

Engineering Properties of Roller-Compacted Concrete

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An investigation was conducted to develop a procedure for the design of roller-compacted concrete (RCC) pavements. This paper is a report on the laboratory portion of the investigation that was conducted to determine the engineering properties of RCC. Specimens for the laboratory tests were obtained from a full-scale test section constructed using a 10-ton vibratory roller. Specimens were tested for flexural, split-tensile, and compressive strength; modulus of elasticity; and fatigue properties. The engineering behavior of RCC was determined to be similar to that of conventional concrete. Test results for RCC made using 243 to 285 lb/yd³ of cement show that RCC is capable of providing relatively high in-place strength. As with conventional concrete, RCC strengths produced are even higher when higher cement contents are used. In another phase of the investigation, mix proportioning procedures for RCC were investigated. Specimens were prepared using a vibrating table with a surcharge and the modified Proctor procedure. RCC mixes studied contained 3.5 and 6 bags/yd³ of cement. Specimens prepared by using the vibrating table produced significantly lower densities and strengths because the moisture content was lowered.

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 relatively low-strength materials with 28-day compressive strengths of less than about 1,000 psi. RCC used for paving can be designed to achieve 28-day compressive strengths similar to or greater than those of conventional concrete.

Since the application of roller-compacted concrete for dam construction in the United States during the 1970s, its use has been increasing for other applications such as paving. Early use was made of RCC for paving in western Canada to provide durable pavements in remote areas. Because of its low cost, ease of placement, and good performance record in western Canada, RCC use is becoming widespread 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 loads,
4. Log-sorting yards,
5. Truck-parking areas,
6. Airfield apron areas, and
7. Tank apron (hardstands).

BACKGROUND

The first large-scale use of RCC as paving was in British Columbia in 1976. This installation was a 4-acre log-sorting yard on Vancouver Island. The RCC pavement was 14 in. thick and was placed in two lifts. The first lift, with a compacted thickness of 8 in., contained 8 percent cement by weight. The second lift had 13 percent cement by weight. Since 1976 several large paving projects have been constructed using RCC in British Columbia. Most of these RCC projects used aggregate graded from 100 percent passing the 3/4-in. sieve to a maximum of about 14 percent passing the No. 200 sieve. Cement contents used have been about 13 percent by weight. Fly ash, in the range of from 15 to 20 percent by weight of total cementitious materials, was used on some projects. Typical RCC core strengths from some British Columbia projects are given in Table 1. A field evaluation of several RCC projects in British Columbia during 1980 indicated that the RCC pavements subjected to heavy loads were performing well (*1*).

The first significant use of RCC for paving in the United States was at Fort Hood in Texas. An 18,000-yd² area of 10-in.-thick RCC pavement was constructed for use as a parking apron for tanks and other tracked vehicles. The RCC mix at Fort Hood contained 300 lb/yd³ of cement and 160 lb/yd³ of fly ash. Most of the RCC used 1 1/2-in. maximum size aggregate. Beams obtained from the RCC pavement produced flexural strengths at 28 days of between 800 and 900 psi.

Another major use was made of RCC at the Port of Tacoma, Washington. The South Intermodal Yard constructed during early 1985 consisted of 52,000 yd² of 12- and 17-in.-thick RCC pavement. Crushed aggregate with 5/8-in. maximum size was used. Cement content specified was 450 lb/yd³ and fly ash specified was 100 lb/yd³. The pavement was constructed using a conventional asphalt paver equipped with a vibrating screed. Average flexural strength at 28 days measured from sawed beams averaged about 750 psi. The

TABLE 1 TYPICAL RCC CORE STRENGTHS FOR SOME BRITISH COLUMBIA PROJECTS

Project	Year Built	Date of Sample	Compressive Strength (psi)
Caycuse log-sorting yard	1976	1980	4,210 ^a
		1984	5,880 ^a
Lynterm container port	1977	1980	4,690 ^a
Fraser Mills log-sorting yard	1982	1983	4,700 ^b
Bullmoose coal mine	1983	1983	2,200 ^b
Fraser Surrey dock	1984	1984	4,570 ^b

^aFrom Tayabji et al. (1).

^bFrom Piggott (2).

North Intermodal Yard, constructed during the summer of 1985, consisted of 29,000 yd² of 12- and 17-in.-thick RCC. Aggregate type and cementitious content were similar to those for the South Intermodal Yard. Part of the paved area was constructed using a Barber Green asphalt paver equipped with a vibrating screed and part was paved using a German-made ABG paver, which is equipped with two tamping bars that consolidate the RCC to near specified density before rolling. Preconsolidation by the ABG paver helps to produce a nearly level surface.

A 40,000-yd² aircraft-parking apron was constructed during the summer of 1985 at the Portland International Airport. The aggregate consisted of a modification to the Oregon Department of Transportation specification for 3/4-in. maximum sized aggregate for asphalt pavements. The gradation was modified to include a higher percentage of fines, between 5 and 10 percent passing the No. 200 sieve. Specified cement content was 488 lb/yd³ and specified fly ash content was 119 lb/yd³. On this project, the 14-in.-thick pavement was constructed in two equal lifts using the German ABG paver equipped with two tamping bars. An 8-ton combination vibratory steel-wheeled and multitired roller was used to provide final compaction. Surface finish met requirements of a maximum of 1/4-in. roughness in 10 ft established by the Federal Aviation Administration for aircraft-parking aprons.

During October 1986 RCC was used for pavement construction of 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 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.

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. On some projects, fly ash, in the range of 15 to 20 percent by weight of cementitious materials, was used.
3. RCC is usually placed using an asphalt paver. The maximum compacted lift thickness that can be placed using currently available pavers is about 9.0 to 10.0 in. However, 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.

OBJECTIVE OF THE PROJECT

The objective of the project was to develop data and procedures for the design of RCC pavements. The scope of work 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.

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

ENGINEERING PROPERTIES OF RCC

Although RCC has been in use for paving for many years, no detailed study has been carried out to investigate its engineering properties. In general, available information on RCC for paving involves only compressive strength. The reported 28-day compressive strengths for RCC range from about 3,000 psi to more than 5,000 psi.

The objectives of the PCA study were to investigate the different strength characteristics of RCC and to compare its engineering behavior with that of conventional concrete. The following strength-related information was considered necessary:

1. Compressive strength,
2. Flexural strength,
3. Split-tensile strength,

4. Modulus of elasticity, and
5. Fatigue behavior.

A laboratory test program was designed to provide preliminary data on proportioning and compaction of RCC mixes. The laboratory test program was used to identify four mixes for construction of full-scale test slabs. Specimens were obtained from the full-scale test slabs and tested for strength, modulus of elasticity, and fatigue properties.

Laboratory Test Program

RCC mixes were prepared in the laboratory to investigate the influence of coarse aggregate volume, paste-to-mortar volume, and water-to-cementitious material ratio on consistency, compactibility, and compressive strength of RCC. The laboratory mixes were designed using procedures discussed in the American Concrete Institute's Committee 207 report on Roller Compacted Concrete (3). Although this report, published in 1980, was limited in its applicability, at the time it was the only available reference containing a detailed discussion on different aspects of RCC.

Material Characteristics

The following materials were used:

- Cement: Type I,
- Fly ash: Class F, and
- Aggregate: locally available gravel and sand.

Coarse aggregate was a bank-run gravel from Elgin, Illinois. The coarse aggregate had a maximum aggregate size of 1 1/2 in. and was blended to meet the gradation requirements of Size 467 of ASTM C 33. The fine aggregate was Elgin sand. The gradations of the coarse and fine aggregate are given in Table 2.

TABLE 2 AGGREGATE GRADATIONS FOR LABORATORY MIXES

Sieve Size	Percentage Passing	
	Actual	ASTM C 33 ^a
Coarse Aggregate		
1 1/2 in.	100.0	95-100
3/4 in.	61.3	35-70
3/8 in.	10.9	10-30
No. 4	2.2	0-5
Fine Aggregate		
No. 4	100.0	95-100
No. 8	100.0	80-100
No. 16	61.8	50-85
No. 30	39.2	25-60
No. 50	16.8	10-30
No. 100	3.1	2-10

^aCoarse aggregate gradation is for Size 467.

Laboratory Mixes

The mixes prepared in the laboratory incorporated the following parameters:

- Cement content: 282 lb/yd³,
- Coarse aggregate volume: 52 to 59 percent,
- Fine aggregate volume: 23 to 28 percent,
- Fly ash/cement (by weight): 0 to 20 percent,
- Water/(cement + fly ash) (by weight): 0.55 to 0.60,
- Fine aggregate/mortar (by volume): 60 percent,
- Paste/mortar (by volume): 38 to 42 percent, and
- Theoretical unit weight: 156 to 158 pcf (air free).

Consistency of the mix was measured using Vebe equipment. Details of the test procedure using Vebe equipment are given elsewhere (3). The consistency value is the number of seconds required to consolidate the volume of concrete into a 9.5-in.-diameter bucket mounted on a vibrating table assembly. For testing RCC mixes, a 27.5-lb surcharge was used instead of the standard 7.5-lb surcharge.

Cylinders for measuring compressive strength were prepared on a vibrating table. A surcharge of 27.5 lb was used for the 6- by 12-in. cylinders. The cylinders were compacted in a single lift. The cylinders were also used to obtain densities. The effect of vibration time on density and on compressive and flexural strengths was also evaluated. Beams for flexural strength were compacted in one lift using a surcharge of 50 lb for 6- by 6- by 30-in. beams.

Test Results

The following test results were obtained:

1. Vibration time in excess of 1 min did not have a significant effect on either compacted density or compressive and flexural strengths.
2. There exists an optimum coarse aggregate volume for obtaining maximum compressive strength. For the mixes tested, the optimum coarse aggregate volume was determined to be 55 percent.
3. There did not appear to be an optimum paste-to-mortar ratio for the mixes.
4. Although the mixes were designed to provide a 28-day compressive strength of about 3,000 psi, measured compressive strengths were generally between 4,000 and 5,000 psi.
5. Use of up to 20 percent Class F fly ash by weight of cement did not have a noticeable effect on 28-day compressive strengths.

As stated, the preliminary laboratory test program was undertaken to provide an understanding of the effects of different mixes and specimen preparation methods on the compacted properties of RCC. On the basis of results from the laboratory program, the following parameters were selected for construction of a full-scale test slab.

1. Use vibrating time of 1 min and surcharge of 27.5 lb for compacting 6- by 12-in. compressive strength cylinders in one lift,
2. Use vibrating time of 1 min and surcharge of 50 lb for compacting beams for flexural strength in one lift,
3. Use coarse aggregate volume of about 60 percent of the total volume, and
4. Use a paste-to-mortar ratio of about 0.40.

Full-Scale Test Panels

Four full-scale test panels were constructed in an outdoor location at the facilities of the Portland Cement Association in Skokie, Illinois, during September 1984. Each panel was constructed using a different mix, designated Mixes A, B, C, and D. Panels constructed with Mixes A, B, C, and D were designated Panels A, B, C, and D, respectively.

Details of Test Section

Test panels were 13.5 ft wide and about 12 ft long. Panels were designed to have a compacted thickness of 8 in.

Mix Designs

Details of the mixes used are given in Table 3. The mixes were designed to obtain the following information:

1. Effect of fly ash: Mix A versus Mix B for same mortar and paste content,
2. Effect of mortar content: Mix B versus Mix C for same fly ash-to-cement ratio, and

3. Effect of fly ash-to-cement ratio: Mix B versus Mix D for same mortar volume.

The test program was also designed to allow a comparison to be made between molded test specimens and specimens obtained from the full-scale test panels.

Construction of Test Panels

The RCC for each test panel was batched at a local ready-mix concrete plant. The RCC material was then transported to the site in a transit mixer and deposited on a prepared 4-in.-thick granular subbase. The RCC material was spread manually between wood forms that were staked into the ground to provide restraint during compaction. The uncompacted thickness was maintained at about 10 in.

After the RCC material had been uniformly spread, a tandem vibratory roller was used to obtain the desired compaction. Details of the vibratory roller are as follows:

- Model: Case 752;
- Drum width: 63 in.;
- Drum diameter: 47 in.;
- Total applied force: 445 lb/in. width of drum, 28,000 lb/drum;
- Frequency: 2,000 vpm; and
- Amplitude: 0.08 in. (peak to peak).

For each area undergoing compaction, one pass was made in the static mode followed by four passes in the vibratory mode. Density was measured after each pass by means of a nuclear gauge operated in the back-scatter mode. Measured density data are given in Table 4. Final measured compacted wet densities ranged from 152.2 to 154.2 pcf.

TABLE 3 MIXES USED FOR FULL-SCALE TEST PANELS

	Mix			
	A	B	C	D
CA (lb/yd ³)	2,734	2,749	2,556	2,707
FA (lb/yd ³)	1,044	1,049	1,156	1,069
C (lb/yd ³)	285	243	266	263
F (lb/yd ³)	0	48	54	45
W (lb/yd ³)	151	139	161	142
F/C (weight)	0	0.20	0.20	0.17
W/C+F (weight)	0.53	0.48	0.50	0.46
W/C+F (volume)	1.67	1.46	1.54	1.41
CA volume (%)	60	61	57	60
FA volume (%)	23	23	26	24
Mortar volume (%)	37	37	41	38
Paste volume (%)	14	14	16	14
CA specific gravity	2.68	2.68	2.68	2.68
FA specific gravity	2.68	2.68	2.68	2.68
C specific gravity	3.15	3.15	3.15	3.15
F specific gravity	—	2.66	2.66	2.66
Theoretical unit weight (pcf, air free)	159.2	159.8	158.5	159.7

NOTE: Mortar and paste volumes are air free. Air content of 2 percent by volume is assumed. CA = coarse aggregate, FA = fine aggregate, C = cement, F = fly ash, and W = water.

TABLE 4 MEASURED WET DENSITY DATA

Roller Pass	Slab			
	A	B	C	D
As spread	127.8	128.7		129.7
Static	149.7	147.6		146.2
First vibratory	150.9			
Second vibratory	152.9	152.1		151.2
Fourth vibratory	152.9	154.2	152.2	153.4

NOTE: Densities (pcf) were measured using a nuclear gauge operated in the back-scatter mode.

The as-placed RCC material appeared to be slightly drier than optimum moisture. However, under vibratory rolling, mortar appeared to be migrating upward toward the surface, and the surface appeared to be rebounding under the vibratory loading. The four panels were constructed over a period of 2 days. Daytime temperature during construction was about 85°F. Compaction of each panel was generally completed within 30 min after placement of the RCC material.

The as-constructed surfaces of the test panels had localized areas where the coarser aggregate was exposed without adequate mortar.

Each test panel was covered with a layer of polyethylene on completion of compaction. For the next 7 days, the test panel surfaces were wet-cured by regularly spraying with water and then recovering them with polyethylene sheets. After 7 days of wet-cure, a clear curing compound was applied.

Preparation of Beams and Cylinders

Beam and cylindrical specimens were prepared during construction of the test panels. These specimens were prepared to make possible comparison with cores and beams obtained from the test panels. During construction of each test panel, samples of RCC material were obtained for preparing the molded specimens. All beams and cylinders were moist-cured until testing.

Cylindrical Specimens Cylinders were prepared using conventional steel molds 6 in. in diameter by 12 in. deep. Cylinders were compacted full depth (in a single layer) on a vibrating table using a surcharge weight of 27.5 lb and vibrating time of 1 min. A total of 22 cylinders were prepared for each RCC mix.

Beam Specimens Beams were prepared using conventional steel molds for making 6- by 6- by 30-in. beams. Beams were compacted full depth (in a single layer) on a vibrating table using a surcharge weight of 50 lb and vibration time of 1 min. A total of eight beams were prepared for each RCC mix.

Obtaining Cores and Sawed Beams from Test Panels

Initially, three cores were obtained from each test panel 7

days after construction of the panels. Cores were nominally 4 in. in diameter. Subsequently, twelve 4-in. nominal diameter cores and 12 beams were obtained from each test panel 28 days after construction of the test panels. Beams were cut to provide a nominal width of 6 in. and a length of 30 in. All beams and cores were moist-cured until they were tested.

Testing Program

The testing program was developed to determine the following strength-related characteristics of the RCC mixes:

1. Compressive strength,
2. Flexural strength,
3. Split-tensile strength,
4. Modulus of elasticity, and
5. Fatigue behavior.

Details of the planned testing program are given in Table 5.

Test Results

Test results obtained for compressive, flexural, and split-tensile strength and modulus of elasticity are summarized in Table 6 for the four RCC mixes.

Compressive Strength Compressive strength of cores was generally lower than that of molded cylinders. Core compressive strength at 7 days ranged from 1,800 psi for Mix D to 3,610 psi for Mix C. Core compressive strength at 28 days ranged from 2,480 psi for Mix D to 4,390 psi for Mix C. Core and cylinder strengths are compared in Figure 1. Compressive strength development with time is shown in Figure 2 for cores.

TABLE 5 PLANNED TEST PROGRAM

Test	No. of Specimens tested at ^a		
	7 days	28 days	90 days
Compressive strength			
6-in. cylinders	3	3	3
4-in. cores	3	3	3
Flexural strength			
Molded beams	3	3	3
Sawed beams		4	
Split-tensile strength			
6-in. cylinders		3	
4-in. cores		3	
Modulus of elasticity			
6-in. cylinders		3	
4-in. cores		3	
Fatigue testing			
Molded beams			
Sawed beams			5 ^b

^aNumbers of specimens tested are for each RCC mix/test panel.

^bFatigue testing was performed at an age of about 7 months.

TABLE 6 SUMMARY OF TEST RESULTS

Test	Mix			
	A	B	C	D
Compressive strength (psi)				
4-in. cores at 7 days	3,050	3,180	3,610	1,800
6-in. cylinder at 7 days	3,720	2,970	4,010	2,250
4-in. cores at 28 days	3,820	3,660	4,390	2,480
6-in. cylinder at 28 days	4,440	4,010	4,820	3,720
4-in. cores at 90 days	4,280	3,560	4,620	3,500
6-in. cylinder at 90 days	4,620	4,280	5,970	4,260
Flexural strength (psi)				
Sawed beams at 28 days	670	595	625	480
Molded beams at 28 days	705	600	490	490
Sawed beams at 7 months	685	770	740	585
Molded beams at 9 months	755	700	725	700
Split-tensile strength (psi)				
4-in. cores at 28 days	610	540	575	450
6-in. cylinder at 28 days	450	390	510	410
Modulus of elasticity (million psi)				
4-in. cores at 28 days	3.65	4.08	4.29	2.77
6-in. cylinder at 28 days	5.02	4.92	4.88	4.70
Pulse velocity (ft/sec)				
4-in. cores at 28 days	15,750	16,410	16,890	16,320
6-in. cylinder at 28 days	15,860	16,260	16,260	16,360
Density (psi)				
4-in. cores	154.8	155.8	156.0	154.8
6-in. cylinders	150.1	153.3	154.8	152.3
Sawed beams	154.8	156.5	156.5	157.2
Molded beams	150.7	153.4	150.8	144.8

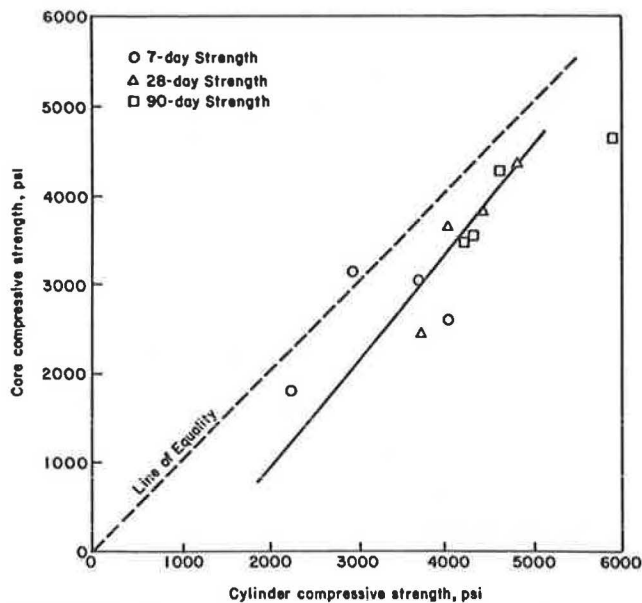


FIGURE 1 Comparison of core and cylinder compressive strengths.

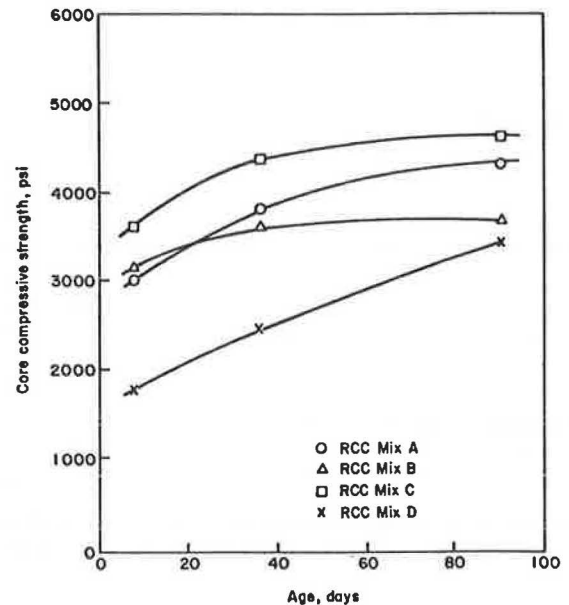


FIGURE 2 Compressive strength development with time (cores).

Flexural Strength Flexural strength measured for sawed beams at 28 days ranged from 480 psi for Mix D to 670 psi for Mix A. Values for molded and sawed beams were generally similar. The relationship between the 28-day flexural strength and the 28-day core compressive strength is shown in Figure 3. The relationship between flexural (sawed beam) and core compressive strengths can be approximated as follows:

$$\text{RCC Mix A } f_r = 10.8 (f_c)^{0.5}$$

$$\text{RCC Mix B } f_r = 9.8 (f_c)^{0.5}$$

$$\text{RCC Mix C } f_r = 9.4 (f_c)^{0.5}$$

$$\text{RCC Mix D } f_r = 9.6 (f_c)^{0.5}$$

$$\text{Conventional concrete } f_r = C (f_c)^{0.5}$$

where

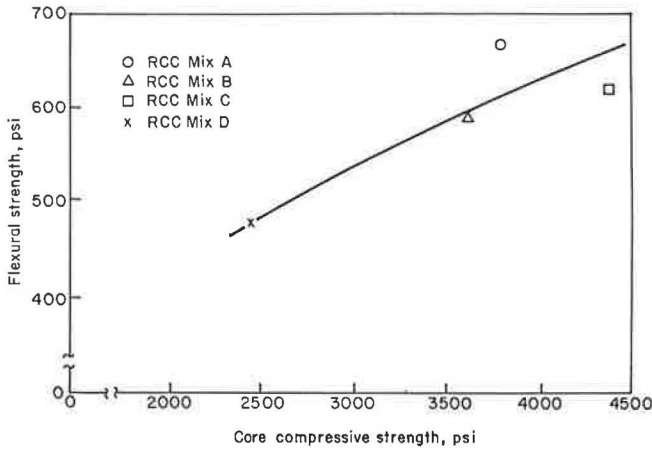


FIGURE 3 Flexural strength versus compressive strength (28-day values of cores).

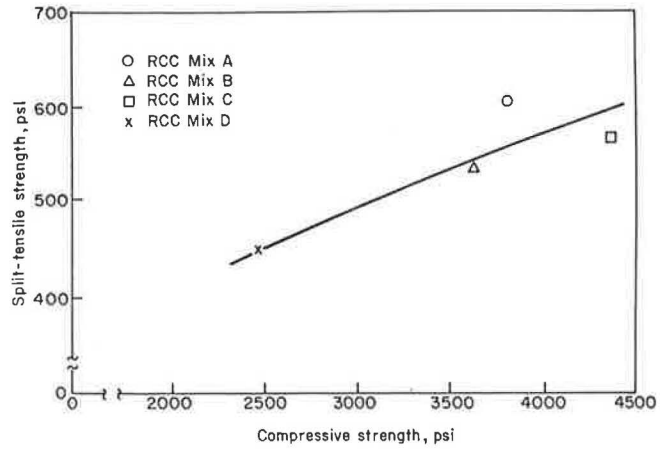


FIGURE 4 Split-tensile strength versus compressive strength (cores).

f_r = average flexural strength of sawed beams at 28 days (psi),
 f_c = average compressive strength of cores at 28 days (psi),
 and
 C = constant = 8.0 to 12.0.

Split-Tensile Strength Split-tensile strength of cores measured at 28 days ranged from 450 psi for Mix D to 610 psi for Mix A. Split-tensile strengths for cores were generally higher than those obtained for molded cylinders. The relationship between split-tensile and compressive strength for cores is shown in Figure 4. The relationships among split-tensile, compressive, and flexural strength can be approximated as follows:

$$\begin{aligned} \text{RCC Mix A } f_t &= 0.91 f_r = 9.8 (f_c)^{0.5} \\ \text{RCC Mix B } f_t &= 0.91 f_r = 8.9 (f_c)^{0.5} \\ \text{RCC Mix C } f_t &= 0.92 f_r = 8.7 (f_c)^{0.5} \\ \text{RCC Mix D } f_t &= 0.94 f_r = 9.0 (f_c)^{0.5} \end{aligned}$$

where f_t is average split-tensile strength (psi) of cores at 28 days.

Modulus of Elasticity Measured modulus of elasticity values for cores ranged from 2.77 million psi for Mix D to 4.29 million psi for Mix C. The modulus values measured for cores were generally lower than those measured for cylinders. The relationship between modulus of elasticity and compressive strength for cores is shown in Figure 5 and can be approximated as follows:

$$\begin{aligned} \text{RCC Mix A: } E &= 59,000(f_c)^{0.5} \\ \text{RCC Mix B: } E &= 67,000(f_c)^{0.5} \\ \text{RCC Mix C: } E &= 65,000(f_c)^{0.5} \\ \text{Conventional concrete: } E &= 57,000(f_c)^{0.5} \quad (4) \end{aligned}$$

Pulse Velocity Pulse velocity was measured at 28 days for both cores and cylinders. Pulse velocity values ranged from 15,750 to 16,890 ft/sec. For conventional paving concrete, pulse velocity is about 14,000 to 16,000 ft/sec.

Density Densities of cores, cylinders, molded beams, and sawed beams were measured. Densities were generally higher

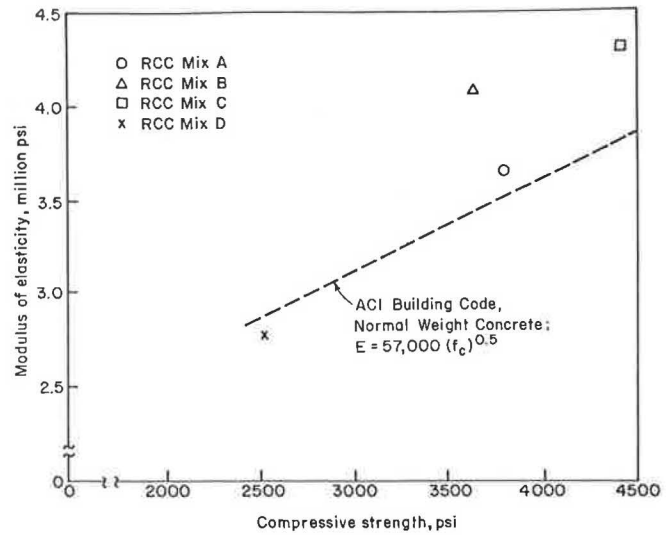


FIGURE 5 Modulus of elasticity versus compressive strength (cores).

for cores and sawed beams than for cylinders and molded beams. Densities of cores and sawed beams were about 1 to 2 pcf higher than those measured at the time of construction by the nuclear density gauge.

Fatigue Behavior Tests were conducted to determine flexural fatigue characteristics of RCC using beam specimens sawed from the test panels. Five beams from each panel were used. Beams were nominally 6 by 6 by 30 in. In general, two tests were performed on a single beam. In addition, beam sections were also used to determine static flexural strength. Fatigue tests were performed at the age of about 7 months.

Repeated load tests were conducted on beam sections supported on an 18-in. span and loaded at third points. Loads were selected to produce applied stress-to-flexural strength ratios ranging from about 0.50 to 0.95. Repeated load was applied with a hydraulic actuator. Loading frequency was maintained at 10 cycles/sec. To prevent impact loading, a minimum static force of 10 percent of maximum applied load was maintained in each load cycle. Testing was automatically terminated when the beam cracked. Each beam was kept in a

moist condition for the duration of the test by means of wet burlap wrapped around the beam and covered with plastic.

Fatigue test results are summarized in Table 7 and shown in Figure 6. Linear regression was used to develop a fatigue curve for the combined results of Mixes A, B, C, and D. The fatigue test results of the RCC mixes are compared in Figure 7 with results from fatigue tests on conventional concrete conducted by Murdoch and Kesler (5) and Ballinger (6). In addition, the PCA fatigue curve used for design of concrete pavements (7) is also shown in Figure 7. The Murdoch-Kesler curve for conventional concrete shown in Figure 7 was drawn so that 95 percent of the test results would fall above the line. The PCA fatigue curve used for pavement design shown in Figure 7 is conservatively set below the Murdoch-Kesler curve.

A design fatigue curve for RCC was developed using a degree of conservatism similar to that used to develop PCA's design fatigue curve for conventional concrete. The design curve for RCC, also shown in Figure 7, is set about 15 percent below the 95 percent curve for RCC. The use of the RCC design curve for thickness design of pavements is discussed in a companion paper by Tayabji and Halpenny in this Record.

MIX PROPORTIONING OF RCC

A study was conducted to investigate the factors that affect the mix proportioning of RCC. The following factors were investigated.

1. Compaction procedure
 - Vibratory table with a surcharge
 - Modified Proctor (10-lb rammer, 18-in. drop)
2. Maximum size of aggregate
 - 1 1/2 in.
 - 3/4 in.
3. Cement content
 - 3.5 bags per cubic yard
 - 6 bags per cubic yard

The objective of mix proportioning of RCC mixes is to obtain a mix that will provide either maximum density or maximum strength as measured by compressive strength under a compaction effort that closely simulates field vibratory roller compaction effort. The mix proportioning procedure involves development of moisture content-density and moisture content-strength relationships. This procedure closely resembles the approach used to determine the relationship between the moisture content and density of soils and granular materials. For soils and granular materials, the relationship is used to establish the optimum moisture content that will result in maximum compacted density.

Early studies of RCC made use of the Vebe test procedure to establish the optimum moisture content. Preliminary testing at PCA's laboratories indicated that the Vebe test is not very consistent, partly because it is a subjective test. For the PCA study, it was therefore decided to measure compacted density and strength of test specimens compacted by two different procedures. In the first procedure, specimens were

TABLE 7 FATIGUE TEST DATA

RCC Mix	Stress Ratio	No. of Load Repetitions to Failure
A	0.59	268,050
	0.61	372,930
	0.79	1,550
	0.84	770
	0.91	1,440
B	0.53	982,460
	0.59	678,270
	0.62	90,300
	0.69	4,590
	0.71	3,000
C	0.83	1,620
	0.91	1,270
	0.50	1,716,560
	0.62	337,580
	0.67	130,450
D	0.74	14,140
	0.89	790
	0.48	3,018,740
	0.72	11,890
	0.80	1,600
	0.85	1,600
	0.91	21,300
	0.96	620

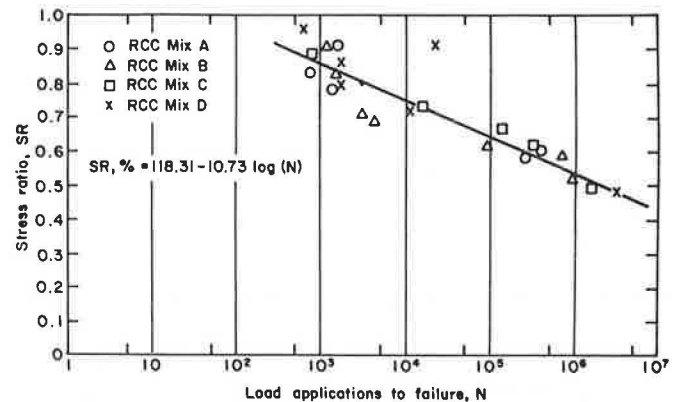


FIGURE 6 Fatigue relationship for RCC.

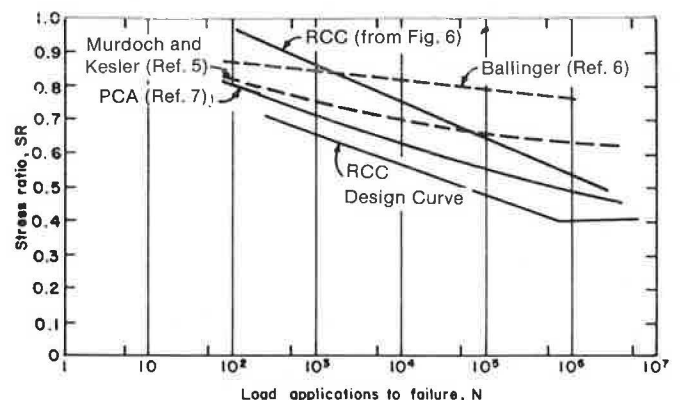


FIGURE 7 Comparison of fatigue relationships of RCC and conventional concrete.

compacted on a vibrating table using a surcharge weight of 27.5 lb for a period of 1 min. The second procedure was the modified Proctor method. For each test procedure, 6-in.-diameter by 12-in.-high cylindrical specimens were prepared using standard steel molds for making concrete specimens.

The modified Proctor method generally followed the procedures of ASTM D 1557-78 (10-lb rammer and 18-in. drop). The ASTM procedure requires use of a mold 4.584 in. high and compaction of the specimen in five equal layers with each layer subjected to 56 blows. In the PCA procedure, the mold was 12 in. high, the specimen was compacted in increments of 2 in., and 122 blows were used per increment. A compactive effort of 122 blows per increment was selected to maintain a compactive effort per unit volume that was the same as that required for the ASTM procedure.

It should be noted that the compactive effort used in preparing laboratory specimens does not have a direct correlation with compaction obtained with different equipment in the field. However, data obtained during construction of the full-scale test panels indicated that densities of specimens compacted on the vibrating table for 1 min were quite close to those measured for the test panels.

The test specimens prepared using the two procedures were used to determine both the compacted density and the 28-day compressive strength.

Test Program

Four RCC mix combinations were selected for the test program:

- Mix Combination P: 1 1/2-in. maximum size aggregate (MSA), 3.5 bags/yd³ cement;
- Mix Combination Q: 3/4-in. MSA, 3.5 bags/yd³ cement;

- Mix Combination R: 3/4-in. MSA, 6 bags/yd³ cement; and
- Mix Combination S: 1 1/2-in. MSA, 6 bags/yd³ cement.

Coarse and fine aggregates were blended to obtain the desired gradations for each of the two aggregate types. The combined gradations for aggregates with 1 1/2-in. MSA and 3/4-in. MSA are shown in Figure 8.

Mix Proportioning

For each mix combination, mixes were prepared at four different moisture contents. The procedure used was to determine the required amount of coarse and fine aggregate and cement to be used for each mix combination and then to add different amounts of water to each of the four mixes used for each mix combination. Details of the mix proportions are given in Tables 8-11 for Mix Combinations P, Q, R, and S, respectively. Batched total moisture content ranged from 4.3 to 7.5 percent.

Each mix was batched to provide about 1.8 ft³ of material. Mixing was done in a laboratory paddle mixer. As soon as mixing was completed, a small sample was obtained and oven dried to determine the total moisture content of the mixed material.

Test Specimen Fabrication

For each mix, four specimens were compacted using the vibrating table and a surcharge of 27 1/2 lb and four specimens were compacted using the modified Proctor procedure. Each specimen was weighed after compaction. Specimens were retained in the steel mold for 1 day and then

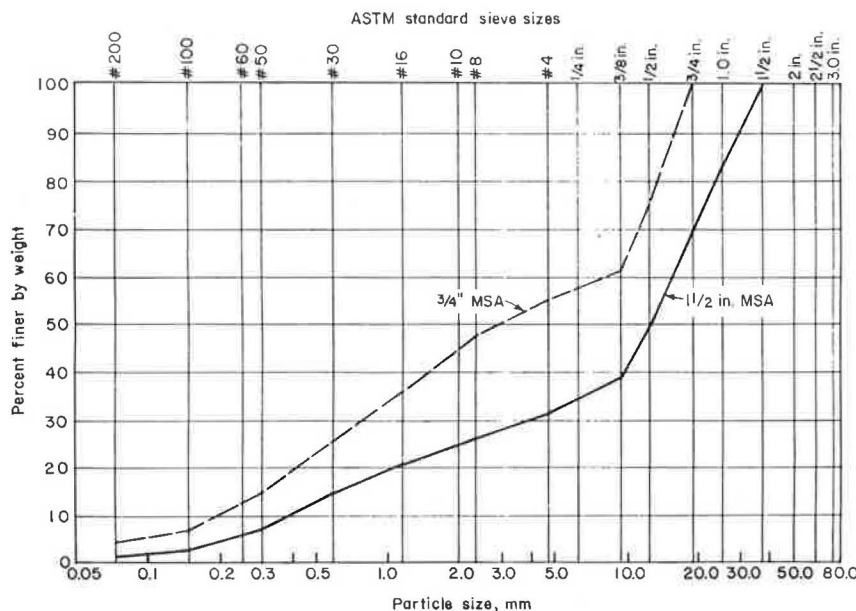


FIGURE 8 Gradations of aggregates with 1 1/2-in. and 3/4-in. MSA.

TABLE 8 PROPORTIONS FOR MIX COMBINATION P (1 1/2-in. MSA, 3.5 BAGS CEMENT)

	Mix Designation			
	4	5	6	7
Proportions (lb/yd ³ air free)				
Aggregate (SSD)	3,888	3,836	3,950	3,922
Cement	326	322	331	329
Water	133	154	108	120
Total	4,347	4,312	4,389	4,371
Air-free unit weight (lb/ft ³)	161.0	159.8	162.6	161.9
Water-to-cement ratio (by weight)	0.41	0.48	0.33	0.36
As-batched total moisture content (%)	4.9	5.5	4.3	4.6

NOTE: Absorption coefficient of aggregate = 1.74 percent. SSD = saturated surface dry.

TABLE 9 PROPORTIONS FOR MIX COMBINATION Q (3/4-in. MSA, 3.5 BAGS CEMENT)

	Mix Designation			
	8	9	10	11
Proportions (lb/yd ³ air free)				
Aggregate (SSD)	3,885	3,758	3,658	3,819
Cement	336	322	316	330
Water	125	175	216	151
Total	4,346	4,258	4,190	4,300
Air-free unit weight (lb/ft ³)	161.0	157.8	155.2	159.3
Water-to-cement ratio (by weight)	0.37	0.54	0.68	0.46
As-batched total moisture content (%)	5.0	6.4	7.5	5.7

NOTE: Absorption coefficient of aggregate = 1.74 percent. SSD = saturated surface dry.

TABLE 10 PROPORTIONS FOR MIX COMBINATION R (3/4-in. MSA, 6 BAGS CEMENT)

	Mix Designation			
	12	13	14	15
Proportions (lb/yd ³ air free)				
Aggregate (SSD)	3,452	3,548	3,499	3,406
Cement	552	568	560	545
Water	219	178	199	239
Total	4,223	4,294	4,258	4,190
Air-free unit weight (lb/ft ³)	156.4	159.1	157.7	155.1
Water-to-cement ratio (by weight)	0.40	0.32	0.36	0.44
As-batched total moisture content (%)	7.0	5.8	6.4	7.5

NOTE: Absorption coefficient of aggregate = 1.74 percent. SSD = saturated surface dry.

TABLE 11 PROPORTIONS FOR MIX COMBINATION S (1 1/2-in. MSA, 6 BAGS CEMENT)

	Mix Designation			
	16	17	18	19
Proportions (lb/yd ³ air free)				
Aggregate (SSD)	3,551	3,429	3,509	3,469
Cement	560	541	554	547
Water	181	233	199	216
Total	4,292	4,203	4,262	4,232
Air-free unit weight (lb/ft ³)	159.0	155.7	157.9	156.8
Water-to-cement ratio (by weight)	0.32	0.43	0.36	0.40
As-batched total moisture content (%)	5.8	7.3	6.3	6.8

NOTE: Absorption coefficient of aggregate = 1.74 percent. SSD = saturated surface dry.

transferred to a moist-curing chamber and cured there until the day of test. Specimens were tested for compressive strength at 28 days. Specimen height generally was 12 in. However, some of the specimens compacted on the vibrating table were slightly shorter than 12 in.

Test Results

Test results for each mix are given in Table 12. Also included in Table 12 are values for both the as-batched total moisture content and the measured total moisture content. The measured total moisture content was generally lower than the as-batched moisture content. This difference ranged from about 0.1 to about 1.4 percent. The variation is attributed primarily to the problem of obtaining representative samples of the mix for oven drying. Inclusion of larger amounts of large-sized aggregate particles can significantly affect the value of the measured moisture content.

The moisture content-density and moisture content-strength relationships are shown in Figures 9-12. These relationships are shown using the as-batched moisture contents.

Test results follow.

1. Specimens compacted on the vibrating table had lower 28-day compressive strengths than specimens compacted using the modified Proctor procedure.

2. For both compaction procedures used, a distinct moisture content-strength relationship was obtained from which the optimum moisture content for maximum strength could be established.

3. The modified Proctor procedure did not provide a distinct relationship between either dry or wet density and

moisture content. It appears that, within the narrow range of moisture contents used, the modified Proctor procedure could not discriminate between "dry" and "wet" mixes. On the other hand, the vibrating table compaction procedure did result in reasonably distinct moisture content and density relationships from which it was possible to identify an optimum moisture content that would result in maximum wet or dry density.

4. For the mix combinations used, the optimum as-batched total moisture content values given in Table 13 were obtained. A lower optimum moisture content was obtained for mix combinations with lower cement contents. Also, a lower optimum moisture content was obtained for mix combinations with the 1 1/2-in. MSA.

5. Specimens prepared using the vibrating table produced significantly lower densities and strengths at lower moisture contents.

SUMMARY

Results of an investigation conducted to develop engineering data for the design of RCC have been presented. It is clear that the engineering behavior of RCC is similar to that of conventional normal-weight concrete. Test results for RCC made with 243 to 285 lb/yd³ of cement show that RCC is capable of providing relatively high-strength concrete.

On the basis of test results, it is recommended that RCC be treated much like conventional concrete when designing thickness of a pavement. Thus existing thickness design procedures used for concrete pavements are considered applicable to the design of RCC pavements when used in conjunction with the design RCC fatigue curve.

TABLE 12 TEST RESULTS

Mix Type	Mix No.	Total Moisture Content (%)		Vibrating Table			Modified Proctor		
		Theoretical	Measured	Wet Density (pcf)	Dry Density (pcf)	f_c^a (psi)	Wet Density (pcf)	Dry Density (pcf)	f_c^a (psi)
P									
(1 1/2-in. MSA, 3.5 bags cement)	4	4.9	4.8	155.3	148.2	5,000	158.0	150.8	5,770
	5	5.5	6.7	157.3	147.4	3,770	157.4	147.5	4,420
	6	4.3	3.2	140.0	135.7	2,170	156.7	151.8	4,290
	7	4.6	4.4	154.6	148.1	4,930	158.8	152.1	5,320
Q									
(3/4-in. MSA, 3.5 bags cement)	8	5.0	4.8	138.0	131.7	2,020	152.0	145.0	3,450
	9	6.4	5.6	151.1	143.1	3,920	154.5	146.3	4,310
	10	7.5	6.8	151.3	141.7	3,170	153.9	144.1	3,700
	11	5.7	5.9	151.8	143.3	3,760	156.0	147.3	4,500
R									
(3/4-in. MSA, 6 bags cement)	12	7.0	6.0	144.8	140.4	6,200	155.9	147.1	7,320
	13	5.8	4.8	138.9	132.5	4,680	156.4	149.2	6,670
	14	6.4	5.4	148.4	140.8	5,640	156.3	148.3	6,900
	15	7.5	6.4	150.5	141.4	6,110	156.0	146.6	6,700
S									
(1 1/2-in. MSA, 6 bags cement)	16	5.8	4.7	156.2	149.2	6,000	160.0	152.8	7,050
	17	7.3	6.3	155.9	145.3	6,430	156.4	145.8	6,740
	18	6.3	5.2	144.9	137.7	4,760	158.1	150.3	6,310
	19	6.8	5.4	155.0	147.1	6,230	157.4	149.3	7,090

^aMeasured at 28 days of age.

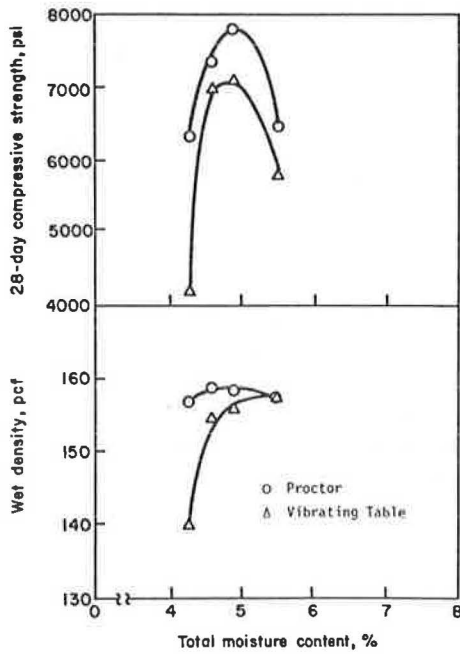


FIGURE 9 Moisture-density-strength relationship for RCC Mix P.

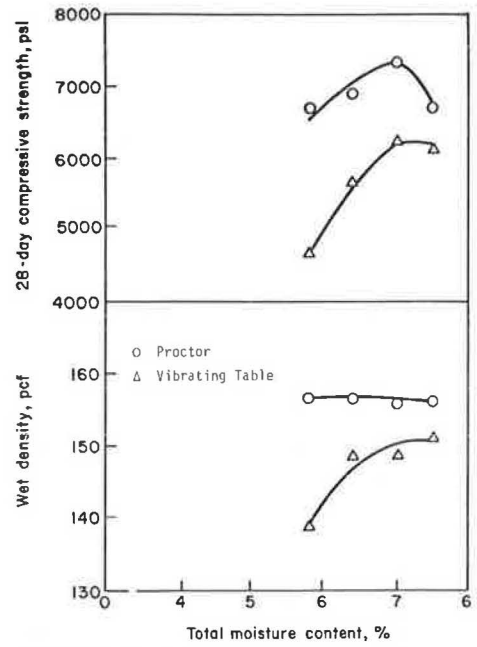


FIGURE 11 Moisture-density-strength relationship for RCC Mix R.

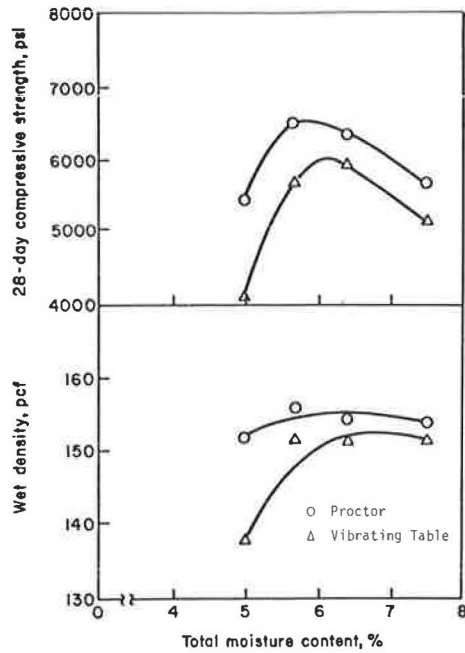


FIGURE 10 Moisture-density-strength relationship for RCC Mix Q.

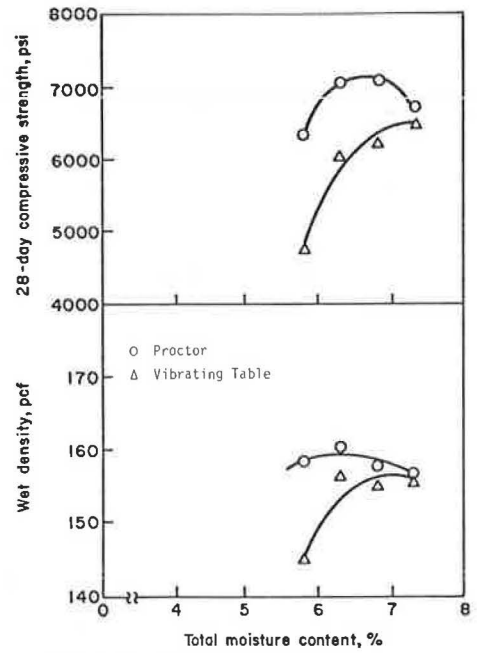


FIGURE 12 Moisture-density-strength relationship for RCC Mix S.

TABLE 13 OPTIMUM AS-BATCHED TOTAL MOISTURE CONTENT

Mix Combination	Optimum Moisture Content (%)		
	DVT	SVT	SP
P (1 1/2-in. MSA, 3.5 bags cement)	5.0	4.8	5.0
Q (3/4-in. MSA, 3.5 bags cement)	6.5	6.0	6.0
R (3/4-in. MSA, 6 bags cement)	7.3	7.2	7.0
S (1 1/2-in. MSA, 6 bags cement)	7.0	7.0	6.5

Note: DVT = Based on density and vibrating table compaction. SVT = Based on strength and vibrating table compaction. SP = Based on strength and modified Proctor compaction.

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REFERENCES

1. S. D. Tayabji, P. J. Nussbaum, and A. T. Ciolko. Evaluation of Heavily Loaded Cement-Stabilized Bases. In *Transportation Research Record 839*, TRB, National Research Council, Washington, D.C., 1982, pp. 6-11.
2. R. W. Piggott. Roller-Compacted Concrete for Heavy Duty Pavements—Past Performance, Recent Projects, and Recommended Construction Methods. In *Transportation Research Record 1062*, TRB, National Research Council, Washington, D.C., 1986, pp. 7-13.
3. *Manual of Concrete Practice*. American Concrete Institute, Detroit, Mich., 1985, ACI 207.5R-80: Roller Compacted Concrete.
4. *Manual of Concrete Practice*. American Concrete Institute, Detroit, Mich., 1985, ACI 318-83: Building Code Requirements for Reinforced Concrete.
5. J. W. Murdoch and C. E. Kesler. Effect of Range of Stress on Fatigue Strength of Plain Concrete Beams. *Journal of the American Concrete Institute*, Vol. 30, No. 2, Aug. 1958.
6. C. A. Ballinger. Cumulative Fatigue Damage Characteristics of Plain Concrete. In *Highway Research Record 370*, HRB, National Research Council, Washington, D.C., 1971, pp. 48-60.
7. R. G. Packard. *Thickness Design of Concrete Highway and Street Pavements*. Publication EB109. Portland Cement Association, Skokie, Ill., 1984.

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