

Thickness Design of Roller-Compacted Concrete Pavements

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Roller-compacted concrete (RCC) is a relatively stiff or zero-slump concrete mixture that is compacted by vibratory roller. RCC is capable of providing concrete with relatively high in-place strength, and its engineering behavior is similar to that of conventional concrete. RCC is being used as a paving material at off-highway facilities such as container ports, intermodal yards, log-sorting yards, truck parking areas, and tank aprons (hardstands). An investigation was recently conducted to develop engineering data and procedures for design of RCC pavements. A procedure for thickness design of RCC pavements is presented in this paper. The design approach used for RCC pavements is similar to the procedure used by the Portland Cement Association for design of concrete airfield and heavy industrial pavements. The proposed procedure requires computation of allowable pavement stress based on the number of total load applications and computation of expected pavement stress due to the design wheel loading. A design thickness is selected such that the expected pavement stress is less than the allowable pavement stress. The proposed procedure is also applicable to mixed traffic loading.

Roller-compacted concrete (RCC) is a relatively stiff or zero-slump concrete mixture that is compacted by vibratory rollers. Although the term roller-compacted concrete is of recent origin (early 1970s), similar materials—mixtures of cement, aggregate, and water—have been used for a much longer time. These mixtures have been called cement-treated base (CTB), cement aggregate mixture (CAM), or granular soil cement (SC). However, CTB, CAM, and granular SC usually are lower-strength materials with 28-day compressive strengths of less than about 1,000 psi. RCC as used for paving can be designed to achieve 28-day compressive strengths similar to those of conventional concrete.

Since the first use of RCC in dam construction in the United States during the 1970s, its use has been increasing for other applications such as paving. Early use of RCC for paving was made in western Canada where pavements were constructed in remote areas. Because of its low cost, ease of placement, and good performance record in western Canada, RCC use is increasing in the United States for off-highway facilities subjected to heavy vehicle loading. RCC has been used principally for off-highway facilities such as

1. Container ports,
2. Intermodal yards,

3. Log-haul roads,
4. Log-sorting yards,
5. Truck-parking areas,
6. Airfield apron areas, and
7. Tank aprons (hardstands).

BACKGROUND

The first large-scale use of RCC as paving was made in British Columbia in 1976. Since then several large paving projects using RCC have been constructed in British Columbia and elsewhere in Canada. Since 1984 RCC has also been used in the United States for paving. During 1985 a total of 81,000 yd² of 12- and 17-in.-thick RCC pavement was constructed at an intermodal yard in Tacoma. On this project, crushed aggregate with 5/8-in. maximum size aggregate was used. Cement content specified was 450 lb/yd³, and fly ash specified was 100 lb/yd³. Average flexural strength at 28 days measured from sawed beams was about 750 psi.

During 1985 a 40,000-yd² aircraft parking apron was also constructed using RCC at the Portland International Airport. On this project pavement thickness was 14 in. Cement content of 488 lb/yd³ and fly ash content of 119 lb/yd³ were used for the RCC. During 1986 several large RCC paving projects were constructed in the United States.

During October 1986, RCC was used for pavement construction at Berths 11 and 12 of the Conley Terminal in Boston. The RCC mix used contained 600 lb/yd³ of cement and 100 lb/yd³ of fly ash. The aggregate was well graded with a maximum aggregate size of 3/4 in. Pavement thickness was 18 in. Lanes were constructed in two or three lifts. Lanes were 450 ft long and about 15 ft wide. Figure 1 (top) shows a view of the pugmill, aggregate stockpile, and a test section that was constructed about 1 month before actual construction. Figure 1 (bottom) shows the placement of RCC using two pavers placing adjacent lanes.

To summarize the experience with RCC pavements, the following items are noted:

1. RCC is generally mixed in a twin-shaft pugmill.
2. Cement content used has ranged from about 300 to 600 lb/yd³. At some projects, fly ash was used in the range of 15 to 20 percent by weight of cementitious materials.
3. RCC is usually placed using an asphalt paver. Maximum compacted lift thickness that can be placed using currently available pavers is about 9 to 10 in. However,

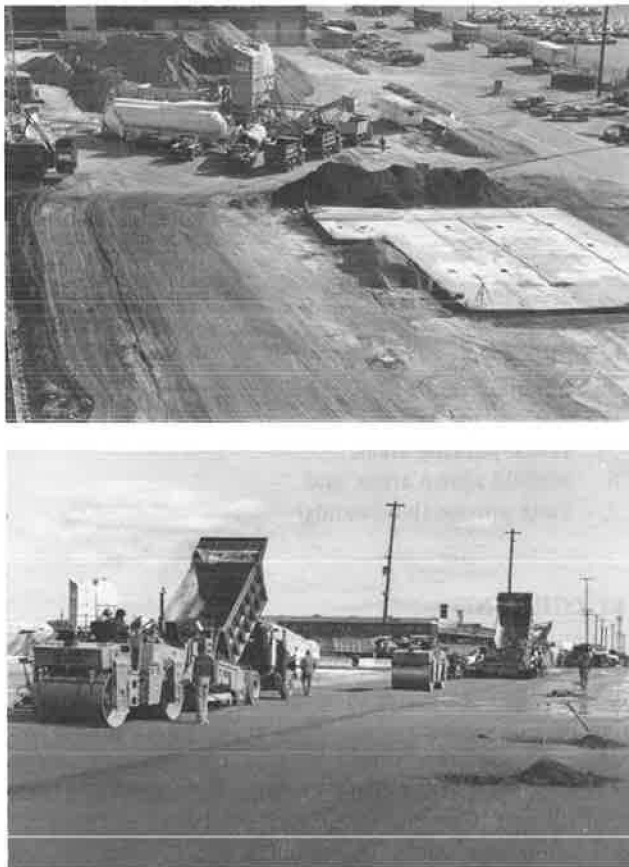


FIGURE 1 RCC pavement construction: (top) pugmill and (bottom) two-lane placement of RCC.

pavers can be modified to provide a compacted lift of about 12 in.

4. RCC is compacted using 10- to 12-ton vibratory rollers to achieve specified density.

5. Contraction joints are not provided in RCC pavements. Instead, shrinkage cracking is allowed to occur naturally. Spacing of shrinkage cracks is about 50 to 60 ft.

6. Pavements constructed with RCC have excellent performance records under very heavy vehicle loadings.

PROJECT OBJECTIVES

Although RCC has been in use for paving for many years, no detailed study has been carried out to investigate its engineering properties and to establish a thickness design procedure for RCC pavements. A study was recently sponsored by the Portland Cement Association (PCA) to develop engineering data and procedures for design of RCC pavements. The scope of work of the PCA study included the following items:

1. Evaluation of engineering properties of RCC,
2. Evaluation of mix proportioning procedures,
3. Evaluation of RCC durability, and
4. Establishment of a thickness design procedure for RCC pavements.

Results of the first two work items are presented in a companion paper by Tayabji and Okamoto in this Record. A procedure for thickness design of RCC pavements is presented here. Investigation of RCC durability is still in progress.

ENGINEERING PROPERTIES OF RCC

The PCA's evaluation of the engineering properties of RCC indicates that the behavior of RCC is similar to that of conventional concrete. This evaluation was based on testing of specimens obtained from a full-scale test section and review of test data from several RCC paving projects. RCC can be made with 3 to 6 bags of cement per cubic yard of RCC. Depending on the cement content, the 28-day compressive strength of RCC can range from about 3,500 to more than 5,000 psi, and the 28-day flexural strength can range from about 500 to more than 700 psi. Data on strength characteristics of RCC are given in the paper by Tayabji and Okamoto in this Record.

FATIGUE BEHAVIOR OF RCC

As part of the PCA's investigation, tests were conducted to determine flexural fatigue characteristics of RCC. Flexural fatigue testing was performed on beam specimens obtained from a full-scale section. Fatigue test results are shown in Figure 2. Linear regression was used to develop a fatigue curve for the test data for the four different RCC mixes used.

Fatigue test results of the RCC mixes are compared in Figure 2 with results from fatigue tests on conventional concrete conducted by Murdoch and Kesler (1) and Ballinger (2). In addition, the PCA fatigue curve used for design of concrete pavement (3) is shown in Figure 3. The Murdoch-Kesler curve for conventional concrete shown in Figure 3 was drawn so that 95 percent of the test results would fall above the line. The PCA curve for conventional concrete pavement design is conservatively set below the 95 percent Murdoch-Kesler curve.

A design fatigue curve for RCC was developed using a degree of conservatism similar to that used to develop the design fatigue curve for conventional concrete. The design fatigue curve for RCC, shown in Figure 4, is set about 15 percent below the 95 percent curve for RCC. Information for the design fatigue curve is given in Table 1.

THICKNESS DESIGN OF RCC PAVEMENTS

Although RCC pavements have primarily been used for off-highway facilities, RCC pavements can also be used for industrial driveways and truck-parking areas. As discussed earlier, the engineering behavior of RCC can be considered similar to that of conventional paving concrete at equal strength levels. Properly designed and constructed RCC can provide compressive and flexural strengths comparable to those generally specified for conventional paving concrete.

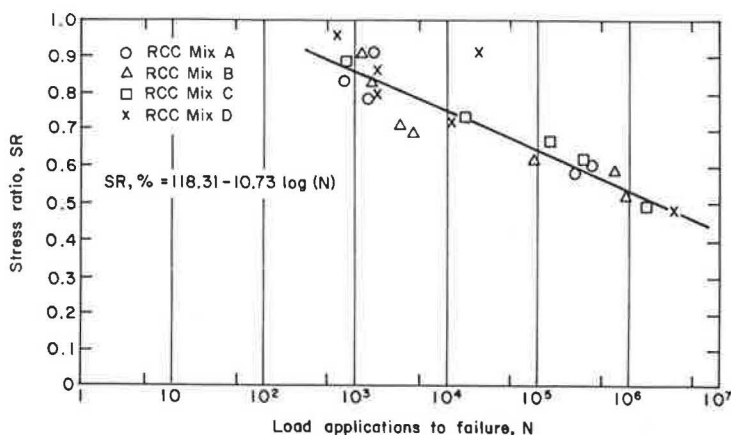


FIGURE 2 Fatigue relationship for RCC.

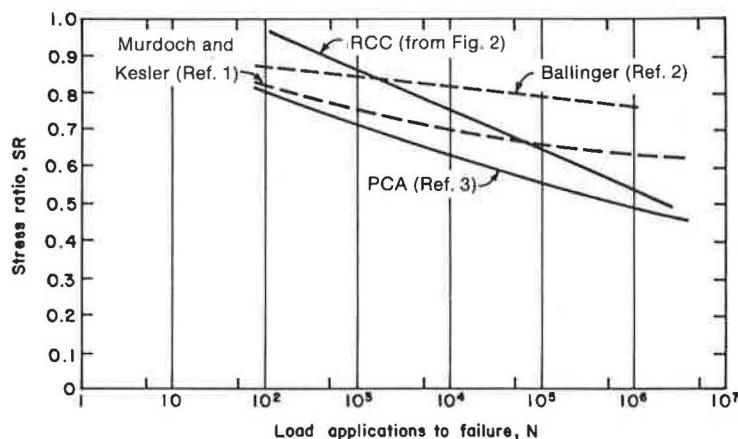


FIGURE 3 Comparison of fatigue relationship.

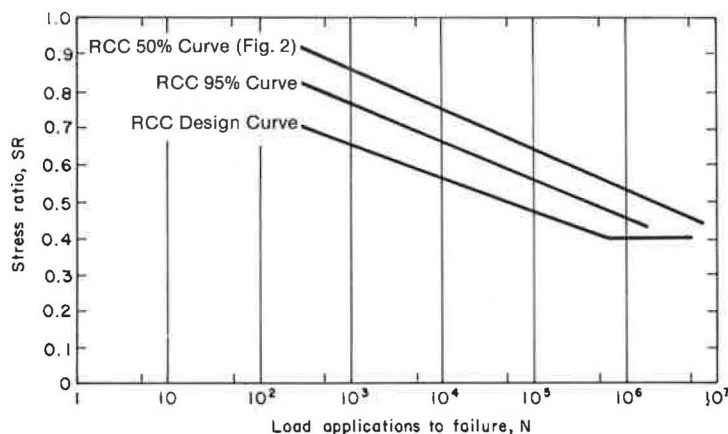


FIGURE 4 Design fatigue curve for RCC.

Design Procedure

Because the engineering properties of RCC are similar to those of conventional paving concrete, the thickness design procedures used for concrete pavements can be directly applied to design of RCC pavements. The primary parameters affecting thickness design of concrete pavements are concrete flexural strength and concrete fatigue behavior. The design fatigue relationship for RCC presented earlier is considered applicable to thickness design of RCC pavements.

For facilities using RCC pavements, the critical load placement is considered to be at the interior of the pavement. Use of the interior load placement is based on the following reasoning:

1. Transverse shrinkage crack spacing for RCC pavements is generally about 50 to 60 ft with little intermediate cracking.
2. Traffic at off-highway facilities and industrial driveways and yards is at relatively low speeds and is generally two

TABLE 1 STRESS RATIO AND ALLOWABLE LOAD REPETITIONS FOR DESIGN OF RCC PAVEMENTS

Stress Ratio	Allowable Repetitions	Stress Ratio	Allowable Repetitions
0.40	600,000	0.56	9,700
0.41	465,000	0.57	7,500
0.42	360,000	0.58	5,800
0.43	280,000	0.59	4,500
0.44	210,000	0.60	3,500
0.45	165,000	0.61	2,700
0.46	130,000	0.62	2,100
0.47	100,000	0.63	1,600
0.48	76,000	0.64	1,200
0.49	59,000	0.65	950
0.50	46,000	0.66	740
0.51	35,000	0.67	570
0.52	27,000	0.68	440
0.53	21,000	0.69	340
0.54	16,000	0.70	260
0.55	12,000		

NOTE: Stress ratio is pavement stress due to wheel load divided by RCC flexural strength. Design fatigue for RCC.

$\log(N) = 10.258 - 11.198(SR)$ where N is allowable load repetitions and SR is stress ratio.

directional. Thus problems of faulting and pumping at joints are minimized or nonexistent.

3. Field surveys of facilities using RCC pavements show no consequential problems at shrinkage cracks (4, 5).

The design procedure proposed for RCC pavements is similar to the procedure used by PCA for concrete airfield and heavy industrial pavements.

Design Requirements

A variety of vehicles may be used at facilities with RCC pavements. These vehicles include large-capacity forklift trucks, straddle carriers, log stackers, and logging or heavy freight trucks. Wheel loads on these vehicles may range up to 100,000 lb, greatly exceeding those of highway trucks. Total loads on these vehicles are equal to and sometimes greater than those of the heaviest commercial aircraft.

For design of RCC pavements, charts have been prepared to enable computation of the required pavement thickness. These charts were prepared using Pickett's extension (6) of Westergaard's analysis for loads at the interior of a slab supported by a dense liquid subgrade (7). Pickett's extension of Westergaard's analysis has been programmed for solution using IBM-compatible personal computers (8). The design charts presented for single wheel loading and for dual wheel loading require the following information:

1. Supporting strength of the subgrade;
2. Vehicle characteristics
 - Wheel loads,
 - Wheel configuration, and
 - Tire characteristics;

3. Flexural strength of RCC; and
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 (ASTM D 1196) 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 total volume displaced 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).

When time and equipment are not available to determine k -values, the relationships shown in Figure 5 are satisfactory for estimating the k -value. These k -values are based on correlation with 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 configurations, 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 of the lift trucks, straddle carriers, and other heavy vehicles that will use the pavement.

Usually the vehicle with 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 one-half of the heaviest axle load for the vehicle at its rated maximum capacity. 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 (closer than three times the radius of relative stiffness) it is necessary to consider the effect of more than one wheel load in the computation of pavement stress. In this regard, the wheel configurations of almost all heavy vehicles at terminals and industrial storage areas are classified as either single wheel load (e.g., a single wheel on each side of an axle) or dual wheel load (e.g., dual wheels on each side of an axle; in this case two

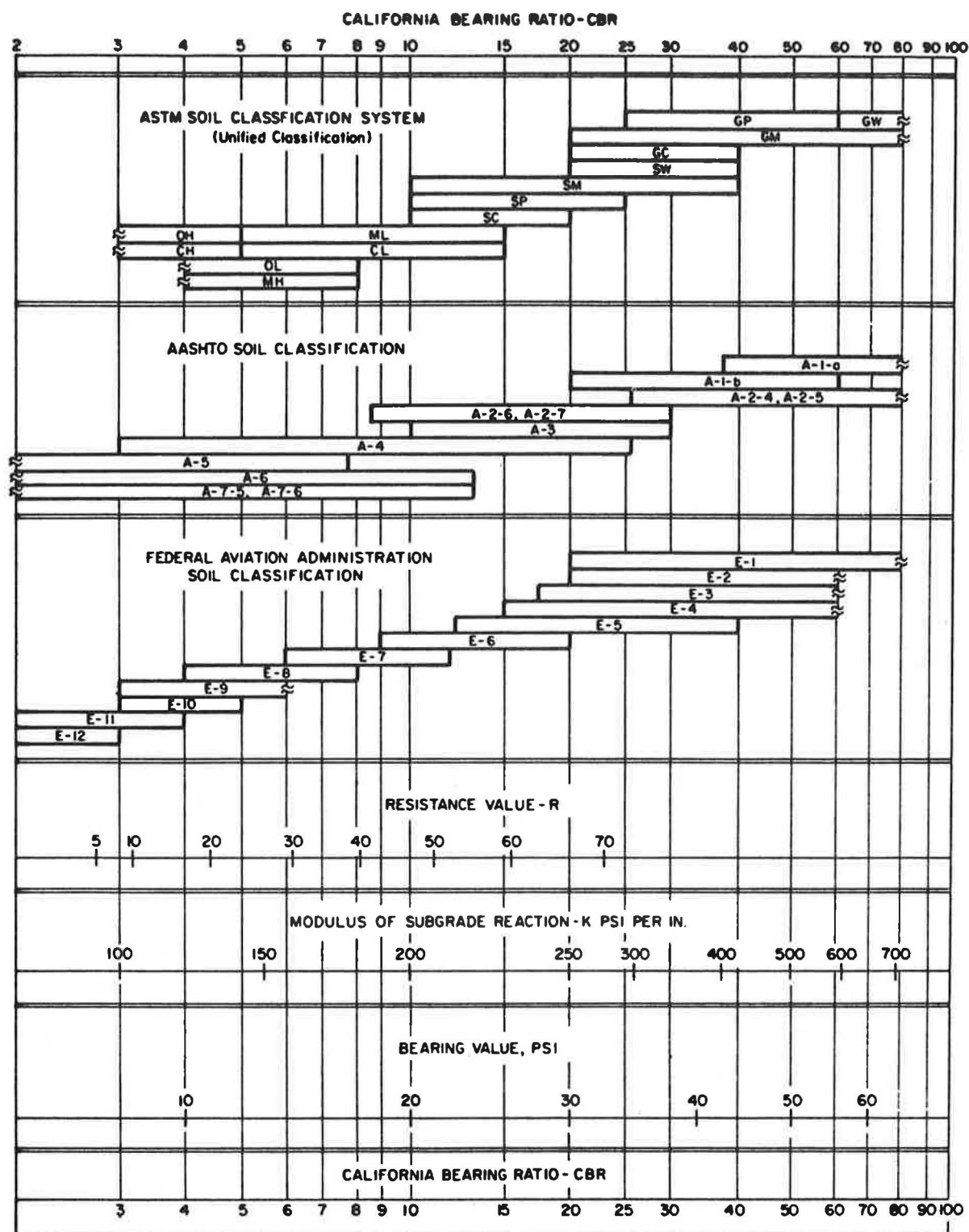


FIGURE 5 Estimation of modulus of subgrade reaction.

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.

Allowable Pavement Stress

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

TABLE 2 EFFECT OF SUBBASE THICKNESS ON k -VALUES

Subgrade k -Value (pci)	Subbase k -Value (pci) at				
	4 in.	6 in.	8 in.	9 in.	12 in.
Granular subbase					
50	65	75		85	110
100	130	140		160	190
200	220	230		270	320
300	320	330		370	430
Stabilized subbase					
50	170	230	310		
100	280	400	520		
200	470	640	830		

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. When the number of load repetitions during the design period is known, the allowable stress ratio (SR) can be obtained from Table 1. Then the allowable pavement stress is computed as follows:

$$\text{Allowable stress} = \text{Stress ratio} \times \text{RCC flexural strength}$$

Determination of the design pavement thickness on the basis of single and dual wheel loads is discussed next.

Charts for Determining Pavement Thickness

The chart shown in Figure 6 is for computing stress due to single wheel loading and the chart shown in Figure 7 is for computing stress due to dual wheel loading. For a more complex wheel configuration, the computer program available for IBM-compatible personal computers may be used (8).

Examples

Examples are presented to illustrate the 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:

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

where

- E = RCC modulus of elasticity (psi);
- h = RCC pavement thickness (in.);
- μ = RCC Poisson's ratio, usually assumed to be 0.15; and
- k = modulus of subgrade reaction (pci).

Values of l are given in Table 3.

Design Example 1 (single wheel) The vehicle is a straddle carrier. The following parameters are taken into consideration:

- Number of wheels = 4;
- Maximum single wheel load = 26,000 lb;
- Tire inflation pressure = 100 psi;
- Tire contact area = 260 in.²;
- RCC flexural strength = f_r = 700 psi;
- Subgrade strength, k = 100 pci;
- Daily number of channelized wheel load applications (design) = 20;
- Number of wheel load applications over 20-year design period = 146,000;
- Design stress ratio (Table 1), $SR \approx 0.45$;
- Allowable stress, $\sigma = f_r \times SR = 700 \times 0.45 = 315$ psi; and
- Allowable stress per 1,000-lb load

$$= \frac{\sigma}{P/1,000} = \frac{315}{26} = 12.1 \text{ psi/kip.}$$

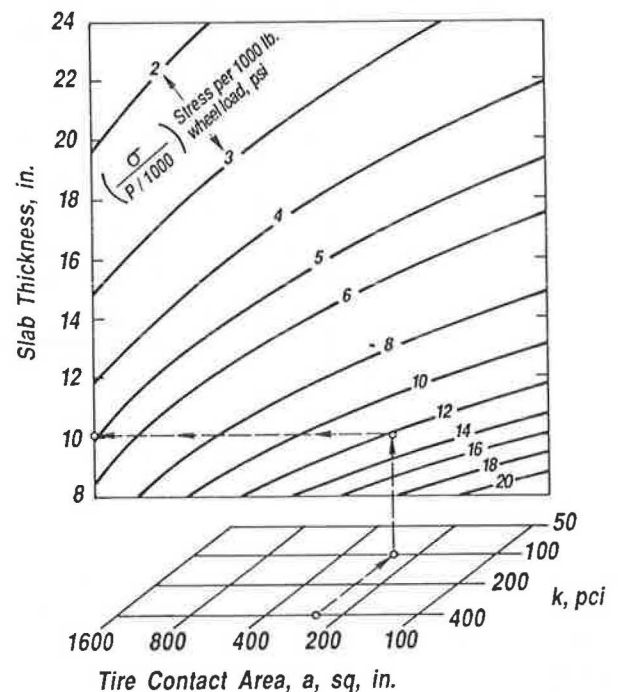


FIGURE 6 Design chart for single wheel load.

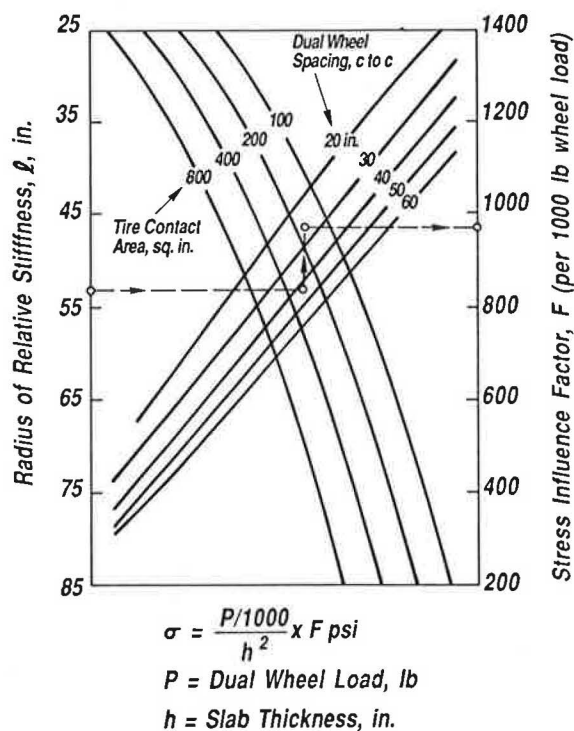


FIGURE 7 Design chart for dual wheels (sequence: *l* to area to spacing to *f*).

Enter the design chart for single wheels (Figure 6) at the bottom with a tire contact area of 260 in.² 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 the chart is shown by the dashed-arrow line.

Design Example 2 (dual wheels) The vehicle is a mobile gantry crane (lift capacity 40 tons). The following parameters are taken into consideration:

- Number of wheels = 8 (4 duals);
- Maximum dual wheel load = 90,000 lb;
- Dual wheel spacing = 26 in. center to center;
- Tire inflation pressure = 160 psi;
- Tire contact area (each tire) = 90,000/2/160 = 281 in.²;
- RCC flexural strength, f_r = 700 psi;
- Subgrade-subbase strength, k = 200 pci;
- Daily number of channelized dual wheel load applications = 40;
- Number of wheel load applications over 20-year design period = 292,000;
- Design stress ratio (Table 1), SR = 0.43; and
- Allowable stress, $\sigma = f_s \times SR = 700 \times 0.043 = 301$ psi.

TABLE 3 VALUES OF *l*, RADIUS OF RELATIVE THICKNESS

<i>h</i> in.	<i>k</i> = 50	<i>k</i> = 100	<i>k</i> = 150	<i>k</i> = 200	<i>k</i> = 250	<i>k</i> = 300	<i>k</i> = 350	<i>k</i> = 400	<i>k</i> = 500
6	34.84	29.30	26.47	24.63	23.30	22.26	21.42	20.72	19.59
6.5	36.99	31.11	28.11	26.16	24.74	23.64	22.74	22.00	20.80
7	39.11	32.89	29.72	27.65	26.15	24.99	24.04	23.25	21.99
7.5	41.19	34.63	31.29	29.12	27.54	26.32	25.32	24.49	23.16
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	53.10	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

NOTE: In inches $E = 4,000,000$ psi and $\mu = 0.15$

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

The first step in the use of the design chart for dual wheels is to arbitrarily select a trial slab thickness, say 15 in.

Corresponding to this thickness and a k -value of 200 pci, an l -value of 49.0 is determined from Table 3.

From the determined l -value on the design chart (Figure 7) 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 1,000-lb dual wheel load) of 930.

Compute stress due to load as

$$\begin{aligned} \text{Stress} &= \frac{\text{Dual wheel load}}{1,000} \times \frac{1}{(\text{Slab thickness})^2} \times \frac{1}{F} \\ &= \frac{90,000}{1,000} \times \frac{1}{15^2} \times 930 = 372 \text{ psi.} \end{aligned}$$

The process is repeated to determine stresses for other trial slab thicknesses and data are tabulated as follows:

Trial Slab Thickness (in.)	l -Value (in.) from Table	F (from design chart)	Stress Due to Load (psi)
15	49.0	930	372
16	51.4	955	336
17	53.3	970	302

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, the design thickness is 17 in.

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, the cumulative fatigue damage due to the mixed traffic needs to be calculated. This approach requires the following steps:

1. Select pavement thickness.
2. Compute pavement stress (σ) using Figure 6 or 7 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) for each type of wheel loading using Table 1.
5. Determine the fatigue consumption by each type of wheel loading as follows:

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

where

$$F_n = \text{fatigue consumption for wheel load } n,$$

$$\begin{aligned} N_{e,n} &= \text{expected number of load repetitions of wheel load } n \text{ during the design period, and} \\ N_{a,n} &= \text{allowable number of load repetitions of wheel load } n \text{ (see Step 4).} \end{aligned}$$

6. Add the fatigue consumption for all wheel loadings.

7. If fatigue consumption is more than 100 percent or less than 100 percent, repeat Steps 2-6 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 percent or less.

ADDITIONAL NOTES

RCC is placed in a single lift when pavement thickness is about 10 in. or less. When pavement thickness is more than 10 in., RCC may be placed in two or three lifts. Minimum lift thickness is about 5 in. When a multiple-lift placement procedure is used, sufficient consideration must be given to the time interval between placement of successive lifts. In warm weather, the time interval between placement of successive lifts should not be greater than 1 hr. In cooler weather and if wind conditions permit, a time interval of 2 to 3 hr may be permissible. The time interval is critical to ensure adequate bonding at the interface of successively placed lifts. Adequately bonded interfaces should develop shear strength of at least 200 psi at 90 days. If adequate shear strength is not developed at the interface, each lift may behave independently of the other lifts. This behavior would reduce the load-carrying capability of the pavement. The thickness design procedure presented in this paper assumes that the RCC pavement behaves monolithically when a multiple-lift construction procedure is used.

RCC is a dense material that is mixed, placed, and compacted in a relatively dry state. Because of the nature of the material, it has not been practical to entrain air in RCC mixtures on field projects. Many of the projects constructed in the past were located in coastal areas where numerous freeze-thaw cycles occur but where winter temperatures are not necessarily severe. During 1986 RCC pavements were constructed in the Denver and Boston areas. During 1985 the Corps of Engineers reported the results of an investigation conducted to evaluate frost resistance of RCC samples taken from nine field projects (9). Samples of RCC were tested for air content, parameters of air void system, resistance to rapid freezing and thawing, critical dilation, and compressive and flexural strengths. The Corps of Engineers' investigation indicated that the air void systems observed in many of the RCC samples should be sufficient to protect the pavement against frost damage in all but the most severe environments.

RCC samples obtained from field projects have not shown good durability when tested in the laboratory according to the procedures of ASTM C 666. However, this does not necessarily mean that RCC may not be durable in the field. Although ASTM C 666 is a useful test for evaluating durability of conventional concrete, its direct applicability to RCC is not clear. The best indicator of RCC durability is its performance in the field. The recently constructed RCC

pavements in the Denver and Boston areas will help to resolve the concern about RCC durability.

SUMMARY

In this paper are presented results of an investigation conducted to develop data and procedures for design of RCC pavements. Results of the investigation show that RCC is a viable paving alternative capable of providing satisfactory long-term performance.

The procedure for thickness design of RCC pavements is based on flexural fatigue considerations. This approach is similar to the PCA procedure for design of concrete pavements for off-highway facilities and industrial driveways and parking areas. However, the procedure for RCC pavements uses a newly established design fatigue relationship for RCC.

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DISCUSSION

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The design charts presented by the authors suffer from a number of limitations. The most important of these is that the charts are not plotted in terms of the variable that really controls the behavior of the system analyzed, namely the ratio (a/l) of the radius of the applied load to the radius of relative stiffness (l). In addition, Figure 7 assumes the use of the English unit system, while Figure 6 is even more restrictive in the sense that it only applies exactly for the E - and μ -values assumed in its derivation. These values are not explicitly given in the paper. There is no reason why two charts should be necessary because the single wheel load (SWL) case is simply the special dual wheel load (DWL) case in which spacing equals zero. Furthermore, ideally the SWL chart should give the same results as the Westergaard equation for the maximum stress under interior loading (2). Checking this, however, would be a tedious task in view of the way the chart is presented.

The purpose of graphic solutions is to present a concise picture of the phenomenon observed and to provide a fast but accurate way of determining the desired result. For these reasons, Figure 8 is submitted as an improvement of Figures 6 and 7. In this figure, the authors' charts are replotted in terms of a/l . The new graph was derived from and includes all of the SWL and DWL data presented in the paper (the dotted portions are extrapolations). The zero-spacing curve can easily be checked now and it is found to be in nearly perfect agreement with Westergaard's predictions for the SWL case. The effect of spacing is clearly shown in Figure 8. It would be a simple exercise in curve fitting to quantify the spacing effect as a function of the nondimensional ratio of the spacing to the load radius (S/a) and for a correction term to be added to the Westergaard equation. Similar correction terms for the finite size of the slab can also be obtained from nondimensional plots presented elsewhere (3).

Note that the abscissa in Figure 8 is the nondimensional stress ($\sigma h^2/P$). Because three dimensionless ratios are used,

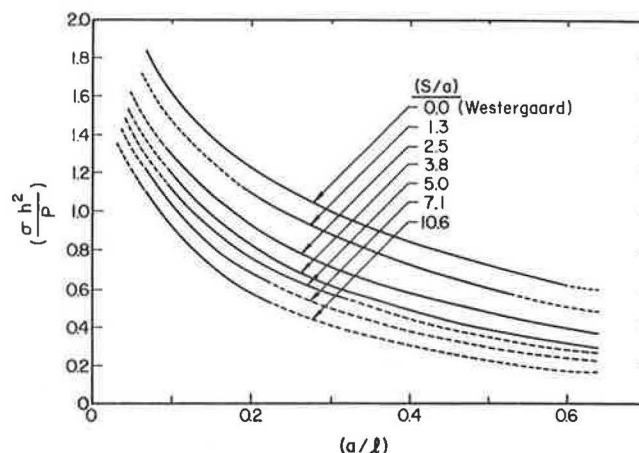


FIGURE 8 Nondimensional plot of effect of spacing.

Figure 8 can accommodate any system of units. It is noted that the authors' f -factor in Figure 7 is simply 1,000 times the nondimensional stress in the new graph. In obtaining Figure 8, E and μ for the slab were assumed to be 4 million psi and 0.15, respectively, but because of its nondimensional nature this plot applies to any selected parameters. The loaded areas were assumed to be circular, but this is of little consequence. Using Figure 8 is much simpler and involves one step only, compared with the iterative process required by the authors' charts. The ratio (S/l) could have been used instead of (S/a) in presenting the spacing effect in Figure 8 [as is done, for example, by the FAA according to Yoder and Witczak (4)] without any loss of generality. This is because (S/a) may be converted to (S/l) through multiplication by the governing ratio (a/l) . Because it is admitted that "the behavior of RCC is similar to that of conventional concrete," the charts in Figures 6, 7, and 8 can be applied to the latter as well.

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AUTHORS' CLOSURE

The authors appreciate Ioannides' effort in trying to simplify Figures 6 and 7. The authors deliberately developed Figures 6 and 7 as separate figures to make them easy for practicing engineers to use. Figure 8, though correct and concise, may be more useful as a teaching aid.

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