A GUIDE FOR DESIGN AND CONSTRUCTION OF ROLLER-COMPACTED CONCRETE PAVEMENTS

by

David W. Pittman
Geotechnical Laboratory

and

Steven A. Ragan
Structures Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

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Abstract:
Roller-compacted concrete pavement (RCCP) provides a lower-quality, economical alternative to slipform and fixed-form concrete pavements. It is ideally suited for areas where heavy, low speed vehicles such as tanks or container handlers are the primary users of the pavement.

RCCP is constructed by placing a zero-slump portland cement concrete mixture with an asphalt paver and compacting it with several passes of a vibratory roller. By using this construction method, wherein large quantities of concrete can be placed quickly with a minimal amount of labor and equipment, savings of 30 percent over conventional concrete paving methods have been reached. The final RCCP surface is not as smooth as a conventionally constructed concrete pavement, and the surface texture resembles that of an asphaltic concrete pavement surface.
6a. NAME OF PERFORMING ORGANIZATION

USAEWES
Geotechnical Laboratory
Structures Laboratory

6b. OFFICE SYMBOL

WESGP-EC
WESSC-CG

18. SUBJECT TERMS (Continued).

Pavements
Roller-compact concrete pavements (RCP)
Vibratory compaction
Zero-slump concrete

19. ABSTRACT (Continued).

Quality control and assurance consist of testing materials going into the concrete, checking the plant calibration regularly, measuring the in situ density of RCCP using a nuclear density gage, checking the smoothness of the finished RCCP with a straightedge, and taking cores to check the pavement strength, density, and thickness. Inspectors at the plant and on the jobsite are vital to ensure that a quality RCCP is being built.
The study reported herein was sponsored by the Office, Chief of Engineers, US Army, as a part of the work effort "Roller-Compacted Concrete Pavement and Criteria Development" of the Facilities Investigation and Studies (FIS) Program. The study was conducted during the period from December 1984 to March 1985.

Engineers of the US Army Engineer Waterways Experiment Station (WES) who were actively engaged in the planning, research, and reporting phases of this study were Messrs. D. W. Pittman, Pavement Systems Division, Geotechnical Laboratory (GL), and S. A. Ragan, Concrete and Grout Unit, Structures Laboratory. The work was performed under the general supervision of Drs. W. F. Marcuson III and P. F. Hadala, Chief and Assistant Chief, respectively, GL. This report was prepared by Messrs. Pittman and Ragan. Ms. Odell F. Allen, Information Products Division, Information Technology Laboratory, edited the report.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.
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CONVERSION FACTORS, NON-SI TO SI (METRIC)  
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

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<tr>
<th>Multiply</th>
<th>By</th>
<th>To Obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>cubic yards</td>
<td>0.7645549</td>
<td>cubic metres</td>
</tr>
<tr>
<td>feet</td>
<td>0.3048</td>
<td>metres</td>
</tr>
<tr>
<td>inches</td>
<td>2.54</td>
<td>centimetres</td>
</tr>
<tr>
<td>pounds (force) per square inch</td>
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<td>kilopascals</td>
</tr>
<tr>
<td>square feet</td>
<td>0.09290304</td>
<td>square metres</td>
</tr>
<tr>
<td>square yards</td>
<td>0.8361274</td>
<td>square metres</td>
</tr>
<tr>
<td>tons (2,000 pounds, mass)</td>
<td>907.1847</td>
<td>kilograms</td>
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1. Roller-compacted concrete pavement (RCCP) employs a concrete paving technology that involves laydown and compaction of a zero-slump concrete mixture using equipment similar to that used in placement and compaction of asphaltic concrete (AC) pavement. By using these construction techniques, the potential exists to save one-third or more of the cost of conventional concrete pavement. Although the concept and technology behind RCCP are relatively new, RCCP has already proven itself cost-effective in several projects including log-sorting yards, port facilities, heavy equipment parking areas, tank trails, and haul roads.

2. The concept of roller-compacted concrete (RCC) had its beginning in the early 1970's for use in mass concrete structures. It was thought that soil-cement applications and earth and rock-fill technology could be extrapolated to include a cement-enriched granular fill that could be placed in layers and compacted with several passes of a vibratory roller (American Concrete Institute 1983). The US Army Corps of Engineers has successfully used RCC at the Lost Creek Dam, Oregon; the Chena River Project, Alaska; and the Willow Creek Dam at Hepner, Oregon, which was completed in 1982. The Willow Creek Dam contains over 400,000 cu yd* of RCC and was constructed at about one-third the cost of a conventional concrete dam (Schrader in preparation). The use of RCC for pavements has been studied by the Office, Chief of Engineers, and the US Army Engineer Waterways Experiment Station (WES) at Vicksburg, Miss., since 1975. Two test sections of RCCP have been built at WES, one to study the use of marginal materials for aggregates in RCCP (Grau 1979) and one to study the compaction of zero-slump concrete with various vibratory rollers (Burns 1976). In July 1983 a 265-ft-long segment of a tank access road was built at Fort Stewart, Ga., and in July 1984 a 180,000-sq-ft parking area for tanks and

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.
other heavy equipment was built at Fort Hood, Tex.* In September 1984 small test sections of different thicknesses were built at Fort Stewart to determine the performance of RCCP under tank traffic. A 700-ft-long road was built at Fort Lewis, Wash., in October 1984 for tracked and rubber-tired vehicles.** In November 1984 a small test section was built at the Cold Regions Research and Engineering Laboratory (CRREL) to study the in situ freeze-thaw durability of RCCP. Other Corps of Engineers and Air Force RCCP projects are in the planning stage. Much work with RCCP has been done in British Columbia, Canada, since 1976. RCCP has been used there extensively for log sorting and storage yards, coal storage yards, dock facilities, and haul roads for coal transportation. These pavements undergo numerous freeze-thaw cycles and regularly handle axle loads in excess of 120 tons.† RCCP has performed well at all these locations under various loading and environmental conditions.

Objectives and Scope

3. The objectives of this study were to perform a literature search and field research of the use of RCC for pavements and to recommend procedures for designing and constructing RCCP. It is anticipated that follow-up studies will be needed as the state of the art of this progressively changing, relatively new technology advances. These areas include material acceptance testing, mixture proportioning, thickness design, placement and compaction, curing, jointing, and quality control and assurance.

4. These objectives were accomplished by reviewing several design and construction practices both in the literature and in the field. Recommendations were then made based on these observations and reviews.

* D. W. Pittman. 1984. "Memorandum for Record: Trip to Fort Hood, Texas to Discuss Roller Compacted Concrete Pavement (RCCP), 1-3 August 1984," US Army Engineer Waterways Experiment Station, Vicksburg, Miss.
** E. R. Brown. 1985. "Memorandum for Record: Roller Compacted Concrete Pavement Test Section-Fort Lewis, Washington," US Army Engineer Waterways Experiment Station, Vicksburg, Miss.
PART II: DESIGN

Materials Selection

5. One of the most important factors in determining the quality and economy of concrete is the selection of a suitable aggregate source. This applies to RCC as well as conventional concrete. Aggregate for RCC should be evaluated for quality and grading and should comply with the provisions outlined in TM 5-822-7/AFM 88-6 (Headquarters, Departments of the Army and the Air Force 1977) with exceptions as noted in the following discussion.

6. The coarse aggregate may consist of crushed or uncrushed gravel, crushed stone, or a combination thereof. Although the quality of coarse aggregate used by the Corps to date in RCCP has generally complied with American Society for Testing and Materials (ASTM) C 33 (ASTM 1984a), satisfactory RCC may be produced with coarse aggregate not meeting these requirements. Local state highway department coarse aggregate grading limits should generally be acceptable. A primary consideration should be that, regardless of the grading limits imposed, the grading of the aggregate delivered to the project site be relatively consistent throughout the production of RCC. This is an important factor in maintaining control of the workability of the concrete mixture.

7. The nominal maximum aggregate size normally should not exceed 3/4 in., particularly if pavement surface texture is a consideration. When aggregate larger than 3/4 in. is used, segregation and resulting rock pockets are likely to occur.

8. The fine aggregate may consist of natural sand, manufactured sand, or a combination of the two and should be composed of hard, durable particles. The fine aggregate quality should generally be based on the limits given in ASTM C 33 (ASTM 1984a) except that consideration should be given to relaxing the maximum 5.0 percent limit of material finer than the No. 200 sieve. The amount of material passing the No. 200 sieve has been increased in Canada to 8 percent of the total weight of aggregates with good results.* Sands with higher quantities of silt may be beneficial as mineral filler and allow some

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reduction in the amount of cementitious material required. However, mixtures
made with fine aggregates having an excessive amount of clay may have a high
water demand with attendant shrinkage, cracking, and reduced strength.
Table 3-4 of EM 1110-2-2908 (Headquarters, Department of the Army 1985)
establishes limits on the maximum allowable percentage of fine aggregate
passing the No. 200 sieve based on the Atterberg limits of the fine aggregate.
Determination of the specific gravity and absorption of these sands with high
quantities of fines should be made according to Note 3 in ASTM C 128 (ASTM
1984d).

9. Recent experience with RCC has shown that aggregate produced for
uses other than portland cement concrete may also be successfully used as
aggregate for RCC. Materials produced for asphalt paving and base course have
been used effectively as RCC aggregate. These materials typically have a
higher percentage of fines passing the No. 200 sieve than conventional con­
crete aggregates and as a result may produce a "tighter" pavement surface
texture. Because these aggregates range in size from 3/4 in. to the No. 200
sieve, control of the grading may be more difficult due to segregation.
Therefore, careful attention must be directed toward stockpile formation and
subsequent handling of single size group aggregate.

10. If sulfate exposure is not a problem, then any available portland
cement, blended hydraulic cement, or combination of portland cement with poz­
zolan or blended hydraulic cement with pozzolan should be investigated, with
the exception of Type III portland cement. If sulfate exposure is a problem,
either Type II, Type V, or a moderate sulfate-resistant blended hydraulic ce­
ment should be used. The use of Type III portland cement will almost never be
justified or practical for use in RCC. Further guidance on the use or selec­
tion of cements or pozzolans may be found in CEGS 02520 (Headquarters, Depart­
ment of the Army, in preparation).

11. A proper air-void system must be provided to prevent frost damage
in conventional concrete which freezes when critically saturated. Air­
entraining admixtures have not proven to be effective in creating such air­
void systems in RCC, even when added at dosage rates 10 times that of conven­
tional concrete. Therefore, the most practical means of preventing frost
damage in RCC is by using mixtures with sufficiently low water-cement ratios
so that the paste has only small capillaries with very little freezable water.
Good compaction techniques to lower the air-void content of the concrete also
improve performance under freeze-thaw conditions. Such concrete would have a low permeability and should not absorb water in wet weather. The WES is currently investigating the durability of such RCC mixtures.

12. Neither water-reducing nor retarding admixtures have improved the fresh properties of RCC in limited laboratory investigations. If the use of these admixtures is proposed, such use should be based on investigations which show these admixtures to produce benefits greater than their cost.

**Mixture Proportions**

13. The basic mixture proportioning procedures and properties of conventional concrete and RCC are essentially the same; however, conventional concrete cannot be reproportioned for use as RCC by any single action such as (1) altering proportions of the mortar and concrete aggregates, (2) reducing the water content, (3) changing the water-cement ratio, or (4) increasing the fine aggregate content. Differences in mixture proportioning procedures and properties are mainly due to the relatively dry consistency of the fresh RCC and the selected use of nonconventionally graded aggregates. The primary differences in the proportioning properties of RCC are (1) RCC generally is not air-entrained, (2) RCC has a lower water content, (3) RCC has a lower paste content, and (4) RCC generally requires a higher fine aggregate content to limit segregation. A number of methods have been used to proportion RCC including those found in American Concrete Institute (ACI) 211.3-75 (ACI 1984b), ACI 207.5R (ACI 1984a), EM 1110-2-2908 (Headquarters, Department of the Army 1985), and ASTM D 558 (ASTM 1984h). The first three methods follow an approach similar to that used in proportioning conventional concrete. The fourth method treats the material as soil cement rather than concrete and establishes a relationship between moisture and density obtained from a particular compactive effort.

14. The WES has used the method described in ACI 207.5R with some modifications on all RCCP mixtures proportioned to date. The primary consideration when using this method is proper selection of the ratio (P_v) of the air-free volume of paste (V_p) to the air-free volume of mortar (V_m). This selection is based primarily upon the grading and particle shape of the fine aggregate. The P_v affects both the compactibility of the mixture and the resulting surface texture of the pavement. Ratios of 0.36 to 0.41 have been
found to be satisfactory for mixtures having nominal maximum size aggregate of 3/4 or 1-1/2 in. The fraction of fine aggregate finer than the No. 200 sieve should be included in $V_p$ when calculations are made using $P_v$.

15. Since RCC has no slump, an alternative means of measuring mixture consistency must be used. Two consistency measurement methods have been used to date. One uses the modified Vebe apparatus as described in EM 1110-2-2908 (Headquarters, Department of the Army 1985). The second method follows the procedures generally described in ACI 207.5R (ACI 1984a). This method consists of measuring the time required to fully consolidate a sample of no-slump concrete by external vibration. Although both methods have been used successfully, the latter is more subjective and requires the use of a vibrating table having sufficient frequency and amplitude to fully consolidate the sample. Some commercially available tables have been found unsuitable without the use of a sample surcharge weight. A suggested minimum amplitude and frequency necessary to consolidate an RCC sample without using a surcharge weight is 0.0625 in. and 60 Hz, respectively.

16. The strength of an RCC mixture is controlled primarily by the water-cement ratio and the degree of compaction attained. All RCCP mixtures placed by the Corps to date have had water-cement ratios ranging from 0.30 to 0.40. Laboratory strength determinations are made using fabricated flexural, compressive, and splitting tensile strength specimens. Conventional ASTM testing methods cannot be followed when fabricating these specimens due to the dry consistency of the concrete. The procedure being used is to fill cylinder molds in two layers and beam molds in a single layer and consolidate each layer of concrete on a vibrating table. Vibration of each layer is continued until paste is discernible over the entire surface area. The use of a surcharge weight may be necessary to achieve this degree of consolidation. All specimens fabricated in the laboratory are to be cured according to ASTM C 192 (ASTM 1984f).

17. Test specimens fabricated and cured in the laboratory generally exhibit higher strengths than those cored or sawn from an RCCP. This is probably due to the higher unit weights normally associated with the fabricated specimens and the more efficient laboratory moist curing. Laboratory test specimens generally have unit weights which are from 98 to 99 percent of the theoretical (air-free) weight of the mixture while core samples taken from RCCP normally have unit weights ranging from 95 to 98 percent of the
theoretical weight. Therefore, fabrication of a companion set of test specimens having the lowest relative density allowed by the contract specifications should be considered during the laboratory mixture proportioning studies.

18. Studies are currently being conducted at WES to determine if a proportioning method similar to ASTM D 558 (ASTM 1984h) is viable for RCC. Such a method would produce the optimum moisture content necessary to obtain maximum density for a particular set of materials and compaction procedures. Previous tests conducted at WES indicate that the optimum moisture content obtained by Method 100 (CE 55) of MIL-STD-621 (Department of Defense 1964) may produce a mixture too wet to allow efficient operation of a vibratory roller (Saucier 1984).

Thickness Design

19. The thickness design procedure for RCCP is the same as that used for conventional nonreinforced concrete pavements, as outlined in TM 5-822-6/AFM 88-7 (Headquarters, Department of the Army 1977). Beams sawn from RCCP at Fort Stewart, Fort Hood, and Fort Lewis and tested for flexural strength indicate that the actual flexural strength of the pavement is from 20 to 50 percent higher than the design strength used for those pavements. This suggests that the thickness design for compacted RCCP should be modified based upon the 28-day strength of beams sawn from a test section constructed using the same aggregate, cement, and construction procedure as planned for the entire work. However, until additional performance records and testing procedures are developed for RCCP, conventional pavement thickness design will be used.

20. In 1985 load transfer tests were conducted on naturally occurring shrinkage cracks in the RCCP at Fort Stewart and Fort Hood. The tests were conducted to determine if the assumption of a 25 percent load transfer sometimes considered in conventional concrete pavement design would be appropriate for RCCP thickness design. These tests revealed an average of 18.6 percent and 16.7 percent load transfer at transverse cracks at Fort Hood and Fort Stewart, respectively. Therefore, it is recommended that, if natural shrinkage cracks are allowed, the pavement should be designed for free-edge loading (and not 25 percent load transfer) conditions.

21. The maximum thickness of a lift of RCCP is governed by the ability of the pavers to place the RCCP in a smooth and continuous fashion. This
maximum uncompacted thickness is usually from 10 to 12 in. The maximum uncompacted thickness can be approximated by multiplying the design thickness by 1.25, thus accounting for the reduction in thickness due to compaction. Should this maximum thickness exceed the capacity of the paver, the RCCP should be placed in two or more lifts, thus creating a horizontal joint (or horizontal plane between the layers) in the RCCP. Point-load tests performed at WES on cores extracted from RCC several lifts thick indicate that the fresh horizontal joints (top lift placed within 1 hr of bottom lift) developed about 90 percent of the tensile strength of the parent concrete, and the cold joint strength (see "Joints" in Part V) varied from 25 to 50 percent of the tensile strength of the parent concrete (Saucier 1984). This suggests that enough bond develops at a fresh horizontal joint in RCCP to allow the use of a monolithic thickness design; otherwise the thickness should be designed as a rigid overlay of a rigid base pavement (Headquarters, Department of the Army 1977). The surface of the lower lift should be kept moist and clean until the upper lift is placed, and the upper lift should be placed and compacted within an hour of compacting the lower lift to ensure that the bond between lifts is formed.

22. In two-lift construction, the uncompacted thickness of the first lift should be two-thirds the total uncompacted height of the RCCP (or the maximum lift thickness the paver can handle, whichever is smaller). The thinner section in the upper lift aids in creating a smoother final surface, and, because of the smaller volume of material, allows the paver placing the second lift to move quicker than and follow closer behind the paver placing the first lift. Multiple lifts will be necessary if the total uncompacted thickness of the RCCP is greater than twice the maximum lift capacity of the paver. The minimum thickness of any lift should be 4 in.

Subgrade and Base Course

23. The subgrade and base course should conform to the requirements outlined in TM 5-822-6/AFM 88-7 (Headquarters, Department of the Army 1977) or TM 5-824-3/AFM 88-6 (Headquarters, Departments of the Army and the Air Force 1979) where applicable. The freeze-thaw durability of RCCP is not fully understood yet but is presently being studied at WES and CRREL. Good performance has been observed in the field; however, acceptable performance has not
been observed in the laboratory. For this reason, in areas where the pavement or base course might be subjected to seasonal frost action, particular attention should be given to providing a base course that will adequately drain any water that infiltrates through the pavement or subgrade.
24. A test section should be constructed to determine the ability of the contractor to mix, haul, place, compact, and cure RCCP. The test section should be constructed at least 1 month prior to the construction of the RCCP at a location near the jobsite. The test section should be large enough to establish the rolling pattern for the vibratory and finish rollers, the correlation between laboratory and nuclear gage densities, and the correlation between the number of passes and relative density. The test section should contain both longitudinal and transverse cold joints and a fresh joint. A suggested minimum size is three 12- to 14-ft-wide lanes (each 150 ft long) with one and one-half lanes placed the first day and the other one and one-half placed the next day.

25. During the test strip construction, a nuclear gage operated in the direct transmission mode (ASTM 1984i) and standardized with a calibration block should be used to determine the optimum number of passes with the vibratory roller to reach maximum density. The density should be measured by inserting the nuclear gage probe into the same hole after each pass of the vibratory roller. The hole should be made with an instrument specifically designed for the purpose and should be formed using the same method throughout the test section and main construction. This rolling and measuring procedure should be continued until there is less than a 1 percent change in successive readings. These data may be used in conjunction with the nuclear gage to laboratory density correlation (explained in the next paragraph) to determine the minimum number of passes needed to achieve or slightly exceed the specified density in the RCCP construction. However, a minimum of four vibratory passes should be used, and this minimum will probably prevail in most cases.

26. After a reasonable estimate is made of the optimum number of passes needed for compaction, a correlation between the value of in situ RCCP density as measured with the nuclear gage and the value obtained by weighing a sample of the RCCP in air and water should also be determined. This should be accomplished by measuring the final compacted density (after four or more passes with the vibratory roller) in 10 locations with the nuclear gage, which has been standardized with a calibration block. The measurement should be made by inserting the probe the full depth of the lane. Then, at 14 days, a pair of cores should be taken on 6-in. centers on either side of the remaining nuclear
gage holes and the density of the cores measured in the laboratory by weighing them in air and water. For each of the 10 holes, the average of the pair of laboratory densities should be compared with its corresponding nuclear gage density, and a constant relationship between the nuclear gage and laboratory densities should be developed by averaging the algebraic differences in these readings. This difference should be combined with future field readings to obtain an adjusted reading, which can be compared to the specified density. In the past a specified density of 96 percent of theoretical weight as defined in ASTM C 138 (ASTM 1984e) has been achieved. If the adjusted nuclear gage density is less than the specified density, additional passes should be made on the RCCP until the specified density is reached. Two nuclear density gages should be calibrated (using the same holes) during the test section construction so that an extra gage is available during final construction.

27. Ten cores and beams should be taken from the test section after 28 days to determine a correlation between flexural strength (ASTM 1984c) and splitting tensile strength (ASTM 1984g) and/or compressive strength (ASTM 1984b) of the RCCP. This reduces the amount of sawing necessary to obtain beam samples during further construction. Although both the splitting tensile and compressive strength data would be useful for historical reference, only one of these tests is needed for quality control testing of the RCCP construction. After the correlation is determined, the appropriate splitting tensile and/or compressive strength that correlates to the specified design flexural strength should be used in any further quality control testing.
PART IV: BATCHING, MIXING, AND TRANSPORTING

28. RCCP needs a vigorous mixing action to disperse the relatively small amount of water evenly throughout the matrix. This action has been best achieved by using a twin-shaft pugmill mixer commonly used in AC mixing. Batching of the concrete may be accomplished successfully in either a continuous-mixing or a weigh-batch plant. The continuous-mixing plant is recommended for batching RCC because it is easier to transport to the site, takes less time to set up, and has a greater output capacity than the weigh-batch plant. The weigh-batch plant allows more accurate control over the proportions of material in each batch but generally does not have enough output capacity to allow efficient operation for larger paving jobs. The output of the plant should be such that the smooth, continuous operation of the paver(s) is not interrupted, and for all but the smallest jobs (1,000 sq yd or smaller), the capacity of the plant should be no less than 250 tons/hr. The output (or production) of the plant should be neither greater than the laydown capacity of the paver(s) nor greater than the rolling capacity of the rollers. The plant should be located as close as possible to the paving site but in no case should the haul time between the batch plant and the pavers exceed 15 min.

29. The RCC should be hauled from the mixer to the paver(s) in dump trucks. These trucks should be equipped with protective covers to guard against adverse environmental effects on the RCC such as rain or extreme cold or heat. The truck should dump the concrete directly into the paver hopper.
PART V: CONSTRUCTION

**Placing**

30. For most pavement applications, RCCP should be placed with an asphalt paver or similar equipment. The paver should be equipped with automatic grade control devices such as a traveling ski or electronic stringline grade control device. A paver having a vibratory screed or one equipped with a tamping bar is recommended to provide a satisfactory surface texture and some initial compaction when the RCCP is placed. Necessary adjustments on the paver to handle the RCC include enlarging the feeding gates between the feed hopper and screed to accommodate the large volume of stiff material moving through the paver and adjusting the spreading screws in front of the screed to ensure that the RCC is spread uniformly across the width of the paving lane. Care should be taken to keep the paver hopper from becoming empty to prevent any gaps or other discontinuities from forming in the pavement.

31. The concrete should be placed within 45 min after water has been added to the batch. When paving adjacent lanes, the new concrete should be placed within 90 min of placing the first lane (forming a "fresh" joint), unless procedures for cold joint construction are followed (see "Joints" below). The height of the screed should be set even with the uncompacted height of the adjacent lane, thus allowing simultaneous compaction of the edges of the adjacent lanes to become a fresh joint. When paving rectangular sections, paving should be in the short direction in order to minimize the length and number of cold longitudinal and transverse joints. Two or more pavers operating in echelon may reduce the number of cold joints by one-half or greater and are especially recommended in road construction where the entire width of the road can be placed at the same time.

**Compaction**

32. RCCP is best compacted with a dual-drum (10-ton) vibratory roller making four or more passes over the surface to achieve the design density (one back-and-forth motion is two passes). To achieve a higher quality pavement, the primary compaction should be followed with two or more passes of a 20-ton rubber-tired roller (90-psi minimum tire pressure) to close up any surface
voids or cracks. The use of a dual-drum static (nonvibratory) roller may be required to remove any roller marks left by the vibratory or rubber-tired roller. A single-drum (10-ton) vibratory roller has been used successfully to compact RCCP, but a rubber-tired or dual-drum static roller may be required to remove tire marks.

33. Ideally, the consistency of the RCCP when placed should be such that it may be compacted immediately after placement without undue displacement of the RCCP. However, no more than 10 min should pass between placing and the beginning of the rolling procedure. The rolling should be completed within 45 min of the time that water was added at the mixing plant. A good indication that the RCCP is ready for compaction is obtained by making one or two static passes on the RCCP within 1 ft of the edge of the lane before vibrating begins and observing the material during these two passes to ensure that undue displacement does not occur. If the RCCP is too wet or too dry for compaction upon placing, the water content should be adjusted at the plant. Only minor changes in water content from the design mix should be made; otherwise, a new mix design may be needed. With practice, the roller operator should be able to tell whether the consistency of the RCCP is satisfactory for compaction.

34. After making the static passes, the vibratory roller should make four vibratory passes on the RCCP using the following pattern: two passes should be made on the exterior edge of the first paving lane (the perimeter of the parking area, or the edge of a road) so that the rolling wheel extends over the edge of the pavement 1 to 2 in. This is done to "confine" the RCCP to help prevent excessive lateral displacement of the lane upon further rolling. The roller should then shift to within 12 to 18 in. of the interior edge and make two passes. This will leave an uncompacted edge to set the height of the screed for an adjacent lane, and allows both lanes of the fresh joint to be compacted simultaneously. Any remaining uncompacted material in the center of the lane should be compacted with two passes of the roller. This pattern should be repeated once to make a total of four passes on the lane (or more if the specified density is not achieved). If the interior edge will be used to form a cold joint, it should be rolled exactly as the exterior edge was rolled, maintaining a level surface at the joint and not rounding the edge.

35. When the adjacent lane is placed, two passes should be made about 12 to 18 in. from the outer edge of the lane (again, to confine the concrete),
followed by two passes on the fresh joint. The first two passes should extend 1 to 2 in. over the outer edge of this adjacent lane if the lane will form an outer edge of the completed pavement. Any remaining uncompacted material in the lane should be rolled with two passes of the roller. This pattern should be repeated to make a total of four passes over the RCCP. Additional passes may be necessary along the fresh joint to ensure smoothness and density across the joint.

36. When the end of a lane is reached, the roller should roll off the end of the lane, rounding off the end in the process. This rounded end should be trimmed with a motor grader or a sawing/pick axe combination to form a vertical face through the entire depth of the pavement. An alternative method involves confining the uncompacted end of the lane with a crosstie or beam anchored to the base course, thereby forming a vertical face at the end of the lane after compaction.

37. During the course of the vibratory compaction, the roller should never stop on the pavement in the vibratory mode. Instead, the vibrator should be turned on only after the roller is in motion and should be turned off several feet before the roller stops moving. The stopping points of successive rolling passes should be staggered to avoid forming a depression in the RCCP surface. The roller should be operated at the speed, amplitude, and frequency to achieve optimum compaction. Best compaction will probably occur at a high amplitude and low frequency (because of the thick lifts) and at a speed not exceeding 2 mph.

38. The vibratory compaction should be followed immediately with two or more passes of the rubber-tired roller so that the surface voids and fissures close to form a tight surface texture. This rolling may be followed by a light dual-drum roller to remove any roller marks on the surface, but this will probably not be necessary. It is very important that all exposed surfaces of the RCCP be kept moist with a light water spray after the rolling process until the curing procedure is implemented.

Joints

39. A cold joint in RCCP is analogous to a construction joint in conventional concrete pavement. It is formed between two adjacent lanes of RCCP when the first lane has hardened to such an extent that the uncompacted edge
cannot be consolidated with the fresher second lane. This happens when there is some time delay between placement of adjacent lanes such as at the end of the day's construction. This hardening may take from one to several hours, depending on properties of the concrete and environmental conditions. Nevertheless, the adjacent lane should be placed against the first lane within 90 min, or otherwise be considered a cold joint.

40. Before placing fresh concrete against hardened in-place pavement to form a longitudinal cold joint, the edge of the in-place pavement should be trimmed back to sound concrete to form a vertical face along the edge. This vertical face should be dampened before placement of the fresh lane begins. The height of the screed should be set to an elevation of about 25 percent higher than the desired thickness of the compacted concrete using shims between the screed and the compacted surface of the hardened lane. The screed should overlap the edge of the hardened concrete lane 2 or 3 in. The excess fresh concrete should be pushed back to the edge of the fresh concrete lane with rakes or lutes and rounded off so that a minimal amount of fresh material is left on the surface of the hardened concrete after compaction. The loose material should not be broadcast over the area to be compacted (this may leave a rough surface texture after rolling). The edge of the fresh lane adjacent to the hardened concrete should be rolled first with about a foot of the roller on the fresh concrete to form a smooth longitudinal joint.

41. Transverse cold joints are constructed in a similar manner. After cutting back the rounded-off edge and wetting the vertical face, the paver is backed into place and the screed set to the proper elevation using shims sitting on top of the hardened concrete. The excess material should be pushed back and a static pass made in the transverse direction across the first 1 ft of the freshly placed lane. Care should be exercised in rolling the joint to ensure a smooth surface transition across the joint.

42. The sawing of contraction joints in RCCP has proven to be unnecessary in past projects. Cracks were allowed to form naturally in all of the Canadian-built RCCP, and virtually no distress has been observed at the cracks. These pavements have endured over 7 years of very heavy loads and numerous freeze-thaw cycles. Attempts to saw joints at Fort Hood and Fort Lewis produced a ragged edge along the saw cut where pieces of cement paste and aggregate were kicked out by the saw blade. Until a suitable method is developed for sawing joints in RCCP, this method is not to be used.
43. The stiff consistency of RCCP does not lend itself to application of load transfer devices such as dowels or keyed joints, although dowels were used in cold joint construction at Fort Stewart. The dowels were driven into the RCCP before final set, and the adjacent fresh lane was carefully worked around the dowels by hand. Until an efficient method is developed to insert and align dowels properly in RCCP, the use of dowels should be limited.

44. In two-lift construction, care should be taken to align the cold transverse and longitudinal joints in the upper and lower lifts to form a uniform, vertical face through the depth of the pavement along the joint. If the edge of the upper lift is not even with the edge of the lower lift, the lower lift should be cut even with the edge of the upper lift.

Curing Procedures

45. Due to the low water content used in an RCCP mixture, a combination of moist curing and membrane curing is recommended to prevent drying and scaling of the RCCP surface. The pavement surface should be kept continuously moist after final rolling for at least 24 hr by means of a water spray truck, sprinkler (fog spray) system, or wet burlap or cotton mat covering. If burlap or mats are used, they should be thoroughly wetted, placed on the RCCP so that the entire surface and exposed edges are covered, and be kept continuously wet. After the initial moist curing period, the RCCP should be cured until it is at least 7 days old by one of the following methods: water-spray curing, burlap or cotton mat covering, or membrane-forming curing material. The curing material may be a white-pigmented membrane curing compound or an asphalt emulsion. The curing compound or emulsion must form a continuous void-free membrane, and should be maintained in that condition throughout the curing period. An irrigation sprinkler system has been used to cure RCCP in Canada and at Fort Lewis, but caution should be exercised so that the fines in the surface of the RCCP are not washed away by excessive spraying.

46. Continuous moist curing of the RCCP for at least 7 days should be considered if frost resistance is a concern. Preliminary results of laboratory freezing and thawing tests conducted at WES and the North Pacific Division Laboratory indicate RCCP which has a sufficiently low water-cement ratio and has been moist-cured for an extended period tends to be more frost-resistant. The improved frost resistance may be due to more complete
hydration resulting in a reduction in fractional volume of freezable water at saturation.

47. All vehicular traffic should be kept off the RCCP for at least 14 days. If it is absolutely necessary, a water-spraying truck and membrane-spraying truck may be driven onto the RCCP prior to 14 days, but this practice should be kept to a minimum.
48. Quality control and quality assurance consist of testing of materials going into the concrete, checking the plant calibration regularly, measuring the in-place density of the RCCP using a nuclear density gage, and checking the smoothness of the finished RCCP with a straightedge. Core samples should be taken from the RCCP and tested for density, strength, and thickness.

49. Moisture contents of the fine and coarse aggregates should be determined daily as necessary and appropriate changes are made in the amount of mixing water. Gradation tests should be run on the combined aggregates three times per day: in the morning, at midday, and in the afternoon. The samples should be taken from the conveyor before the cement or fly ash is added to the combined aggregates. The calibration of the plant should be checked each day before production begins. The samples used for calibration should be taken from the conveyor belt between the cement and fly ash hoppers and the pugmill. Washout tests should be performed on the freshly mixed concrete three times per day by washing the concrete over No. 4 and No. 100 sieves and weighing the material in each size category to determine approximately if the proportions in each size category conform to predetermined limits.

50. Field density tests should be performed on the RCCP using a nuclear density gage operated in the direct transmission mode (ASTM 1984i). At least one field reading should be taken for every 100 ft of each paving lane. The readings should be taken as closely behind the rolling operation as possible. The readings should be adjusted using the correlation determined in the test section construction and checked against a specified density. Areas that indicate a deficient density should be rolled again with the vibratory roller until the specified density is achieved.

51. Cores should be taken from the RCCP for strength testing when the pavement is 28 days old. One core should be taken for every 500 ft of each paving lane and checked for strength, density, and pavement thickness. The finished surface of the RCCP should not vary more than 3/8 in. from the testing edge of a 10-ft straightedge. Smoothness should be checked as closely behind the finish roller as possible, and any excessive variations in the surface shall be corrected with the finish roller. Particular attention should be given to smoothness across fresh and cold joints as this is usually a critical area for surface variations. A skilled vibratory roller operator is
essential in minimizing smoothness problems. The final surface texture of the RCCP should resemble that of an AC pavement surface.

52. Inspections are vital in the quality control operations. At least one inspector should be stationed at the mixing plant and at the jobsite to ensure that a quality pavement is being built.

53. At the mixing plant, the inspector should check mixing times occasionally and spot-check the consistency and appearance of the mix coming out of the plant. The inspector should also coordinate the aggregate moisture content tests, the gradation tests, the calibration of the plant, and the washout tests to see that they are performed properly and at the right frequency.

54. At the jobsite, the inspector should make sure that the base course and cold joints are moistened before the RCC is placed against them and that the RCC is placed and compacted within the proper time limitations. He should check the paver operation to ensure that proper grade control is continuously maintained and to make sure no gaps or discontinuities are left in the pavement before rolling. He should also make sure that the roller begins compaction at the proper time and that the proper rolling pattern and number of passes are used. He should make sure that adequate smoothness across joints is achieved and that the surface texture is tight after final rolling. He should spot-check the final compacted thickness of the RCCP on occasion and correct it accordingly, if appropriate. He should make sure that the curing procedures are implemented as specified, that all exposed surfaces of the RCCP are kept moist at all times, and that the curing compound, if used, is applied properly and in a continuous fashion. He should also coordinate the nuclear gage density test, the coring procedures, and the surface smoothness test to see that they are performed properly and at the required frequency.
PART VII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

55. Roller-compacted concrete pavement provides a strong, economical alternative to conventional concrete pavement. It is ideally suited for areas where heavy, low-speed traffic is the primary user of the pavement.

Recommendations

56. Guidance and recommendations given in this paper are based on limited data and observations and are subject to change as more work is done in these areas. Almost all areas of RCCP design and construction are in need of research including mixture proportioning, freeze-thaw durability, thickness design, jointing, compaction, curing, sample fabrication, and quality control requirements.
REFERENCES


