Report on Roller-Compacted Concrete Pavements

Reported by ACI Committee 325

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This report covers the present state of the art for roller-compacted concrete pavements. It contains information on applications, material properties, mix proportioning, design, construction, and quality control procedures. Roller-compacted concrete use for pavements is relatively recent and the technology is still evolving. The pavement consists of a relatively stiff mixture of aggregate, cementitious materials, and water, that is compacted by rollers and hardened into concrete.

Keywords: Aggregates; cements; compaction; concrete construction; concrete durability; concrete pavements; consolidation; curing; construction joints; density; mixing; placing; Portland cement; roller compacted concrete, strength.

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CHAPTER 1—INTRODUCTION

This state-of-the-art report contains information on applications, material properties, mix proportioning, design, construction, and quality control procedures for roller compacted concrete pavements (RCCP). Roller compacted concrete (RCC) use for pavements is relatively recent and the technology is still evolving. Over the last ten years several major pavement projects have been constructed in North America using RCC and the performance of these pavements has generally been favorable. Roller compacted concrete pavements are also gaining acceptance in several European countries and Australia.

The advantages of using RCC include cost savings as a result of the construction method and the increased placement speed of the pavement. RCC pavements do not use dowels, steel reinforcement, or forms. This also results in significant savings when compared to the cost of conventionally constructed concrete pavements.

Roller compacted concrete is used in two general areas of engineered construction: dams and pavements. In this document, RCC will be discussed only in the context of its use in pavements. RCC for mass concrete is discussed in ACI 207.5R.

Roller compacted concrete for pavements can be described as follows:

> A relatively stiff mixture of aggregate [maximum size usually not larger than $^3/_4$ in. (19 mm)], cementitious materials and water, that is compacted by vibratory rollers and hardened into concrete. When RCC is used as a surface course, a minimum compressive strength of 4000 psi (27.6 MPa) is generally specified.

The materials for RCC are blended in a mixing plant into a heterogeneous mass which has a consistency similar to damp gravel or zero slump concrete. It is placed in layers usually not greater than 10 in. (254 mm) compacted thickness, usually by an asphalt concrete paving machine. The layers are compacted with steel wheel vibratory rollers, with final compaction sometimes provided by rubber tire rollers. The pavement is cured with water or other means to provide a hard, durable surface. RCC pavements are usually designed to carry traffic directly on the finished surface. A wearing course is not normally used, although a hot mix asphalt overlay has been added, in some cases, for smoothness or rehabilitation. Transverse and longitudinal contraction joints for crack control are not usually constructed in RCC pavements.

RCCP has been used for a wide variety of applications. These include log sorting yards, lumber storage, forestry and mining haul roads, container intermodal yards, military vehicle roads and parking areas, bulk commodity (coal, wood chips) storage areas, truck and automobile parking, and to a lesser extent, municipal streets, secondary highways, and aircraft parking ramps.

CHAPTER 2—BACKGROUND

The first RCC pavement in North America was identified by the Seattle office of the U.S. Army Corps of Engineers. The project was a runway at Yakima, Washington, constructed around 1942. A form of roller compacted concrete paving was reported in Sweden as early as the 1930s.[1]

The first RCC pavement in Canada was built in 1976 at a log sorting yard at Caycuse on Vancouver Island, British Columbia. The decision to build RCC was the outgrowth of a pavement design which called for a 14 in. (356 mm) thick cement stabilized aggregate base and 2 in. (51 mm) asphalt concrete surface. As an alternative to the asphalt concrete surface, the owners decided to increase the cement content of the top 6 in. (152 mm) of cement stabilized material to 13 percent by weight to improve wear and freeze/thaw resistance. Cement content in the 8 in. (203 mm) base layer was set at 8 percent. The final result was a 4 acre (1.6 hectares) log sorting yard with an exposed, cement stabilized crushed gravel operating surface. No bonding grout was used between the two cement stabilized layers. Special effort was made by the contractor to complete both layers on the same day. Some minor delamination occurred after a few years of log stacker traffic. This observation lead to the requirement for a limitation on the maximum time between lifts. The

Caycuse Log Sorting yard has been in continuous use since 1976. The area of RCC pavement was doubled to 9 acres (3.6 hectares) in a 1978 expansion. A thin asphalt overlay was applied in 1987 as a minimum cost maintenance operation to improve pavement smoothness.

Following the success of the paving at Caycuse, three more RCC dry-land log sorting yards were built on Queen Charlotte Islands off the coast of British Columbia during 1976 to 1978. These pavements continue to perform well with little maintenance. By 1980 nearly 20 acres (8 hectares) of log sorting yards constructed with RCC were in operation in British Columbia. The next milestone in Canadian RCC pavement history came when a decision was made to build 12 miles (19.3 kilometers) of 7 in. (179 mm) thick RCC pavement for a coal mine haul road at Tumbler Ridge in British Columbia. A 4 acre (1.6 hectares) coal storage area was also built with a 9-in.-thick (229 mm) roller compacted concrete. The haul road was surfaced with bituminous concrete while the storage area remains as an exposed RCC pavement. This region of British Columbia undergoes severe winter conditions, with frost penetration to a depth of 8 ft (2.4 m). No distress from the severe winter climate is evident at the coal storage area, although some failures have occurred in the loaded wheel paths of the haul road.

While these developments were going on in Canada, there was growing interest in RCC by various organizations in the United States where RCC for dams was being evaluated in several test projects. During the early 1980s, engineers at the United States Army Corps of Engineers started studying the use of RCC for pavement construction at military facilities. A small test road for tracked vehicles, 9 in. to 13 in. (229 mm to 330 mm) thick, 470 yd^2 (392 m^2) was built at Ft. Stewart, Georgia, in 1983, and a tank test road 10 in. to 13 in. (254 mm to 330 mm), 590 yd^2 (493 m^2), was constructed at Ft. Gordon, Georgia, in the same year. RCC test road construction by the Corps of Engineers continued in 1984 when 1870 yd^2 (1564 m^2) of 8.5 in. (216 mm) thick pavement was built for a tank trail at Ft. Lewis, Washington.

In 1984, the question of freeze/thaw durability of RCC remained to be addressed. The Corps of Engineers constructed a full scale test pavement at the Cold Regions Research Engineering Laboratory in Hanover, New Hampshire, where a complete range of climatic conditions could be simulated. The test program was successful, and in a memorandum to all field offices, dated Jan. 25, 1985, the use of RCC paving for "horizontal construction" was encouraged, where appropriate, for all facilities administered by the Corps of Engineers.[2]

The first full scale RCC pavement designed and built by the Corps of Engineers was a tactical equipment hardstand at Ft. Hood, Texas, in 1984.[3] The area of the project was 18,150 yd^2 (15,175 m^2). A 10 in. (254 mm) thick slab was specified and a flexural strength of 800 psi (5.5 MPa) was achieved. This project provided the Corps of Engineers with valuable information about maximum aggregate size, single versus multiple lift construction methods, compaction procedures, curing and sampling of RCC material. During 1986, the Corps of Engineers built a tracked vehicle hardstand at Ft. Lewis, Washington. The area of the pavement was 26,000 yd^2 (21,753 m^2) with a thickness of 8.5 in. (216 mm).

The interest in RCC heavy duty pavement began to expand beyond the logging and mining industries by the mid-1980s. The Burlington Northern Railroad selected RCC for 53,000 yd^2 (44,313 m^2) of paving at a new intermodal facility at Houston, Texas in 1985,[4] and 128,000 yd^2 (107,021 m^2) of intermodal yard paving at Denver, Colorado, in 1986. In 1985 the Port of Tacoma, Washington, constructed two areas of RCC pavement totalling 17 acres (6.9 hectares).[5,6] Also, large areas of RCC pavement were constructed at the Conley and Moran Marine Terminals in Boston between 1986 and 1988.

The largest RCC pavement projects undertaken to date include the more than 650,000 yd^2 (543,464 m^2) of 8 and 10 in. -(203 and 254 mm) thick RCC pavement placed at the General Motors Saturn automobile plant near Spring Hill, Tennessee, and 89 acres (36 hectares) of 10 in.- (254 mm) thick RCC pavement placed at Ft. Drum, NY. Both were constructed in 1988-89 and were used as parking areas and roads.

Apart from the reported use of RCC at Yakima, Washington, in 1942, the only example of an airport installation is at the Portland International Airport in 1985.[7,8] The 14-in. (356 mm) RCC pavement with an area of 9 acres (3.6 hectares) is used for overflow short term aircraft storage.

There has been a growing interest in the use of RCC paving for low to moderate traffic streets, and secondary highways. Municipal street pavements have been built in Portland, Oregon; Regina, Saskatchewan; and Mackenzie, British Columbia.

Fig. 2.1 to 2.4 illustrate typical RCC pavement practices. Fig. 2.5 illustrates typical RCC pavement surface at Ft. Drum, New York, and Fig. 2.6 shows a close-up of the pavement surface adjacent to a sawed longitudinal construction joint. Fig. 2.7 shows a close-up of an acceptable RCC pavement surface at Ft. Bliss, Texas, and Fig. 2.8 shows a close-up of an excellent RCC pavement surface.

CHAPTER 3—MATERIALS

3.1—General

Pavement design strength, durability requirements, and intended application all influence the selection of materials for use in RCC pavement mixtures. The basic materials used to produce RCC include water, cementitious materials (cement and fly ash), and fine and coarse aggregates. Generally, the cost of materials selected for use in RCC pavements is almost the same as the cost of materials used in conventional portland cement concrete. However, some material savings may be possible due to the lower cement contents normally needed in RCC pavement mixtures to achieve strengths equivalent to those of conventional concrete.

3.2—Aggregates

The aggregates comprise approximately 75 to 85 percent of the volume of an RCC pavement mixture and therefore significantly affect both the fresh and hardened concrete

Fig. 2.1—RCC placement using modified asphalt pavers

Fig. 2.2—Vibratory roller compaction

properties. Proper selection of suitable aggregates will result in greater economy in construction and longer serviceability of RCC pavements. In freshly mixed RCC, aggregate properties affect the workability of a mixture and its potential to segregate and the ease with which it will properly consolidate under a vibratory roller. The strength, modulus of elasticity, thermal properties, and durability of the hardened concrete are also affected by the aggregate properties.

Aggregates used in RCC pavement mixtures contain both fine [finer than the 4.75 mm (No.4) sieve] and coarse fractions, although the fractions may be preblended and stockpiled as a single aggregate on large projects. The coarse aggregate usually consists of crushed or uncrushed gravel, crushed stone, or a combination thereof. The fine aggregate may consist of natural sand, manufactured sand, or a combination of the two.

For high quality RCC, both the coarse and fine aggregate fractions should be composed of hard, durable particles and the quality of each should be evaluated by standard physical property tests such as those listed in ASTM C 33. If lower

Fig. 2.3—Rubber-tired roller compaction

Fig. 2.4—Fog curing of freshly placed RCC pavement

quality RCC is acceptable, then aggregates which do not meet established grading and quality requirements may be satisfactory as long as design criteria are met. RCC containing uncrushed gravel generally requires less water to attain a given consistency than that containing crushed gravel or stone. RCC containing crushed gravel or stone may require more effort to compact, and is less likely to segregate. It is also more stable during compaction and usually provides a higher flexural strength.

RCC mixtures are typically not as cohesive as conventional concrete and therefore, aggregate segregation is an important concern. Greater economy may be realized by using the largest practical nominal maximum size aggregate (NMSA). Increasing the NMSA reduces the void content of the aggregate and thereby reduces the paste requirement of a mixture. However, in order to minimize segregation during handling and placing of RCC and to provide a relatively smooth pavement surface texture, the NMSA should not exceed $^3/_4$ in. (19

Fig. 2.5—RCC pavement — Ft. Drum, New York

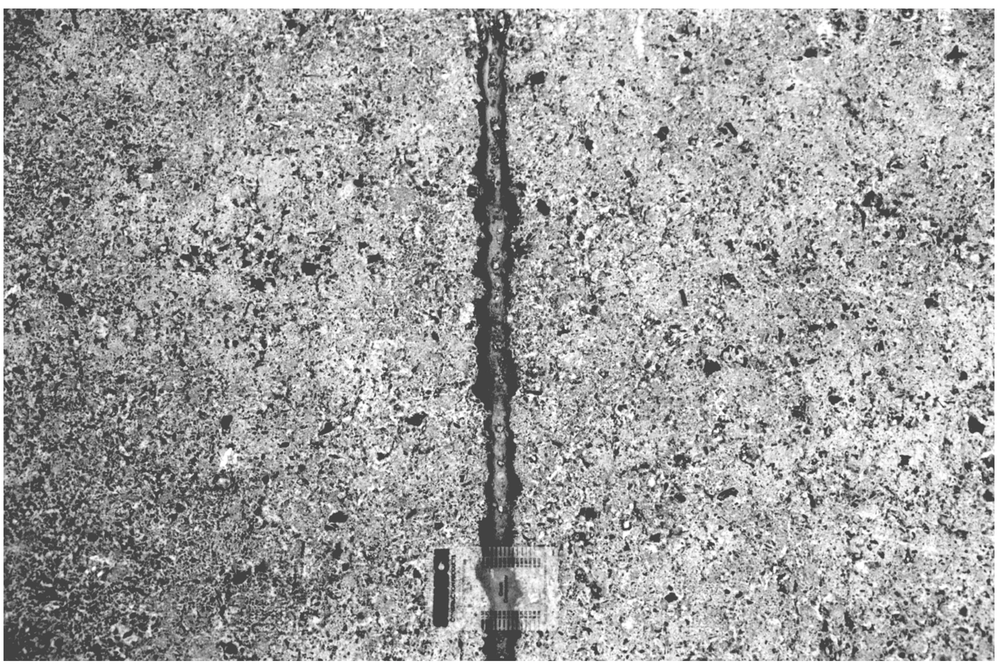


Fig. 2.6—RCC pavement surface texture — Ft. Drum, New York

mm). If the coarse and fine aggregate fractions are preblended and stockpiled as a single size group, segregation may make grading control difficult. Careful attention must be given to stockpile formation and subsequent handling of single-size group aggregate.

The range of aggregate gradings used in RCC pavement mixtures has included standard graded concrete aggregates having normal size separations to pit- or bank-run aggregate with little or no size separation. If longitudinal and transverse pavement smoothness are of importance, the coarse and fine aggregates should be combined such that a well-graded aggregate blend is produced which approaches a maximum-density grading.

Grading limits that have been used to produce satisfactory RCC pavement mixtures are shown in Fig. 3.2. The use of aggregate fractions finer than the 75 micrometers (No. 200) sieve, if nonplastic, may be a beneficial means to reduce fine aggregate voids. However, their effect on the fresh and hardened RCC properties should be evaluated in the mixture proportioning study.

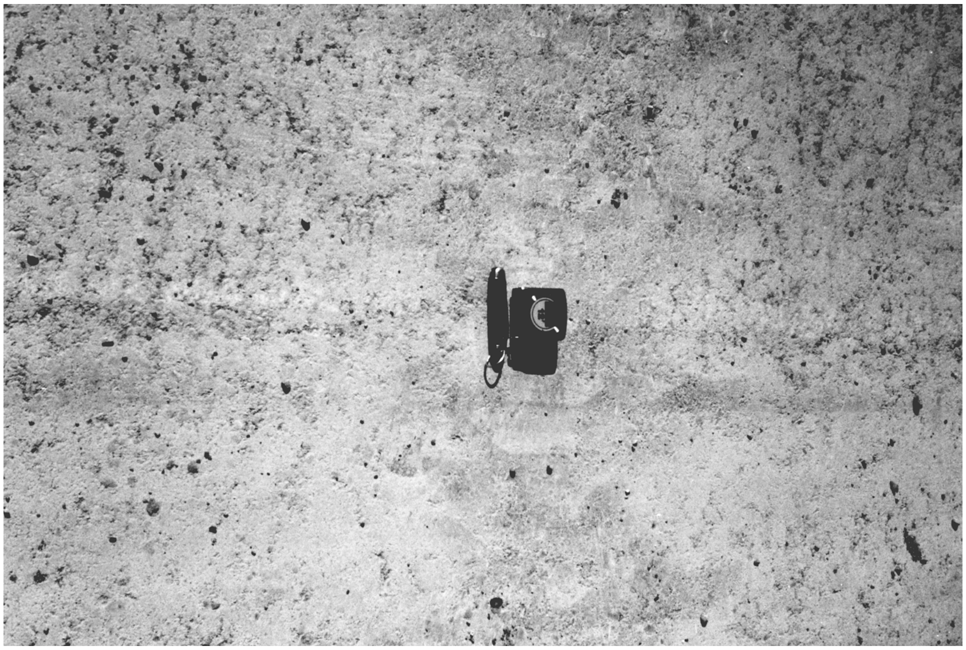


Fig. 2.7—Acceptable RCC pavement surface — Ft. Bliss, Texas

Fig. 2.8—Excellent RCC pavement surface — Ft. Bliss, Texas

3.3—Cementitious materials

Cementitious materials used in RCC pavement mixtures include portland cement or blended hydraulic cement, and may include pozzolan, or a ground granulated blast furnace slag. The selection of cement type should be based in part upon the design strength and the age at which this strength is required. In addition, applicable limits on chemical composition required for exposure conditions and alkali reactivity should follow standard concrete practice. A detailed discussion on the selection and use of hydraulic cements may be found in ACI 225R. Many of the RCC pavements constructed to date have been constructed using Type I or II Portland cement and Class F or Class C fly ash.

The use of fly ash in RCC is an effective means of providing additional fine material needed to assure adequate compaction, particularly in those RCC mixtures that contain standard graded concrete fine aggregate. Fly ash contents generally range from 15 to 20 percent of the total volume of cementitious material. The selection of any pozzolan for use in RCC should be based on its conformance with applicable

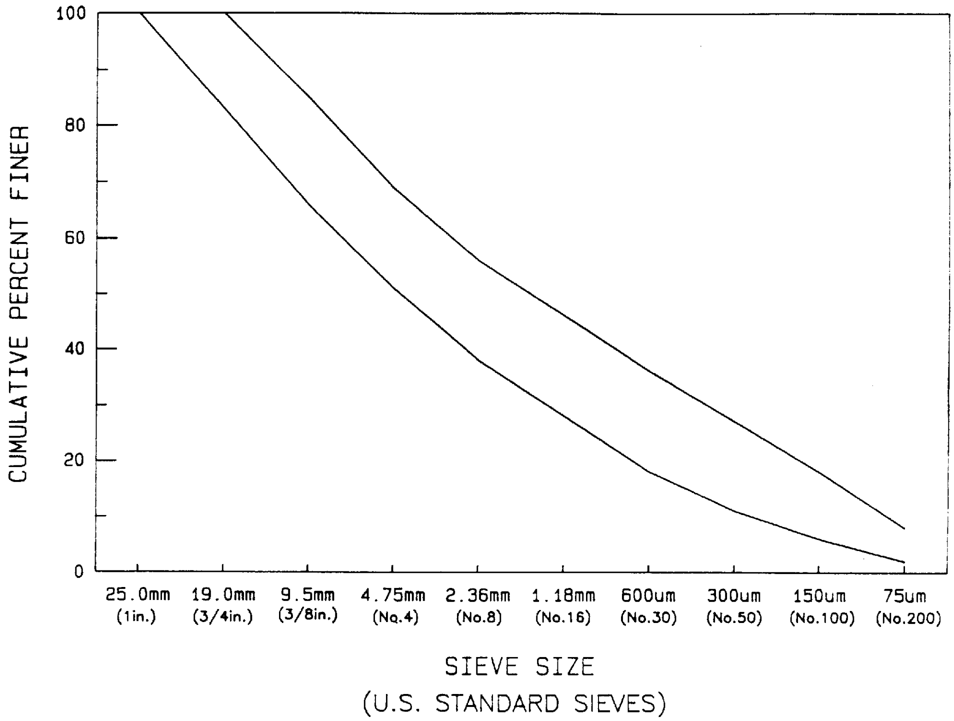


Fig. 3.2—Typical range of RCC pavement aggregate gradation

standards or specifications, its performance in concrete, and its availability at the project location. Guidance on the use of pozzolans and other finely divided mineral admixtures in concrete is given in ACI 226R.

3.4—Water

Water quality for RCC pavement is governed by the same requirements as for conventional concrete.

3.5—Admixtures

Air-entraining admixtures have had only limited use in RCC pavement mixtures. However, laboratory research has conducted at the U.S. Army Engineer Waterways Experiment Station has indicated that RCC pavement mixtures can be properly air-entrained using commercially available air-entraining admixtures at dosage rates 5 to 10 times greater than conventional concrete. The practicality of producing air-entrained RCC in the field has not yet been demonstrated. To date, minimizing frost damage in RCC has been achieved by proportioning mixtures with sufficiently low water-cementitious material ratios (w/c) so that the permeability of the paste is low. Once concrete has dried through self-desiccation, it is difficult to again become critically saturated by outside moisture. The use of proper compaction techniques which lower the entrapped air-void content, increase strength, and lower the permeability of the concrete should also improve the pavement's frost resistance. However, proper air-entrainment of RCC is the best way to assure adequate frost resistance.

Chemical admixtures, including water-reducing admixtures and retarding admixtures, have had only limited use in RCC, primarily in test sections and laboratory investigations. The ability of a water-reducing admixture to lower the water requirements or to provide additional compatibility to an RCC mixture appears to be somewhat dependent on the amount and type of aggregate finer than the No. 200 (75-µm) sieve. Retarding admixtures may be beneficial in delaying the setting time of the RCC so that it may be adequately compacted or so that the bond between adjacent lanes or succeeding layers is improved.

CHAPTER 4—MIXTURE PROPORTIONING

4.1—General

RCC mixture proportioning procedures and properties differ from those used for conventional concrete due to the relatively stiff consistency of the fresh RCC and the use of unconventionally graded aggregates. The primary differences in proportions of RCC pavement mixtures and conventional concrete pavement mixtures are:

1. RCC is generally not air-entrained
2. RCC has a lower water content
3. RCC has a lower paste content
4. RCC generally requires a larger fine aggregate content in order to produce a combined aggregate that is well-graded and stable under the action of a vibratory roller
5. RCC usually has a NMSA not greater than $^3/_4$-in. (19 mm) in order to minimize segregation and produce a relatively smooth surface texture.

The relatively high cementitious material contents and high quality aggregates used in RCC distinguish it from soil cement and cement-treated base course. In order for RCC to be effectively consolidated, it must be dry enough to support the weight of a vibratory roller, yet wet enough to permit adequate distribution of the paste throughout the mass during the mixing and compaction operations. Concrete suitable for compaction with vibratory rollers differs significantly in appearance, in the unconsolidated state, from that of concrete having a measurable slump. There is little evidence of any paste in the mixture until it is consolidated. However, RCC mixtures should have sufficient paste volume to fill the internal voids in the aggregate mass. Several methods have been used to proportion RCC pavement mixtures. These methods can be placed into one of two broad categories:

1) proportioning by use of concrete consistency tests
2) proportioning by use of soil-compaction tests

4.2—Proportioning by evaluation of consistency tests

This method essentially involves proportioning the RCC mixture for optimum workability at the required level of strength, using an apparatus such as the Vebe described in ACI 211.3. The Vebe apparatus has been modified by the Corps of Engineers and the Bureau of Reclamation in order to make it more suitable for use with RCC. It consists of a vibrating table of fixed frequency and amplitude, with a metal container having a volume of approximately 0.33 ft^3 (.0094 m^3) securely attached to it. A representative sample of RCC is loosely placed in the container under a surcharge having a mass of 29.5 or 50 lb (13.3 or 22.7 kg), depending on which modified apparatus is selected. The measure of consistency is the time of vibration, in seconds, required to fully consolidate the concrete, as evidenced by the formation of a ring of mortar between the surcharge and the wall of the container. Although modified Vebe times of 20 to 30 seconds have been reported as appropriate for RCC containing $1^1/_2$- to 3-in. (38 to 76 mm) NMSA and used in mass concrete applications, these times normally represent concrete that has a consistency too wet to properly place and compact in pavement applications.

Limited laboratory research indicates that modified Vebe times, as determined under a 50-lb (22.7 kg) surcharge, of 30 to 40 seconds are more appropriate for RCC pavement mixtures.[9] The modified Vebe time should be determined for a given RCC mixture and compared with the results of on-site compaction tests conducted on RCC compacted by vibratory rollers to determine if adjustments in the mixture proportions are necessary. The optimum modified Vebe time is influenced by the water content, NMSA, fine aggregate content, and the amount of aggregate finer than the 75 micrometers (No. 200) sieve. RCC mixtures containing more than approximately five percent aggregate finer than the No. 200 sieve may be difficult to accurately test using the modified Vebe apparatus, because the mortar in these mixtures is difficult to bring to the surface under vibration.

Mixture proportioning methods using consistency tests usually require fixing specific mixture parameters such as water content, cementitious materials content, or aggregate content, and then varying one parameter to obtain the desired level of consistency. In this way, each mixture parameter can be optimized to achieve the desired fresh and hardened RCC properties. One of the primary considerations when using the methods described in ACI 207.5R which, use consistency tests, is the proper selection of the ratio (*pv*) of the air-free volume of paste to the air-free volume of mortar. RCC pavement mixtures should contain sufficient paste volumes to fill all internal voids between the aggregate particles. The *pv* affects both the compatibility of the mixture and the resulting surface texture of the pavement.

4.3—Proportioning by soil compaction methods

Methods that use these tests involve establishing a relationship between dry or wet unit weight and moisture content of the RCC by compacting specimens over a range of moisture contents. It is similar to the method used to determine the relationship between the moisture content and the unit weight of soils and soil-aggregate mixtures. The apparatus and compactive effort used to fabricate the moisture-density specimens corresponds to that described in ASTM D 1557, Method D.

The cementitious material content is determined by the strength and durability requirements of the pavement, and is often expressed as a percentage of the dry total weight of materials (cementitious and aggregate). Cementitious material contents ranging from 10 to 17 percent by dry weight are typical for RCC pavement mixtures. This range corresponds to approximately 350 to 600 lb of cementitious material/yd^3 (208 to 356 kg/m^3) of RCC.

The fine and coarse aggregates, as previously noted, are combined to create a well-graded blend. The unit volume of fine and coarse aggregate per unit volume of RCC may be calculated after the optimum moisture content of the RCC mixture is determined.

The optimum moisture content of the mixture is defined as the moisture content corresponding to the peak of the moisture content-density curve, and is dependent on the properties of the aggregates used and the cementitious material content. Strength loss will occur in a mixture that has a moisture content significantly below the optimum due to the presence of additional entrapped air voids. Strength loss will also occur in a mixture if the moisture content is significantly above the optimum due to an increase in the water-cementitious material ratio (w/cm). Moisture-density curves are normally established over a range of cementitious material contents in order to determine the minimum cementitious material content which will meet the design requirements. Moisture-density tests are conducted and a moisture-density curve is established for each cementitious material content-desired. Strength test specimens are then compacted at the optimum moisture content for each particular cementitious material content. From these tests, a curve of strength versus cementitious material content (or water-cementitious material ratio) is established to select the cementitious materials content.

4.4—Fabrication of test specimens

Conventional concrete specimen fabrication procedures, such as those currently standardized by ASTM, cannot be used to fabricate RCC test specimens due to the stiff consistency of the concrete. Although a number of procedures have been used, none have yet been standardized. The procedures frequently used involve vibrating the fresh RCC sample on a vibrating table under a surcharge, or compacting the sample with some type of compaction hammer following the procedures of ASTM D 1557.

For specimens compacted by vibration, the number of lifts used by various agencies has varied from one to three depending on the type of specimen. The surcharge has varied from 25 to 200 lb (11.3 to 90.7 kgs), or approximately 1 to 7 psi (0.0069 to 0.0483 MPa), again depending on the type of specimen. Complete compaction of RCC specimens may be difficult when using a vibrating table as evidenced by the fact that samples sawed or cored from RCC pavements sometimes have unit weights greater than those of fabricated specimens of similar age and moisture content. This incomplete specimen compaction in the laboratory may be particularly prevalent when a vibrating table is used that has a low amplitude when a surcharge is used. Vibrating tables used to date have included the Vebe table, those meeting the requirements of the relative density test for cohesionless soils (ASTM D 4253 and D 4254), and those meeting the requirements of ASTM C 192. Depending on the mixture proportions and the vibrating table available for use, it may be beneficial to produce trial batches at moisture contents slightly higher than optimum to facilitate compaction of the concrete.

Specimens compacted by means of a compaction hammer may have unit weights approximating those of samples taken from RCC pavements, however a significant number of blows may be required for adequate compaction. The number and height of the blows are normally maintained constant between specimens to achieve uniformity of results. Although compaction of cylinders may be feasible using a compaction hammer, uniform compaction of beam test specimens for flexural strength with this method may be impractical.

ASTM Subcommittee C09.45 on Roller Compacted Concrete is developing procedures for fabricating laboratory test specimens for determination of unit weight and strength of concrete having consistency similar to that of roller compacted concrete.

CHAPTER 5—ENGINEERING PROPERTIES

5.1—General

A review of the reported engineering properties of RCC indicates that they are similar to those of conventional paving concrete. Strength properties of RCC pavements are primarily dependent on the cementitious material content, aggregate quality and degree of compaction. Although RCC has been in use for paving for several years, only a limited number of investigations has been carried out to evaluate its engineering properties. Currently, no standard procedure exists for fabricating and testing RCC specimens in the laboratory. Therefore, it is not possible to directly compare properties of laboratory prepared “RCC” specimens without considering the procedures used to fabricate test specimens. As a result, the data base on engineering properties of RCC is based primarily on tests of specimens (cores and beams) obtained from actual paving projects or from a few full-scale test sections.

5.2—Compressive strength

Table 5.2.1 shows compressive strengths of cores obtained from Canadian projects after several years of service. This data is based on only a limited number of cores obtained from each project. Table 5.2.2 shows compressive strength of cores obtained from several U.S. projects. It is seen from Tables 5.2.1 that high compressive strengths can be achieved and that the strength levels are comparable to strength levels obtained for conventional concrete using similar cement contents.

5.3—Flexural strength

Because of the difficulty of obtaining sawed beam specimens from actual pavement sites, there is not much information available on flexural strength of RCC. Typical results from tests of sawed beams from selected RCC pavement projects are given in Table 5.3. These data are also based on a limited number of specimens obtained from each project.

Table 5.2.1—RCC core compressive strengths for British Columbia projects[10]

Project	Age of core, years	Cement content, percent	Compressive strength, psi (MPa)
Caycuse log sort yard	4	13, 8[1]	4210 (29.0)
Caycuse log sort yard	8	13	5880 (40.5)
Lynterm container port	3	8	4690 (32.3)
Fraser Mills log sort yard	1	13	4700 (32.4)
Bullmoose coal mine	1	14[2]	2200 (15.2)
Fraser surrey dock	1	12	4570 (31.5)

Notes:

1. Two lift construction—top 6 in. (152 mm) lift with 13 percent cement content, bottom 8 in. (203 mm) lift with 8 percent content.

2. 50 percent cementitious content was natural pozzolan.

Table 5.2.2—RCC core compressive strength results for several U.S. projects

Project	Age, months	Nominal lift thickness tested, in. (MPa)	Specified compressive strength, psi (MPa) at 28 days	Average compressive strength, psi (MPa)		
				Top half of core	Bottom half of core	Uncut core
A	9	7 (178)	4500 (31.0)	8120 (56.0)	6350 (43.8)	6760 (46.6)
B	19	6.5 (165)	5000 (34.5)	—	—	4740 (32.7)
C	19	8.5 (216)	5000 (34.5)	4330 (29.9)	2450 (16.9)	4560 (31.4)
D	18	8.5 (216)	3670 (25.3)	—	—	7030 (48.5)
E	12	10 (254)	2000 (13.8)	2290 (15.8)	4630 (31.9)	—
F	28	7 (178)	4500 (31.0)	5260 (32.3)	4230 (29.2)	—
G	32	8.5 (216)	5000 (34.5)	6890 (47.5)	4910 (33.9)	—

Source: Unpublished data, S. Tayabji.

The Table also contains corresponding splitting tensile strengths of companion cores.

Based on beams and cores obtained from a test section, it was determined that the relationship between compressive and flexural strengths of RCC was similar to that for conventional concrete, the relationship being of the form:[12]

$$fr = C\sqrt{fc} \tag{5.1}$$

where

fr = flexural strength (third-point loading), psi (MPa)
fc = compressive strength, psi (MPa)
C = a constant between 9 and 11 depending on actual RCC mix

More actual data may be needed to define the range of C with sufficient confidence.

5.4—Splitting tensile strength

Splitting tensile strength of cores obtained from actual RCC pavement projects range from about 400 to over 600 psi (2.8 to over 4.1 MPa) at 28 days depending on the cementitious content of the mix. The tensile strength characteristics of RCC are more easily and reliably measured by performing split tensile strength tests on cores than by performing flexural strength tests on sawed beams. Typical splitting tensile strength data from selected projects are listed in Table 5.3.

5.5—Modulus of elasticity

Modulus of elasticity has generally not been measured on specimens from actual RCC projects. Limited tests on cores obtained from a full-scale test section indicate that the RCC modulus of elasticity values may be similar to or slightly higher than those for conventional concrete with similar cement contents.[12]

5.6—Fatigue behavior

Only limited testing has been conducted to evaluate the fatigue behavior of RCC. Like conventional concrete and other construction materials, RCC is subject to the effects of fatigue. Fatigue failure is defined as material rupture after continued repetitions of loads that cause stresses less than the strength of the material. Results of fatigue tests on beams obtained from a full-scale test section incorporating four different RCC mixtures indicate that the fatigue behavior of RCC is similar to that of conventional concrete.[12]

5.7—Bond strength

Bond strength at the interface of RCC lifts is a critical engineering property. Bond strength determines whether RCC pavement constructed in multiple lifts will behave as a monolithic layer or as partially bonded or unbonded lifts. The load carrying capacity of partially bonded or unbonded lifts is significantly lower than that of bonded lifts of equal total thickness.

Bond strength development is low for untreated cold joints. Ideally, interface bond strength should be at least 50 percent of the strength of the parent RCC material based on good engineering practice. Data on interface bond strength is given in Table 5.7.1. This data was developed by testing cores obtained from RCC test pads constructed at Tooele Army Depot in Utah.[13] The data in Table 5.7.1 indicates that sufficient interface bond strength can be achieved for properly constructed RCC pavements. However, data from limited testing at Conley Terminal given in Table 5.7.2 show that bond strength development along edges of longitudinal construction joints may not be as good as in interior locations.

Table 5.3—Flexural and splitting tensile strength data from U.S. RCC projects[11]

Project	Age, days	Sawed beam and core test results: Average flexural strength, psi	Average splitting tensile strength, psi
Ft. Stewart	90	1010	—
Ft. Hood	7	661	—
	28	830	—
Harvey Barracks	7	—	338
	28	783	402
Ft. Campbell	7	647	398
	28	—	—
Aberdeen Proving Ground	7	553	379
	28	627	452

5.8—Durability

Because of the manner in which RCC is mixed and placed, it has not been practical to entrain air in RCC mixtures on field projects. Many of the projects constructed in the past which are performing well are located in coastal areas (northwestern U.S. and western Canada) where numerous freeze-thaw cycles occur. Recently, large scale RCC pavements were constructed in severe freeze-thaw areas such as Denver, Boston, and the State of New York (Ft. Drum). However, these projects have not been in service long enough to enable any conclusion to be drawn regarding freeze-thaw durability of RCC.

RCC samples obtained from pavement field projects have not shown good freeze-thaw durability when tested and evaluated in the laboratory according to the procedures of ASTM C 666. However, this does not necessarily mean that RCC will 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 Denver, Boston, and at Ft. Drum will help resolve the question of RCC durability.

5.9—Summary

Evaluation of test data from RCC paving projects shows that the structural behavior of RCC is similar to that of conventional normal weight concrete. Thus, RCC can be treated much like conventional concrete when designing thickness of a pavement.

It is clear that only a limited data base exists on engineering properties of RCC mixtures. No definitive studies have been performed to determine influences of various parameters on the engineering properties of RCC.

The properties of RCC discussed above are not applicable to RCC material within 12 to 18 in. (305 to 457 mm) to edges

Table 5.7.1—Direct tensile strength at lift interface at Tooele Army Depot, Utah[13]

Sample No.	Pad	Lane	Sta	Direct tensile strength, psi		T_{LJ}*, percent	Lift exposure time (min)
				Interface	Parent		
1	1	1	100	260	334	78	50
2	1	1	52	420	295	142	50
4	1	3	200	332	338	98	75
5	1	4	215	290	362	80	85
6	2	1	200	15	305	5	80
7	2	2	45	198	328	60	60
8	2	10	40	365	285	128	35
†	1	1	208	234	272	86	70
†	1	2	230	61	393	16	60
†	1	3	100	249	261	95	75
†	1	4	60	162	287	56	85
†	1	5	200	137	301	46	115
†	2	8	60	246	381	65	30
†	2	14	55	215	284	76	35
†	2	15	60	11	305	4	35
Average				213	315	69	63
Range				11-420	261-393	4-142	30-115
Standard deviation				116	38		
Coefficient of variation, percent				55	12		
Average excluding 3 low values				259	311	84	64

* Coefficient of lift bond — T_{LJ}".

$$\frac{\text{Direct tensile strength at interface (psi)} \times 100}{\text{Direct tensile strength of parent RCC (psi)}}$$

† Thickness cores taken at early age. Other cores taken with sawn beams. All tested at 5 months of age.
(SI conversion; 1 MPa = 145 psi)

Table 5.7.2—Core test results — Conley Terminal, Boston

Site	Location	Core No.	Layer	Thickness, in. (mm)	Shear strength, psi (MPa)		Splitting tensile strength, psi (MPa)
					Parent	Interface	
A	Interior	1	Top	6.25 (159)	—	295 (2.0)	680 (4.7)
				5.50 (140)	—	—	565 (3.9)
	Edge	2	Middle	6.25 (159)	—	185 (1.3)	320 (2.2)
				6.00 (152)	—	—	320 (2.2)
B	Interior	3	Top	6.00 (152)	—	—	520 (3.6)
				None	—	—	—
	Edge	4	Middle	6.25 (159)	—	—	315 (2.2)
				None	—	—	—
C	Interior	5	Top	6.25 (159)	—	340 (2.3)	565 (3.9)
				6.00 (152)	495 (3.4)	—	—
	Edge	6	Middle	6.00 (152)	255 (1.8)	—	—
				None	—	—	—
D	Interior	7	Top	5.75 (146)	—	—	545 (3.8)
				None	—	—	—
	Edge	8	Middle	6.00 (152)	—	Separated	340 (2.3)
				6.25 (159)	—	—	350 (2.4)
Average	Interior				495 (3.4)	320 (2.2)	575 (4.0)
	Edge				255 (1.8)	185 (1.3)	329 (2.3)

Source: Tayabji, S. D., 1987, Unpublished data on core testing at Conley Terminal, Boston.

that are unsupported during compaction. Because of inadequate compaction along these areas, strengths of RCC at these locations may be less than at interior locations.

CHAPTER 6—THICKNESS DESIGN

6.1—Basis for design

Because the structural behavior of RCC is similar to that of conventional paving concrete, the design procedures used for RCC pavements follow very closely the procedures used for design of conventional concrete pavements. The thickness design of conventional concrete and RCC pavements is based on keeping the flexural stresses and fatigue damage in the pavement caused by wheel loads within allowable limits. Stresses and fatigue damage are greatly influenced by wheel load placement — there is a greater effect for loads placed along edges and joints and less at the interior location of the pavement.

6.2—Design procedures

Thickness design procedures for RCC pavements have been developed by the Portland Cement Association

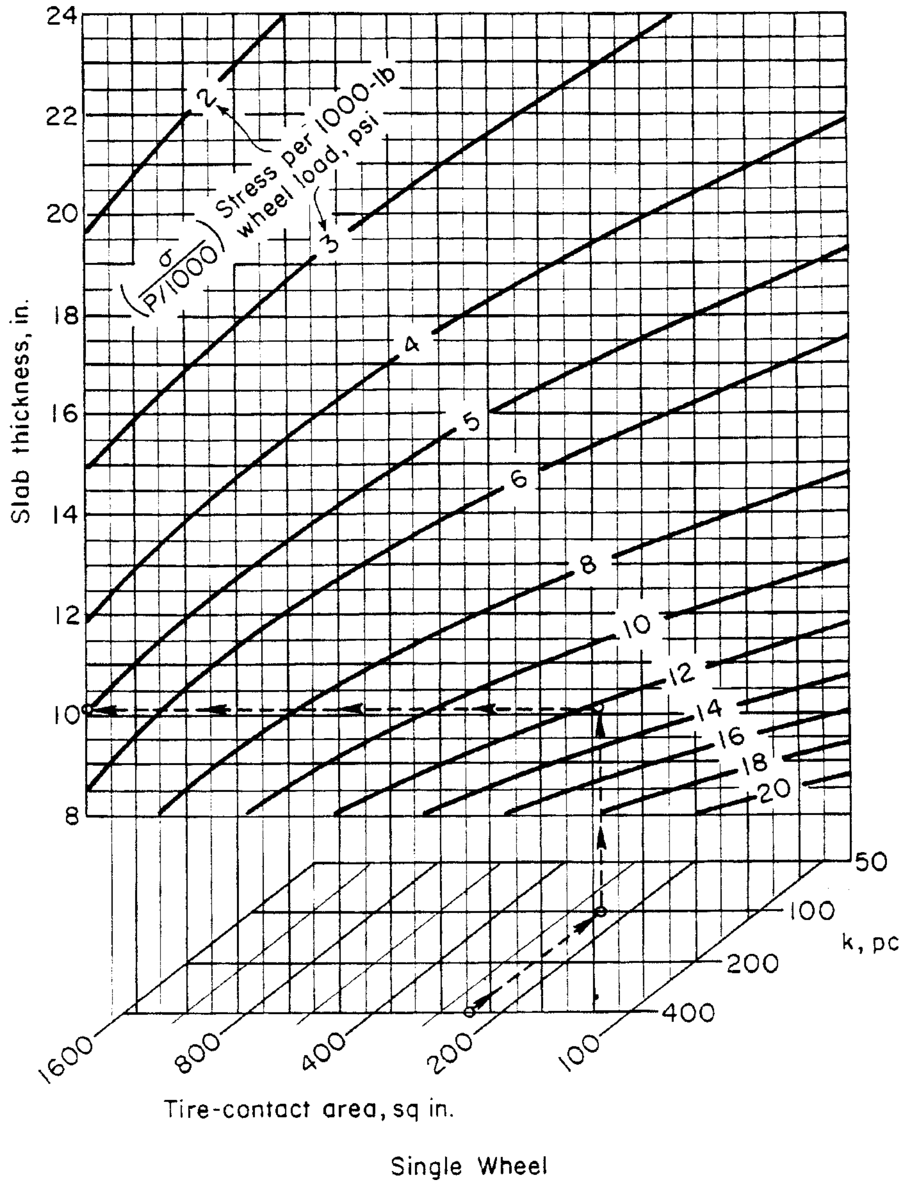


Fig. 6.2.1—PCA design chart for single wheel loads

(PCA)[14] and the U.S. Army Corps of Engineers.[15] The PCA procedure is applicable primarily to industrial pavements but can be used for similar paving applications. The procedure is based on interior load condition and uses a unique design fatigue relationship for RCC paving material. This procedure is very similar to the PCA procedure for the design of concrete industrial pavements. To use the PCA procedure, the following information is needed:

1. Supporting strength of subgrade or subbase/subgrade combination
2. Vehicle characteristics
   a) Wheel loads
   b) Wheel spacing
   c) Tire characteristics
   d) Number of load repetitions during the design life
   e) Flexural strength of RCC
   f) Modulus of elasticity of RCC

A typical design chart for single wheel loading is shown in Fig. 6.2.1.

The Corps of Engineers' thickness design procedure for RCC pavement is also similar to the Corps' procedure for conventional concrete pavements. It assumes no load transfer at joints for airfield applications but uses interior loading condition for other types of pavement applications. A typical thickness design chart for roads, streets, open storage areas and parking areas is given in Fig. 6.2.2. Fig. 6.2.2 requires use of a "Design Index" for traffic. The determination of the design index is given in Table 6.2.

6.3—Multiple-lifts considerations

RCC pavements thicker than about 10 in. (254 mm) are generally constructed in multiple lifts to ensure adequate compaction of each lift. Testing of core samples obtained from RCC paving projects indicates that properly constructed multiple-lift PCC pavements develop sufficient bond at

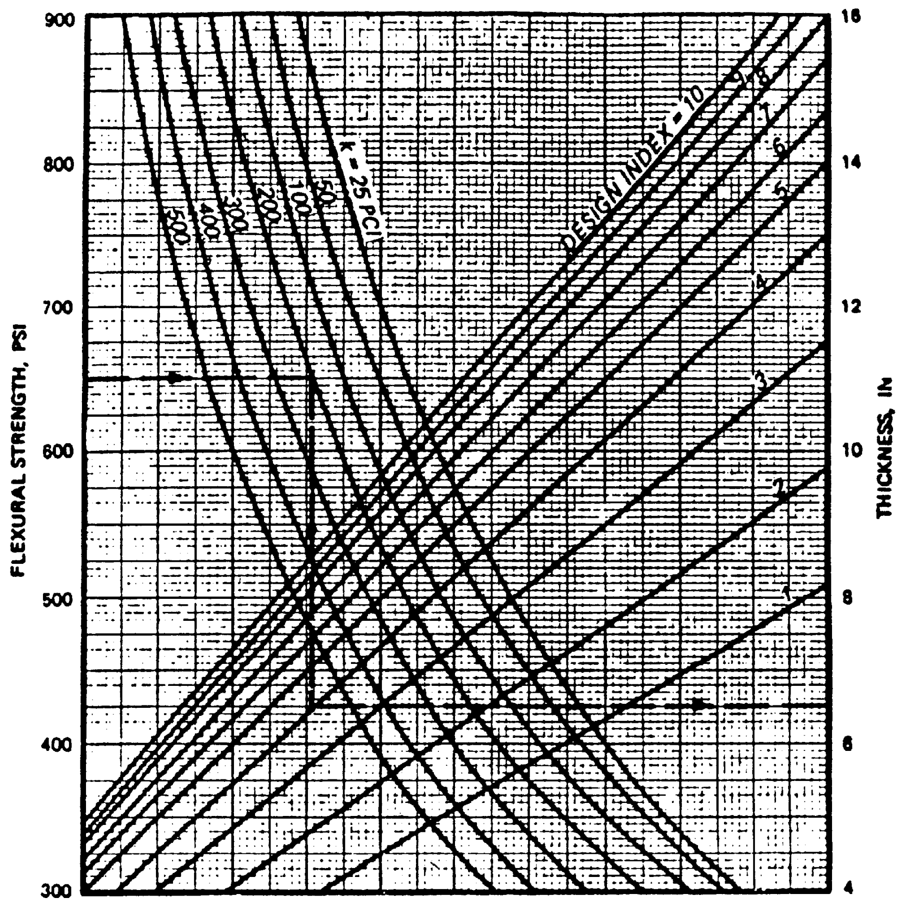


Fig. 6.2.2—Corps of Engineers design chart for RCC pavements

the interface of the multiple lifts to be considered monolithic, except along edges that were unsupported during compaction. As a result, this assumption is used in most RCC pavement thickness design procedures. However, it is emphasized that the proper procedures need to be followed in multi-lift construction to assure that adequate bond between lifts is achieved. The surface of the lower lift is kept moist and clean until the upper lift is placed, which should be done within the time limits (generally 1 hr) stated in the project specifications. When these recommendations cannot be met due to unforeseen delays or other factors, a cement slurry or a sand-cement grout is used to assure bonding of the multiple lifts. When a slurry or grout is used to assure bonding because of delays, sufficient time should be allowed for the lower lift to gain adequate strength prior to placing and compacting the upper lift. If final set of the lower lift has occurred, placement and compaction of the upper lift may result in cracking of the lower lift if an adequate strength has not been achieved.

6.4—Pavement design considerations

Geometric design of RCC pavements follows standard practice for conventional pavements. Irregularly shaped areas of limited size and access may require placement of conventional concrete pavement. Transverse joints, when used, have typically been spaced between 30 ft and 70 ft (9.1 and 21.3 m) apart. Longitudinal contraction joints are not used with RCC pavements. The direction of paving, and consequently the direction of the longitudinal construction joints, has usually been in the long dimension of the pavement. Occasionally, in order to minimize the number of cold longitudinal construction joints, the direction of paving has been in the short direction of the pavement. This practice has been successful in reducing cracking and providing better durability of the RCC along the longitudinal construction joints.

CHAPTER 7—CONSTRUCTION

7.1—General

RCC pavement construction involves the laydown and compaction of a very stiff concrete mixture using equipment and techniques similar to those for asphalt pavement construction. Consequently, relatively large quantities of concrete pavement may be placed rapidly with minimal labor and equipment. RCC pavements do not use dowels, steel reinforcement, or forms. This typically results in significant savings when compared to the cost of conventionally constructed concrete pavements. Construction of RCC pavement typically involves the preparation of subgrade and base course(s); batching, mixing, and transportation; placing, compaction, and joint construction; and curing and protection.

7.2—Subgrade and base course preparation

The subgrade and base course (where used) for RCC pave-

Table 6.2—U.S. Army Corps of Engineers rigid pavement design index values

	Rigid pavement design index for road or street					
	Classification					
Traffic category	A	B	C	D	E	F
I	2	2	2	1	1	1
II	3	2	2	2	2	1
III	4	4	4	3	3	2
IV	5	5	5	4	4	3
V [60-kilopound (kip) track-laying vehicles, 15-kip forklift trucks]:						
500/day	7	7	7	7	7	a
200/day	6	6	6	6	6	a
100/day	6	6	6	6	6	6
40/day	6	6	6	5	5	5
10/day	5	5	5	5	5	5
4/day	5	5	5	5	4	4
1/day	5	5	5	4	4	4
VI (90-kip track-laying vehicles, 20-kip forklift trucks):						
200/day	9	9	9	9	9	a
100/day	8	8	8	8	8	8
40/day	7	7	7	7	7	7
10/day	6	6	6	6	6	6
4/day	6	6	6	6	6	6
1/day	5	5	5	5	5	5
1/week	5	5	5	4	4	4
VII (120-kip track-laying vehicles, 35-kip forklift trucks):						
100/day	10	10	10	10	10	10
40/day	9	9	9	9	9	9
10/day	8	8	8	8	8	8
4/day	7	7	7	7	7	7
1/day	6	6	6	6	6	6
1/week	5	5	5	5	5	5

ments must meet the same requirements as those for conventional concrete pavements. The subgrade and base courses are prepared to provide sufficient support to permit full compaction of the RCC throughout the entire thickness of the pavement. The base course is often used to drain water from the underside of the pavement to prevent saturation of the concrete in areas where the bottom of the pavement is subjected to freeze-thaw cycling. Adequate smoothness of the base course is a requirement for pavements which have relatively tight smoothness tolerances. The surface of the base course is typically wetted immediately before the concrete is placed to help prevent moisture being absorbed from the concrete. This is especially important for these very dry mixes. String lines are generally set up on the base course to guide the paver screed to the proper grade and height above the base course, and to properly align the paver in the longitudinal direction.

7.3—Batching, mixing, and transporting

RCC requires a vigorous mixing action to disperse the relatively small amount of mixing water evenly throughout the matrix. Batching of the concrete has been accomplished successfully using either a continuous-mixing pugmill or batch rotary-drum plant. A continuous-mixing pugmill plant is commonly used because it may be easily transported and set up at the site, has a relatively large output capacity, and provides excellent mixing efficiency (Fig. 7.3). Weigh-batch systems generally allow more accurate control of the proportions of material in each batch than a continuous-mixing plant, but the output capacity of the plants may not be sufficient to allow smooth, continuous operation of the paver on larger paving projects [greater than 5000 yd^2 (4180 m^2)]. For larger projects, plant capacities of 250 tons (254,000 kg) per hour or larger have been used successfully. On smaller projects, where the cost of a large capacity on-site plant may not be justified, a modified local asphalt concrete weigh-batch plant and a truck-mounted, mobile concrete mixing plant [60 yd^3 (46 m^3) per hour capacity], has been used successfully.

In continuously mixing pugmills, a gobb hopper attached to the end of the final discharge belt has been used to reduce the free-fall height of the concrete (and thereby reduce segregation), and to temporarily hold the concrete discharge between subsequent dump trucks. The use of the gobb hopper allows the plant to operate more or less continuously, thereby improving mix uniformity. The plant is generally located as close as possible to the paving site to minimize the haul time of the concrete to the paver(s). Rear dump trucks are used to transport the concrete to the paver, and are sometimes equipped with covers when necessary to protect the concrete against adverse environmental effects, such as rain, wind, cold or heat. The dump trucks back up to the paver and discharge the concrete directly into the paver hopper, as the paver pushes the dump truck ahead of it.

7.4—Placing

RCC is typically placed with an asphalt paver, modified as

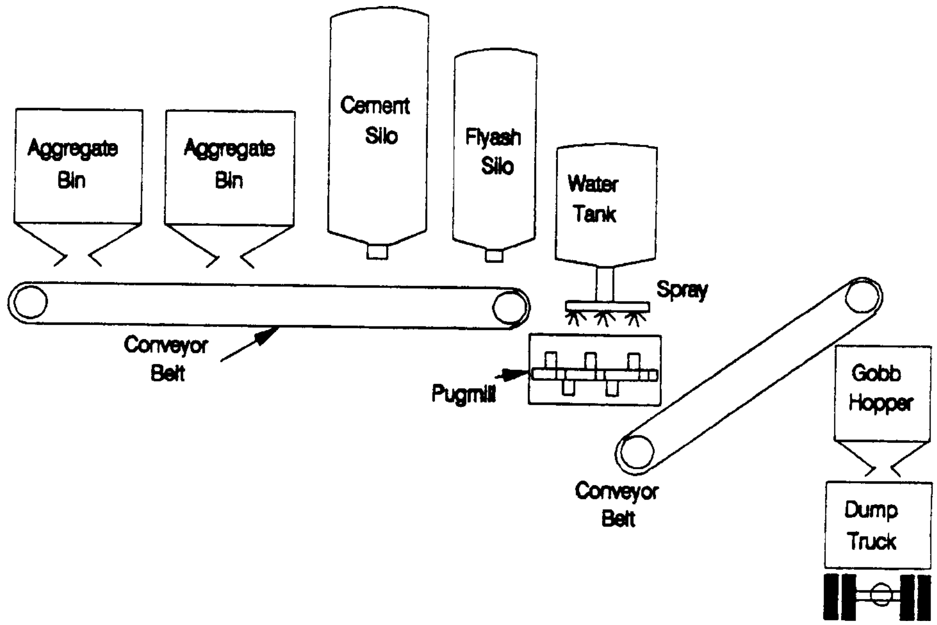


Fig. 7.3—Schematic of continuous mixing pugmill plant

necessary to accommodate the relatively large amount of material (a function of layer thickness) moving through the paver. These modifications may include enlarging the gates between the feed hopper and screed. Adjusting the spreading screws in front of the screed to insure that the concrete is spread uniformly across the width of the paving lane is similar to usual hot mix asphalt paving practices. The paver is usually equipped with automatic grade-control devices, such as a traveling ski or electronic stringline grade control device. For best finished smoothness, a stringline is used on both sides of the screed for the first lane, and on the outside edge of the screed on subsequent lanes using the finished edge as the guide on the other side. Maintaining continuous forward motion with the paver helps prevent the formation of bumps or depressions on the final pavement surface. This is achieved by balancing paver speed with maintainable concrete delivery rate. The pavers are typically equipped with vibratory screeds to provide some initial external compaction.

Recent paver models have included one or more tamping bars in addition to the vibration to increase the compactive effort and therefore the initial density behind the screed, with beneficial effects on final smoothness and density. However, the increased compactive effort, especially at the surface of the pavement, has been suggested as the cause of a network of interconnected superficial cracks and fissures sometimes observed in the pavement surface directly behind the heavy-duty screeds. These cracks may be removed partially or totally during the rolling process. The formation of these cracks seems to be related to the moisture content of the RCC mixture and the amount of pressure applied by the screed to the surface.

The timing of the placement and compaction of the paving lanes is critical to obtaining adequate density and smoothness in the finished RCC pavement. The concrete is usually placed and compacted while it is still fresh and workable, usually within 45 to 90 minutes after the addition of water at the plant, depending on environmental conditions. This time limitation for compaction of the concrete governs the time between placement of adjacent lanes, since the joint area is generally the last portion of the lane to be compacted (see “Joint Construction”). One method of accommodating the time limitation between placement of adjacent lanes is to limit the length of the paving lanes. Two or more pavers moving in echelon will also help reduce the time between adjacent lanes.

Curbs, gutters, and recessed drains have been often installed before and after the RCC placement. When installed before the RCC is placed, they provide confinement to aid compaction of the edge of the pavement. When installed after the RCC is placed, their height may be more easily matched to the surface of the RCC pavement. Manholes are more easily installed after the RCC is placed and compacted, by building the manhole level with the grade of the base course, covering it with a steel plate, and paving over the manhole. The next day, a block of RCC is sawn full depth and removed from over the manhole, the manhole built up to the pavement surface, and conventional concrete used to fill the remaining void.

7.5—Compaction

RCC is usually compacted with a 10-ton dual-drum vibratory roller, immediately after the concrete is placed. A common roller pattern involves making two static passes (one back-and-forth motion equals two passes) on the fresh concrete surface to “set” the surface before the vibratory rolling begins. The static passes are followed by several vibratory passes until the specified density is achieved, usually after four or more passes. The vibratory compaction may then be usually followed by several passes of a 10 to 20 ton rubber-tire roller to tighten any surface voids or fissures. Finally, a static roller may be used to remove any roller marks left by

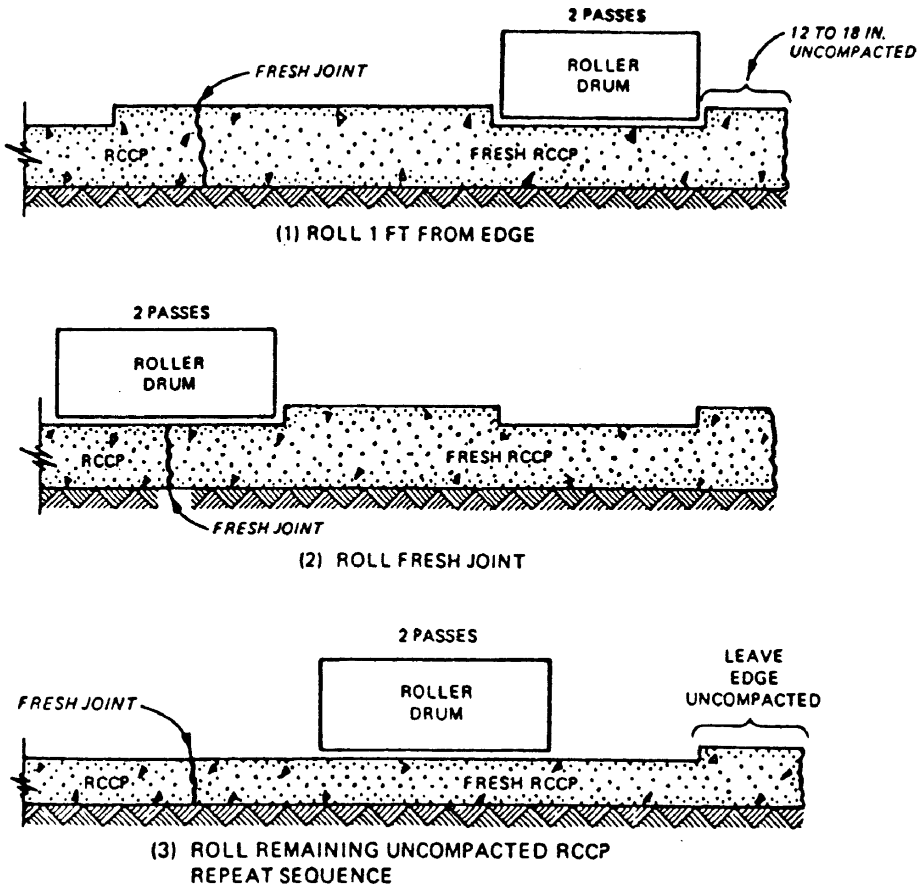


Fig. 7.6.1—Roller pattern for fresh construction joint[16]

the vibratory or rubber-tire rollers. Variations in this roller pattern have included; a) not using the vibratory mode of the roller, and increasing the number of static passes; and b) not using a rubber-tire roller to tighten the surface texture. Vibratory rollers with rubber-covered steel drums have also been used.

Since there is no standardized means of determining the consistency of RCC, a good indication that the RCC is ready for compaction is by observation of the behavior of the fresh RCC under the static roller passes. RCC which is of the proper consistency for compaction will deflect uniformly under the roller passes. If the RCC is too wet for proper compaction, the surface will appear shiny and pasty, and the RCC will exhibit “pumping” behavior under the roller and even under foot traffic. If the RCC is too dry, the surface will appear dusty or grainy and may even shear horizontally; the roller will not make a deep impression in the surface; and the specified density will be difficult to obtain, especially in the lower portion of the lift. Only minor adjustments in the water content, for workability, should be made or a new mix design may be needed.

Provided the RCC is placed on a uniform graded and compacted base, the rolling operation is the most critical element of the construction process in obtaining a desirable density, smoothness, and surface texture. The skill of the roller operator plays a key role in obtaining these desirable qualities. During the course of vibratory compaction, the roller operator should not stop on the pavement in the vibratory mode, and successive roller passes have been staggered to avoid creating a depression across the pavement surface. At the end of the paving lane, the rollers roll off the unconfined end of the lane, creating a rounded ramp of concrete which is removed before the next lanes are placed.

7.6—Joint construction

The joints in an RCC pavement are the most critical areas for obtaining adequate smoothness and density. Longitudinal joints are formed between adjacent paving lanes in the direction of paving, and transverse joints are formed at the ends of paving lanes perpendicular to the direction of paving. A “fresh” joint is formed between successive paving lanes when the time interval between placing and compacting the lanes is short enough to allow the lanes to be compacted together to form a monolithic juncture of the lanes. This time interval is usually one hour, more or less, depending on wind, temperature, and humidity.

Fresh longitudinal joints are constructed by leaving the outer 12 to 18 in. (305 to 457 mm) of the paving lane uncompacted during the rolling operation. This uncompacted edge is then used to set the height of the paver screed for paving the adjacent lane. After the adjacent lane is placed, the joint is compacted by centering the roller drum over the joint and compacting the adjacent lane edges simultaneously as illustrated in Fig. 7.6.1. More passes may be needed at the joint

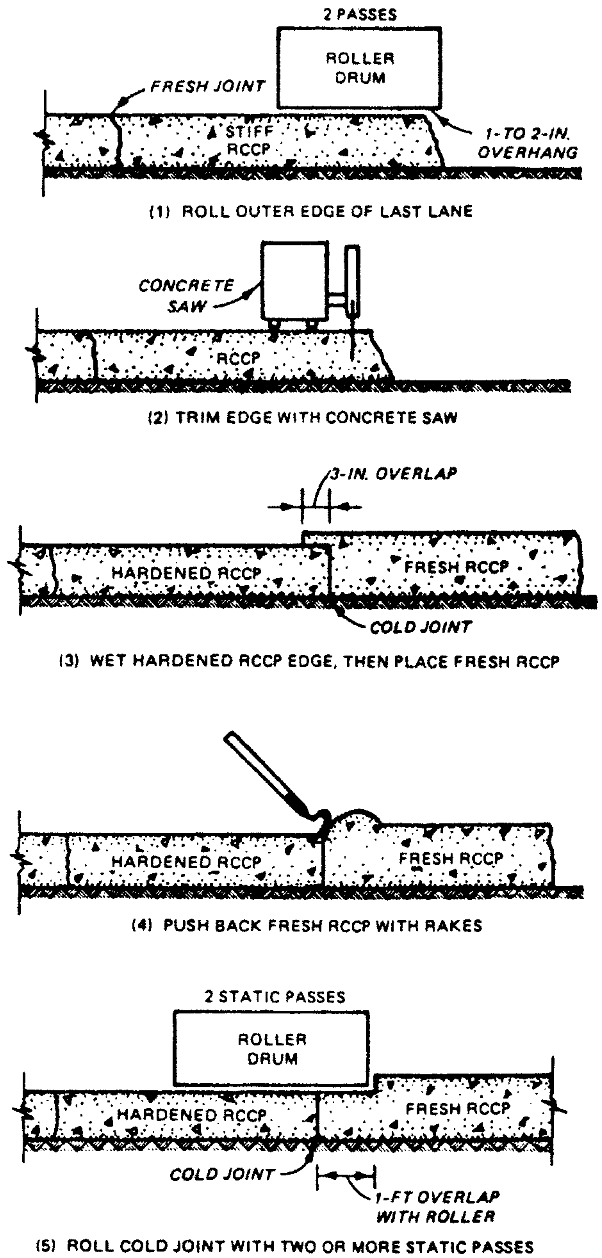


Fig. 7.6.2—Roller pattern for cold construction[16]

than the interior portion of the lane to obtain the specified density and adequate smoothness across the joint. Construction joints (often referred to as "cold" joints in RCC pavements) are formed between adjacent lanes when the concrete in the older lane has hardened to the extent that it cannot be compacted with the fresher lane. This usually occurs after the concrete in the older lane has been in place, without being compacted, for over an hour (more or less depending on environmental conditions). Construction joints are usually constructed by trimming away the outer uncompacted edge of the paving lane with a concrete saw, and paving against the resulting clean vertical edge as illustrated in Fig. 7.6.2.

Transverse construction joints are usually formed by trimming away the rounded end ramps with a concrete saw, and paving the successive lanes against the remaining vertical edge. Fresh overlapping material which is left on top of the older hardened lane at construction joints very frequently results in undesirable raveling and spalling at the construction joint at later ages. The overlapping material is usually removed before the joint is compacted.

Sawed contraction joints (used to control cracking) were typically not used in earlier RCC pavements, with the pavements being allowed to crack naturally. This practice contributed to the economy of constructing RCC pavements. However, the resultant natural cracks may ravel. In general, it is not clear whether the cracks significantly affect the serviceability of the pavements, but the desire for a more aesthetically pleasing surface has led to the use of sawed contraction joints in few recent RCC pavements. These joints are usually sawed within 48 hours after compaction of the RCC, with the least raveling during the sawing operation occurring at the latter part of this interval.

The transverse joint spacings have typically ranged from 30 to 70 feet (9.1 to 21.3 m), depending on natural crack patterns noticed in RCC pavements of similar geometry or in test sections. The depth of the sawcuts has ranged from $^1/_4$ to $^1/_3$ the pavement depth. Longitudinal contraction joints are typically not sawed, since the width of the longitudinal pass is limited by paver screed width, and has usually been sufficient to prevent avoid random longitudinal cracking. Naturally occurring cracks are usually not sealed, again in the interest of economy; however, sawed joints usually are sealed. Isolation joints have been used in RCC pavements to isolate fixed structures occurring within or along the pavement boundaries, such as building foundation slabs, gutters, and manholes. The isolation joint material is usually tacked to the cold joint face, gutter, or building before the adjacent lane is placed.

7.7—Curing and protection

Because RCC has a relatively low water content, moist curing has been used for most projects. Moist curing benefits the pavement by allowing the concrete to develop the design strength and to help prevent scaling and raveling of the hardened surface. RCC is typically moist cured for a minimum of seven days. A water truck equipped with a spray bar is commonly used to keep the surface moist on the first day, after which an irrigation sprinkler system, wetted burlap, or continued use of the water truck is used to keep the surface moist for the remainder of the curing period. Depending on environmental conditions, water spray trucks have sometimes been unable to provide water at a fast enough rate to avoid some surface drying.

A membrane-forming compound was used to cure an earlier RCC pavement, but this resulted in wide-spread scaling and raveling of the hardened pavement surface. An asphalt emulsion has been used in Canada and Europe with some success in curing RCC, but is often then covered with an asphalt concrete overlay. All vehicular traffic except for water spray trucks is usually kept from the pavement surface for a minimum of 14 days. A common practice in Europe is to allow the opening of an RCC pavement after 24 hrs, usually after the application of an asphalt concrete or chip seal wearing course to protect the surface from traffic abrasion. This practice takes advantage of the stability of the new RCC pavement, but the effects of early loading on the long-term durability and fatigue characteristics of the concrete are unknown.

RCC pavements have been placed under misty conditions with very little effect on the final surface texture. However, a steady rain during compaction can result in a high water/cement ratio slurry or paste forming on the surface, or the erosion of surface fines from the fresh surface leaving an exposed-aggregate condition. Protective practices similar to those for conventional concrete have been suggested for placing RCC when the ambient temperature is hot (85 F or greater) or cold [40 F (4.4 C) or less]. Particular attention is given to keeping the surface moist at all times in hot, dry, or windy weather.

CHAPTER 8—INSPECTION AND TESTING

8.1—General

Inspection and testing procedure for RCC pavements are similar to those for conventional concrete pavements, with a few exceptions. To ensure that a quality pavement is constructed, inspection and testing are typically the joint responsibility of the contractor and the owner/engineer. The extent of the inspection and testing will depend on the nature and the size of the project and will be specified in the contract documents. Generally, a minimum of two inspectors is required to ensure that a quality RCC pavement is being constructed; one inspector should be stationed at the mixing plant and one at the job site.[17]

8.2—Preconstruction inspection and testing

Preconstruction inspection and testing typically include quality testing of materials, inspection of mixing plant, plant calibration, inspection of equipment, and the construction, inspection and testing of a test section.

8.2.1 *Materials testing*—Sampling and testing of materials for RCC paving are typically the same as for conventional concrete. Prior to construction, materials are sampled and tested in accordance with specified standards and are accepted or rejected in accordance with contract specifications. Materials to be tested include aggregates, cementitious materials, water, and admixtures.

As with conventional concrete materials, materials for RCC paving should be transported, handled and stored in strict compliance with contract specifications. Because of the great importance of aggregate segregation, special attention should be given to handling and storage of aggregates to avoid breakage, segregation and contamination.

8.2.2 *Mixture proportioning*—Following materials testing, mixture proportioning studies are conducted, as described in Section 4, to assure that design requirements for strength, durability and other properties can be met.

8.2.3 *Mixing plant*—Prior to beginning paving operations, the mixing plant is thoroughly inspected for compliance with contract specifications. Two items of particular importance to the construction of RCC pavements are plant capacity and mixer type. A mixing plant is selected to provide the minimum capacity needed to feed adequately mixed RCC to the paver without delays and starting and thus minimize cold joints. The mixer type is selected to assure that the stated plant capacity can be attained while ensuring adequate mixing of the RCC materials. The mixing plant is typically a stationary twin-pugmill mixer. Tilt drum mixers and truck mounted mobile mixing plants with a screw auger mixing chamber have produced satisfactory RCC for smaller jobs. Plant capacities of 200 to 500 tons/hr have typically been used on medium to large size projects.

8.2.4 *Equipment*—It is essential that all the equipment meet the requirements of the contract specifications an be maintained in satisfactory working condition. Equipment typically used for RCC pavement construction include RCC pavers, rear dump trucks, vibratory steel-wheeled rollers, rubber-tired rollers, and finish steel-wheeled rollers.

8.2.5 *Test section*—A significant deviation from conventional concrete pavement is the requirement for a test section prior to construction. The purpose of the test section is to allow the contractor to develop and demonstrate the proposed techniques of mixing, hauling, placing, compacting, finishing (smoothness and surface texture), curing, and the preparation of the construction joints. Additionally, the test section provides the contractor the opportunity to demonstrate laydown method and rate, rolling pattern, rolling method for both fresh and cold construction joints, start-up and finishing procedures, curing, testing methods and plant operations.

The test section should be constructed on an approved compacted base course using the same equipment, materials and construction techniques to be used on subsequent work. Sampling and testing of the RCC pavement test section are to be completed prior to the start of paving operation. The test section generally includes constructing both longitudinal and transverse cold joints and a fresh joint. This usually requires three 12 to 14 ft (3.7 to 4.3 m) wide lanes, each 150 ft (45.7 m) long with $1^1/_2$ lanes placed the first day and the rest placed the next day. Special attention is given to construction of fresh and cold joints, rolling pattern of rollers, correlation between laboratory and nuclear gauge densities, and correlation between density and number of passes of rollers and achieving full density through full depth of each lift. Upon completion of the test section, the surface is checked for smoothness, tears, and surface smoothness.

8.3—Inspection and testing during construction

During construction, the mixing plant is routinely checked and calibrated as necessary to ensure that it is producing an RCC mixture within the tolerances specified in the contract specification.

Gradation tests, aggregate moisture tests, moisture-density tests, field density and moisture tests, surface smoothness determinations, fabrication and testing beams or cylinders, and plant calibration are performed at the frequencies specified in the contract specifications. Generally, gradation tests have been run 3 times a day, or every 500 yd^3 (382 m^3). Aggregate moisture tests have been run daily, or as often as required. Moisture content of RCC has been checked, as required, using a microwave oven. Density tests have been performed every 100 ft (30 m) by nuclear density gages. Nuclear density gage readings have been checked against a specified density, such as a standardized block of RCC pavement.[18]

Prior to paving operations, the base course is checked for grade and density. The base course is generally moistened prior to paving. During paving operations, the paver is continuously monitored to ensure that it is adjusted and its speed is regulated so that the RCC pavement surface is smooth and continuous without tears, that the RCC pavement is the required depth, and that it conforms to the required grade and smoothness after compaction. Surface smoothness is generally checked using a straightedge or profilometer. Acceptable tolerances have generally ranged from $^1/_4$ to $^3/_8$ in. (6.4 to 9.5 mm) deviation from a 10 or 12-ft (3 or 3.7 m) straightedge; however, the end use of the pavement is an important factor in setting these requirements. Placement procedures are checked to ensure that all RCC mixture is placed and compacted within the time limit specified, generally 45 to 60 min, and in a pattern whereby cure water from previous placements does not affect the placement and compaction of fresh RCC.

Compaction of the RCC is closely monitored to ensure compaction begins and is completed within the specified time limits, and that compaction is accomplished using the rolling pattern and procedure developed during construction of the test section. After initial vibratory rolling, preliminary inspection and testing for density, smoothness and surface texture are completed and deficiencies are noted and corrected before final rolling is continued. After deficiencies, if any, are corrected, rolling is continued until the required density is obtained. Density testing is performed according to specified standards and at the specified frequencies. Measurement of density using the sand cone method has not been successful due to the difficulty of performing the test around construction operations and to possible damage of the hole by compacting equipment. Nuclear density readings have been performed with backscatter, single-probe and double-probe gages. Experience with backscatter and single-probe gages indicates that they may not accurately indicate the density in the lower portion of RCC pavements. Double-probe gages have been used to measure density changes with depth in the pavement.

Construction of joints is routinely inspected to ensure that all completed joints have the same texture, density and smoothness as the other sections of pavement. Particular attention is given to ensure that all joints, cold or fresh, are prepared and compacted as specified in the contract documents.

After rolling is completed in each area, the surface of the RCC pavement is inspected to verify that it is kept continuously wet for the minimum time specified. After initial curing, the pavement is inspected to assure that it is cured for the duration and by the methods specified.

8.4—Post construction inspection and testing

For projects requiring sawed joints, the initial sawcut operations are monitored to ensure that sawing of joints is being performed to the required alignment and without chipping, spalling, tearing and cracking of the concrete. After final curing has been completed, the joint widening operation is inspected to ensure that the joint reservoir is sawed to the depth and width required and that the sawed joint faces are free from undercutting and washing caused by early sawing. Joints can be cleaned and sealed.

Following construction, coring of the RCC pavement is often used to check thickness. Some projects have required sawing of beams or coring of the pavement to determine flexural strength and compressive strength, respectively. Coring and sawing are inspected to insure that they are accomplished in the manner and quantity specified and that areas are refilled. The date and location are recorded for each sample taken. Test ages are as specified and generally include one or more of the following ages: 7, 14, 28, and 90 days.

CHAPTER 9—PERFORMANCE

9.1—General

Performance of pavements may be described in qualitative or quantitative terms as the ability to perform its intended function. Qualitative descriptions, being subjective, are easier to apply and may be the truest indicator of performance; that is if the owner or user of a pavement describes it as “performing well,” then for all practical purposes, it is. However, qualitative descriptions are by nature not directly translatable from one user to another, or one pavement to another, and therefore their use as an engineering tool is very limited. Quantitative descriptions, based on some type of objective criteria, are perhaps more complex but should allow some translation between users and different pavement types. This chapter will present quantitative descriptions of various aspects of RCC pavements, such as surface condition, skid resistance, surface smoothness, rideability, durability in freezing and thawing conditions, and load transfer.

9.2—Surface condition

The surface condition of RCC pavements has been quantitatively expressed in a research study conducted by the U.S. Army Corps of Engineers[9] to evaluate the performance of RCC pavements in freezing and thawing conditions. Eleven RCC pavement sites, located in the United States, West Germany, Norway, and Sweden, were visually surveyed using a procedure similar to the pavement condition index (PCI) rating system developed by the Corps of Engineers.[19] The RCC condition survey procedure identified five distress categories: 1) fresh and cold joints, sawed joints, and cracks; 2) weathering and raveling; 3) joint sealant damage; 4) patching and utility cuts;* and 5) shattered area. Three severity levels — low, medium, and high — were identified for each distress category, and a “deduct value” assigned to each combination of category, severity level, and “density,” or the extent of the distress and severity within a survey area. The PCI is then calculated by subtracting the deduct values from

* It should be noted that utility cuts are not a measure of inherent performance of RCC or any other material — their presence is happenstance, as opposed to patching required due to material distress, load-induced local failures, etc.

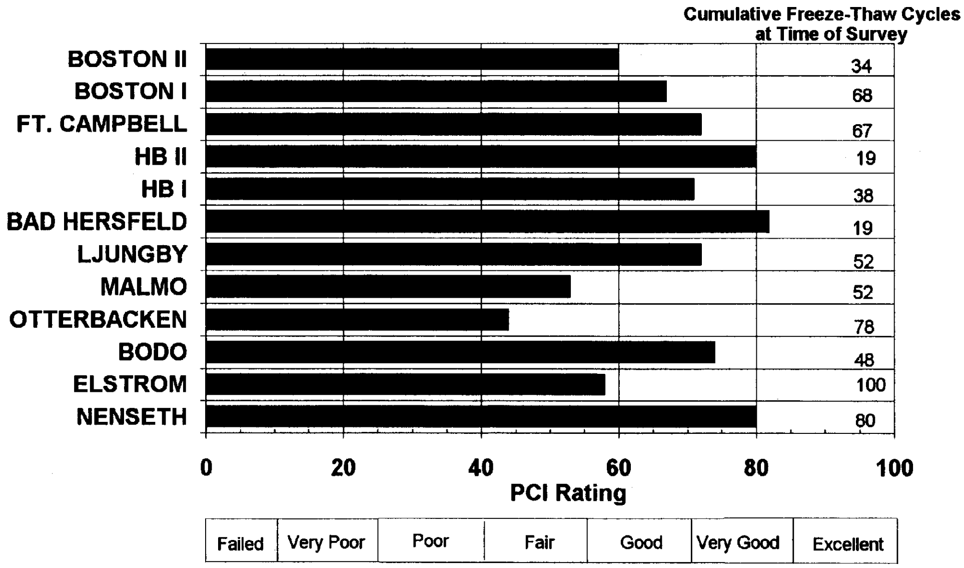


Fig. 9.2.1—PCI rating and estimated cumulative freeze-thaw cycles at time of survey

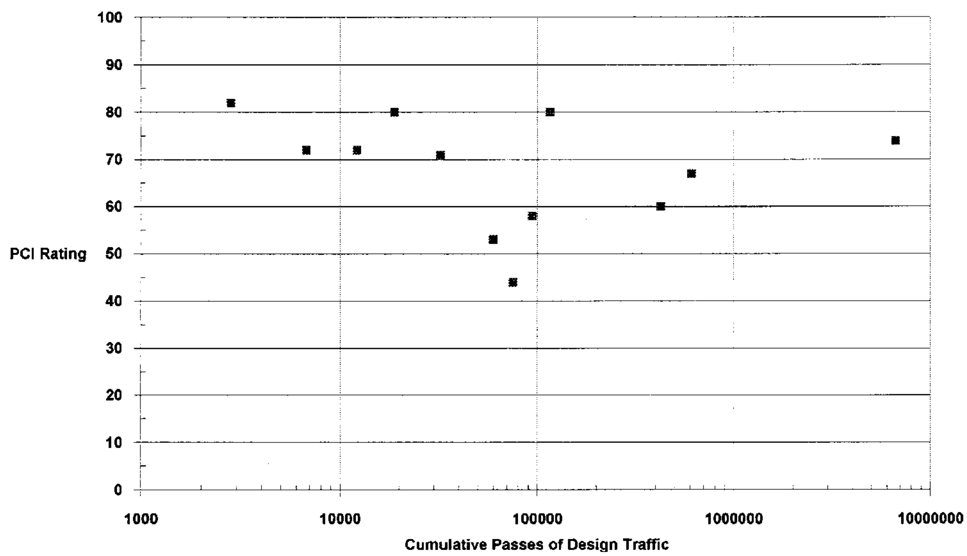


Fig. 9.2.2—Variation in PCI with cumulative passes of traffic

100, yielding a number between 0 and 100, with 0 being failed and 100 being excellent.

The results of the survey are presented in Fig. 9.2.1. The ratings ranged from 44 (fair) to 82 (very good). The causes of the distresses were not specifically identified; however, since the objective of the research was to investigate the effects of freezing and thawing on the surface of nonair-entrained RCC pavements, the number of cumulative ambient freezing and thawing cycles experienced by the pavement at the time of the survey was compared to the PCI. This illustrated a possible trend of deteriorating surface condition with an increasing number of cumulative freezing and thawing cycles. However, the PCI would be expected to decrease with time and with increased repetitions of traffic, as illustrated in Fig. 9.2.2, even without freezing conditions. In this study, the effect of freezing and thawing *by itself* on the surface condition could not be quantified.

9.3—Skid resistance

The skid resistance of RCC pavements was not of great concern to the earlier users, chiefly because the primary applications of the pavement were for heavy-duty industrial, low-speed vehicles, such as log loaders and container handlers. However, as the use of RCC pavement for high-speed vehicular or aircraft traffic was contemplated, the necessity of determining the skid properties of an RCC pavement surface became apparent.

Skid resistance tests have been conducted on RCC pavements in several locations in the United States and Australia. Greene[20] reported that skid resistance tests were conducted in accordance with ASTM Standard Test Method E-670-87 on Tuscany Way, a 2500 ft-long (762 m) RCC access road in Austin, Texas. Due to the curvature of the road, only 40 mph tests were conducted with the "Mu Meter" (a rolling-wheel friction measurement devise); however, both wet and dry skid resistance values were obtained. The test results (MU values) of 0.72 average (0.63 to 0.77 range) in the dry condition, and 0.40 (0.31 to 0.47 range) and 0.34 (0.25 to 0.53 range) in the wet condition, indicated that the friction characteristics of the RCC road were poor to marginal, based on Air Force skid resistance criteria (AFWL-TR-73-165[21] and AFCEC-TR-75-3[22]). Greene attributed the low friction characteristics of the 9 month-old RCC pavement to the macrotexture and microtexture of the surface. The macrotexture is created in conventional concrete pavements by brooming, burlap drag, wire comb, or saw-cut grooving to remove water from under the tire during braking. The RCC pavement did have discontinuous, superficial surface tears created by the paver screed and/or rolling process during construction which were deep enough to remove water from under the tire. However, the discontinuous nature of the tears did not allow the water to escape from under the tire during braking, resulting in some hydroplaning. The microtexture, usually provided by the fine, gritty texture of the surface between the tears did not assist in providing good skid resistance, as it was virtually nonexistent on the RCC pavement surface. The macrotexture and microtexture of any particular RCC pavement are most likely a function of the mixture proportions, exertion of a shearing force by the paver screed on the pavement surface, and the action of the steel-wheel and rubber-tire roller on the pavement surface; they are therefore likely to be different from one RCC pavement to another.

Jameson et al.[23] reported that skid resistance tests were conducted on a test section installed in Wells Road, Seaford, Australia, using the VIC ROADS' SCRIM machine (an Australian friction testing devise). The tests were conducted at average speeds of 32 to 50 mph (51 to 80 km/h), resulting in sideways force coefficient values ranging from 45 to 62 for the lower speed, and 38 to 51 for the higher speed, which are substantially lower than those for new asphalt or chip seal surfaces.

Brett[24] reported that skid resistance tests conducted on Tea Tree Road in Tasmania, Australia, using the British Portable Tester (Method T105) indicated results ranging from 42 to 76 percent, with a mean of 58.5 percent. These values were considered by the user to be satisfactory for the road location and usage. All of these results are considered to be poor to marginal base of U.S. Air Force skid criteria.

9.4—Surface smoothness

Surface smoothness refers to the deviation of the RCC pavement surface from a plane; the "smoother" a pavement, the less deviation. The smoothness of RCC pavement surfaces (or lack thereof) has been one of the primary factors limiting the use of RCC to applications where relatively low-speed traffic is the primary user of the pavement, such as log sorting yards, port facilities, intermodal shipping yards, and tank parking areas.[25] The surface smoothness of RCC pavements is greatly influenced by the construction procedure itself, primarily the variation in the degree of compaction and smoothness achieved with the paver screed, and the operation of the vibratory roller during final compaction. The advent, around 1985, of heavy-duty paver screeds equipped with tamper bars, used to place RCC resulted in better smoothness tolerances being obtained, due to the greater and more uniform densities achieved directly behind the paver.[26] Cortez et al.[27] has suggested that not using the steel-wheel roller to compact the RCC pavement (thereby relying solely upon the paver screed for compaction) might result in a smoothness suitable for high-speed traffic; however, the probable effect of reduced density in the RCC layer could result in an unacceptably low strength or durability. This may or may not be compensated for with an increased cement factor, air-entraining agent, etc. Munn[28] has reported that the RCC pavement at the Saturn automobile plant near Spring Hill, Tennessee, was rolled with a steel-wheel roller in the static (nonvibratory) mode only, presumably to improve the smoothness of the surface.

The degree of smoothness typically achieved for RCC pavements was recognized by the U. S. Army Corps of Engineers in preparation of their guide specifications for construction. The current version[29] allows a $^3/_8$ in. (9.5 mm) deviation from a 12 ft.-long (3.7 m) straightedge for tank hardstands, open storage areas, and parking areas. By comparison, the Corps' guide specification for conventional concrete pavements[30] allows a $^1/_4$ in. (6 mm) deviation [using a 10-ft (3 m) straightedge] for the same applications, and only a $^1/_8$ in. (3 mm) deviation from a 12-ft (3.7 m) straightedge in the longitudinal direction of runways and taxiways. Pittman[31] reported that the Corps' $^3/_8$ in. (9.5 mm) in 12 ft (3.7 m) specification criteria was met during the construction of an RCC tank hardstand at Harvey Barracks in Kitzingen, Germany (formerly West Germany), with an average of $^3/_{16}$, $^1/_4$, and $^5/_{16}$ in. (5, 6, and 7 mm) deviation for tests conducted in the longitudinal and transverse directions, and transverse across the longitudinal joints, respectively. Hess[32] reported that a $^1/_4$ in. (6 mm) in 12 ft (3.7 m) specification criteria was met in 82 percent of longitudinal and 76 percent of transverse surface smoothness measurements of an RCC ammunition storage pad at Tooele Army Depot, Utah. Keifer[26] reported that an average $^3/_{16}$ in. (5 mm) deviation was achieved when using a 10-ft (3 m) straightedge to measure transverse smoothness during construction of an RCC test road at Ft. Lewis, Washington. A tactical equipment shop pavement constructed at Ft. Lewis achieved average smoothness results of $^1/_4$ in. (6 mm) in the transverse direction, and $^3/_{16}$ in. (5 mm) in the longitudinal direction, using a 10-ft (3 m) straightedge.*

9.5—Roughness

Pavement roughness may be referred to as the ride sensation experienced by a vehicle passenger as the vehicle passes over a pavement surface. It is a function of road profile, vehicle characteristics, and speed of the vehicle.[33] Studies have shown that roughness is most influenced by the longitudinal profile of the pavement surface in the wheel path, particularly the amplitude and frequency of longitudinal surface profile wavelengths.[34] The surface smoothness measurements

* Unpublished data, Quality Control Results of RCC Pavement at Ft. Lewis, Washington.

Table 9.5—Summary of roughness measurements from Australia

		Roughness measurements (counts/kilometer)			
Location	Measuring device	Mean	Range	Standard deviation	Coefficient of variation, percent
Duncan Road, Tasmania	NAASRA roughness meter	143	77-253	37	26
Tea Tree Road, Tasmania	NAASRA roughness meter	119	86-153	19	16
Wells Road, Victoria Lane 1	ARRB	81	54-112	20	24
Lane 2	Profilometer	87	61-110	18	21
Lane 1	Profile beam	87	74-97	7	8
Lane 2	Profile beam	87	74-109	10	12

discussed previously are simply indications of the maximum amplitude within a limited range of wavelengths. Therefore, measurements of this type are of limited use in determinations of roughness. Roughness measurements may be made with several types of devices, including profilometers, road meters, and roughometers. The units depend upon the type of device used.

Roughness measurements have been reported by Brett[24] and Jameson et al.[23] on several RCC roads placed in the states of Tasmania and Victoria, Australia, respectively (Table 9.5). The roughness measurements were made using several different devices, but the results were all correlated to or reported in terms of counts/kilometer (counts/kilometer refers to 15.2 mm relative movements between the rear axle and body of a modified meter, measured over a 1-km distance). The Department of Main Roads of New South Wales recommends that the roughness measurements of the class "Main Roads" not exceed 70 counts/kilometer for new construction, and suggests rehabilitation for readings above 150 counts/kilometer. As can be seen from the results, none of the pavements met the roughness requirements for new construction, but were also less than that recommended for rehabilitations. Brett[24] suggested that the roughness results would improve with further experience, and Jameson et al.[23] report roughness measurements in one short stretch of the Wells Road of 54 to 58 counts/kilometer, suggesting the potential of RCC as a high-speed wearing surface

9.6—Freeze-thaw durability

The durability of RCC pavements in freezing and thawing conditions has been of some concern to engineers since its first use in Canada in 1976.[25] Although the RCC pavements in British Columbia were reported to have no visual signs of freeze-thaw deterioration, the primary concern was derived from the fact that most RCC pavement placed in North America has been nonair-entrained.[25] This concern led to the development of several research studies at the U. S. Army Corps of Engineers Waterways Experiment Station (WES) to determine the frost resistance of cores taken from existing pavements, test sections, and laboratory fabricated specimens.[35,9] The results of these studies are presented in Table 9.6. The references "1" and "2" in Table 9.6 pertain to the WES research studies conducted to evaluate the frost resistance of RCC pavements[35] and the frost resistance of air-entrained and nonair-entrained RCC pavement mixtures,[9] respectively.

The results in Table 9.6 indicate that air-entraining admixtures (AEA's) had not been used in most of the samples taken from in-place pavements; most of the samples containing AEA's were laboratory fabricated samples, or samples taken from test sections. For most of the samples, the air-void content was determined from microscopical examination of hardened cores according to ASTM C 457, Modified Point-Count Method.[36] Voids with a chord length (C.L.) less than 0.04 in. (1 mm) were considered entrained air voids (even if AEA's were not used in the RCC); these entrained air voids and the total air void content are expressed in the table. Although most of the voids were irregularly shaped rather than spherical, they were counted in the air void content determinations. Rapid freezing and thawing tests (ASTM C 666, Procedure A[37]) were conducted on most of the samples, and the results reported as the percentage of the dynamic frequency modulus (DFE) remaining at the end of the test (relative DFE). The spacing factor was also determined from the microscopical void examination.

The determination of frost susceptibility presented in Table 9.6 was based upon the average relative DFE value and the spacing factor for each sample. According to Neville,[38] a relative DFE of 60 or greater means that the concrete is probably satisfactory with respect to frost resistance; a relative DFE of 40 or less indicates probable unsatisfactory frost resistance; and a relative DFE between 40 and 60 indicates doubtful performance. A spacing factor of less than 0.008 in. (0.2 mm) is typically associated with concrete having good resistance. These dual criteria were applied to all the samples, and the frost susceptibility question was answered "No" if the relative DFE was 60 or greater and the spacing factor was less than 0.008 in. (0.2 mm), "Yes" if the relative DFE was 40 or less and the spacing factor was 0.008 (0.2 mm) or greater, and "Mixed" for all the other combinations of relative DFE and spacing factor. The answers in parentheses indicate determinations based upon one criterion only.

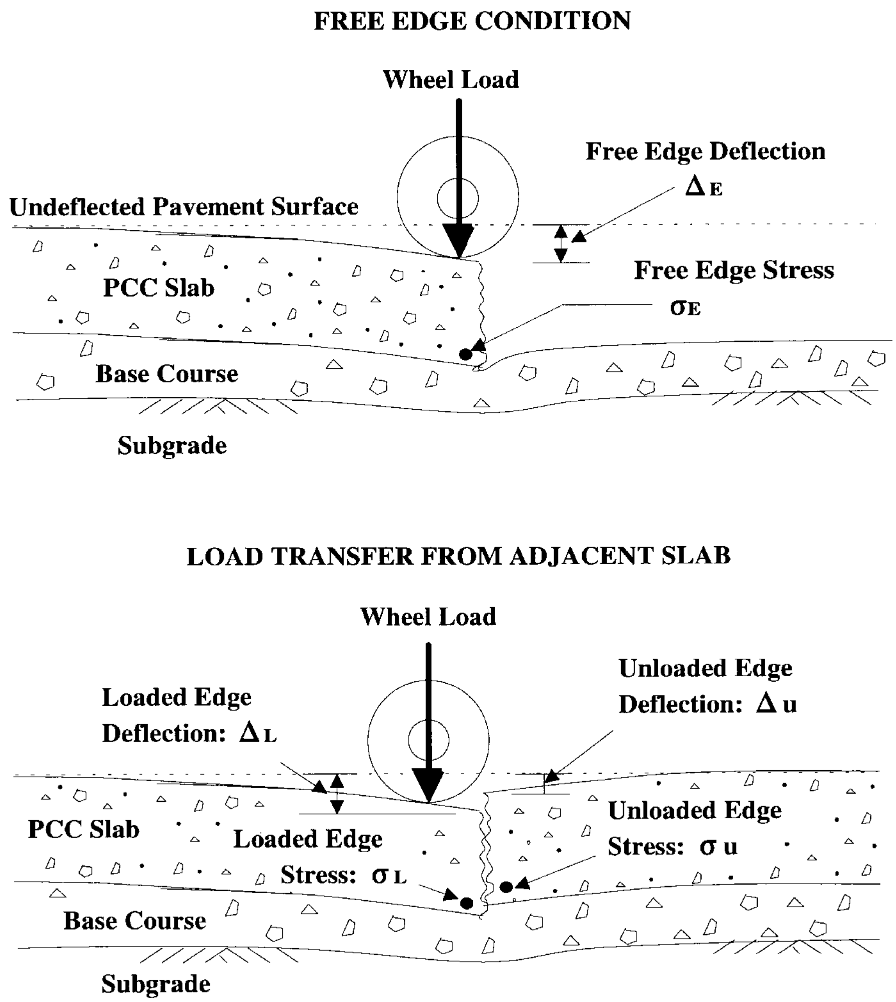
Generally, the results of these two studies showed that those mixtures not containing AEA's were susceptible to frost damage, and those containing AEA's were not susceptible to frost damage. There were exceptions to both cases. Ragan[35] postulated that the non-AEA mixtures having air-void systems with low spacing factors and resulting good frost resistance might

Table 9.6—Results of WES freeze-thaw studies

Reference	Location	Specimen No.	Compressive strength psi	Compressive strength kPa	AEA used?	Air content, percent C.L. < 0.04 in.	Air content, percent Total	Average DFE	Spacing factor in.	Spacing factor mm	Frost susceptible?
1	Ft. Stewart, GA	2T1	5220	35,991	No	1.9	5.3	8	0.020	0.508	Yes
1	Ft. Hood, TX	5	4780	32,957	No	—	—	10	0.012	0.305	Yes
1	Ft. Lewis, WA	5A	5790	39,921	No	2.5	5.1	44	0.012	0.305	Mixed
		9B	5790	39,921	No	1.9	2.1	71	0.005	0.127	No
		10B	5790	39,921	No	9.6	10.4	20	0.011	0.279	Yes
		17A	8920	61,501	No	1.6	4.7	59	0.015	0.381	Mixed
		17B	8920	61,501	No	1.8	4.0	44	0.018	0.457	Mixed
1	USA CRREL	1B	2930	20,202	No	2.3	6.1	89	0.008	0.203	No
		3B	6500	44,816	No	3.6	8.6	75	0.010	0.254	Mixed
		2T	4370	30,130	Yes	2.9	5.2	81	0.010	0.254	Mixed
1	Port of Tacoma	2A-T	5220	35,991	No	5.5	7.1	84	0.010	0.254	Mixed
		1DT			No	3.0	4.5	75	0.013	0.330	Mixed
		2HB			No	6.1	10.6	82	0.010	0.254	No
1	Caycuse	2A			No			3	0.026	0.660	Yes
1	WES fabricated beams	1 (Mix A)	6250	43,092	No	1.1	3.1	10	0.030	0.762	Yes
		1 (Mix B)	5740	39,576	Yes	2.5	4.6	48	0.013	0.330	Mixed
1	NPDL fabricated beams	2	6900	47,574	No	0.6	1.7	10	0.018	0.457	Yes
		8			No	0.9	1.7	—	0.019	0.483	(Yes)
		9				1.1	3.9	11	0.022	0.559	Yes
2	WES fabricated beams, FT study	AHLSCS	4485	30,923	Yes	9.9	11.1	90	0.003	0.076	No
		ALLSCS	5145	35,474	Yes	6.4	7.2	94	0.003	0.076	No
		ALLSFS	4915	33,888	Yes	6.1	6.9	98	0.004	0.102	No
		ALNSCS	5420	37,370	Yes	5.3	5.5	98	0.004	0.102	No
		ALNSFS	4840	33,371	Yes	9.6	10.7	98	0.003	0.076	No
		AULSFS	5450	37,576	Yes	5.6	6.8	87	0.006	0.152	No
		BHLSFS	4745	32,716	Yes	7.1	8.4	93	0.003	0.076	No
		BLNSCS	5880	40,541	Yes	3.2	3.8	95	0.006	0.152	No
		BLNSFS	5335	36,784	Yes	3.5	3.6	92	0.005	0.127	No
		BUNSCS	6020	41,506	Yes	3.3	7.8	54	0.006	0.152	Mixed
		BUNSFS	5395	37,197	Yes	2.9	3.1	77	0.005	0.127	No
		CZLSCS	7410	51,090	No	1.6	3.6	4	0.016	0.406	Yes
		CZLSFS	6545	45,126	No	2.9	4.3	13	0.013	0.330	Yes
		CZNSCS	7135	49,194	No	1.6	2.8	15	0.015	0.381	Yes
		CZNSFS	6645	45,816	No	5.8	7.1	85	0.008	0.203	No
		DHNSCS	5525	38,094	Yes	1.9	2.5	88	0.005	0.127	No
		DHNSFS	4900	33,784	Yes	3.6	4.4	92	0.004	0.102	No
		DLLSCS	5950	41,024	Yes	2.7	4.9	91	0.006	0.152	No
		DLLSFS	5355	36,921	Yes	—	—	92	0.007	0.178	No
		DLNSCS	5750	39,645	Yes	4.5	5.3	92	0.008	0.203	No
		DLNSFS	5310	36,611	Yes	4.9	5.7	90	0.006	0.152	No
2	WES test slab sawed beams	1	4995	34,439	No	4.3	5.3	39	0.009	0.229	Mixed
		2	3450	23,787	Yes	5.4	5.8	76	0.005	0.127	No
		3	3482	24,008	Yes	6.6	7.6	52	0.004	0.102	Mixed
		4	2925	20,167	Yes	4.1	5.6	65	0.004	0.102	No
2	Ft. Drum cores	Control	4120	28,406	No	0.9	7.8	—	0.013	0.330	(Yes)
		Mix 1, Lo	4030	27,786	Yes	1.7	8.4	—	0.009	0.229	(Yes)
		Mix 2, Hi	4090	28,200	Yes	3.0	9.0	—	0.006	0.152	(No)
2	Field core samples	Nenseth	6305	43,471	Yes	—	3.1	43	0.011	0.279	Mixed
		Elstrom	9830	67,775	Yes	—	5.9	—	0.008	0.203	(No)
		Bodo	8857	61,067	No	—	5.2	87	0.007	0.178	No
		Otterbacken	6258	43,147	No	—	7.7	7	0.010	0.254	Yes
		Malmo	6910	47,643	No	—	5.8	57	0.007	0.178	Mixed
		Ljungby	9260	63,845	No	—	3.8	93	0.008	0.203	No
		Ft. Campbell	3980	27,441	No	—	3.6	10	0.012	0.305	Yes
		Boston	4987	34,384	No	—	3.0	25	0.011	0.279	Yes

Note: 145 psi = 1 MPa; 1 in. = 25.4 mm.

be related to pugmill mixing, the cohesiveness of the mixture, and the method of compaction. An important result of the latter WES study[9] was that RCC mixtures could be successfully air-entrained in the laboratory for a variety of AEA types, dosage rates, and aggregate gradings. Air-entrained RCC mixtures were also placed and compacted in small test sections at WES, and a small section of air-entrained RCC was placed and compacted during the construction of a tank hardstand at Ft. Drum, New York; thus, the feasibility of obtaining air-entrained RCC mixtures in field applications was demonstrated.



$$\text{Load Transfer Efficiency (\%)} = \frac{\Delta_u}{\Delta_L} \times 100$$

$$\text{Load Transfer (\%)} = \left(1 - \frac{\sigma_L}{\sigma_E}\right) \times 100$$

Fig. 9.7.1—Mechanism of load transfer and efficiency due to aggregate interlock

9.7—Load transfer

Load transfers refers to the amount of load (in percent) which is carried by an unloaded concrete slab due to a load applied to an adjacent slab. Stresses due to the applied load are transferred to the unloaded slab through a shearing action at the vertical interface of the joint between the slabs (Fig. 9.7.1). Load transfer is important to the performance of concrete pavements because it reduces the amount of stress experienced in a concrete slab at the joint due to an applied load. Load transfer may even be an inherent part of the thickness design procedure. The U. S. Army Corps of Engineers[39] and the Federal Aviation Administration[40] rigid pavement design procedures assume 25 percent load transfer at most concrete pavement joint types.

Load transfer is typically achieved in conventional concrete pavements through aggregate interlock, dowels, tiebars, or keyways formed into the sides of the concrete slabs. Since no dowels, tiebars, or keyways are typically used in RCC pavements, load transfer across joints or cracks depends upon the degree of aggregate interlock obtained at the joint. Load transfer due to aggregate interlock is largely dependent upon the joint opening or crack width;[41] the narrower the crack width, the greater the degree of load transfer achieved. Similarly, the crack width is largely dependent upon the crack spacing; the larger the crack spacing, the larger the average crack width, and subsequently the lower the load transfer typically achieved. For a given crack spacing, the crack width will also vary as the concrete expands and contracts with changes in the average slab temperature; hence, the load transfer obtained at an RCC crack would be expected to vary between summer and winter seasons, and possibly between day and night conditions. Since RCC pavements are typically allowed to crack naturally, the crack spacing over a large area may vary considerably, and therefore, the degree of load transfer obtained at RCC pavement cracks may be expected to vary considerably. Crack spacings ranging between 40 to 70 (12 to 21.3 m) feet for one job are typical values reported.[26,42]

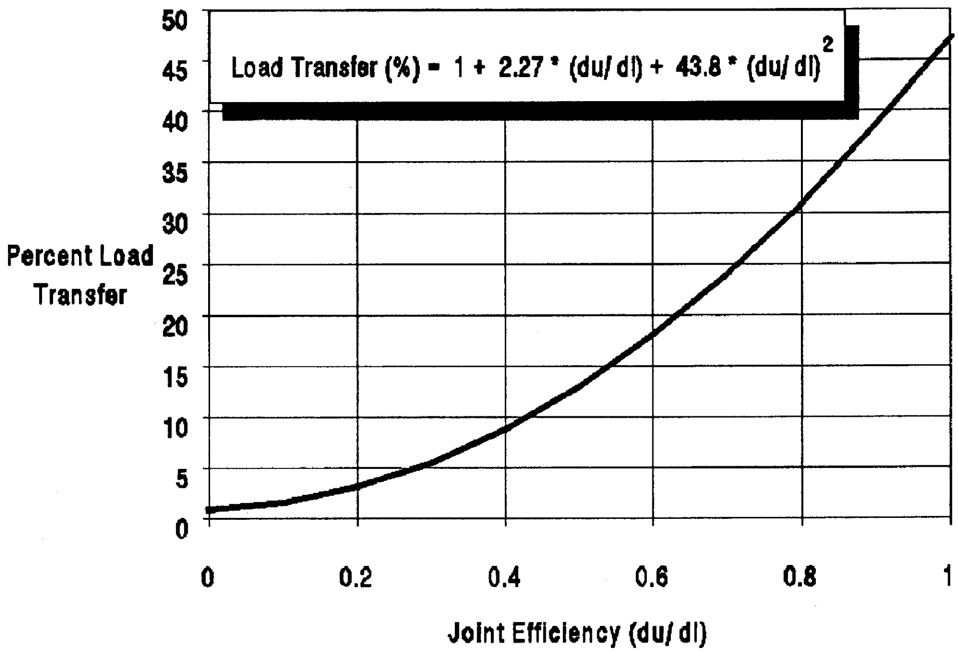


Fig. 9.7.2—Corps of Engineers relationship between joint efficiency and load transfer

Table 9.7—Results of Corps of Engineers load transfer tests on RCC pavements

Location	Type of joint	Number of tests	Load transfer, percent			Average crack width		Average crack spacing	
			Mean	Range	Coefficient of variation	in.	mm	ft	m
Ft. Hood, TX	Transverse crack	168	18.6	—	36	—	—	48.9	14.9
	Longitudinal cold joints	8	12.3	—	45.5	—	—	13.5	4.1
Austin, TX (Tuscany Way)	Transverse crack (Sept. 1991)	25	20.2	6.4 to 33.2	42.1	0.05	1.27	30.5	9.3
	Transverse crack (Jan. 1992)	25	15.9	6.1 to 33.0	48.4	0.06	1.52	30.5	9.3

Load transfer is difficult to measure directly because stresses (or strains) in slabs on grade are difficult to measure. However, load transfer can be estimated from deflection measurements of slabs on either side of a joint as one of the slabs is loaded. The ratio of the deflection of the unloaded slab to the deflection of the loaded slab, or the joint efficiency, has been related to the load transfer obtained for that loading condition by finite-element analysis (Fig. 9.7.2). While the joint efficiency may range from 0 to 100 percent, the load transfer may range from 0 to 50 percent, when one half of the load or stress is carried by the adjacent slab.

The U.S. Army Corps of Engineers has conducted joint efficiency tests at several RCC pavement sites around the United States. These joint efficiencies were used to calculate the load transfer at the joints; some of the results are presented in Table 9.7. The tests at Ft. Hood were conducted with the WES 16-kip vibrator, while the tests in Austin were conducted using a falling-weight deflectometer. The average load transfer values ranged from about 12 to 20 percent, with coefficient of variations ranging from 36 to 48 percent. The effect of summer versus winter conditions are also apparent; although the average temperature of the RCC pavement in Austin was only 11 F lower in the winter tests than in the summer tests (60 versus 71 F), the average load transfer decreased from 20 percent to 16 percent, for the exact same cracks. The average crack width increased from 0.05 in. to 0.06 in. (1.5 to 1.5 mm) from the summer tests to the winter tests, respectively. Fig. 9.7.3 shows the relationship between joint efficiency and average crack spacing for Ft. Drum, New York, for both the summer and winter conditions for the exact same joints; Fig. 9.7.4 shows the relationship between joint efficiency and crack width for the summer and winter condition.

CHAPTER 10—RESEARCH NEEDS

Even though considerable progress has been made in RCC pavements, it is evident that more work is needed in the development of many areas. These include:

a) Improved surface quality and smoothness of RCC pavements, particularly when high-speed traffic applications are considered

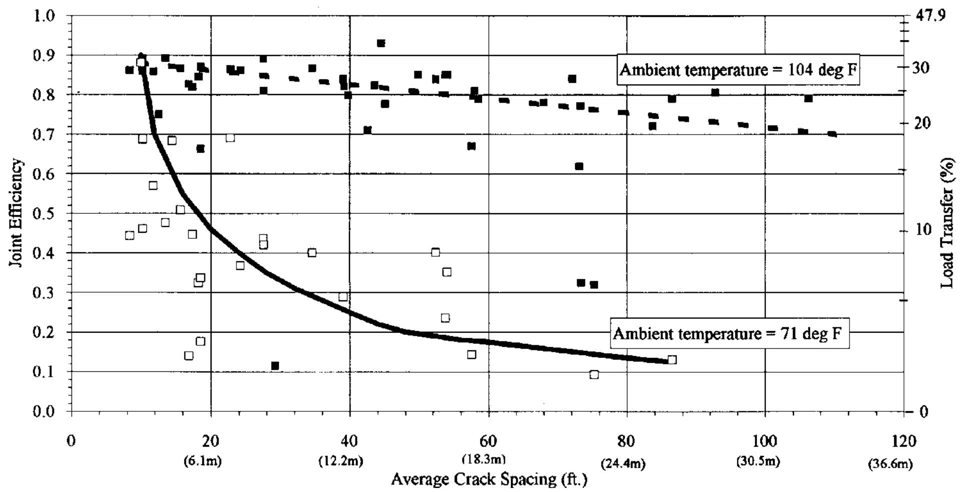


Fig. 9.7.3—Relationship between joint efficiency, load transfer, and average crack spacing, Ft. Drum, New York

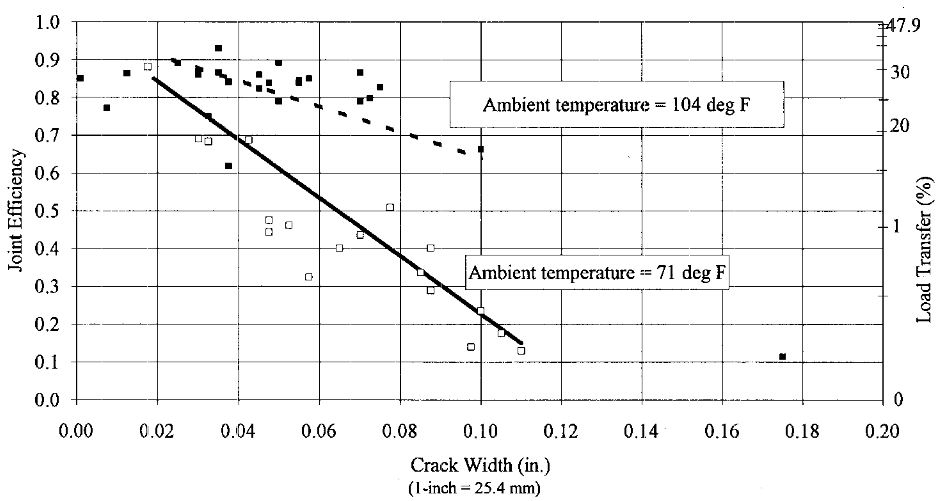


Fig. 9.7.4—Relationship between joint efficiency, load transfer, and crack width, Ft. Drum, New York

b) Defining the desirable degree of consolidation to be attained by the paver, and optimizing roller sequence and number of passes
c) Improved methods for construction and performance assessment of vertical joints and horizontal joints in multilayer pavements
d) Satisfactory field and laboratory methods to determine mix compatibility, optimum water content, density and strength
e) Standardized test procedures so that quality control can be achieved and independent investigators can reproduce test results and correlate their findings

Standards for mixture proportioning and sample fabrication are particularly needed. Current work in these areas by ASTM Subcommittee 09.45 - Roller Compacted Concrete, is addressing many of the above concerns.

Fundamental research is needed for the purpose of providing more data on physical properties so that design procedures can be established on a more rational basis. RCC paving involves both construction technology and a material, therefore research must address both material and construction aspects. Investigations should be directed towards the study of the following issues:

- Effect of mix constituents and grain size distribution
- Fatigue
- Strength gain with age
- Volume changes due to water migration and temperature differential
- Abrasion and skid resistance
- Durability. Effect of air-entrainment, fines and deicing salts on freeze-thaw resistance
- Effect of curing time and technique
- Mechanical properties variability as a function of continuous mixing as opposed to batching
- Addition of fibrous reinforcement
- Bond strength of multiple-lift construction
- Load transfer at cracks and joints
- Surface quality
- Smoothness

- Jointing
- Consolidation/compaction
- Quality control procedures and standard test methods for density and strength

CHAPTER 11—REFERENCES

11.1—Recommended references

The documents of the various standards producing organizations referred to in this document are listed below with their serial designations.

American Concrete Institute

207.5R	Roller Compacted Mass Concrete
211.3	Standard Practice for Selecting Proportions for No-Slump Concrete
225R	Guide to the Selection and use of Hydraulic Cements

ASTM

C 33	Specification for Concrete Aggregate
C 192	Test Method of Making and Curing Concrete Test Specimens in the Laboratory
C 457	Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete
C 666	Test Method for Resistance of Concrete to Rapid Freezing and Thawing
D 425	Maximum Index Density and unit Weight of Soil Using a Vibratory Table
D 1557	Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort 56,000 (ft-lb/ft^3) (2700 kN-m/m^3)
D 4253	Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table
D 4254	Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density
E 670	Test Method for Sede Force Friction on Paved Surfaces Using the Mu-Meter

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O Box 9094
Farmington Hills, Mich. 48333-9094

American Society for Testing and Materials
100 Barr Harbor Dr.
West Conshohocken, Pa. 19428

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SI Metric conversions

1 yd^2	= 0.8361 m^2
1 in.	= 25.4 mm
1 ft	= 0.3048 m
1 psi	= 0.0069 MPa
1 acre	= 0.4047 hectare

1 lb	=	0.4536 kg
1 ton	=	1016 kg
1 ft^3	=	0.03832 m^3
1 lb/ft	=	16.02 kg/m^3
1 yd^3	=	0.7646 m^3
(deg F – 32)*5/9	=	deg C
miles per hour x 1.609	=	kilometer per hour

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