



Concrete Pavement Thickness Design

presented by Steve Waalkes, P.E., MCA's Director of Engineering – W. Mich.

Tuesday, April 14, 2020 10:00 to 11:00 am Eastern

Topics Covered Today

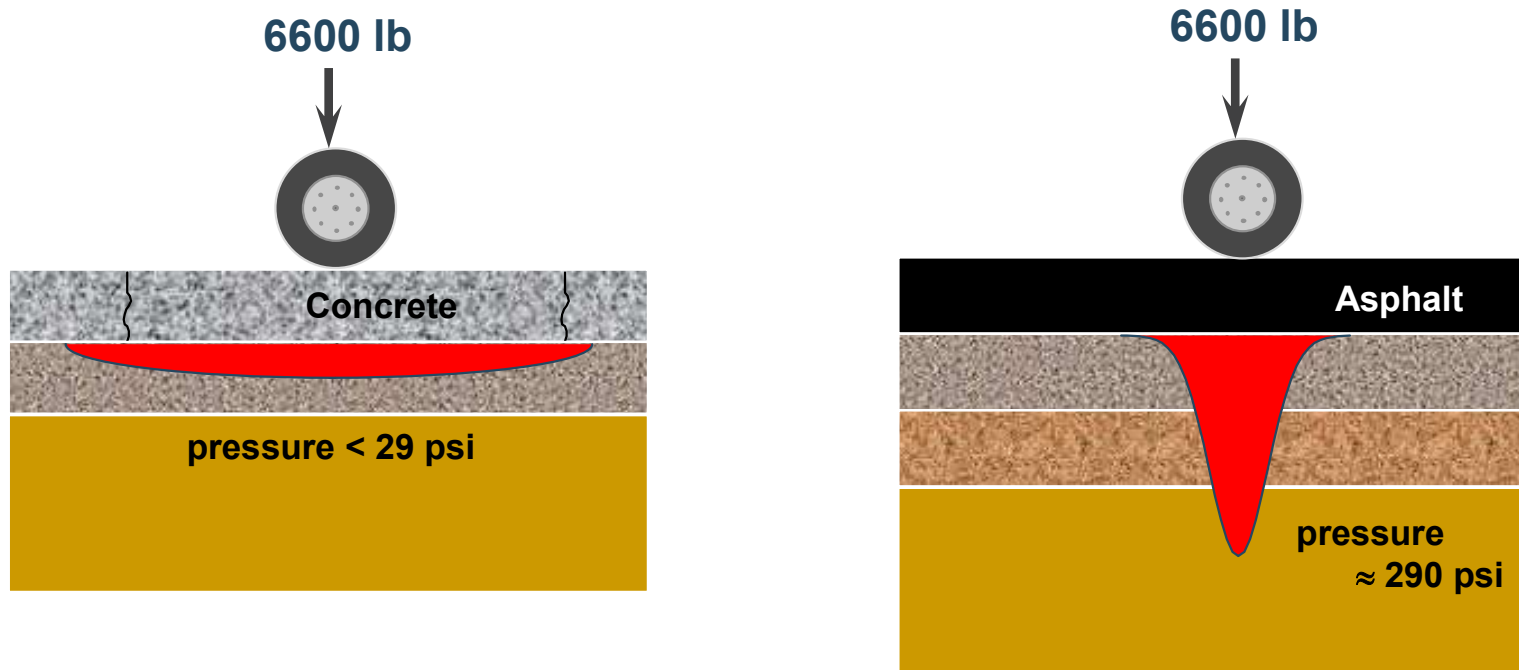
Basic Principles of Concrete Pavement Thickness Design for:

- Highways
- Streets
- Parking Lots
- Industrial / Trucking Facilities

Available guidance documents / software
Design Examples



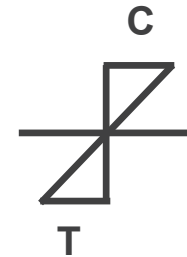
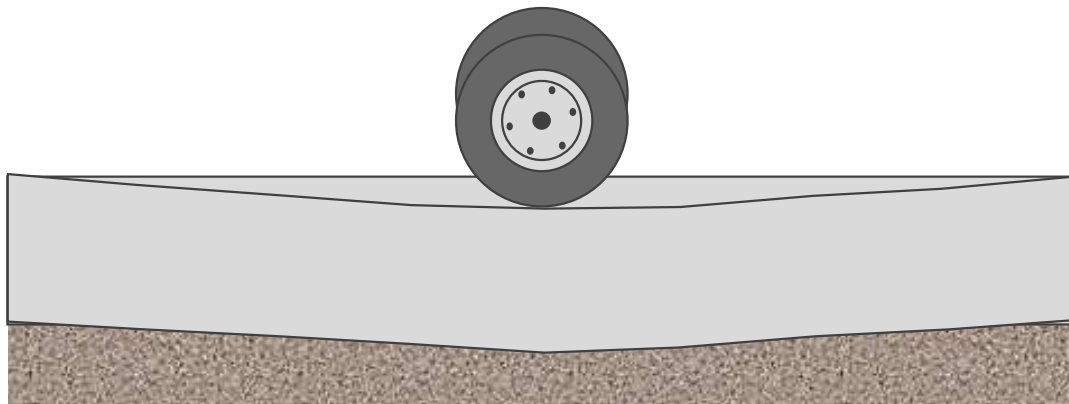
Differences in How Pavements Carry Loads



Concrete's rigidity spreads the load over a large area and keeps pressures on the subgrade low.

Pavement Design Principle #1:

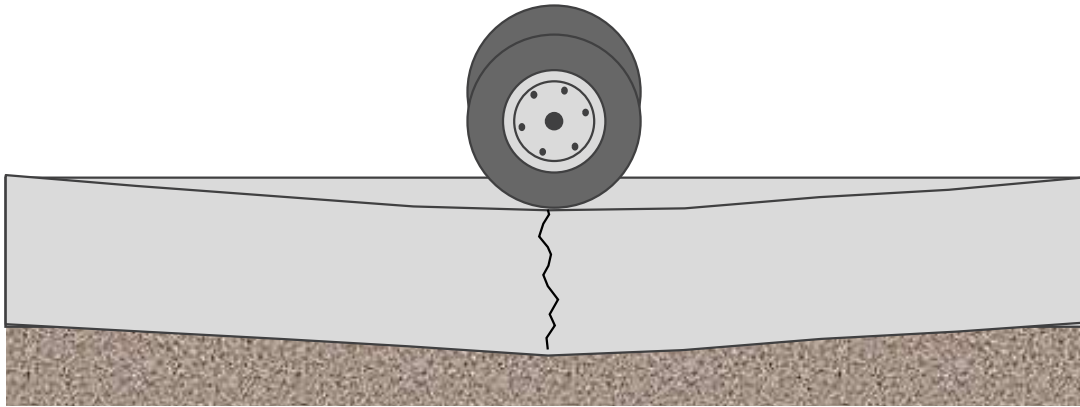
Stress / Fatigue



- Compressive strength: ~4000 psi
- Flexural strength: ~600 psi

Pavement Design Principle #1:

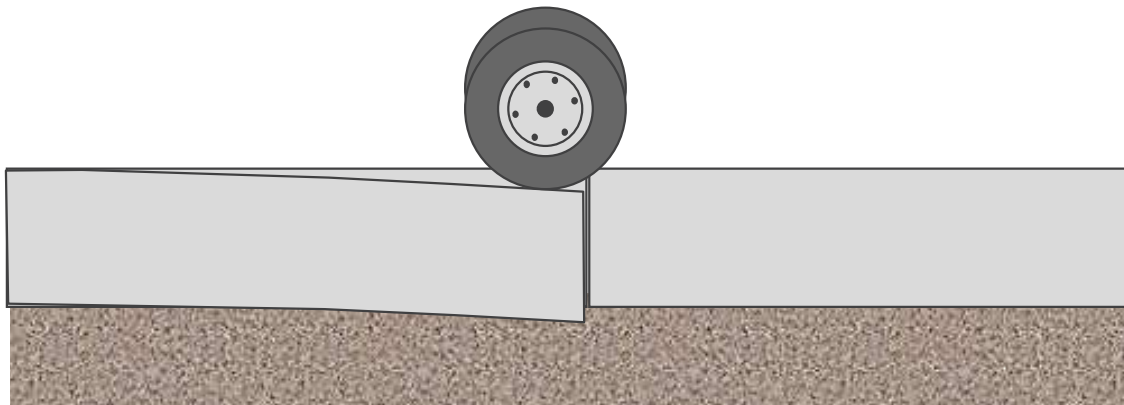
Stress / Fatigue



- Limit stresses to reduce fatigue due to repeated loadings
- Design slab to account for certain amount of fatigue at design life

Pavement Design Principle #2:

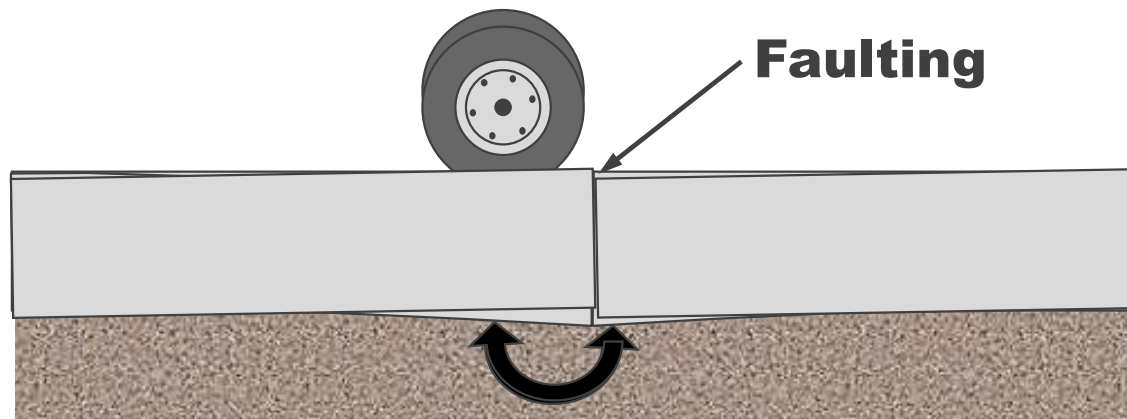
Deflection / Erosion / Pumping



- Better support (higher k-value) will lower deflections
- Load transfer will lower deflections

Pavement Design Principle #2:

Deflection / Erosion / Pumping



- Non-erodible base (agg. instead of soil) will help limit erosion/pumping/faulting
- Load transfer will help too

Concrete Pavement Thickness Design

- Directly related to the amount of truck traffic
- Also:
 - Subgrade (soil) and base layers
 - Concrete strength
 - Load transfer between slabs



Concrete Pavement Thickness Design

- Basic inputs you need:
 - Design life (typ. 20+ yrs)
 - Traffic (ADT, % trucks)
 - Subgrade / base (soil type, agg. thickness)
 - Concrete strength (flexural)
 - Reliability (typ. 80% to 95%)

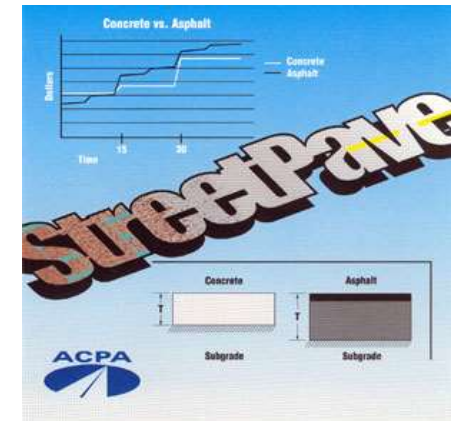
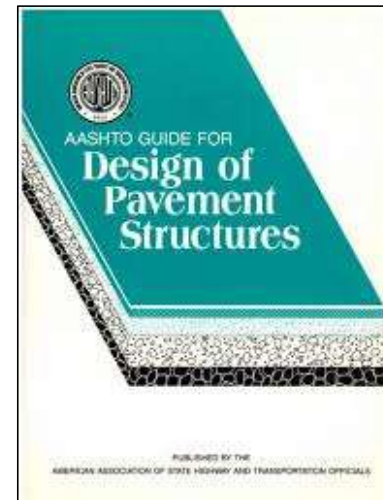


**Design Methodologies,
Publications, Guides,
Software, Programs, etc.**



Concrete Pavement Design Methodologies

- AASHTO 1993 Pavement Design Procedure
- 1984 PCA / ACPA StreetPave
- Pavement ME
- Westergaard analysis



$$\sigma_c = \frac{3P}{h^2} \left[1 - \left(\frac{a_1}{l} \right)^{0.6} \right]$$

$$\sigma_e = \frac{0.572P}{h^2} \left[4 \log_{10} \left(\frac{l}{b} \right) + 0.359 \right]$$

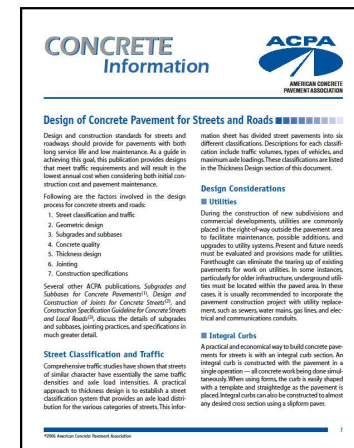
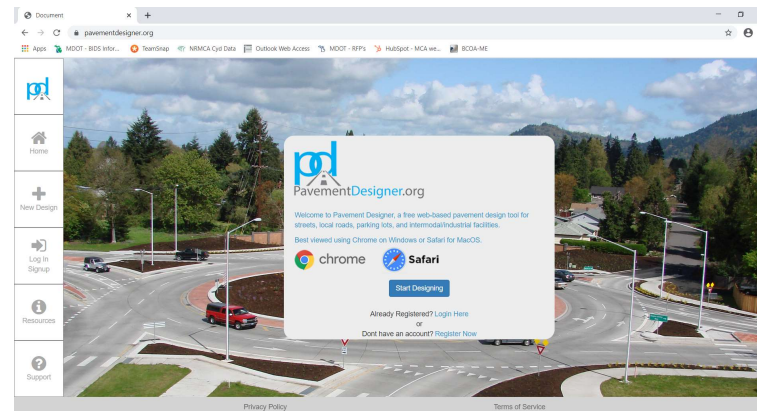
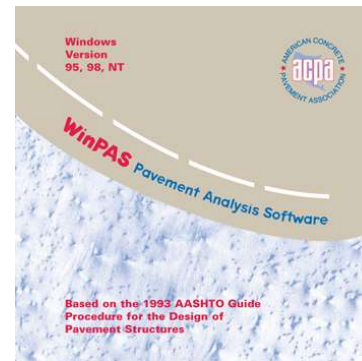
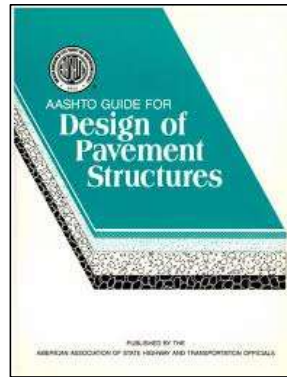
$$\sigma_i = \frac{0.316P}{h^2} \left[4 \log_{10} \left(\frac{l}{b} \right) + 1.069 \right]$$
$$b = \sqrt{1.6a^2 + h^2} - 0.675h$$



Guides / Software to Use by Pavement Type

Highways

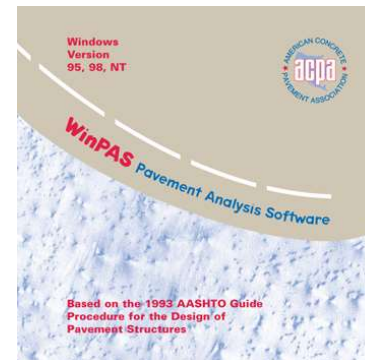
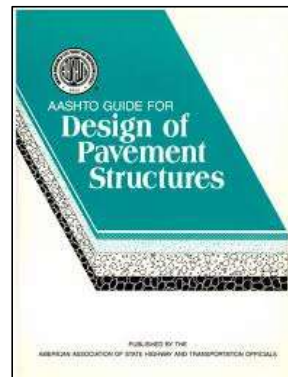
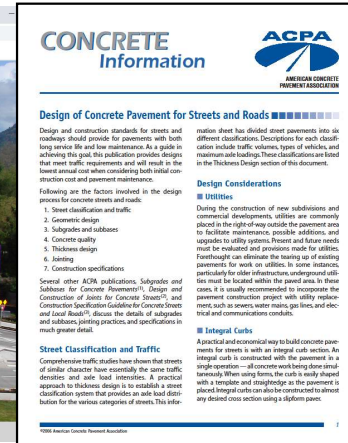
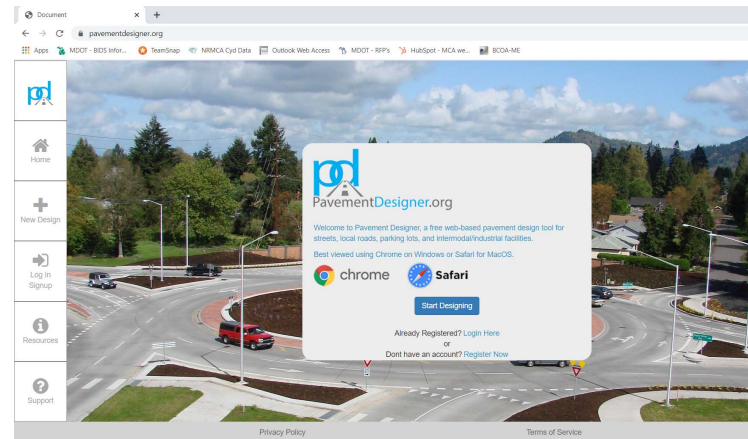
- AASHTO 93
 - WinPAS
- Pavement ME
 - \$\$\$\$\$
- StreetPave
 - www.pavementdesigner.org



Guides / Software to Use by Pavement Type

Roads / Streets

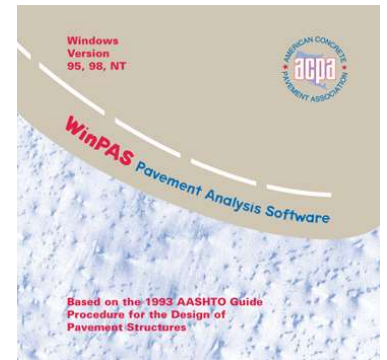
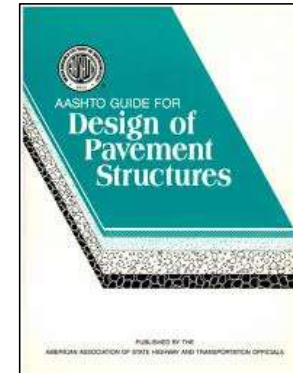
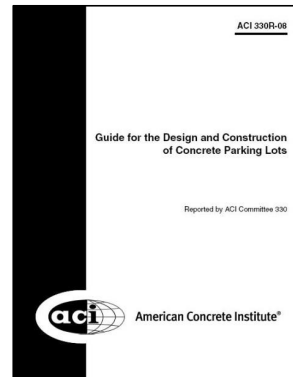
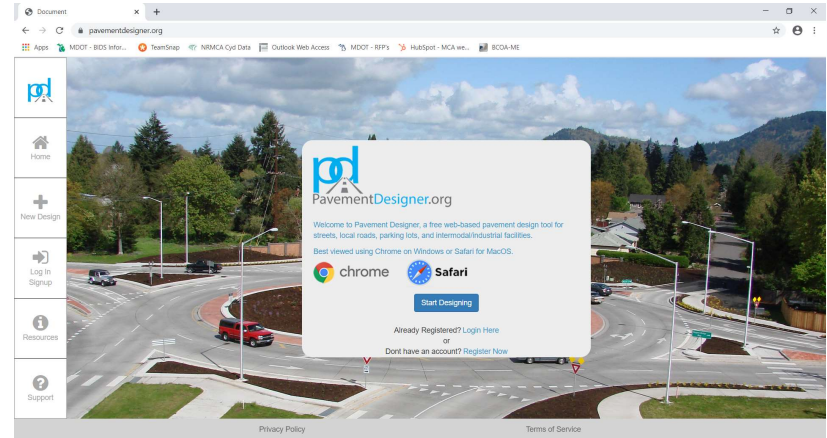
- StreetPave
- www.pavementdesigner.org
- AASHTO 93
 - WinPAS
- Pavement ME
 - \$\$, \$\$\$



Guides / Software to Use by Pavement Type

Parking Lots

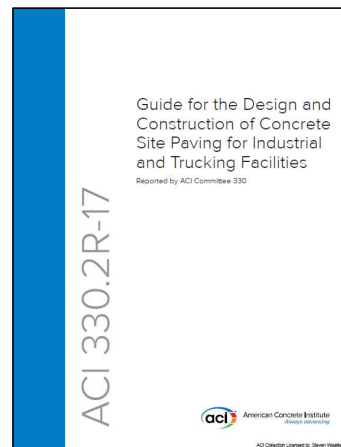
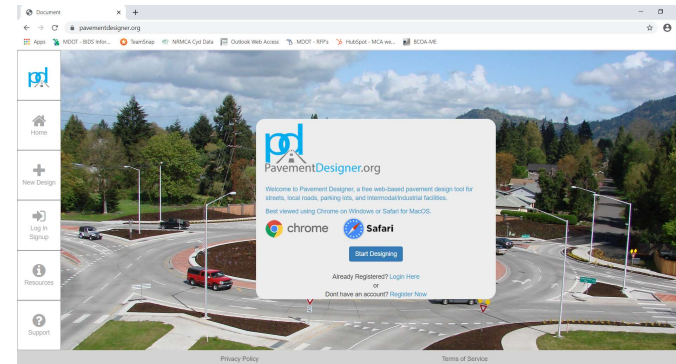
- StreetPave
 - www.pavementdesigner.org
- ACI 330R-08
 - guide
- AASHTO 93
 - WinPAS



Guides / Software to Use by Pavement Type

Industrial / Trucking

- StreetPave
 - www.pavementdesigner.org
- ACI 330.2R-17
 - guide
- Westergaard analysis
 - spreadsheet



$$\sigma_i = \frac{0.316P}{h^2} \left[4 \log_{10} \left(\frac{l}{b} \right) + 1.069 \right]$$
$$b = \sqrt{1.6a^2 + h^2} - 0.675h$$

Design Examples

Highway – using AASHTO 93 / WinPAS



Highway Example

20,000 ADT; 7% trucks



Concrete

Agg. base

Subgrade modulus = 3500 psi

Other design inputs & decisions: Design Life; Reliability/Deviation; Concrete Strength & Elasticity; Dowels/Edge Support; Agg. Base Thickness; Serviceability

Highway Example – Design Inputs

- 10,000,000 ESALs (18-kip equivalent single axle loads)
 - Roughly equal to 20,000 ADT; 7% trucks; 20-year design
- 90% reliability; 0.35 overall deviation
- 670 psi flexural strength; 4,200,000 psi elastic modulus
- Doweled joints ($J = 2.7$)
- k -value = 185 psi/in; (3500 psi subgrade modulus w/ 6" agg. base)
- $C_d = 1.0$; Initial Serviceability = 4.5; Terminal Serv. = 2.5

Highway Example – AASHTO 93 Thickness Design

WinPAS software:

Rigid Pavement Design

Rigid Design Inputs

PCC Thickness	8.92	inches
Design ESAL	10,000,000	
Reliability	90.00	percent
Overall Deviation	0.35	
Modulus of Rupture	670.0	psi
Modulus of Elasticity	4,200,000.0	psi
Load Transfer, J	2.70	
Mod. Subgrade Reaction, k	185.0	psi/in
Drainage Coefficient	1.00	
Initial Serviceability, Po	4.50	
Terminal Serviceability, Pt	2.50	

Cross Section

OK

?

Solve For

Pavement Thickness
8.92 inches

Solve For

Recommended Design:

- 9" PIM concrete (3500HP)
- 6" agg. base (21AA crushed conc.)
- Dowels
- Tied concrete shoulders

MDOT designs typ. range from 9" to 13"

Design Examples

Street/Local Road – using pavementdesigner.org



Street / Road Example

Minor Arterial: 10,000 ADT; 5% trucks



Concrete

Agg. base

Subgrade modulus = 3500 psi

Other design inputs & decisions: Design Life; Reliability/% Slabs Cracked; Concrete Strength & Elasticity; Fibers/Edge Support; Agg. Base Thickness

Street / Road Example – Design Inputs

- 4-Lane Minor Arterial; 10,000 ADT; 5% trucks; 20-year design
 - 50% directional split; 90% in design lane (right lane)
- 80% Reliability; 10% Slabs Cracked
- 670 psi flexural strength; 4,200,000 psi elastic modulus
- No macrofibers in mix; Tied curb & gutter
- k-value = 189 psi/in; (3500 psi subgrade modulus w/ 6" agg. base)

Street / Road Example – pavementdesigner.org

Project-Level Inputs:

Document | pavementdesigner.org/projectTypes/street/concrete/projectLevelForm

1 PROJECT LEVEL 2 PAVEMENT STRUCTURE 3 SUMMARY

Project Type: Street Concrete

TRAFFIC

Minor Arterial

Design Life: 20 (Years)

User Defined Traffic Info

Trucks/Day: 500

Traffic Growth Rate: 1 (% per year)

Directional Distribution: 50 (%)

Design Lane Distribution: 90 (%)

GLOBAL

Reliability: 80 (%)

% of Slabs Cracked at End of Design Life: 10 (%)

TRAFFIC SUMMARY DETAILS

AXLE LOAD (kips)	AXLES/1000 TRUCKS	AXLE LOAD (kips)	AXLES/1000 TRUCKS	AXLE LOAD (kips)	AXLES/1000 TRUCKS
30	9.45	52	1.19	70	0
25	0.85	48	2.91	64	0
25	1.78	44	6.01	58	0
24	9.21	40	21.31	52	0
22	7.85	36	56.25	46	0
20	16.33	32	103.63	40	0
18	25.15	28	121.22	34	0
16	31.62	24	72.54	28	0
14	47.73	20	85.94	22	0
12	182.02	16	99.34	15	0

CALCULATED TRAFFIC RESULTS

Avg Trucks/Day in Design Lane over the Design Life: 248

Total Trucks in Design Lane over the Design Life: 1,809,549

Change Design Type | Privacy Policy | Terms of Service | SAVE | PAVEMENT STRUCTURE

Pavement Structure:

Document | pavementdesigner.org/projectTypes/street/concrete/pavementStructureForm/PCP

1 PROJECT LEVEL 2 PAVEMENT STRUCTURE 3 SUMMARY

Project Type: Street Concrete JPCP

SUBGRADE

Known MRSG Value

MRSG Value: 3,500 psi

CONCRETE

28-Day Flex Strength

2nd Point Loading 28-Day Flex Strength: 670 psi

Modulus of Elasticity: 4,200,000 psi

Macrobinders in Concrete: Yes No

Edge Support: Yes No

STRUCTURE

Subbase Layers: 1

Layer Type: Granular Base

Resilient Modulus: 15,000 psi

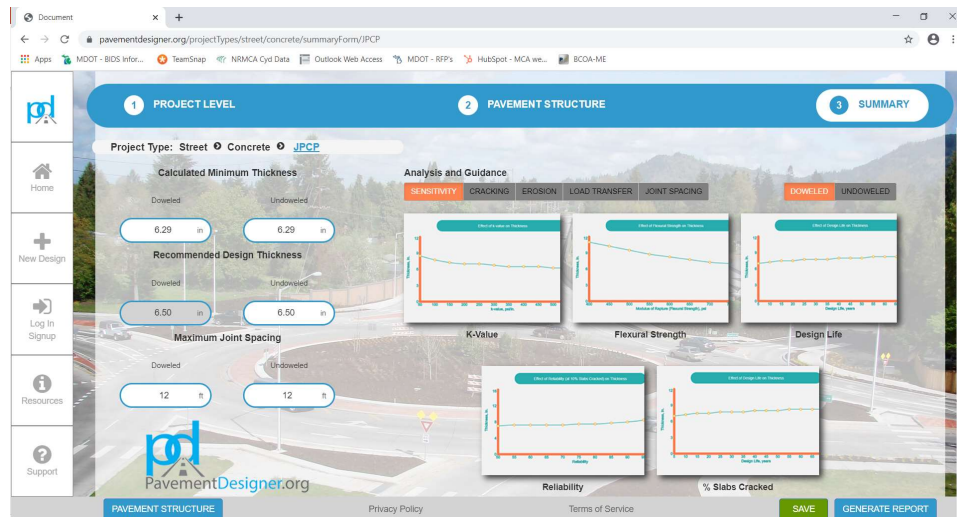
Layer Thickness: 6 in

Calculated Composite K-Value of Substructure: 199 psi/in

Project Level | Privacy Policy | Terms of Service | SAVE | DESIGN SUMMARY

Street / Road Example – pavementdesigner.org

Summary:



Recommended Design:

- 6.5 inches of concrete
- 6" agg. base (21AA crushed conc.)
- Tied curb & gutter
- 12 foot joint spacing

Typ. Michigan Concrete Road/Street Designs

- | | |
|---------------------------------|--------------------------|
| • Residential | ⇒ 3 to 50 trucks/day |
| • 4"-6" concrete, 3500 psi min. | → $M_R = 650$ psi |
| • 4" to 6" agg. base | → $k = 125$ psi/in |
| <hr/> | |
| • Collector, Business | ⇒ 50 to 700 trucks/day |
| • 5"-7" concrete, 3500 psi min. | → $M_R = 650$ psi |
| • 4" to 6" agg. base | → $k = 125$ psi/in |
| <hr/> | |
| • Arterial, Industrial | ⇒ 300 to 1500 trucks/day |
| • 6-9" concrete, 4000 psi min. | → $M_R = 650$ psi |
| • 4" to 8" agg. base | → $k = 150$ psi/in |

* NOTE: "Truck" = any heavy vehicle, i.e. delivery trucks, buses, etc.



Design Examples

Parking Lot– using ACI 330R-08



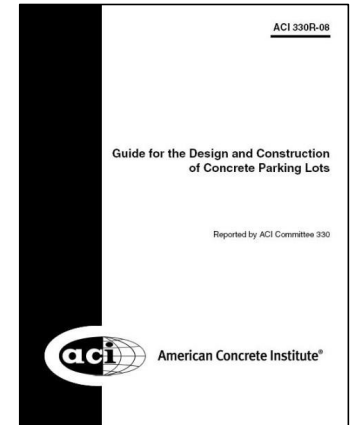
Parking Lot Example

Car parking: ~1 truck/day



Concrete
Agg. base

Subgrade modulus = 3500 psi



Other design inputs & decisions: Agg. Base Thickness; Concrete Strength

Parking Lot Example – ACI 330R-08

Traffic:

Subgrade / Base:

Table 3.3—Traffic categories*

1. Car parking areas and access lanes—Category A
2. Shopping center entrance and service lanes—Category B
3. Bus parking areas, city and school buses
Parking area and interior lanes—Category B
Entrance and exterior lanes—Category C
4. Truck parking areas—Category B, C, or D

Truck type	Parking areas and interior lanes	Entrance and exterior lanes
Single units (bobtailed trucks)	Category B	Category C
Multiple units (tractor trailer units with one or more trailers)	Category C	Category D

*Select A, B, C, or D for use with Table 3.4.

Table 3.1—Subgrade soil types and approximate support values (Portland Cement Association 1984a,b; American Concrete Pavement Association 1992)

Type of soil	Support	k , psi/in.	CBR	R	SSV
Fine-grained soils in which silt and clay-size particles predominate	Low	75 to 120	2.5 to 3.5	10 to 22	2.3 to 3.1
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	120 to 170	4.5 to 7.5	29 to 41	3.5 to 4.9
Sand and sand-gravel mixtures relatively free of plastic fines	High	180 to 220	8.5 to 12	45 to 52	5.3 to 6.1

Notes: CBR = California bearing ratio; R = resistance value; and SSV = soil support value. 1 psi = 0.0069 MPa, and 1 psi/in. = 0.27 MPa/m.

Table 3.2—Modulus of subgrade reaction k^*

Subgrade k value, psi/in.	Sub-base thickness			
	4 in.	6 in.	9 in.	12 in.
Granular aggregate subbase				
50	65	75	85	110
100	130	140	160	190
200	220	230	270	320
300	320	330	370	430

Parking Lot Example – ACI 330R-08

Table 3.4—Twenty-year design thickness recommendations, in. (no dowels)

MOR, psi:		$k = 500$ psi/in. (CBR = 50; $R = 86$)				$k = 400$ psi/in. (CBR = 38; $R = 80$)				$k = 300$ psi/in. (CBR = 26; $R = 67$)			
		650	600	550	500	650	600	550	500	650	600	550	500
Traffic category*	A (ADTT = 1)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.5
	A (ADTT = 10)	4.0	4.0	4.0	4.5	4.0	4.0	4.5	4.5	4.0	4.5	4.5	4.5
	B (ADTT = 25)	4.0	4.5	4.5	5.0	4.5	4.5	5.0	5.5	4.5	4.5	5.0	5.5
	B (ADTT = 300)	5.0	5.0	5.5	5.5	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0
	C (ADTT = 100)	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0
	C (ADTT = 300)	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0	5.5	6.0	6.0	6.5
	C (ADTT = 700)	5.5	5.5	6.0	6.0	5.5	5.5	6.0	6.5	5.5	6.0	6.5	6.5
	D (ADTT = 700) [†]	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
MOR, psi:		$k = 200$ psi/in. (CBR = 10; $R = 48$)				$k = 100$ psi/in. (CBR = 3; $R = 18$)				$k = 50$ psi/in. (CBR = 2; $R = 5$)			
		650	600	550	500	650	600	550	500	650	600	550	500
Traffic category*	A (ADTT = 1)	4.0	4.0	4.0	4.5	4.0	4.5	4.5	5.0	4.5	5.0	5.0	5.5
	A (ADTT = 10)	4.5	4.5	5.0	5.0	4.5	5.0	5.0	5.5	5.0	5.5	5.5	6.0
	B (ADTT = 25)	5.0	5.0	5.5	6.0	5.5	5.5	6.0	6.0	6.0	6.0	6.5	7.0
	B (ADTT = 300)	5.5	5.5	6.0	6.5	6.0	6.0	6.5	7.0	6.5	7.0	7.0	7.5
	C (ADTT = 100)	5.5	6.0	6.0	6.5	6.0	6.5	6.5	7.0	6.5	7.0	7.5	7.5
	C (ADTT = 300)	6.0	6.0	6.5	6.5	6.5	6.5	7.0	7.5	7.0	7.5	7.5	8.0
	C (ADTT = 700)	6.0	6.5	6.5	7.0	6.5	7.0	7.0	7.5	7.0	7.5	8.0	8.5
	D (ADTT = 700) [†]	7.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0

*ADTT = average daily truck traffic. Trucks are defined as vehicles with at least six wheels; excludes panel trucks, pickup trucks, and other four-wheel vehicles. Refer to Appendix A.
 k = modulus of subgrade reaction; CBR = California bearing ratio; R = resistance value; and MOR = modulus of rupture.

[†]Thickness of Category D (only) can be reduced by 1.0 in. (25 mm) if dowels are used at all transverse joints (that is, joints located perpendicular to direction of traffic).

Note: 1 in. = 25.4 mm; 1 psi = 0.0069 MPa; and 1 psi/in. = 0.27 MPa/m.

Recommended Design:

- 4.0 inches of concrete
- 4" agg. base (21AA crushed conc.)

Typ. Michigan Concrete Parking Lot Designs

- | | |
|---------------------------------|-------------------------|
| • Car parking | ⇒ 1 to 2 trucks/day |
| • 4"-5" concrete, 3500 psi min. | → $M_R = 650$ psi |
| • 4" to 6" agg. base | → $k = 125$ psi/in |
| <hr/> | |
| • Drive, Perimeter Lanes | ⇒ Up to 20 trucks/day |
| • 5" concrete, 3500 psi min. | → $M_R = 650$ psi |
| • 4" to 6" agg. base | → $k = 125$ psi/in |
| <hr/> | |
| • Truck Areas | ⇒ 100 to 700 trucks/day |
| • 6-7" concrete, 3500 psi min. | → $M_R = 650$ psi |
| • 4" to 8" agg. base | → $k = 125$ psi/in |

* NOTE: "Truck" = any heavy vehicle, i.e. delivery trucks, buses, etc.

Design Examples

Industrial Facility– using pavementdesigner.org



Industrial Example

Log Storage / Sorting Yard: Front Loader (CAT 986H)



Concrete

Agg. base

Subgrade modulus = 3500 psi

Other design inputs & decisions: Agg. Base Thickness; Concrete Strength & Elasticity

Industrial Example – Design Inputs

- 4 wheels; 130,000 lbs GVW; 90 psi tire pressure
- 670 psi flexural strength; 4,200,000 psi elastic modulus
- k-value = 189 psi/in; (3500 psi subgrade modulus w/ 6" agg. base)

Industrial Example – pavementdesigner.org

Project-Level Inputs:

Project Type: Intermodal

SELECT INTERMODAL PROJECT VEHICLES

Name	# of Wheels	Gross Weight (lb)	Contact Pressure (psi)	Contact Area (sq ft)
Container Handler - Aerial Lift	1	244168	130	1443
Aerial Lift - Marathon Letourneau Model 2682	1	243032	80	1443
Straddle Carrier - Marathon Letourneau SST 100	1	229200	95	1146
Transfainer Crane - Pacoco RT Transfainer	1	252960	124	969
Generic - Straddle Carrier	1	60211	110	260
Container Truck - Taylor TEC - 950L	2	223225	94	564
Container Truck - Taylor TEC - 155H	2	72716	110	157
Container Truck - Taylor TEC - 155L	2	71326	110	154
Container Handler - Taylor TYTC - 1100S	2	265120	108	627
Forklift - Valmet TD 1812	2	154084	60	309
Container Handler - Valmet TD 4212	2	265484	80	613
Wheel Loader - CAT 986H	4	130308	90	172
Wheel Loader - CAT 993K	4	427789	200	254

Vehicle Name: Wheel Loader - CAT 993K
Vehicle Image:

Change Design Type | Privacy Policy | Terms of Service | SAVE | PAVEMENT STRUCTURE

Pavement Structure:

Project Type: Intermodal

SUBGRADE

Known MRSG Value: 3,500

CONCRETE

25-Day Flex Strength: 670

Subgrade Layers

Layer Type: Gravel Base

Resilient Modulus: 15,000

Layer Thickness: 6

Calculated Composite K-Value of Substructure: 189

Project Level | Privacy Policy | Terms of Service | SAVE | DESIGN SUMMARY

Industrial Example – pavementdesigner.org

Summary:

Project Type: Intermodal

Recommended Design Thickness: 8.50 in

Calculated Minimum Thickness: 8.30 in

Maximum Joint Spacing: 15 ft

Stress Ratio: 0.5 %

Results and Guidance

Vehicle Name	Maximum Axle Load	Maximum Stress	Allowable Total Thickness	Thickness
Wheel Loader - CAT 980H	135.43	334.33 psi	541.040	8.3 in

Recommended Design:

- 8.5 inches of concrete
- 6" agg. base (21AA crushed conc.)
- 15 foot joint spacing

Design Examples

Truck Loading/Parking Area– using ACI 330.2R-17



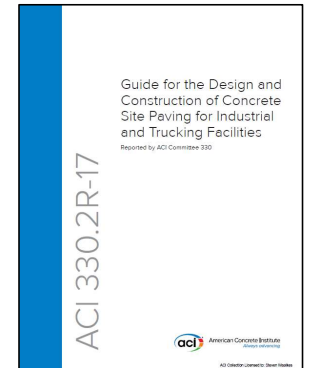
Truck Loading / Parking Area Example

Distribution Center; 250 trucks/day



Concrete
Agg. base

Subgrade modulus = 3500 psi



Other design inputs & decisions: Agg. Base Thickness; Concrete Strength

Thickness tables in ACI330.2R-17 based on 30-year design, 85% reliability, 15% slabs cracked

Truck Area Example – ACI 330.2R-17

Subgrade:

Table 3.3—Modulus of subgrade reaction, k , for typical subgrade soils (ACPA 2006)

Soil type	Support	Typical k -values, pci (MN/m ³)
A. Fine grained with high amounts of silt/clay	Low	75 to 120 (20 to 34)
B. Sand and sand-gravel with moderate silt/clay	Medium	130 to 170 (35 to 49)
C. Sand and sand-gravel with little or no silt/clay	High	180 to 220 (50 to 60)

Base:

Table 3.4.3.1b—Composite k -values for unbound granular subbase on unstabilized subgrade (ACPA 2006)

Soil type*	Soil layer k -value, pci (MN/m ³)	Thickness of unbound granular subbase			
		4 in. (100 mm)	6 in. (150 mm)	9 in. (225 mm)	12 in. (300 mm)
A	100 (27)	130 (35)	140 (38)	160 (43)	190 (52)
B	150 (41)	170 (48)	185 (50)	215 (58)	255 (69)
C	200 (54)	220 (60)	230 (62)	270 (73)	320 (87)

*Refer to Table 3.3.

Truck Area Example – ACI 330.2R-17

Table 4.7.3k—Thickness (d) and joint spacing (JS) for over-the-road truck category major arterial: with dowels in contraction joints; $k = 150$ pci (41 MN/m³)

No. of trucks per day design lane	Modulus of rupture, psi (MPa)					
	550 (3.8)		650 (4.5)		750 (5.2)	
	d , in. (mm)	Max. JS, ft (m)	d , in. (mm)	Max. JS, ft (m)	d , in. (mm)	Max. JS, ft (m)
100	8.0 (200)	15 (4.6)	7.0 (180)	14 (4.3)	6.5 (165)	13 (4.0)
200	8.0 (200)	15 (4.6)	7.5 (190)	15 (4.6)	7.0 (180)	14 (4.3)
500	8.5 (215)	15 (4.6)	7.5 (190)	15 (4.6)	7.0 (180)	14 (4.3)
1000	8.5 (215)	15 (4.6)	8.0 (200)	15 (4.6)	7.0 (180)	14 (4.3)

Recommended Design:

- 7.5 inches of concrete
- 6" agg. base (21AA crushed conc.)
- 15 foot joint spacing
- Doweled joints

Concrete Thickness Design Summary

- Highways: AASHTO 93 (WinPAS: www.acpa.org)
- Streets/Roads: www.pavementdesigner.org
- Parking Lots: ACI 330R (www.concrete.org)
- Industrial: www.pavementdesigner.org
- Trucking: ACI 330.2R (www.concrete.org)

or just contact Steve Waalkes swaalkes@miconcrete.net 616-633-9629



Questions?

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