Construction of Roller-Compacted Concrete Pavements

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ABSTRACT

Roller-compacted concrete pavement (RCCP) is the product of a relatively new concrete paving technology in which a zero-slump portland cement concrete mixture is spread with modified asphalt pavers and compacted with vibratory and rubber-tired rollers. Because of the ease and simplicity of this construction method, savings of one-third or more of the cost of conventional concrete pavement construction are possible. RCCP construction procedures are described, from subgrade and base-course preparation to curing procedures. Equipment needed for mixing, transporting, placing, compacting, and curing RCCP is detailed. Procedures for fresh-joint, cold-joint, and horizontal-joint construction are recommended, and various curing procedures and their results are discussed. Quality control and quality assurance practices, including checking the in situ density of RCCP with a nuclear density gauge and the smoothness with a 10-ft straightedge, are outlined. Applications of RCCP and potential construction problems are described. Advantages and disadvantages of using RCCP instead of conventional concrete pavement are discussed.

Roller-compacted concrete pavement (RCCP) is the product of a new concrete paving technology in which a zero-slump portland cement concrete mixture is spread with a modified asphalt paver and compacted with a vibratory roller. This construction method, which is very similar to asphaltic concrete paving, has the potential for savings of one-third or more of the cost of conventional (slip-form or fixed-form) concrete paving construction, therefore combining the more attractive features of concrete and asphalt paving.

The idea of placing and compacting a zero-slump concrete mixture in lifts originated in the early 1970s for use in mass concrete structures. Almost 0.5 million yd^3 of roller-compacted concrete (RCC) was placed in both the Tarbela Dam, Pakistan, in 1975 and in the Willow Creek Dam in Hepner, Oregon, in 1982 (1). The Willow Creek Dam was constructed at about one-third the cost of a conventional concrete dam (2), illustrating significantly the economic advantages of using RCC.

The mass concrete construction techniques of the early 1970s evolved quite naturally to include pavement structures. Two test sections of RCCP were built at the U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, Mississippi, in the mid-1970s--one to study the compaction of zero-slump concrete with various vibratory rollers (3) and the other to study the use of marginal material for RCCP aggregates (4). At about the same time, the Canadians were experimenting with RCCP in the timber industry as a low-cost alternative for constructing log-sorting and storage yards, which frequently handle axle loads in excess of 100 tons (5). These pavements have performed exceptionally well under harsh loading and environmental conditions, and by 1983 the Canadians had built over 28 acres of storage yards and an 11-mi haul road with RCCP.

The first major use of RCCP by the U.S. Army Corps of Engineers was at Fort Hood, Texas, in July 1984. A 20,000-yd^2 parking area for M1 tanks and armored personnel carriers was built in 11 days at a savings of 15 percent over the cost of reinforced-concrete pavement. In November 1984 a 700-ft-long road was built at Fort Lewis, Washington, for tracked and rubber-tired military vehicles. Railroad shipping terminals in Houston, Texas, and Tacoma, Washington, were built recently to thicknesses up to 18 in. to accommodate heavy loadings applied by container-handling vehicles used to unload freight from rail cars.

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SUBGRADE AND BASE-COURSE PREPARATION

The subgrade and base-course requirements are basically the same for RCCP as they are for conventional concrete pavements. In areas where the pavement or base course might be subjected to seasonal frost action, the base course should adequately drain any water that infiltrates through the pavement or subgrade. The base course should also provide sufficient support so that the RCCP is fully consolidated through its entire thickness upon compaction.

TEST SECTION

Construction of a test section allows the contractor to demonstrate his ability to mix, haul, place, compact, and cure RCCP before the major construction takes place. The test section is usually constructed at least 1 month before the start of the major construction, so that samples for strength testing may be taken directly from the test section.

The test section also serves several other important functions. The rolling pattern should be established, so that optimum density is achieved with a minimal number of passes. Nuclear density gauge readings should be correlated with densities of cores taken from the test section and measured in the laboratory. The nuclear density gauge operated in the direct transmission mode has been reported to be as accurate as the sand cone test and core testing in determining the density of cement-bound materials (6). However, calibration of the nuclear gauge during test section construction ensures that an accurate correlation exists during the major construction.

The test section should contain both longitudinal and transverse cold joints and fresh joints, because these are the most critical areas in obtaining surface smoothness and adequate density. A suggested minimum size is three paving lanes wide, each 150 ft long, with one and one-half lanes placed the first day and the rest placed the next day (Figure 1).

Cores and beams should be taken from the test section after 28 days to determine the correlation between the flexural strength and splitting tensile strength of the RCCP. This eliminates the need for the time-consuming and expensive practice of sawing beams during construction to check the design flexural strength.

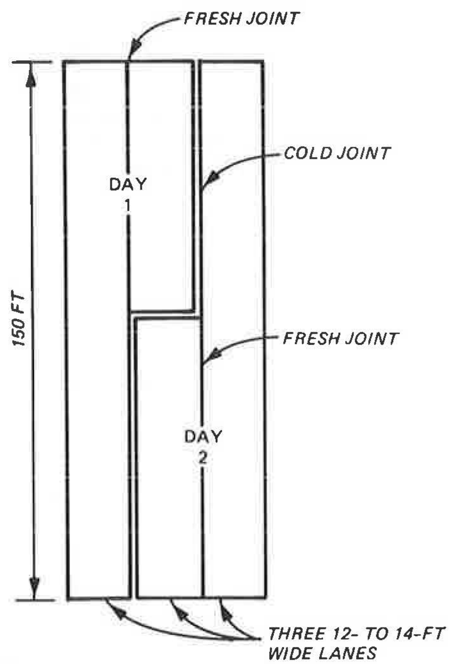

FIGURE 1 Test section.

BATCHING, MIXING, AND TRANSPORTING

RCC 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 asphaltic-concrete mixing. Batching of the concrete may be accomplished successfully in either a continuous-mixing or a weigh-batch plant. The continuous-mixing plant is more advantageous 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 for large paving jobs. The output of the plant should be such that the smooth, continuous operation of the paver or pavers is not interrupted, and for all but the smallest jobs (1,000 yd^2 or smaller), the capacity of the plant should ideally be no less than 250 tons/hr. The output (or production) of the plant should not be greater than the laydown capacity of the pavers nor greater than the rolling capacity of the rollers. The plant should be located as close as possible to the paving site to minimize the haul time between the batch plant and the pavers.

RCC is typically hauled from the mixer to the pavers 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.

PLACING

For most pavement applications, RCCP is placed with an asphalt paver or similar equipment. Automatic grade-control devices, such as a traveling ski or electronic string line, allow the RCCP to be spread at an accurate grade and acceptable smoothness. A paver having a vibratory screed or one equipped with a tamping bar will 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.

The fresh concrete should be placed and compacted within 45 min after water has been added to the batch. When adjacent lanes are paved, 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 section entitled Joints). When rectangular sections are paved, paving in the short direction will 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 suitable in road construction where the entire width of the road can be placed at one time.

COMPACTION

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. A dual-drum static (nonvibratory) roller may be required to remove any roller marks left by the vibratory or rubber-tired roller.

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 addition of water at the mixing plant. A good indication that the RCCP is ready for compaction is found 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 the 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 to correct this. 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.

ROLLING PATTERN

The rolling pattern should be established so that the specified density is achieved with a minimum number of roller passes. After making the static passes for a consistency check, the vibratory roller should make four vibratory passes on the RCCP using the following pattern, which has yielded satisfactory results in earlier projects: Two passes (one back-and-forth motion with the roller) 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 and prevent excessive lateral displacement of the concrete 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. The pattern should be repeated once to make a total of four passes on the lane (or more if the specified density is not achieved) (see Figure 2). If the interior edge will be used to form a cold joint, it should be rolled exactly as the exterior edge was rolled, taking care to maintain a level surface at the joint and not round the edge.

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 (see Figure 3).

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 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.

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 point 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, which will probably occur at a high amplitude and low frequency (because of the thick lifts) and at a speed not exceeding 2 mph.

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 may not be necessary. All exposed surfaces of the RCCP must be kept moist with a light water spray after the rolling

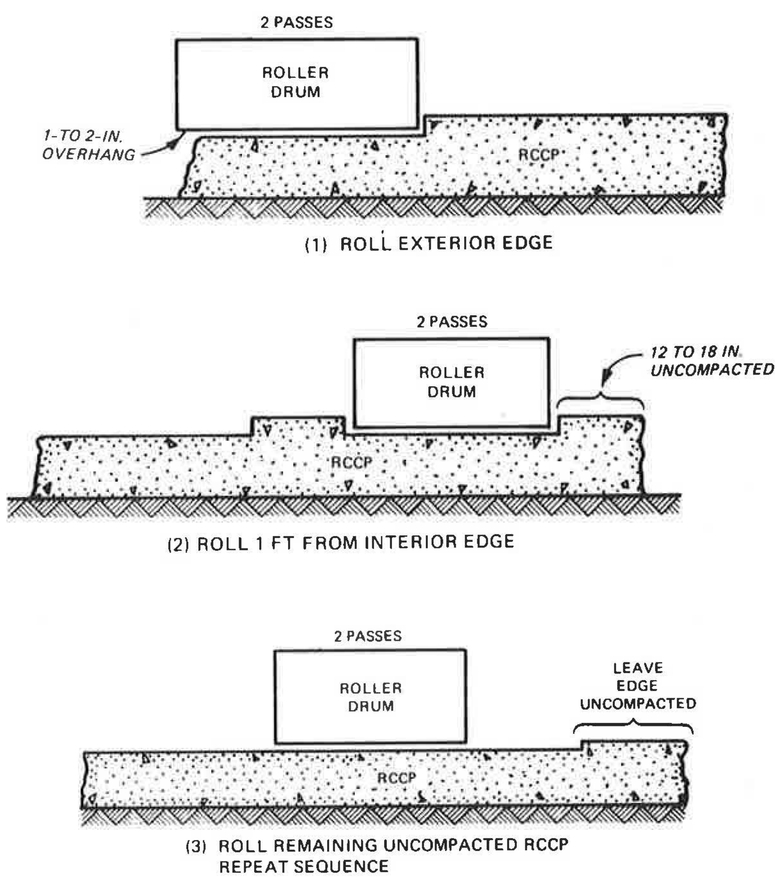

FIGURE 2 Compaction of first paving lane.

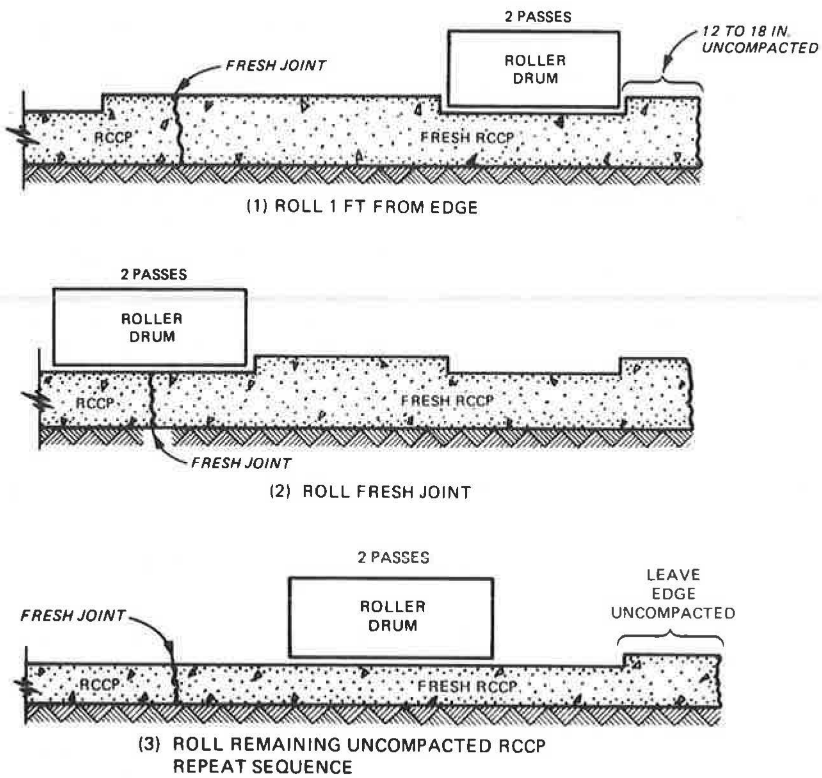

FIGURE 3 Construction of fresh joint.

process until the curing procedure has been completed.

JOINTS

A cold joint 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 a 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 be considered a cold joint.

Before fresh concrete is placed against hardened in-place pavement to form a longitudinal cold joint, the edge of the in-place pavement must 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 approximately 25 percent higher than the desired thickness of the compacted concrete. 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. The loose material should not be broadcast over the area to be compacted because this may leave a rough surface texture after rolling. The edge of the fresh lane adjacent to the hardened concrete should be rolled first in the static mode with about 1 ft of the roller on the fresh concrete to form a smooth longitudinal joint (see Figure 4).

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

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 knocked out by the saw blade.

The stiff consistency of RCCP does not lend itself to the application of load-transfer devices, such as dowels or keyed joints, although dowels were used in cold-joint construction at Fort Stewart. There the dowels were driven into the RCCP before the final set, and the dowels in the adjacent fresh lane were carefully worked around by hand. Until an efficient method is developed to insert and align dowels properly in RCCP, the use of dowels should be limited.

In two-lift construction, the cold transverse and longitudinal joints should be carefully aligned 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 back even with the edge of the upper lift (see Figure 5).

CURING

Because of the lower water content used in an RCCP mixture, a combination of moist curing and membrane

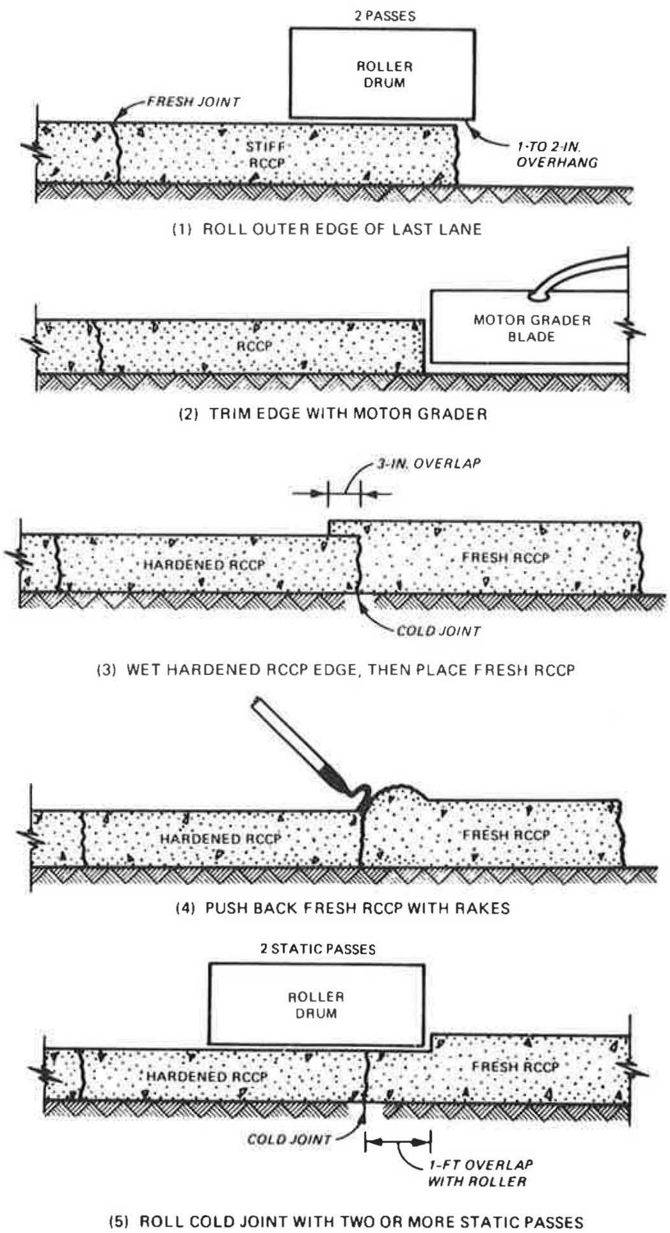

FIGURE 4 Construction of cold joint.

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 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.

Continuous moist curing of the RCCP for at least 7 days should be considered if frost resistance is of concern. Preliminary results of laboratory freezing and thawing tests conducted at WES and the North Pacific Division Laboratory indicate that RCCP with a sufficiently low water-cement ratio that has been moist-cured for an extended period tends to be more frost-resistant.

All vehicular traffic should be kept off the RCCP for at least 14 days. If absolutely necessary, a water-spraying truck and a membrane-spraying truck may be driven onto the RCCP before that age, but this practice should be kept to a minimum.

QUALITY CONTROL AND ASSURANCE

Quality control and quality assurance consist of testing materials going into the concrete, checking the plant calibration regularly, measuring the in-place density of the RCCP with a nuclear density gauge, fabricating cylinders and beams to model in-

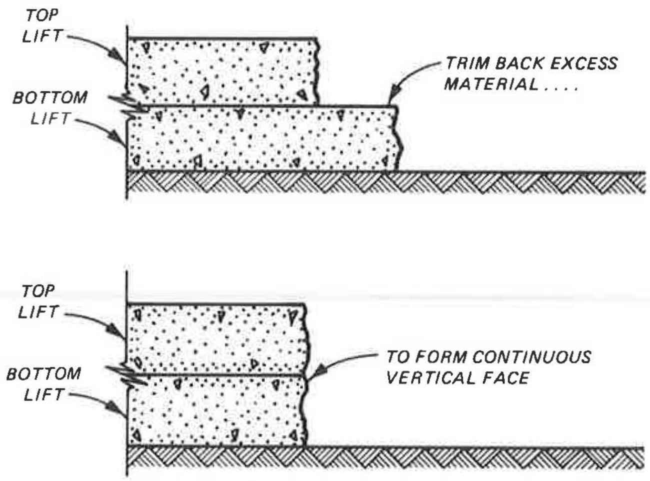

FIGURE 5 Two-lift cold joint.

place density and strength, checking the smoothness of the finished RCCP with a straightedge, and taking core samples from the RCCP for measurement of density, tensile splitting strength, and thickness.

Moisture content of the fine and coarse aggregates should be determined daily as necessary and appropriate changes made in the amount of mixing water. The calibration of the plant should be checked daily before production begins. The samples used for calibration should be taken from the conveyor belt between the cement and fly-ash silos and the pugmill.

Washed gradation tests should normally be performed on the combined aggregates three times a 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 amount of material passing the No. 100 sieve should be determined during this analysis. After each gradation test, a washout test (ASTM C 685) may be performed on the combined dry ingredients on samples taken from the conveyor belt between the cement and fly-ash hoppers and the pugmill. By washing the dry ingredients over the No. 4 and No. 100 sieves and weighing the material in each size category, the approximate proportions of coarse aggregate, fine aggregate, and cement and fly ash combined may be determined and checked against predetermined limits.

Field density tests should be performed on the RCCP with a nuclear density gauge operated in the direct transmission mode according to ASTM D 2922. 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 by using the correlation determined in the test section construction and checked against a specified density. Areas that indicate a deficient density should be rolled until the specified density has been achieved.

Cylinders and beams should be fabricated by filling cylinder molds in two layers and beam molds in a single layer and consolidating each layer of concrete in the field on a vibrating table. Although there is no standardized method for fabricating RCC cylinders or beams, the method described in ASTM C 192 has been used successfully, with and without the use of a surcharge weight to aid in consolidation of the mixture. Whatever method is used should be performed consistently throughout the project. Four beams (one group) should be fabricated during each shift of construction, two to be tested at 14 days and two at 28 days. The beams should be tested for flexural strength according to ASTM C 78. Six cylinders (one group) should be fabricated for every 300 yd^3 of RCC placed, with one group coming from the same batch of RCC as that used in the beams. Two cylinders should be tested each at 7, 14, and 28 days. The cylinders should be tested for splitting tensile strength according to ASTM C 496. Cylinders of RCC used with high fly-ash contents or for airfield pavements may be tested at 90 days.

Cores should be taken from the RCCP when the pavement is 7 days old. One core should be taken at every fifth nuclear gauge density test site within 2 to 5 ft of the test hole. The density and thickness of the core should be measured, and the core should be field cured under conditions similar to the RCCP curing conditions. The cores should be tested for splitting tensile strength (ASTM C 496) when they are 28 days old.

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 should be corrected with the finish roller. Particular attention should be paid to smoothness across fresh and cold joints, because 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 asphaltic-concrete pavement surface.

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

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. He should also coordinate the aggregate moisture content tests, the gradation tests, calibration of the plant, and washout tests to see that they are performed properly and with the right frequency.

At the job site, 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. The paver operation should be checked to ensure that proper grade control is continuously maintained and that no gaps or discontinuities are left in the pavement before rolling. The inspector should make sure that the roller begins compaction at the proper time and that the proper rolling pattern and number of passes are used. Adequate smoothness across joints should be assured as well as the tightness of the surface texture after final rolling. He should spot-check the final compacted thickness of the RCCP on occasion and make corrections if appropriate. He should make sure that the curing procedures are implemented as specified. The inspector should make sure 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 gauge density test, the coring and sample fabrication procedures, and the surface smoothness test to see that they are performed properly and at the required frequency.

ADVANTAGES AND DISADVANTAGES OF USING RCCP

The primary advantage of using RCCP versus conventional concrete pavement is the relatively low construction cost; savings of 15 and 30 percent have been realized at Fort Hood and Tacoma, respectively. As contractors become more confident in their ability to place RCCP efficiently, the total cost of RCCP construction should drop even more. No elaborate paving trains or forms are needed to place RCCP, and only a small construction crew is used. This may open areas for concrete pavement applications that may have been deemed impractical or uneconomical in the past. Some savings in material costs may be realized should fly ash be substituted in RCCP for a portion of the cement (usually the costliest ingredient) as it has been in previous jobs. Some savings in aggregate processing may be achieved if a greater percentage of nondeleterious fines is allowed in RCCP to enhance workability or finishability.

As could be expected of any pavement whose construction technique is in its infancy, RCCP has its drawbacks. The degree of surface smoothness achieved to date has been less than that for conventional concrete pavement, limiting its present applications to parking areas, tank trails, or secondary roads. Also, some raveling of surface material may occur along cold joints and occasional surface areas as a result of improper construction or curing techniques. The freeze-thaw durability of RCCP has not been consistently satisfactory in laboratory tests conducted at WES. Fortunately, these problems can be controlled and corrected if proper mixing, construction, and curing techniques are known and implemented by all of the engineers, contractors, and quality control inspectors involved.

CONCLUSIONS

RCCP combines relatively simple asphaltic pavement construction techniques with the strength and durability of portland-cement concrete to provide an economical alternative to conventional concrete pavements. Because the quality of RCCP depends largely on the timeliness and proper execution of the placing, rolling, and quality-control operations, adequate education of all contractors, engineers, and quality-control personnel is essential in producing a satisfactory pavement. Though a relatively new paving technique, RCCP is rapidly gaining a place in the concrete paving market.

ACKNOWLEDGMENT

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