



CONCRETE

INFORMATION

Structural Design of Roller-Compacted Concrete for Industrial Pavements

This bulletin will provide engineers with a procedure for thickness design of roller-compacted concrete (RCC) pavements at container ports, rail and truck terminals, and industrial yards that are trafficked by the heavy wheel loads of large fork-lift trucks, straddle carriers, log stackers, and mobile cranes.

The design of these heavy-duty pavements presents unique problems. For example: the wheel loads on container and trailer-handling vehicles may greatly exceed those of highway trucks and even of the heaviest modern aircraft; the required service life of the pavement may be shorter than that required for highway and airport pavements; and the pavement serviceability requirements may not have to be as strict as for highway and airport pavements carrying high-speed traffic.

Recent research and a review of roller-compacted concrete performance experience⁽¹⁻³⁾ indicate that a design procedure recognizing RCC's engineering properties can be similar to those used for the design of concrete airport and heavy industrial pavements. Accordingly, the design procedure presented here involves a determination of the pavement's flexural stress and fatigue caused by wheel-load repetitions of the vehicles using the pavement.

This publication deals primarily with pavement thickness design. Other aspects of RCC technology such as aggregate requirements, mix design, material properties, construction techniques, and field control are discussed in References 2 through 8.

Roller-Compacted Concrete

RCC is a stiff, zero-slump concrete mixture that is mixed, placed, and roller compacted with the same commonly available equipment used for asphalt pavement construction.

Because of the low water content used in the mix and resulting low water-cement ratio, RCC typically has high strengths similar to, or even greater than, conventional concrete. RCC is placed without forms, finishing, surface texturing, and joint sawing and sealing. Due to these factors—high strength, ease of construction, and high rate of production—RCC is often more economical than a flexible pavement of equivalent design.

Engineering Properties of RCC

An evaluation of the engineering properties of RCC indicates that they are similar to those of conventional concrete.⁽⁴⁾ This conclusion is based on testing of specimens from a full-scale test section, cores obtained from RCC pavements, and laboratory-molded specimens.

Strength. Depending on the cement content used, 28-day compressive strengths can range from about 3500 to over 5000 psi and flexural strengths from about 500 to over 700 psi. Table 1⁽⁴⁾ shows compressive strengths of cores drilled from projects after several years of service.

Table 1. RCC Core Strengths for British Columbia Projects

Project	Year built	Date of sample	Compressive strength, psi
Caycuse Log Sort Yard	1976	1980	4210
Caycuse Log Sort Yard	1976	1984	5880
Lynterm Container Port	1977	1980	4690
Fraser Mills Log Sort Yard	1982	1983	4700
Bullmoose Coal Mine	1983	1983	2200
Fraser Surrey Dock	1984	1984	4570

Tests results on cores and beams taken from a full-scale test section showed the following relation between compressive and flexural strengths at 28 days:

$$f_r = C \sqrt{f'_c}$$

where

f_r = flexural strength, psi, third-point loading

f'_c = compressive strength, psi

C = a constant between 9.4 and 10.8 depending on different RCC mix designs

Following the practices used for airport pavement design, the 90-day flexural strength is recommended for use as the design value. Usually this is about 10% greater than the 28-day strength.

Modulus of Elasticity. From the same series of tests described above, the average relationship between

modulus of elasticity (E) and compressive strength for several RCC mixes was determined as

$$E = C\sqrt{f'_c}$$

where C is a constant that varied between 59,000 and 67,000 for the different RCC mixtures tested.

Design Values. The specific relationships shown above were determined for a limited number of RCC mixtures. Rather than suggesting these for design use, the data are simply interpreted as evidence that the relationships between RCC properties are similar to the relationships for conventional concrete. Accordingly, the following relationships for RCC are suggested as estimates based on average properties for concrete:

$$f_r = 9\sqrt{f'_c}$$

$$E = 57,000\sqrt{f'_c}$$

The table shows values of the structural properties based on these equations.

Compressive strength, psi	Flexural strength, psi	Modulus of elasticity, psi
3000	490	3,100,000
3500	530	3,400,000
4000	570	3,600,000
4500	600	3,800,000
5000	640	4,000,000

These estimates are useful in the preliminary design stages. For final design analysis, tests to determine these properties, especially the flexural strength, should be performed on specimens of the RCC mixture to be used.

Fatigue Behavior. Like conventional concrete and other engineering materials, RCC is subject to the effects of fatigue. A fatigue failure occurs when a material ruptures under continued repetitions of loads that cause stresses less than the strength of the material.

Since the critical stresses in RCC are flexural, fatigue due to flexural stress is used for thickness design. Stress ratio, as used in fatigue relationships, is the ratio of flexural stress to flexural strength. For example, if a wheel load causes a flexural stress of 400 psi and RCC flexural strength is 650 psi, then

$$\text{Stress ratio} = \frac{400}{650} = 0.62$$

Flexural fatigue research on RCC has shown that its fatigue behavior is very similar to that of conventional concrete. Fig. 1 shows the results of fatigue tests on beams obtained from full-scale pavement test sections for four different RCC mixtures. In the figure, the line marked 50% is the best fit of the research data points and the 95% line includes 95% of the data points. Below these lines, the RCC design curve is set to provide a similar degree of conservatism as used for conventional concrete in PCA design procedures for highways⁽⁹⁾ and airports.⁽¹⁰⁾ Data from this design curve are reproduced in Table 3 for convenience of use in design problems.

Basis for Design

Because the structural behavior of RCC is similar to that of conventional paving concrete, the design procedure given here follows the methodology used for concrete

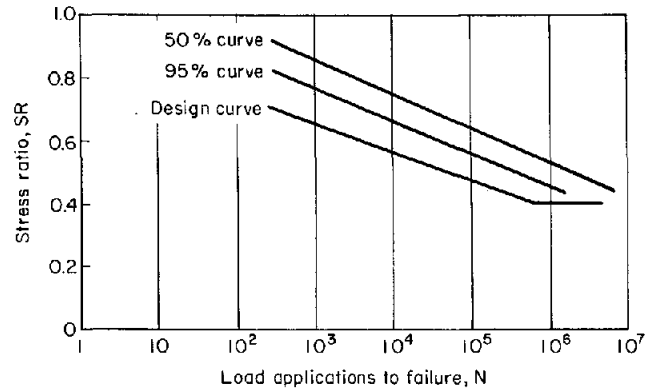


Fig. 1. Fatigue relationships for RCC.

pavements. The principal RCC properties affecting thickness design are its flexural strength and fatigue behavior.

In the design process, a pavement thickness is selected to keep flexural stresses and fatigue effects caused by wheel loads within safe limits. Stresses and fatigue are influenced by wheel-load placement—greater for loads placed at pavement edge and less away from edge. Unlike highways where all wheel loads run very close to the pavement edge, the critical wheel-load placement for industrial facilities is considered to be at the interior of the pavement, away from pavement edges. Where vehicles will be expected to travel at or on and off pavement edges the edge thickness should be increased 20%.

RCC pavements thicker than about 10 to 12 inches are constructed in multiple layers. Research on core samples⁽²⁾ indicates that multiple-layer pavements develop sufficient interface bond to be considered a monolithic structure. As a result, this assumption is used in the procedures given here. However, it is emphasized that proper procedures need to be followed in multilift construction to assure that bond between lifts is achieved. The surface of the lower lift should be kept moist and clean until the upper lift is placed, which should be done within the time limits stated in the construction specifications. When these recommendations are not met due to unforeseen construction delay or other factors, a sand-cement grout should be used to assure bonding of the two layers.

Conservatism is included in the design procedure so that average values of the design factors are used as inputs. First, the design fatigue curve is set conservatively below that determined by fatigue tests. Secondly, like concrete, RCC continues to gain strength with age; over the years of service life of the pavement the flexural strength of the pavement will be significantly greater than the 90-day strength value assumed for design.

Design charts presented in this bulletin, or a micro-computer program,⁽¹¹⁾ are used to determine pavement stresses. These are based on Pickett's extension⁽¹²⁻¹³⁾ of Westergaard's analysis for loads at the interior of a slab supported by a dense liquid subgrade. This basis for the procedure for RCC is the same as that given in PCA publications on airport and industrial pavement design for conventional concrete.

Thickness Design Procedure

To determine the required thickness of an RCC pavement, the following information is needed:

1. Supporting strength of the subgrade or subbase-subgrade combination
2. Vehicle characteristics
 - wheel loads
 - wheel spacing
 - tire characteristics
 - number of load repetitions expected during design life on different areas of the pavement
3. Flexural strength of RCC
4. Modulus of elasticity of RCC

Subgrade Support

The support given to the RCC pavement by the subgrade and by the subbase where one is used, is a major element in thickness design. Subgrade and subbase support is expressed in terms of the Westergaard modulus of subgrade reaction, k . The k -value is determined by a nonrepetitive plate-load test⁽¹⁴⁾ and is equal to the load in pounds per square inch on a 30-in.-diameter plate divided by the deflection in inches for that load, or the total load in pounds divided by the displaced total volume in cubic inches. The k -value is expressed in units of pounds per square inch per inch (psi/in.) or pounds per cubic inch (pci).

Where time and equipment are not available to perform plate-loading tests, the relationships shown in Fig. 2 are satisfactory for estimating the k -value. These k -values are based on correlations to soil strength tests and general soil types. Where a subbase is used there will be an increase in k that should be used in the thickness design. The approximate increase in k may be taken from Table 2.

Vehicle Loads

Estimating the expected traffic is an important factor in pavement design. Required traffic information includes the wheel-load magnitudes, wheel configuration, and frequency of operations of the heaviest vehicles that will use the pavement. As complete data as possible should be gathered from planning and operations departments' and manufacturers' data on the lift trucks, straddle carriers, and other heavy vehicles that will use the pavement.

Usually the vehicle having the heaviest wheel load will control the design, but the design should also be checked for adequacy if other vehicle wheel loads are almost as heavy and travel the pavement frequently.

The maximum wheel load is half of the heaviest axle load for the vehicle at its maximum loading. This information is usually available from the vehicle manufacturer.

The load contact area used in the charts is the area of slab contact of each tire carrying the maximum wheel load. It may be estimated by dividing the wheel load by the tire inflation pressure. The contact area to be used is sometimes referred to as the gross contact area—the

total area encompassed by the contact envelope regardless of the tire tread design.

The distance between wheels of the vehicle can be an important design factor. If this spacing is close (if closer than three times the radius of relative stiffness, see page 6) it is necessary to consider the effect of more than one wheel load in the computation of pavement stress. In this regard, the wheel configuration of almost all heavy vehicles at terminals and industrial storage areas is classified as either a single wheel load (i.e., a single wheel on each side of an axle) or a dual wheel load (i.e., dual wheels on each side of an axle; in this case two wheels are spaced closely enough that their combined effect on pavement stress must be considered). A load on dual wheels creates less pavement stress than the same load on a single wheel. For this reason, separate design charts are shown for single- and dual-wheel loads.

Some straddle-carrier vehicles have a tandem-wheel configuration—two closely-spaced wheels one behind the other as shown in Fig. 3c. For these, the design chart for dual wheels is used and a correction is applied as discussed on page 7.

Design Flexural Strength

Following the practice used for the design of concrete airport and industrial pavements, the 90-day flexural strength value (test method ASTM C 78) is also recommended as the design strength for RCC industrial pavements. The 90-day value is used because there are very few load repetitions during the first few months of pavement life compared to the great number of load repetitions that occur later. RCC, like concrete, will continue to gain strength with age so that pavement strength will soon exceed and remain above the 90-day design value (see Fig. 4).

Allowable Pavement Stress

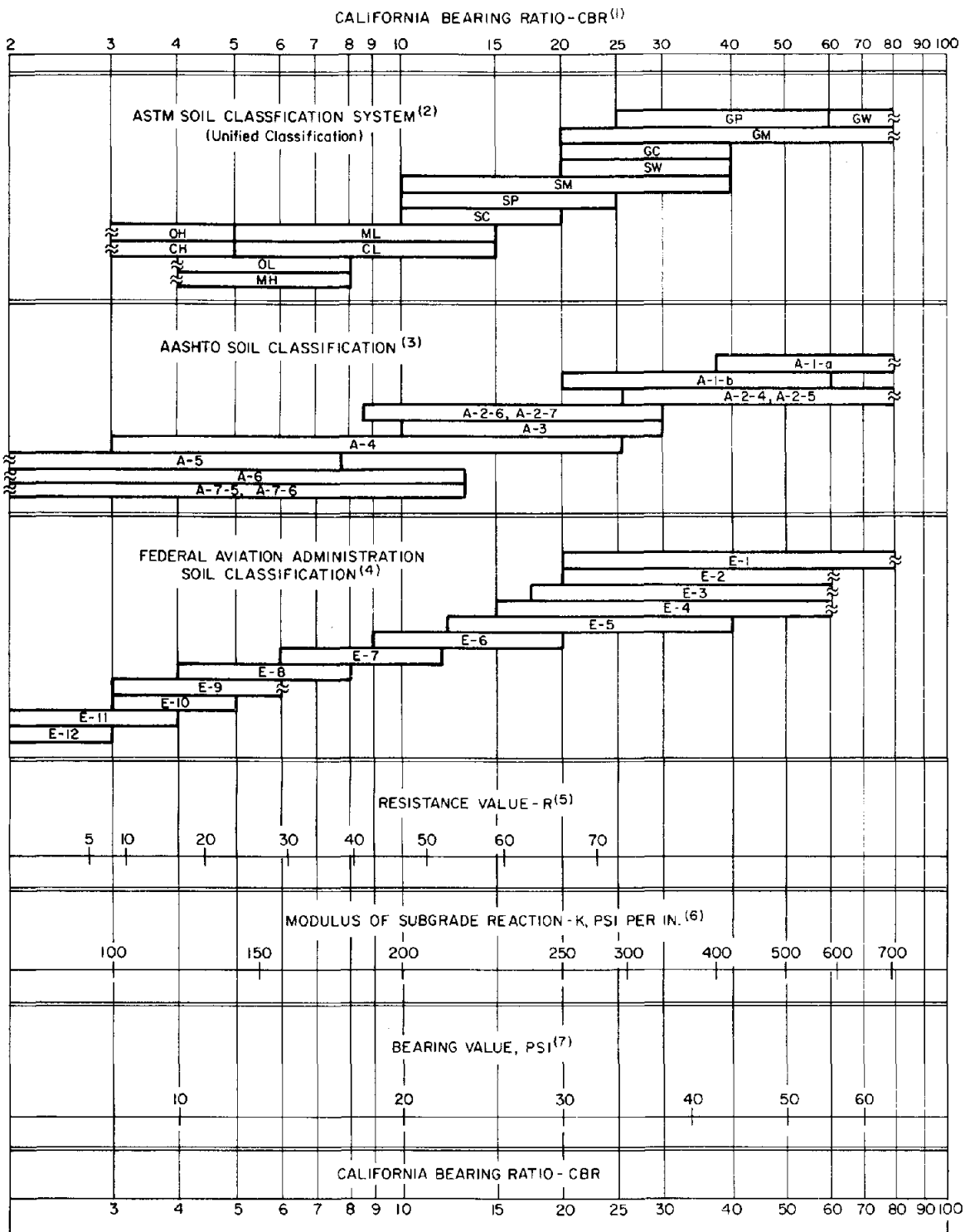
The design procedure requires determination of the allowable pavement stress and the expected pavement stress due to wheel loads. A design thickness is selected such that the expected pavement stress is less than the allowable pavement stress.

The allowable pavement stress is dependent on the number of load repetitions of the design wheel loads anticipated during the design period. Knowing the number of load repetitions during the design period, the allowable stress ratio, SR , is obtained from Table 3. Then the allowable pavement stress is computed as follows:

$$\text{Allowable stress} = (\text{stress ratio}) \times (\text{90-day flexural strength})$$

Charts for Determining Pavement Thickness

The chart given in Fig. 5 is for computing the stress due to single-wheel loading and the chart in Fig. 6 is for computing stress due to dual-wheel loading. For a more complex wheel configuration, the computer program



- (1) For the basic idea, see O. J. Porter, "Foundations for Flexible Pavements," Highway Research Board *Proceedings of the Twenty-second Annual Meeting*, 1942, Vol. 22, pages 100-136.
- (2) ASTM Designation D2487.
- (3) "Classification of Highway Subgrade Materials," Highway Research Board *Proceedings of the Twenty-fifth Annual Meeting*, 1945, Vol. 25, pages 376-392.
- (4) *Airport Paving*, U.S. Department of Commerce, Federal Aviation Agency, May 1948, pages 11-16. Estimated using values given in FAA *Design Manual for Airport Pavements*. (Formerly used FAA Classification; Unified Classification now used.)
- (5) C. E. Warnes, "Correlation Between R Value and k Value," unpublished report, Portland Cement Association, Rocky Mountain-Northwest Region, October 1971 (best-fit correlation with correction for saturation).
- (6) See T. A. Middlebrooks and G. E. Bertram, "Soil Tests for Design of Runway Pavements," Highway Research Board *Proceedings of the Twenty-second Annual Meeting*, 1942, Vol. 22, page 152.
- (7) See item (6), page 184.

Fig. 2. Approximate interrelationships of soil classifications and bearing values.

Table 2. Effect of Untreated Subbase on k Values,

Subgrade k value, pci	Subbase k value, pci			
	4 in.	6 in.	9 in.	12 in.
50	65	75	85	110
100	130	140	160	190
200	220	230	270	320
300	320	330	370	430

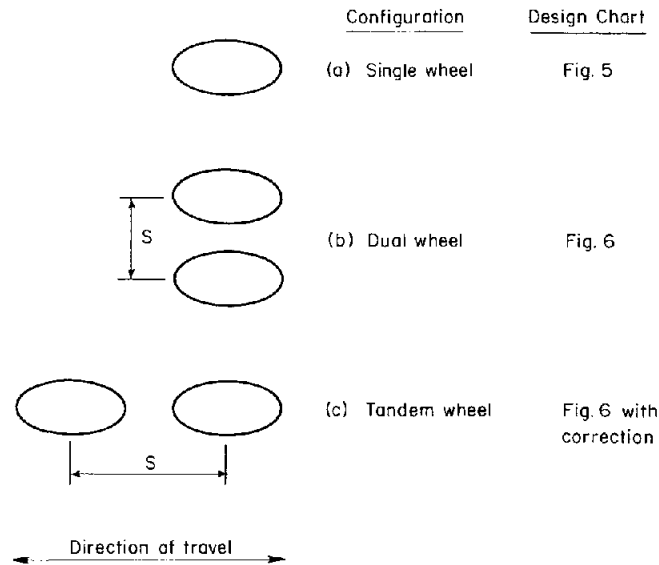


Fig. 3. Wheel configurations for heavy industrial vehicles.

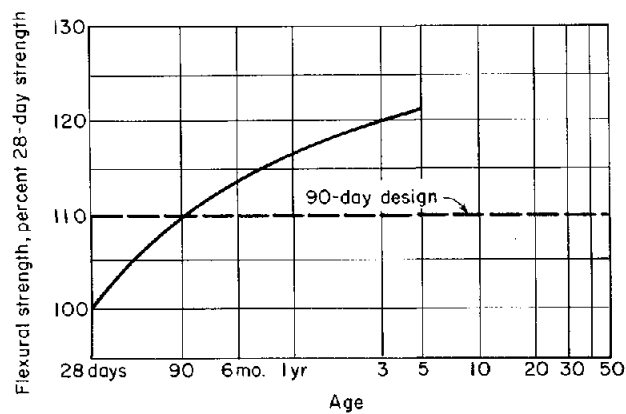


Fig. 4. Flexural strength-age relationship.

Table 3. Stress Ratios and Allowable Load Repetitions

Stress ratio*	Allowable repetitions	Stress ratio	Allowable repetitions
0.41**	465,000	0.56	9700
0.42	360,000	0.57	7500
0.43	280,000	0.58	5800
0.44	210,000	0.59	4500
0.45	165,000	0.60	3500
0.46	130,000	0.61	2700
0.47	100,000	0.62	2100
0.48	76,000	0.63	1600
0.49	59,000	0.64	1200
0.50	46,000	0.65	950
0.51	35,000	0.66	740
0.52	27,000	0.67	570
0.53	21,000	0.68	440
0.54	16,000	0.69	340
0.55	12,000	0.70	260

*Load stress divided by modulus of rupture.
 **Unlimited repetitions for stress ratios of 0.40 or less.

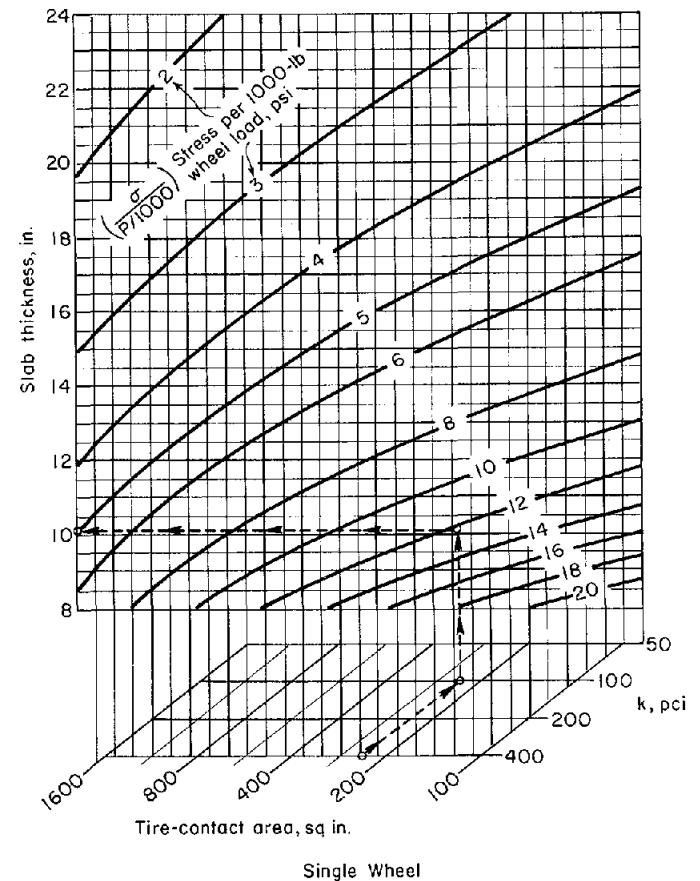


Fig. 5. Design chart for single-wheel loads.

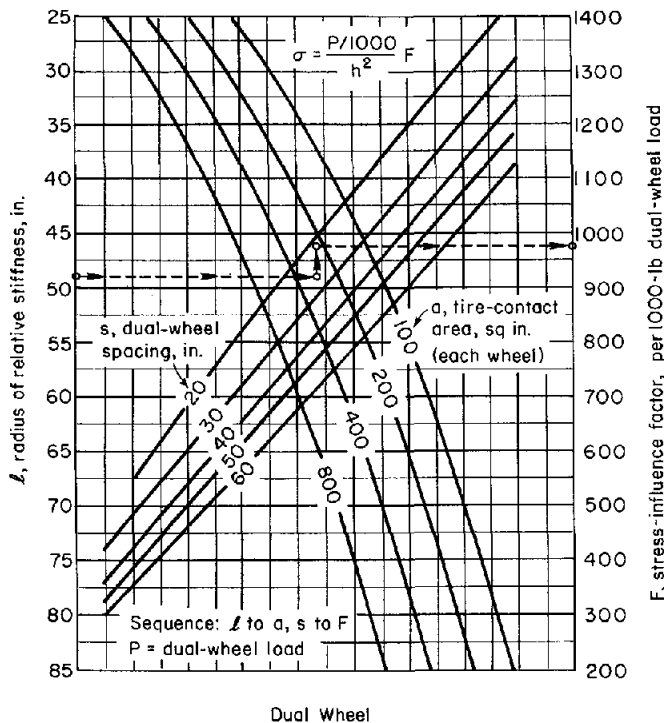


Fig. 6. Stress-influence factor for dual-wheel loads.

available for IBM compatible personal computers may be used.⁽¹⁾

Examples are presented to illustrate use of the design charts. The design chart for dual-wheel loading requires a value for radius of relative stiffness, l . The l -value is given as follows:

$$l = \left[\frac{Eh^3}{12(1 - \nu^2)k} \right]^{0.25}$$

where

- E = modulus of elasticity, psi
- h = pavement thickness, in.
- ν = Poisson's ratio, usually assumed to be 0.15
- k = modulus of subgrade reaction, pci

Values of l are given in Table 4.

The design charts, Figs. 5 and 6, and Table 4 are based on an assumed modulus of elasticity of the RCC of 4,000,000 psi. If the actual modulus of elasticity is substantially different, Figs. 5 and 6 are used but a slight correction in stress values is applied as discussed on page 7.

DESIGN EXAMPLE 1 (SINGLE WHEEL)

Straddle carrier

Number of wheels = 4

Maximum single wheel load, $P = 26,000$ lb

Tire inflation pressure = 100 psi

Tire contact area = 260 sq in.

RCC flexural strength, $f_r = 700$ psi

Subgrade strength, $k = 100$ pci

Daily number of channelized wheel-load applications in pavement area $A = 20$

Number of wheel-load applications over 20-year design period = $20 \times 365 \times 20 = 146,000$

Design stress ratio (Table 3), $SR = 0.45$

Allowable stress, $\sigma = f_r \times SR = 700 \times 0.45 = 315$ psi

$$\text{Allowable stress per 1000-lb load} = \frac{\sigma}{P/1000} = \frac{315}{26} = 12.1 \text{ psi/kip}$$

Enter the design chart, Fig. 5, for single wheels at the bottom with a tire contact area of 260 sq in. and a k -value of 100 pci. For an allowable stress of 12.1 psi/kip, a slab thickness of 10.1 in. is required (use 10 in.). Use of Fig. 5 is shown by the dashed-arrow line.

DESIGN EXAMPLE 2 (DUAL WHEEL)

Large fork-lift truck

Number of wheels = 6 (2 steer wheels and 4 drive wheels)

Maximum load on drive wheels = 65,000 lb on each dual set

Dual wheel spacing = 21 in. (center to center)

Tire inflation pressure = 110 psi

Tire contact area (each tire) = $65,000/2/110 = 295$ sq in.

RCC flexural strength, $f_r = 700$ psi

Subgrade-subbase strength, $k = 200$ pci

Daily number of channelized dual-wheel load applications in pavement area $B = 40$

Number of wheel-load applications over 20-year design period = $40 \times 365 \times 20 = 292,000$

Design stress ratio (Table 3), $SR = 0.43$

Allowable stress, $\sigma = f_r \times SR = 700 \times 0.43 = 301$ psi

1. The first step in the use of the design chart for dual wheels is to select arbitrarily a trial slab thickness, say 15 in.
2. Corresponding to this thickness and a k -value of 200 pci, an l -value of 49.0 is determined from Table 4.
3. From the determined l -value on the design chart, Fig. 6, proceed to the right to intersect with the tire contact area, then move vertically to intersect with the dual-wheel spacing. From this point move to the right to read an F -value (stress-influence factor per 1000-lb dual-wheel load) of 980.
4. Compute stress due to load as

$$\begin{aligned} \text{Stress} &= \frac{\text{Dual-wheel load}}{1000} \cdot \frac{1}{(\text{Slab thickness})^2} \cdot F \\ &= \frac{65,000}{1000} \cdot \frac{1}{15^2} \cdot 980 = 283 \text{ psi} \end{aligned}$$

5. The process is repeated determining stresses for other trial slab thicknesses, and data are tabulated as follows:

Trial number	Trial thickness, in.	l -value, in. (Table 4)	F (Fig. 6)	Stress, psi
1	15	49.0	980	283
2	14	46.5	955	317
3	14.5	47.8	965	298

6. Select a design slab thickness for which the stress due to load is equal to or less than the allowable stress. In this example for an allowable stress of 301 psi, a 14-in. slab is inadequate while a 14.5-in. slab is adequate and is selected as the design thickness.

Table 4. Values of ℓ , Radius of Relative Stiffness,* in.

h , in.	$k = 50$	$k = 100$	$k = 150$	$k = 200$	$k = 250$	$k = 300$	$k = 350$	$k = 400$	$k = 500$
8	43.23	36.35	32.85	30.57	28.91	27.62	26.58	25.70	24.31
8.5	45.24	38.04	34.37	31.99	30.25	28.91	27.81	26.90	25.44
9	47.22	39.71	35.88	33.39	31.58	30.17	29.03	28.08	26.55
9.5	49.17	41.35	37.36	34.77	32.89	31.42	30.23	29.24	27.65
10	51.10	42.97	38.83	36.14	34.17	32.65	31.42	30.39	28.74
10.5	53.01	44.57	40.28	37.48	35.45	33.87	32.59	31.52	29.81
11	54.89	46.16	41.71	38.81	36.71	35.07	33.75	32.64	30.87
11.5	56.75	47.72	43.12	40.13	37.95	36.26	34.89	33.74	31.91
12	58.59	49.27	44.52	41.43	39.18	37.44	36.02	34.84	32.95
12.5	60.41	50.80	45.90	42.72	40.40	38.60	37.14	35.92	33.97
13	62.22	52.32	47.27	43.99	41.61	39.75	38.25	36.99	34.99
13.5	64.00	53.82	48.63	45.26	42.80	40.89	39.35	38.06	35.99
14	65.77	55.31	49.98	46.51	43.98	42.02	40.44	39.11	36.99
14.5	67.53	56.78	51.31	47.75	45.16	43.15	41.51	40.15	37.97
15	69.27	58.25	52.63	48.98	46.32	44.26	42.58	41.19	38.95
15.5	70.99	59.70	53.94	50.20	47.47	45.36	43.64	42.21	39.92
16	72.70	61.13	55.24	51.41	48.62	46.45	44.70	43.23	40.88
16.5	74.40	62.56	56.53	52.61	49.75	47.54	45.74	44.24	41.84
17	76.08	63.98	57.81	53.80	50.88	48.61	46.77	45.24	42.78
17.5	77.75	65.38	59.08	54.98	52.00	49.68	47.80	46.23	43.72
18	79.41	66.78	60.35	56.16	53.11	50.74	48.82	47.22	44.66
19	82.70	69.54	62.84	58.48	55.31	52.84	50.84	49.17	46.51
20	85.95	72.27	65.30	60.77	57.47	54.92	52.84	51.10	48.33
21	89.15	74.97	67.74	63.04	59.62	56.96	54.81	53.01	50.13
22	92.31	77.63	70.14	65.28	61.73	58.98	56.75	54.89	51.91
23	95.44	80.26	72.52	67.49	63.83	60.98	58.68	56.75	53.67
24	98.54	82.86	74.87	69.68	65.90	62.96	60.58	58.59	55.41

*For $E = 4,000,000$ psi and $\mu = 0.15$

Design Procedure for Mixed Traffic

The design procedure presented is applicable when a single type of wheel loading can be identified as the design wheel loading. When mixed traffic exists, then the cumulative fatigue damage due to the mixed traffic needs to be calculated. This approach requires the following steps:

1. Select a trial pavement thickness
2. Compute pavement stress, σ , using Fig. 5 or 6 for each type of wheel loading
3. Compute stress ratio, SR , for each type of wheel loading
4. Determine the allowable number of load repetitions, $N_{a,n}$, for each type of wheel loading using Table 3
5. Determine the fatigue consumption by each type of wheel loading as follows:

$$F_n = \frac{N_{e,n}}{N_{a,n}} \times 100$$

where

F_n = fatigue consumption for wheel load n , percent

$N_{e,n}$ = expected number of load repetitions of wheel load n during the design period

$N_{a,n}$ = allowable number of load repetitions of wheel load n (see step 4)

6. Add the fatigue consumption for all wheel loadings
7. If fatigue consumption is more than 100% or less than 100% repeat steps 2 to 6 with a larger or smaller pavement thickness as the case may be. The design

thickness is the one that results in total fatigue consumption of 100% or less

Correction for Tandem Wheels

Fig. 6, used for dual-wheel configurations, is also used for pavement design for vehicles with tandem wheels—see Fig. 3c. However, a correction to stress values is applied since tandems, for the same conditions, cause higher stresses than duals.

Computer analysis⁽¹²⁾ has shown that the following corrections can be applied based on tire contact area as the most influential factor.

Tire contact area, sq in.	Multiply stress for dual wheels by
100	1.067
200	1.069
400	1.073
800	1.080
1200	1.087

These corrections will give stress values for tandem wheels that are accurate within 1.5% for most conditions.

For tandem wheels, the number of wheel-load repetitions is not doubled; one pass of a tandem set (2 wheels) is taken as one load repetition.

Effect of Modulus of Elasticity

In the calculation of stresses, the modulus of elasticity (E) has minor effects. The design charts in this publica-

tion are based on a E value of 4,000,000 psi, which is appropriate for RCC with structural properties very similar to conventional concrete. If the E -value of the RCC to be used for the pavement is known to be substantially less or greater than 4,000,000 psi, correction may be applied to give a more accurate computation of flexural stresses. If not determined by test (ASTM C 469), the E -value may be estimated from the engineering properties relationships discussed on page 2.

E-value, psi	Correction for E-values different from 4,000,000 psi	
	Multiply allowable stress by	
	for single wheels	for dual wheels
3,000,000	1.038	1.046
5,000,000	0.972	0.968

These corrections will give stress values that are accurate within 1% for most conditions.

It is important to note that, in the procedures given in this booklet, these factors are to be multiplied by the allowable stress*.

If the microcomputer program⁽¹⁾ is used for design, the above correction is not applied since the E -value is an input item.

*Although procedures are not described in this booklet, sometimes it is desired to determine the stress induced by a vehicle on a specified pavement thickness and an E -value different than 4,000,000 psi. In this case, the stress value is divided, rather than multiplied, by the factors shown above.

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An organization of cement manufacturers to improve and extend the uses of portland cement and concrete through market development, engineering, research, education, and public affairs work.