Evaluation of the Frost Resistance of Roller-Compacted Concrete Pavements

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ABSTRACT

An investigation was conducted to evaluate the frost resistance of samples taken from roller-compacted concrete (RCC) pavements with laboratory testing procedures. Nine existing pavements were sampled and tested for microscopic determination of air-void content and parameters of the air-void system, resistance to rapid freezing and thawing, critical dilation, and compressive and flexural strength. The pavements ranged in age from 1 month to 8 years at the time of sampling. Results of the rapid freezing-and-thawing tests indicate that the frost resistance of the concrete is, as might be expected, a function of the bubble spacing factor ($\bar{L}$) of the air-void system. These samples having $\bar{L}$'s smaller than 0.011 in. generally had durability factors (DFE_{300}) of 60 or greater. Those samples having $\bar{L}$'s greater than 0.016 in. generally had DFE_{300}'s less than 40. The samples having $\bar{L}$'s less than 0.016 in. also contained approximately 2.0 to 4.0 percent, by volume, of air voids; in the sections that were counted, chord lengths that were less than 0.04 in. long but irregularly shaped were found. The presence of larger-than-anticipated amounts of small air voids appears to be related to cohesiveness of the mixture, pugmill mixing, and the method of compaction. Preliminary results of the dilation tests indicate that those samples judged to be frost susceptible when tested by rapid freezing and thawing may, in fact, offer some degree of frost resistance. The dilation test may be appropriate, therefore, to determine whether an RCC sample is frost resistant at the time of test or to measure the period of frost immunity.

The Commander, U.S. Army Corps of Engineers, has recommended that all field operating activities having military construction and civil works design responsibilities consider the use of roller-compacted concrete (RCC) for various horizontal concrete construction applications (1). These applications include paving for tactical equipment shops and tracked-vehicle wash facilities, tank trails, open storage areas, and marshalling areas. Significant cost savings are anticipated when RCC is used in lieu of conventional concrete, because of the labor savings associated with the production, placement, and compaction of RCC. However, the frost resistance of RCC pavements is of concern, particularly because results from earlier investigations indicate difficulty in securing entrained air in RCC (2).

The Waterways Experiment Station (WES) is currently conducting an extensive research program on RCC pavement criteria development. Included in this program is an investigation on RCC pavement frost resistance. The initial phase of this investigation, discussed in this paper, consisted of obtaining representative samples from existing RCC pavements and performing laboratory testing on them to determine their air-void system parameters and resistance to frost damage. A second phase is planned in order to determine whether materials and construction criteria can be developed that will produce relatively frost-resistant RCC pavements.

Nine RCC pavements were sampled and tested for microscopic determination of air-void content and parameters of the air-void system, resistance to rapid freezing and thawing, critical dilation, and compressive and flexural strength. Although the majority of testing was conducted at WES, some of the rapid freezing-and-thawing and strength testing was performed by the U.S. Army Corps of Engineers North Pacific Division Laboratory (NPDL) in Troutdale, Oregon, and Southwestern Division Laboratory (SWDL) in Dallas, Texas. A number of no-slump concrete beams were also fabricated by WES and NPDL during mixture proportioning studies and tested for resistance to rapid freezing and thawing and microscopic determination of air-void content and parameters of the air-void system.

RCC PAVEMENT DESCRIPTIONS

Fort Stewart, Georgia

A test section 234 ft long by 20 ft wide was constructed in July 1983. The pavement ranges in thickness from 9 to 13 in. and currently serves as an access from a tracked-vehicle parking area to a series of tank trails.

The materials used in the RCC were batched in a weigh-batch type concrete plant and mixed in revolving-drum truck mixers. The mixture contained crushed coarse aggregate conforming to ASTM C 33 size designation No. 57 and natural fine aggregate. The gradings of both aggregates are shown in Table 1. The mixture also contained approximately 611 lb/yd^3 of Type I portland cement and had a water-cement ratio (W/C) of 0.33. Mixture proportions are given in Table 2.

Concrete was discharged from the truck mixers into a front-end loader bucket, transported to the prepared sand-clay base, and spread to the approxi-

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U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, Miss. 39180-0631.

TABLE 1 RCC Aggregate Gradings

Sieve Size[a]		Cumulative Percent Passing														
						Fort Lewis			USACRREL							
		Fort Stewart		Fort Hood		Natural Concrete				Concrete			WES Beams		NPDL Beams	
Standard	Alternative	Mixture A	Mixture B	Mixture A	Mixture B	Mixture A	Mixture B	Crushed Asphalt	Pit Run	Mixture A	Mixture B	Port of Tacoma	Mixture A	Mixture B	Mixture A	Mixture B
50 mm	2 in.			100												
37.5 mm	1½ in.	100		98												
25.0 mm	1 in.	95		30	100	100			100	100			100		100	
19.0 mm	¾ in.	71		8	97	83		100	99	99		100	93		95	
12.5 mm	½ in.	31		–	–	47		98	–	68		98	–		54	
9.5 mm	³/₈ in.	11		1	42	25		86	77	31	100	85	25		29	100
4.75 mm	No. 4	2	99		8	100 1	100	60	69	2	99	55	4	99	2	97
2.36 mm	No. 8		96		0	90 1	84	41	55	1	87	41	1	87	1	74
1.18 mm	No. 16		86			69	64	29	43		68	31		71		56
600 μm	No. 30		57			45	40	19	33		43	22		42		35
300 μm	No. 50		20			17	15	11	24		15	15		13		15
150 μm	No. 100		4			4	4	6	14		4	10		7		3
75 μm	No. 200		1			1	2	–	8		2	5		–		–

Note: USACRREL = U.S. Army Cold Regions Research and Engineering Laboratory; WES = Waterways Experiment Station; NPDL = North Pacific Division Laboratory. Dashes indicate data not available.

[a] U.S. standard sieves.

TABLE 2 Mixture Proportions

Project	Weight, Saturated Surface–Dry (lb/yd³) Portland Cement	Fly Ash	4.75-19.0 mm	4.75-25.0 mm	4.75-37.5 mm	4.75 mm-75 μm	19.0 mm-75 μm	Water	AEA (oz/cwt)
Fort Stewart	611	–	–	1,971	–	1,406	–	202	–
Fort Hood									
Mixture A	306	162	–	–	2,294	1,285	–	153	–
Mixture B	376	186	2,165	–	–	1,366	–	180	–
Fort Lewis									
Mixture A	320	172	1,967	–	–	1,546	–	176	–
Mixture B	499	–	–	–	–	–	3,468	206	–
USACRREL									
Mixture A	564	–	–	–	–	–	3,336	209	–
Mixture B	567	–	1,745	–	–	1,640	–	199	–
Mixture C	567		1,745			1,640		199	7.0
Port of Tacoma	450	100	–	–	–	–	3,400	256	–
WES beams									
Mixture A	561	–	1,960	–	–	1,472	–	196	–
Mixture B	548	–	1,837	–	–	1,437	–	191	7.5
NPDL beams	351	180	1,936	–	–	1,560	–	169	–

Note: AEA = air-entraining admixture; USACRREL = U.S. Army Cold Regions Research and Engineering Laboratory; WES = Waterways Experiment Station; NPDL = North Pacific Division Laboratory. Dashes indicate material not used.

mate desired grade. A 19,000-lb single steel-drum vibratory roller was used to compact the mixture. A layer of sand approximately 3 in. thick was spread on the compacted pavement surface and moistened periodically for 3 days in order to cure the RCC. Samples were taken from the pavement approximately 3 months after construction.

Fort Hood, Texas

An 18,150-yd² RCC parking area was constructed adjacent to a tactical equipment maintenance shop in July 1984. The 10-in.-thick pavement is designed to support 120,000-lb tracked vehicles as normal traffic.

All concrete materials were mixed in a continuous-mixing pugmill. Two mixtures were used in the pavement: one having a 37.5-mm (1 1/2-in.) nominal maximum size aggregate (NMSA), and the second having a 19.0-mm (3/4-in.) NMSA. Natural fine aggregate was used in both mixtures. Aggregate gradings are shown in Table 1. The 37.5-mm (1 1/2-in.) NMSA mixture contained approximately 306 lb/yd³ Type I portland cement and 162 lb/yd³ Class C fly ash and had a W/C of approximately 0.31. The 19.0-mm (3/4-in.) NMSA mixture contained approximately 376 lb/yd³ Type I portland cement and 186 lb/yd³ Class C fly ash and had a W/C of approximately 0.30. The concrete mixture proportions for both are given in Table 2. Only the pavement containing the 37.5-mm NMSA mixture was sampled and tested in this investigation.

The no-slump concrete was placed on a 6-in.-thick lime-stabilized base with an asphalt paver and compacted with a 20,000-lb dual steel-drum vibratory roller. Damp cotton mats were used to moist-cure the RCC for the first 24 hr, at which time the mats were removed and a pigmented membrane-forming curing compound was applied. The pavement test section was sampled approximately 1 month after its construction.

Fort Lewis, Washington

A 700-ft-long by 22-ft-wide RCC pavement test section, ranging in thickness from 6 to 7 3/4 in., was constructed in October 1984. The test section currently serves as a secondary road for both rubber-tired and tracked vehicles.

Two concrete mixtures were used in the pavement. One contained 19.0-mm NMSA natural coarse aggregate conforming with the grading limits of ASTM C 33, size designation No. 67, and natural fine aggregate. This mixture also contained approximately 320 lb/yd^3 Type I portland cement and 172 lb/yd^3 Class F fly ash and had a W/C of approximately 0.32. The second mixture contained both coarse and fine crushed aggregate graded from a 12.5-mm (1/2-in.) nominal maximum size to the 75-µm (No. 200) sieve size. This aggregate was typical of one that might be used in an asphalt paving mixture. The concrete also contained approximately 499 lb/yd^3 Type I portland cement and had an approximate W/C of 0.41. No fly ash was included in the second mixture. The aggregate gradings and concrete mixture proportions used for this project are given in Tables 1 and 2, respectively.

The concrete materials were mixed in a continuous-mixing pugmill, and the resulting concrete was placed with an asphalt paver. Compaction was achieved with a single steel-drum vibratory roller having a mass of approximately 20,000 lb. A rubber-tired roller was also used to knead and tighten the RCC surface. Following the compaction operations, the concrete was continuously moist-cured for 7 days by use of a water-spray system. Hardened pavement samples representing each mixture were obtained approximately 3 weeks after completion of construction.

U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL)

These nominal 25- by 18-ft by 8-in. RCC pavement test sections were constructed in November 1984. One of the test sections contains concrete having a 19.0-mm nominal maximum size natural aggregate. The aggregate was graded in a single size range to the 75-µm (No. 200) sieve size. Approximately 564 lb/yd^3 of Type II portland cement was used in the mixture. The W/C was approximately 0.37.

A second section was constructed with no-slump concrete containing crushed coarse aggregate having a 19.0-mm nominal maximum size and a natural fine aggregate. The concrete also contained approximately 567 lb/yd^3 of Type II portland cement and had a W/C of approximately 0.35.

The third test section was constructed with a concrete mixture similar to that used in the second test section, except that an air-entraining admixture (AEA) consisting of an aqueous solution of neutralized Vinsol resin was added. The aggregate gradings and concrete mixture proportions used in the three RCC test sections are shown in Tables 1 and 2, respectively.

A pugmill of the batch type, normally used for asphalt production, was used to mix the concrete materials. The concrete was placed with an asphalt paver onto a crushed bank-run gravel base and compacted with a dual steel-drum vibratory roller having a mass of approximately 20,000 lb. The completed test sections were moist-cured 14 days with damp burlap strips. The pavements were sampled approximately 1 month after completion of construction.

Port of Tacoma, Intermodal Railyard Development, Washington

This nominal 90,000-yd^2 RCC pavement varies in thickness from 12 to 17 in. It was constructed in April 1985 and serves as a container storage facility.

The no-slump concrete mixture contained a crushed aggregate including both fine and coarse material having a nominal maximum size of 12.5 mm and graded to the 75-µm sieve size. The aggregate was typical of that used in asphalt paving. The mixture also contained 450 lb/yd^3 Type I portland cement and 100 lb/yd^3 Class F fly ash and had a W/C of approximately 0.43. The aggregate grading is given in Table 1 and the mixture proportions in Table 2.

The materials were mixed in a continuous-mixing pugmill, and the resulting concrete was placed in two equal layers with asphalt pavers onto a crushed gravel base. Dual steel-drum rollers, each having a mass of approximately 20,000 lb, were used to compact the concrete and a rubber-tired roller was used to tighten the pavement surface. Water-spray trucks were used to moist-cure the RCC for 7 days after completion of compaction. Samples were taken from the pavement approximately 3 weeks after construction was completed.

Caycuse, British Columbia

An RCC dry-land log-sorting yard was constructed on Vancouver Island in 1976. It has an area of approximately 22,000 yd^2 and a nominal thickness of 14 in. A single-size-range aggregate having a 19.0-mm nominal maximum size and graded to the 75-µm sieve size was used in the concrete. The aggregate grading and concrete mixture proportions were not available to the author when this paper was prepared. However, the contractor responsible for constructing the pavement has reported that approximately 8 percent of the aggregate, by mass, was finer than the 75-µm sieve and that two mixtures were used in the pavement. A mixture containing approximately 7 percent portland cement, by mass of the aggregate, was used in the lower 8 in., and one containing approximately 12 percent portland cement, by mass of the aggregate, was used in the upper 6 in.

Concrete materials were mixed in a continuous-mixing pugmill. The concrete was placed with an asphalt paver and compacted with single steel-drum vibratory rollers. Samples were taken from the pavement approximately 8 years after it had been constructed.

Laboratory-Fabricated Specimens

In addition to the RCC pavements previously described, specimens were also fabricated for test by WES and NPDL as part of the USACRREL and Fort Lewis mixture proportioning studies. The concrete materials used by both laboratories were mixed in small revolving-drum mixers. Specimens for rapid freezing-and-thawing, compressive strength, and flexural strength tests were fabricated on vibrating tables with the aid of surcharge weights. The aggregate gradings and mixture proportions used in the laboratory studies are given in Tables 1 and 2, respectively.

TEST PROGRAM

As was previously stated, the primary purpose of the investigation discussed here was to characterize the air-void system parameters and evaluate the frost resistance of samples obtained from RCC pavements. At least one representative sample from each pavement described here was microscopically examined in accordance with ASTM C 457, Modified Point-Count Method, in order to determine the air-void content and bubble spacing factor ($\bar{L}$). Initially, the entrained and entrapped air-void content of each sample was determined. The criteria given in the definition of air void in ASTM C 125 were used to distinguish entrained and entrapped air voids. However, the predominant irregular shape of the observed sections of the small air voids, discussed in further detail in the following paragraphs, resulted in very low entrained air-void contents in the samples. These results appeared inconsistent with what one might expect, given the relatively small $\bar{L}$'s determined in a number of the samples. Therefore, the decision was made to characterize the air voids by size only, irrespective of shape. Determinations were made for each specimen of the percentage of voids whose section chord lengths were less than 0.04 in. and the percentage of those whose section chord lengths were greater than 0.04 in.

The rapid freezing-and-thawing tests were conducted in accordance with applicable sections of ASTM C 666, Procedure A. Samples were sawed into prisms 3 1/2 by 4 1/2 by 16 in. and stored in a 73°F water bath for 14 days before the start of testing. Each specimen was continued in test until it was subjected to 300 freezing-and-thawing cycles or until its relative dynamic modulus of elasticity reached 50 percent of the initial modulus, whichever occurred first. The NPDL conducted the freezing-and-thawing tests on the Fort Lewis and Caycuse samples as well as the NPDL-fabricated specimens. The South West Division Laboratory conducted the freezing-and-thawing tests on the Fort Hood samples. WES conducted the testing on the remainder of the samples.

The dilation test (ASTM C 671) was also used as a means to evaluate the potential frost resistance of the samples. The test may also be used to determine whether a specimen becomes frost susceptible during a particular period of interest. Powers (3) stated that concrete frost resistance or durability is not a measurable property, but that the expansion that occurs during a slow-cooling cycle when the concrete or its aggregates become critically saturated is measurable and will provide an indication of potential frost resistance. That is, if a specimen shrinks normally in the freezing range, it is immune to frost action; if it dilates, it is not immune. ASTM C 671 requires that dilation be determined by measuring the vertical distance from straight-line projection of the prefreezing, length-versus-time contraction curve at constant cooling rate and the maximum deviation of the strain from it. The test is conducted by monitoring the length of a specimen as its temperature is lowered.

There were some differences in the dilation test method followed in this investigation and that prescribed by ASTM. The major one was that the 3-in.-diameter by 6-in.-long RCC cores were cooled in water-saturated kerosene from an unspecified but convenient temperature range of 35° to 55°F at a rate of approximately 5°F per hour to a minimum of -10°F. The ASTM method specifies cooling the specimens in water-saturated kerosene from 35° to 15°F at 5°F per hour. Critical dilation (D_c) in ASTM C 671 is defined as the dilation during the last cycle before the dilation begins to increase sharply by a factor of 2 or more. The method states that dilations less than 0.005 percent should not be interpreted as indicating D_c even if the criterion for D_c is met numerically.

A dilation criterion, based on the results of a single test, has also been proposed by Buck (4). He suggests the following:

1. If the dilation is 0.005 percent (= 50 millionths) or less, the specimen may be regarded as frost resistant; that is, the dilation is not critical.
2. If the dilation is 0.020 percent (= 200 millionths) or more, the specimen may be regarded as not frost resistant; that is, D_c has been exceeded.
3. If the dilation is in the range between 0.005 percent and 0.020 percent, an additional cycle or more should be run.

Ten specimens representing six of the nine pavements were tested. At the time that this paper was prepared, only five to seven freezing cycles per specimen had been completed. Test results were evaluated by using both the ASTM dilation criterion and that suggested by Buck.

Compressive and flexural strength tests provided physical data on samples representing each pavement. The tests were conducted in accordance with ASTM C 42.

DISCUSSION OF RESULTS

The air-void size distribution and $\bar{L}$ of each RCC sample are given in Table 3. As was previously noted, the air voids were categorized according to chord lengths of the counted air-void sections, irrespective of section shape. Figure 1 shows a typical RCC and a conventional air-entrained concrete polished section. The irregular shape of the voids in the RCC section is believed to result from compaction operations associated with RCC pavement construction. However, no work was conducted in this investigation to confirm this belief.

The percentage of air voids, by volume, smaller than 0.04 in. ranged from 0.1 to 9.6 in the pavement samples and from 0.6 to 2.5 in the laboratory-fabricated specimens. Large dosages of AEA were added to the mortar fraction of the concrete represented by

TABLE 3 Microscopic Air-Void Data

		Air Content (%) by Chord Length (in.)				
Project	Mixture	Specimen No.	Less Than 0.04	Larger Than 0.04	Total	$\bar{L}$ (in.)
Fort Stewart		1T1	0.2	8.0	8.2	–
		1B1	0.1	3.7	3.8	–
		2T1	1.9	3.4	5.3	0.020
		2B1	0.8	21.6	22.4	–
		3T1	0.6	2.5	3.1	–
		3B1	0.3	4.0	4.3	–
		4T1	0.8	10.0	10.8	–
		4B1	0.2	8.5	8.7	–
Fort Hood	A	1	1.3	1.6	2.9	0.012
Fort Lewis	A	5A	2.5	2.6	5.1	0.012
		9B	1.9	0.2	2.1	0.005
		10B	9.6	0.8	10.4	0.011
	B	17A	1.6	3.1	4.7	0.015
		17B	1.8	2.2	4.0	0.018
USACRREL	A	1T	–	–	5.1	–
		1B	2.3	3.2	6.1	0.008
	B	3T	–	–	5.3	–
		3B	3.6	5.0	8.6	0.010
	C	2T	2.9	2.3	5.2	0.010
		2B	–	–	4.8	–
Port of Tacoma		2A-T	5.5	1.6	7.1	0.010
		2A-B	2.5	0.7	3.2	–
		1D-T	3.0	1.5	4.5	0.013
		1D-B	4.1	0.5	4.6	–
		2H-T	3.5	2.0	5.5	–
		2H-B	6.1	4.5	10.6	0.010
Caycuse		2A	0.5	10.8	11.3	0.026
WES beams	A	1	1.1	2.0	3.1	0.030
	B	1	2.5	2.1	4.6	0.013
NPDL beams		2	0.6	1.1	1.7	0.018
		8	0.9	0.8	1.7	0.019
		9	1.1	2.8	3.9	0.022

Note: Dash indicates data not determined.

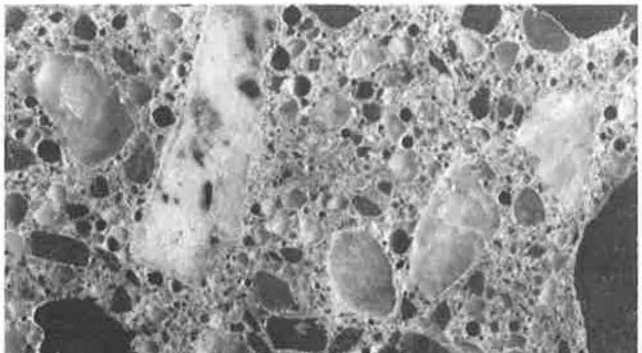

FIGURE 1 Polished sections showing air-void shapes, magnification = 4.1. ***Top:*** **conventional air-entrained concrete;** *bottom:* **RCC.**

USACRREL specimen C-2T and WES specimen B-1. The mortar was mixed for approximately 1 min before the addition of the coarse aggregate. The USACRREL concrete was mixed in a pugmill mixer of the batch type, and the WES concrete was mixed in a small revolving-drum mixer. The effect of the AEA on the concrete air-void system is somewhat ambiguous. Specimen C-2T has 2.9 percent, by volume, of air voids smaller than 0.04 in. and 2.3 percent of the voids larger than 0.04 in. However, USACRREL specimen B-3B, which represents similar concrete without AEA, has 3.6 percent of the air voids smaller than 0.04 in. and 5.0 percent larger. Similarly, USACRREL specimen A-1B, which also represents a non-air-entrained concrete, has 2.3 percent of the air voids smaller than 0.04 in. and 3.2 percent larger than 0.04 in. The $\bar{L}$'s of the three specimens are not significantly different.

WES specimen B-1 had 2.5 percent, by volume, of its air voids smaller than 0.04 in. and 2.1 percent of the voids larger than 0.04 in. WES specimen A-1, which represents similar concrete without AEA, had 1.1 percent of its voids smaller than 0.04 in. and 2.0 percent larger than 0.04 in. However, the $\bar{L}$ of specimen A-1 is approximately 2.5 times that of specimen B-1.

Those specimens representing concrete that was pugmill mixed generally had greater percentages of air voids smaller than 0.04 in. than those specimens representing concrete mixed in revolving-drum mixers. The specimens representing pugmill-mixed concrete also generally had smaller $\bar{L}$'s. Although the mechanisms responsible for creating these desirable air-void systems in the non-air-entrained concrete are not yet fully understood, pugmill mixing appears to be a contributing factor. The cohesiveness of the mixture may also play an important role in the maintenance of the small air voids during compaction. An RCC mixture that is highly cohesive due to a low water content and large aggregate surface area may prevent the escape of a large percentage of the small air voids during the compaction operations. Additional investigative work is needed to confirm these proposed explanations.

RAPID FREEZING-AND-THAWING TESTS

Table 4 summarizes the results of the rapid freezing-and-thawing tests. In general, these values may be interpreted (5) as follows: A DFE_{300} less than 40 means that the concrete is probably unsatisfactory with respect to frost resistance; 40 to 60 is the range for concretes with doubtful performance; and greater than 60, the concrete is probably satisfactory. With these criteria, the test results indicate that the RCC samples associated with Fort Stewart, Fort Hood, and Caycuse were frost susceptible, as were the WES- and NPDL-fabricated specimens. The results of the tests of the Fort Lewis specimens indicate doubtful to satisfactory performance, whereas the USACRREL and Port of Tacoma test results indicate satisfactory performance.

The rapid freezing-and-thawing test results and specimen $\bar{L}$'s are paired in Table 5. This summarization indicates that the frost resistance of RCC is, as expected, a function of the $\bar{L}$. Spacing factors less than 0.008 in. are typically associated with concrete having good resistance to freezing and

TABLE 4 Results of Rapid Freezing-and-Thawing Tests

Project	Mixture	Specimen No.	Avg DFE_{300}
Fort Stewart		1T1-1T6	8
		1B1-1B5	6
		2T1-2T2	9
		2B1-2B3	5
		3T1-3T4	8
		3B1-3B4	4
		4T1-4T4	6
		4B1-4B4	6
Fort Hood	A	5-7	10
		8-10	8
Fort Lewis	A	5A,B; 9A,B; 10A,B	47
	B	17A-17D	59
USACRREL	A	1T-3T	88
		1B-3B	89
	B	1T-3T	39
		1B-3B	69
	C	1T-3T	68
		1B-3B	91
Port of Tacoma		1A-T,B; 2A-T,B	82
		1D-T,B; 2D-T,B	79
		1H-T,B; 2H-T,B	78
		3H-T,B; 4H-T,B	
Caycuse	12 percent cement	1A-1C	6
		2A-2C	3
WES beams	A	1-3	10
	B	1-3	48
NPDL beams		1-4	10
		5-9	11

TABLE 5 Specimen DFE_{300}'s and $\bar{L}$'s

Project	Mixture	Specimen No.	DFE_{300}	$\bar{L}$ (in.)
Fort Stewart		2T1	8	0.020
Fort Hood		5	10	0.012
Fort Lewis	A	5A	44	0.012
		9B	71	0.005
		10B	20	0.011
	B	17A	59	0.015
		17B	44	0.018
USACRREL	A	1B	89	0.008
	B	3B	75	0.010
	C	2T	81	0.010
Port of Tacoma		2A-T	84	0.010
		1DT	75	0.013
		2HB	82	0.010
Caycuse		2A	3	0.026
WES beams	A	1	10	0.030
	B	1	48	0.013
NPDL beams		2	10	0.018
		8	–	0.019
		9	11	0.022

thawing. In the case of the tests of RCC, it was found that $\bar{L}$'s smaller than 0.011 in. generally resulted in DFE_{300}'s of 60 or greater; $\bar{L}$'s of 0.011 to 0.016 in. resulted in DFE_{300}'s of 40 to 60; and $\bar{L}$'s greater than 0.16 resulted in DFE_{300}'s less than 40. The relatively small $\bar{L}$ coupled with the low DFE_{300} of the Fort Hood specimen was unexpected. However, it is not known if the aggregates used in the RCC are frost susceptible. The small $\bar{L}$ and low DF_{300} of Fort Lewis specimen A-10B were unexpected and unexplainable. Figure 2 graphically shows the relationship between DFE_{300} and $\bar{L}$ of the RCC samples. The figure is subdivided into zones of performance based on the criteria noted earlier.

Dilation Tests

The rapid freezing-and-thawing test uses a higher freezing rate than is ordinarily encountered in outdoor weathering. Cooling takes place at approximately 25°F/hr in the laboratory test, whereas in practice 5°F/hr is not normally exceeded. The dilation test was selected as an alternative means of evaluating the frost resistance of some of the pavement samples because the cooling rate used in the test is comparable to natural cooling rates. Powers suggested that when dilation-testing specimens that represent concrete subject to seasonal drying, a period of immunity of approximately 16 weeks (8 freezing cycles) of continuous exposure to water should assure immunity during any winter season (3). Studies by Larson and Cady (6) suggest that the length of the soaking period exerts considerably more influence on the rate of deterioration than does the number of intermediate cooling cycles.

Table 6 shows the specimen dilation test results. It is apparent from this table that a variation of 100 to 200 min between cycles for a specimen is not indicative of damage. Each of the specimens appears to be immune to frost damage, as defined by ASTM C 671, for the first five to seven cycles of test. However, USACRREL specimen A-4, Fort Stewart specimen FS-4, and Fort Hood specimen 20-F each experienced large dilations after six, five, and three cycles,

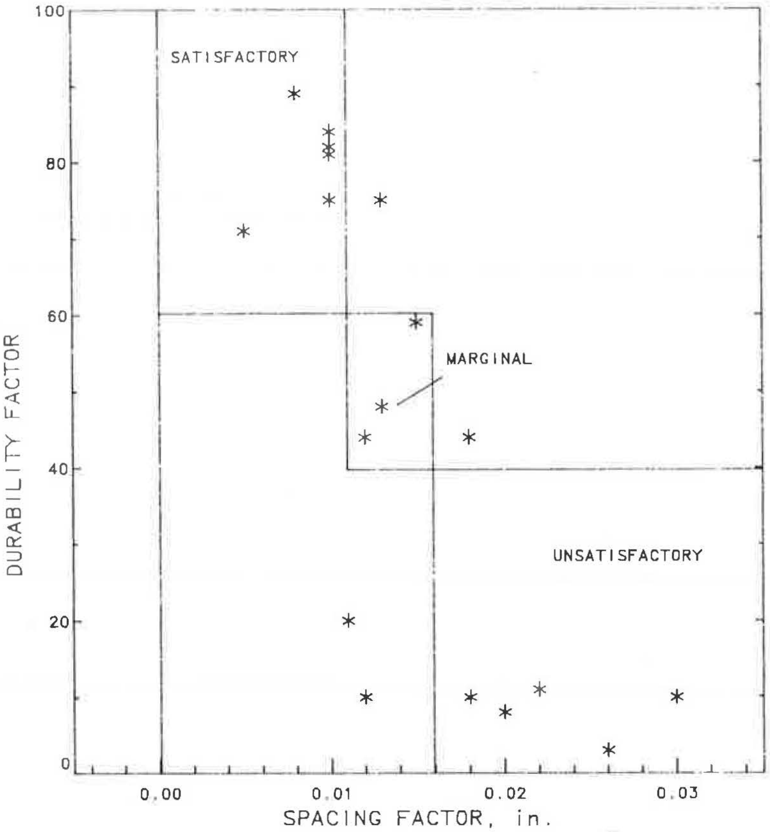

FIGURE 2 Durability factor (DFE_{300}) versus spacing factor ($\bar{L}$) based on data from Table 5.

TABLE 6 Dilation Test Results

Project	Mixture	Specimen No.	Test Cycle													
			1		2		3		4		5		6		7	
			Microinches	Millionths	Microinches	Millionths	Microinches	Millionths	Microinches	Millionths	Microinches	Millionths	Microinches	Millionths	Microinches	Millionths
Fort Stewart		FS-4	375	75	425	85	130	26	250	50	220	50	430	86	325	65
Fort Hood	A	20-F	200	40	230	46	230	46	450	90	500	100	575	115	575	115
USACRREL	A	4	200	40	340	68	300	60	400	80	300	60	300	60	550	110
	B	4	175	35	125	25	125	25	250	50	175	35	250	50	175	35
	C	4	250	50	330	66	330	60	450	90	450	90	–	–	550	110
Port of Tacoma		3A-T	110	22	–	–	190	38	160	32	210	42	–	–	–	–
		3D-T	130	26	175	35	252	55	250	50	225	45	–	–	–	–
		3D-B	130	26	100	20	210	42	200	40	330	66	–	–	–	–
		5H-T	140	28	275	55	200	40	300	60	260	52	–	–	–	–
		5H-B	100	20	100	20	275	55	200	40	290	58				

Note: Dashes indicate malfunction.

respectively, and additional testing may result in dilation in excess of D_c.

The single-test dilation criterion suggested by Buck (4) indicates that, in general, all of the specimens fall in the marginal zone between frost resistant and frost susceptible. That is, the dilation value obtained during the last freezing cycle of each is generally within the range of 50 to 200 millionths. This suggests that additional cycles should be run to determine when the D_c of 200 millionths is exceeded. Regardless of the dilation criterion used to evaluate the results, it is apparent that each of the specimens tested has some resistance to frost damage down to -10°F for at least 5 to 7 cycles (10 to 14 weeks of continuous exposure to water). In the case of those samples having large $\bar{L}$'s, the low W/C ratios were apparently adequate to provide a measure of protection.

Compressive and Flexural Strength Tests

A summary of the sample compressive and flexural strength test results is shown in Table 7. The average compressive strengths range from 2,930 to 8,920 psi, and the average flexural strengths range from 510 to 1,010 psi.

TABLE 7 Compressive and Flexural Strength Test Results

Project	Mixture	Approximate Age (days)	Avg Compressive Strength (psi)	Avg Flexural Strength (psi)
Fort Stewart		90	5,220	1,010
Fort Hood	A	28	4,780	830
Fort Lewis	A	90	5,790	690
	B	90	8,920	960
USACRREL	A	40	2,930	510
	B	40	6,500	860
	C	40	4,370	600
		40	6,500	860
Port of Tacoma		35	5,220	705
Caycuse		8 years	5,880	540
WES beams	A	28	6,250	730
	B	28	5,740	680
NPDL beams		28	6,900	650

CONCLUSIONS

1. The microscopic examinations of representative sections of the RCC pavement samples indicate that air-void systems normally associated with at least partially frost-resistant concrete may be created without the use of AEA. The creation of these air-void systems appears to be related to pugmill mixing, the cohesiveness of the mixture, and the method of compaction. The inclusion of AEA in the mortar fraction of a no-slump concrete mixture that was pugmill mixed did not significantly increase the percentage of air voids smaller than 0.04 in.

2. The shapes of the examined air-void sections were irregular. These irregular shapes are believed to result from the compaction operations associated with RCC pavement construction.

3. The frost resistance of RCC, as evaluated by the DFE_{300}, is a function of $\bar{L}$. Durability factors of 60 or more were associated with those specimens having $\bar{L}$'s smaller than 0.011 in. Those specimens having $\bar{L}$'s of 0.011 to 0.016 in. resulted in DFE_{300}'s of 40 to 60, and those having $\bar{L}$'s larger than 0.016 in. resulted in DFE_{300}'s of less than 40.

4. The dilation test appears to provide an effective measure of the frost resistance of RCC. Use of the test would appear appropriate to determine whether a sample of RCC is frost resistant at the time of test or to measure the period of frost immunity. The latter use might be particularly important in the case of pavements, which are typically subject to seasonal drying.

5. The dilation data indicate some degree of frost resistance for each specimen tested. The frost resistance of specimens having large $\bar{L}$'s may be attributed to the low W/C of the RCC mixtures. Such concrete has little freezable water in the paste, and also has a low permeability. Therefore, it is more difficult to critically saturate.

6. Concrete must meet three requirements before it may be considered immune to frost action. It must be made with non-frost-susceptible aggregates and a proper air-void system and must be cured to an appropriate degree of maturity so as to reduce the fractional volume of freezable water on saturation to limits that can be accommodated by elastic volume change and by the air-void system. RCC pavements can be constructed with non-frost-susceptible aggregates and can be appropriately cured. The air-void systems observed in many of the sampled RCC pavements should be sufficient to protect them against frost damage in all but the most severe environments. Additional investigative work is needed to determine whether an entrained air-void system can be effectively produced in RCC that would cause it to be immune to frost damage in all exposures.

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Construction Techniques for Roller-Compacted Concrete

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ABSTRACT

Roller-compacted concrete (RCC) is a new material that uses a construction technique that applies the material property theories of both soil mechanics and concrete. The resulting product is a construction material with the strength characteristic of conventional concrete. Because RCC is a new material, the construction process for its placement is in a state of trial and adjustment; however, a unique feature of RCC is the use of standard earthmoving equipment for transportation, placement, and compaction. Earthmoving equipment reduces the labor-intensive process necessary for conventional concrete placement. The RCC mix is placed in a solid (no vertical joints) horizontal layer across the total placement area. No cure time is necessary between layers.

In 1970 Raphael presented the idea of a new construction material that would exist between conventional concrete and earth fill (1,pp.221-247). With the equipment and techniques of an earth embankment project, a structure would be constructed with this new material in a continuous-cycle-type operation. The completed structure would, however, develop the strength and material characteristics of conventional concrete. The material would be an intermedium substance having the advantages of both earth fill and conventional concrete; therefore, a more economical structure or project could be achieved through reductions in materials, labor, and time (1).

These ideas become realities with the introduction of zero-slump concrete. The new construction material is known as roller-compacted concrete (RCC), rollcrete, or rolled concrete. As actual project experience is gained, the construction process for RCC is being developed, modified, and adjusted. Projects to date have been approached by applying new ideas to previous earthwork or concrete construction techniques. Engineers around the world have gained experience on a first generation of RCC projects and are beginning to report the results of their field experimentation with RCC placement techniques on those projects (2-5). This paper is a state-of-the-art review of the construction processes used for RCC construction.

MATERIAL FUNDAMENTALS

Materials play an important part in dictating construction processes. RCC construction techniques for mixing, transporting, and placement are controlled

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