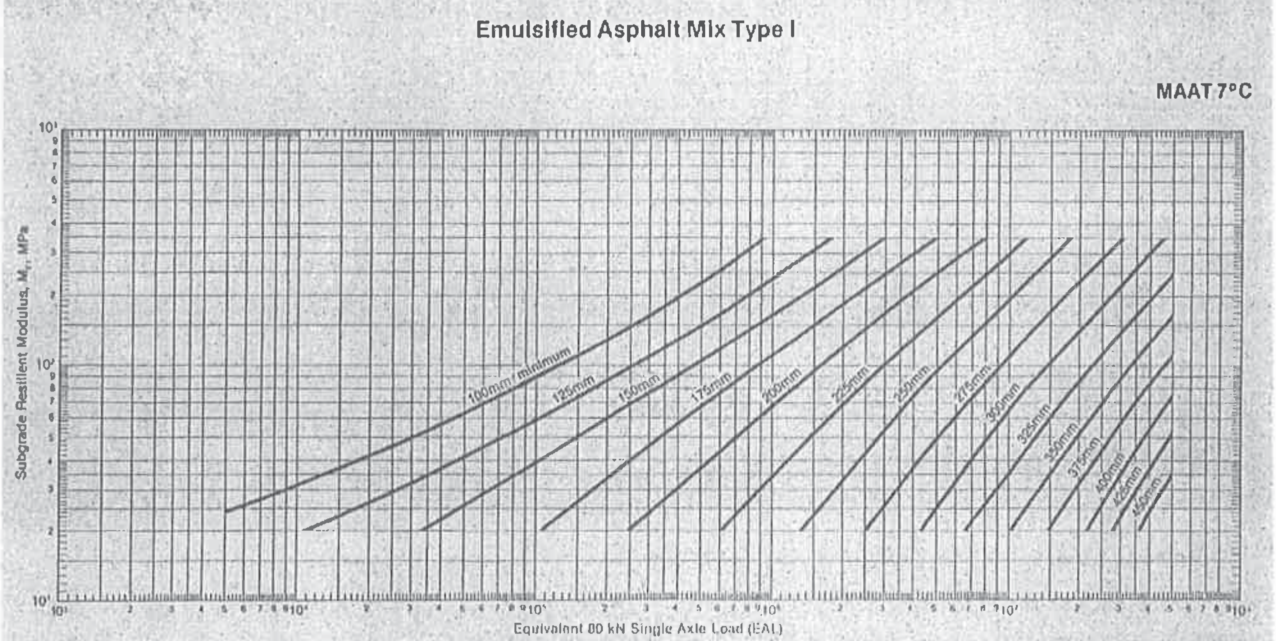
Solution: SN = 5.0

Figure 3.1. Design Chart for Flexible Pavements Based on Using Mean Values for Each Input

Asphalt Institute Flexible pavement Design

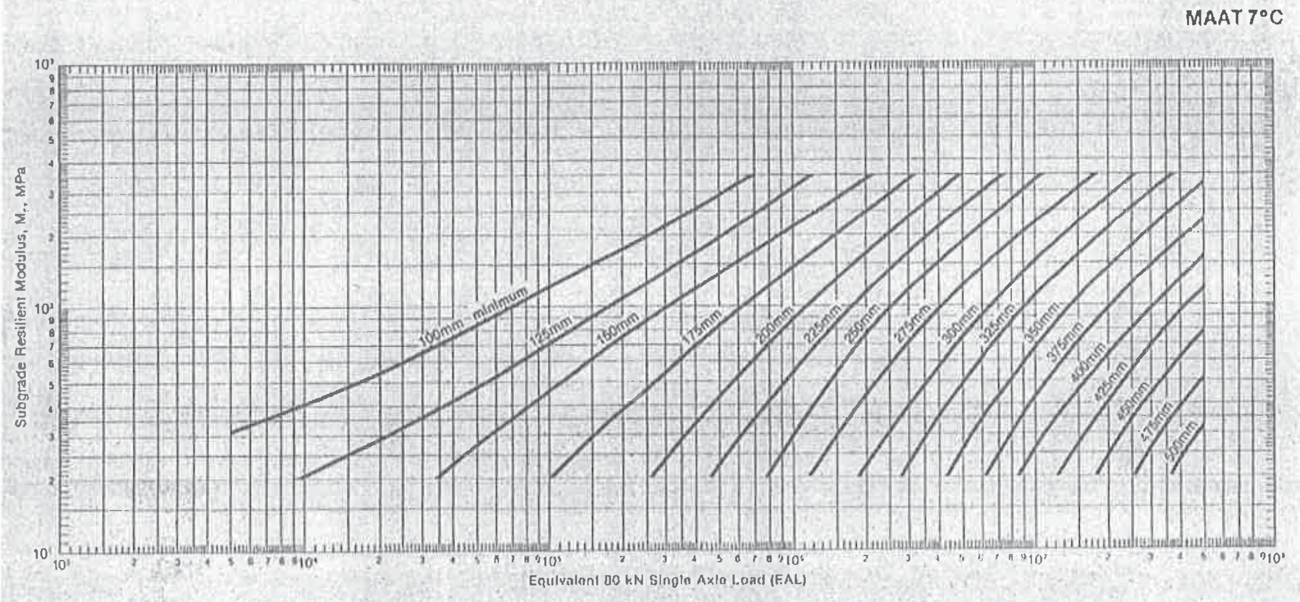


Design Chart A-1



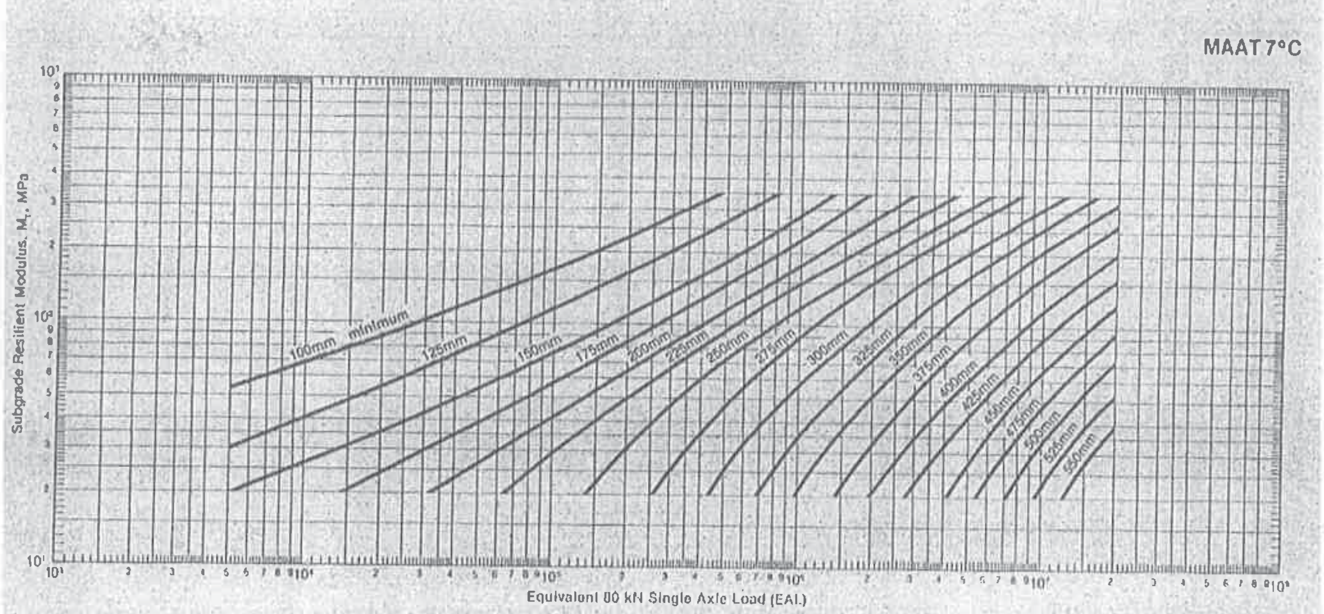
Design Chart A-2

Emulsified Asphalt Mix Type II



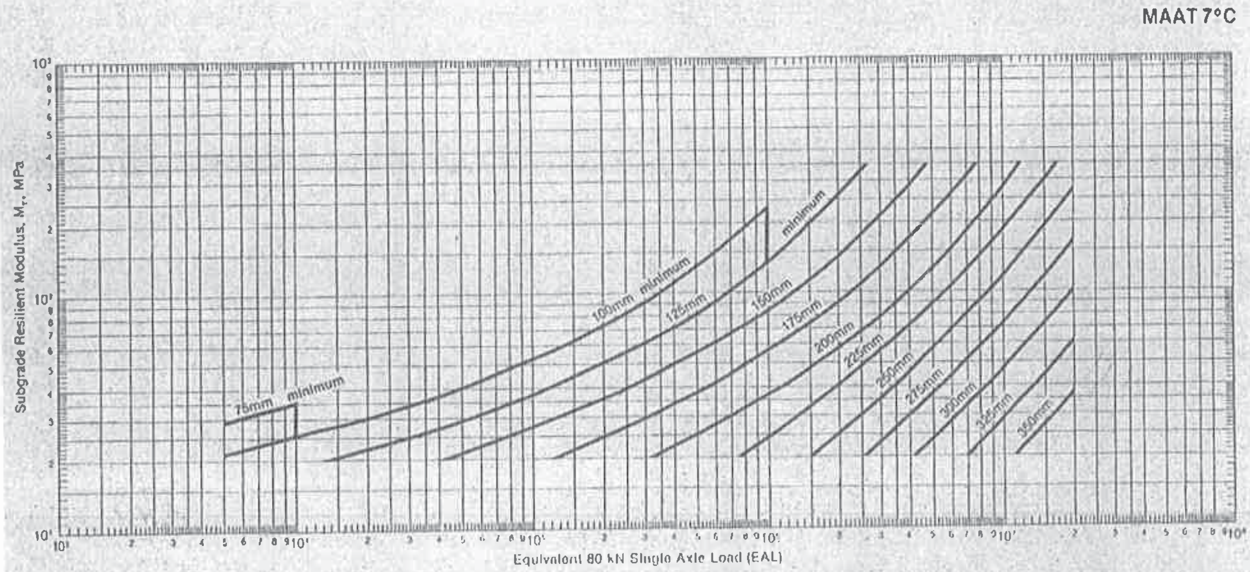
Design Chart A-3

Emulsified Asphalt Mix Type III



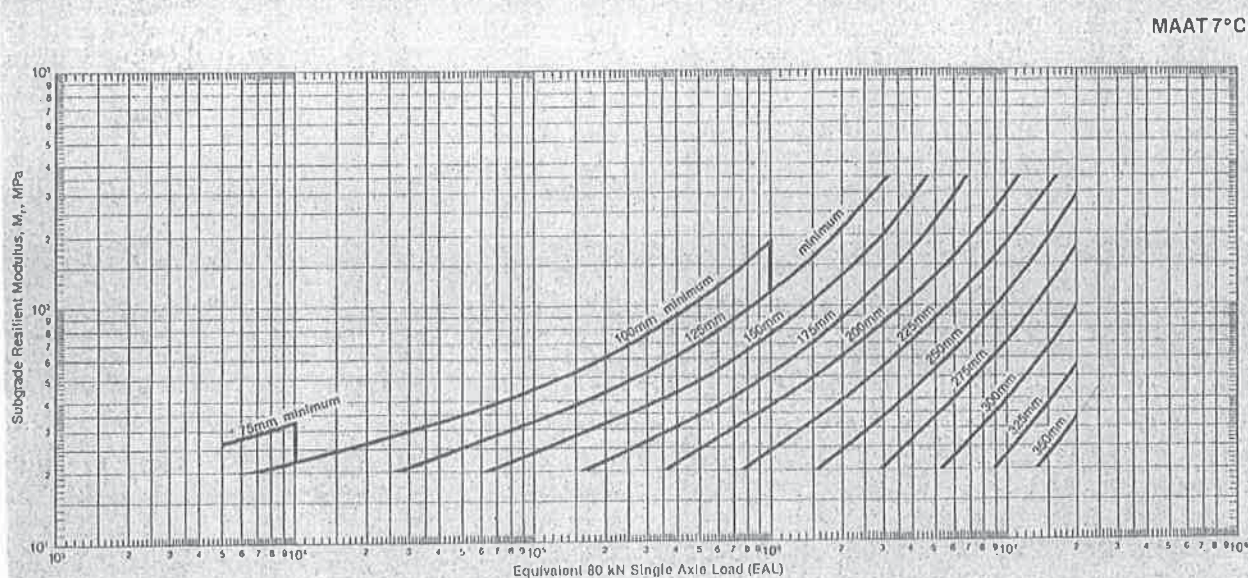
Design Chart A-4

Untreated Aggregate Base 150mm Thickness



Design Chart A-5

Untreated Aggregate Base 300mm Thickness



Design Chart A-6

TABLE VI-2 MINIMUM THICKNESS OF ASPHALT CONCRETE OVER EMULSIFIED ASPHALT BASES

Traffic Level EAL	Type II and III[1]	
	mm	(in.)
10^4	50	(2)
10^5	50	(2)
10^6	75	(3)
10^7	100	(4)
$>10^7$	130	(5)

[1]Asphalt concrete, or Type I emulsified asphalt mix with a surface treatment, may be used over Type II or Type III emulsified asphalt base courses.

TABLE VI-3 MINIMUM THICKNESS OF ASPHALT CONCRETE OVER UNTREATED AGGREGATE BASE

Traffic EAL	Traffic Condition	Minimum Thickness of Asphalt Concrete
10^4 or less	Light traffic parking lots, driveways and light rural roads	75mm (3.0 in.)*
Between 10^4 & 10^6	Medium truck traffic	100mm (4.0 in.)
10^6 or more	Heavy truck traffic	125mm (5.0 in.) or greater

*For Full-Depth ashalt concrete or emulsified asphalt pavements a minimum thickness of 100mm (4 in.) applies in this traffic region, as shown on the design charts.

Geometric design and LCCA equations and tables:

$$d_b = \frac{v^2}{2g(f+G)}$$

$$K = \frac{L}{\Delta G}$$

$$L_{crest} = \frac{SSSD^2 \times A}{200(H + h_1 + 2\sqrt{H \times h_1})}$$

$$K = \frac{SSSD^2}{200(\sqrt{H} + \sqrt{h_1})^2}$$

$$L_{sag} = \frac{SSSD^2 \times A}{200(H + SSSD\ Tan\beta)}$$

$$\frac{Gv^2}{gR} cos\gamma = Gsin\gamma + G(cos\gamma)\mu$$

$$\frac{v^2}{gR} = e + \mu$$

$$R = \frac{V^2}{127(e+\mu)}$$

$$A^2 = L_s R = \frac{2RV \times 1000}{3600}$$

$$A = \sqrt{0.03577V^3}$$

$$L_s = \frac{we}{2s}$$

$$A^2 = R \times L$$

$$A = \sqrt{\frac{RV}{1.8}}$$

$$NPW = IC + \sum_{j=1}^{k}\left(M\&R_j \times \left[\frac{1}{1 + i_{Discount}}\right]^{n_j}\right) - SV \times \left[\frac{1}{1 + i_{Discount}}\right]^{AP}$$

$$EUAC = NPW \times \left[\frac{i_{Discount} \times (1 + i_{Discount})^{AP}}{(1 + i_{Discount})^{AP} - 1}\right]$$

$$\theta = \frac{28.65}{R} S$$

$$m = R\left(1 - \cos\frac{28.65}{R}S\right)$$

$$S = 2R\theta^\circ\left(\frac{\pi}{180}\right)$$

Relative Slope Values

Design speed (km/h)	60	80	90	≥ 100
Relative slope (m/m)	0.006	0.0051	0.0047	0.0044

Clear zone distances for straight sections (m)

Design Speed (km/h)	Design ADT	Fill Slopes 6:1 or flatter	Fill Slopes 5:1 to 4:1	Fill Slopes 3:1	Cut Slopes 3:1	Cut Slopes 5:1 to 4:1	Cut Slopes 6:1 or flatter
≤ 60	< 750	2.0 - 3.0	2.0 - 3.0	see note	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
	750 - 1500	3.0 - 3.5	3.5 - 4.5	see note	3.0 - 3.5	3.0 - 3.5	3.0 - 3.5
	1500 - 6000	3.5 -4.5	4.5 - 5.0	see note	3.5 -4.5	3.5 -4.5	3.5 -4.5
	> 6000	4.5 -5.0	5.0 - 5.5	see note	4.5 -5.0	4.5 -5.0	4.5 -5.0
70 - 80	< 750	3.0 - 3.5	3.5 - 4.5	see note	2.5 - 3.0	2.5 - 3.0	3.0 - 3.5
	750 - 1500	4.5 - 5.0	5.0 - 6.0	see note	3.0 - 3.5	3.5 - 4.5	4.5 - 5.0
	1500 - 6000	5.0 - 5.5	6.0 - 8.0	see note	3.5 - 4.5	4.5 - 5.0	5.0 - 5.5
	> 6000	6.0 - 6.5	7.5 - 8.5	see note	4.5 - 5.0	5.5 - 6.0	6.0 - 6.5
90	< 750	3.5 - 4.5	4.5 - 5.5	see note	2.5 - 3.0	3.0 - 3.5	3.0 - 3.5
	750 - 1500	5.0 - 5.5	6.0 - 7.5	see note	3.0 - 3.5	4.5 - 5.0	5.0 - 5.5
	1500 - 6000	6.0 - 6.5	7.5 - 9.0	see note	4.5 - 5.0	5.0 - 5.5	6.0 - 6.5
	> 6000	6.5 - 7.5	8.0 - 10.0	see note	5.0 - 5.5	6.0 - 6.5	6.5 - 7.5
100	< 750	5.0 - 5.5	6.0 - 7.5	see note	3.0 - 3.5	3.5 - 4.5	4.5 - 5.0
	750 - 1500	6.0 - 7.5	8.0 - 10.0	see note	3.5 - 4.5	5.0 - 5.5	6.0 - 6.5
	1500 - 6000	8.0 - 9.0	10.0 - 12.0	see note	4.5 - 5.5	5.5 - 6.5	7.5 - 8.0
	> 6000	9.0 - 10.0	11.0 - 13.5	see note	6.0 - 6.5	7.5 - 8.0	8.0 - 8.5
≥ 110	< 750	5.5 - 6.0	6.0 - 8.0	see note	3.0 - 3.5	4.5 - 5.0	4.5 - 4.9
	750 - 1500	7.5 - 8.0	8.5 - 11.0	see note	3.5 - 5.0	5.5 - 6.0	6.0 - 6.5
	1500 - 6000	8.5 - 10.0	10.5 - 13.0	see note	5.0 - 6.0	6.5 - 7.5	8.0 - 8.5
	> 6000	9.0 - 10.5	11.5 - 14.0	see note	6.5 - 7.5	8.0 - 9.0	8.5 - 9.0

Clear zone correction factors in curves

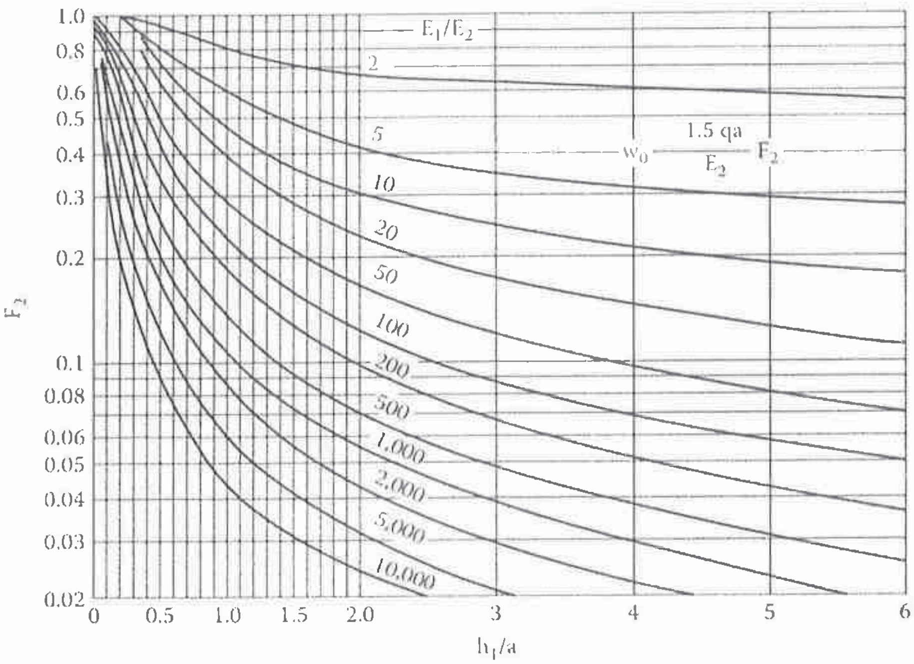
Radius (m)	Design Speed 60	70	80	90	100	110+
900	1.1	1.1	1.1	1.2	1.2	1.2
700	1.1	1.1	1.2	1.2	1.2	1.3
600	1.1	1.2	1.2	1.2	1.3	1.4
500	1.1	1.2	1.2	1.3	1.3	1.4
450	1.2	1.2	1.3	1.3	1.4	1.5
400	1.2	1.2	1.3	1.3	1.4	
350	1.2	1.2	1.3	1.4	1.5	
300	1.2	1.3	1.4	1.5	1.5	
250	1.3	1.3	1.4	1.5		
200	1.3	1.4	1.5			
150	1.4	1.5				
100	1.5					

Note: The clear zone horizontal curve adjustment factor is applied to the outside of curves only. Curve flattor than 900 m do not require an adjusted clear zone.

Friction Coefficients to be used in questions

Vehicle Speed (km/h)	≤ 60	70	80	90	100	110	120
Stopping Coefficient of Friction	0.38	0.37	0.35	0.31	0.30	0.28	0.27
Coefficient of Side Friction	0.17	0.16	0.15	0.12	0.11	0.09	0.07

Stresses and strains in flexible pavements



The deflection under a rigid plate in subgrade

$$w_0 = \frac{\pi(1 - v^2)qa}{2E}$$

Two-Layer System - Vertical surface deflection

$$w_0 = \frac{1.5qa}{E_2} F_2$$

Flexible plate

$$w_0 = \frac{1.18qa}{E_2} F_2$$

Rigid plate