ROLLER-COMPACTED CONCRETE PAVEMENTS

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Roller-compacted concrete pavement (RCCP) is a relatively new type of rigid pavement that utilizes a construction technique similar to asphaltic concrete pavement (ACP) construction to provide a strong, economical pavement. This paper discusses briefly the history and performance of RCCP to date, design and construction procedures used in US Army Corps of Engineers projects, jointing procedures, and in situ properties of RCCP.

Roller-compacted concrete pavement (RCCP) is a concrete paving technology that involves laydown and compaction of a zero-slump concrete mixture using equipment similar to that used for asphaltic concrete paving. By using these construction techniques, the potential exists to save one-third to one-half the cost of conventional concrete pavement (CCP) construction. It is doubtful that any paving technology has ever had the potential for such significant savings as well as the potential for such widespread applications. Although the concept and technology behind RCCP is 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.

Background

The concept of roller-compacted concrete (RCC) had its beginnings in the early 1970's for use in mass concrete structures. It was thought that soil-cement applications 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 (1). 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 (the most noteworthy) at Hepner, Oregon, completed in 1982. This structure contains over 300,000 cu m (400,000 cu yd) of RCC and was constructed at about one-third the cost of a conventional concrete dam (2). The use of RCC for pavements has been studied by the Office, Chief of Engineers, US Army and the US Army Engineer Waterways Experiment Station (WES) at Vicksburg, Mississippi, since 1975. Two test sections of RCCP have been built at WES--one to study the use of marginal materials for aggregates in RCCP (3) and one to study the compaction of zero-slump concrete with various vibratory rollers (4). In July 1983 an 81-m (265-ft)-long segment of a tank access road was built at Ft. Stewart, Georgia, and in July 1984 a 16,700-sq-m (180,000-sq-ft) parking area for tanks and other heavy equipment was built at Ft. Hood, Texas. In September 1984 small test sections of different thicknesses were built at Ft. Stewart to determine the performance of RCCP under tank traffic. A 210-m (700-ft)-long road was built at Ft. Lewis, Washington, in October 1984 for track and rubber tire vehicles. In November 1984 a small test section was built at the Cold Regions Research Engineering Laboratory (CRREL) to study the in situ freeze-thaw durability of RCCP. Other US Army Corps of Engineers RCCP projects in the planning stage include a 8,350-sq-m (90,000-sq-ft) parking area at Ft. Lewis and helicopter pads at Ft. Hood.

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 110,000 kg (120 tons) (5). These pavements are in better condition than some CCP placed for the same purpose at the same time. An interesting comparison of performance between RCCP and CCP is offered at a log-sorting yard on Vancouver Island in British Columbia. A 61-cm (24-in.)-thick CCP ramp built in 1978 was constructed alongside a 43-cm (17-in.)-thick RCCP ramp built in 1976, both on a 15-cm (6-in.)-thick crushed rock base. By 1983, the CCP ramp had cracked and broken up to the point of failure, while the RCCP ramp was still in very good condition. These ramps are in areas of very heavy concentrated traffic and have been subject to many freeze-thaw cycles (5).

Cost

Most of the cost savings achieved by using RCCP versus CCP is reached by placing large volumes of concrete in a relatively short period of time with minimal labor and equipment. Further cost savings are realized since RCCP generally uses one-third to one-half of the cementitious material contained in CCP. This savings is further accentuated when fly ash or other pozzolanic materials are used to replace up to one-half of the more expensive cement (with some sacrifice in early strength), as was done in Canada and at Ft. Hood, Texas. Since a greater percentage of fines is usually allowed in RCCP than in CCP (to enhance workability), some savings in aggregate processing may be achieved if the fines present in the aggregate are not deleterious to the concrete.

RCCP was placed in Canada in 1976 and 1979 at in-place costs of $16/cu m ($21/cu yd) and $18/cu m ($24/cu yd), respectively, using a private contractor. The RCCP tank parking area constructed in 1984 at Ft. Hood, Texas, cost $43.50/cu m ($57/cu yd), a 15 percent savings over estimated CCP costs. The contractor's lack of training and/or experience with RCCP construction probably made his bid price considerably higher than it might have been. As contractors become more confident in their ability to place RCCP efficiently, the total unit cost of RCCP construction should drop significantly.

Potential Applications

It has already been demonstrated that RCCP is ideally suited for areas where heavy, low-speed equipment is the primary user of the pavement. Present technology has advanced to the extent that RCCP may be able to meet smoothness requirements for public highways. However, all of the pavement applications to date have been in areas that receive only low-speed traffic. According to the British Columbia Aviation Council, RCCP may be used in construction of emergency airfields used in some remote areas of British Columbia where jet ambulance aircraft must land (5).

Mix Design

So far, the mix proportioning procedure for RCCP has paralleled that for plain concrete, with some minor adjustments. When selecting proportions for plain concrete, several parameters must be known in advance, slump--a measure of the consistency of the mix--being among these (6). Since RCCP utilizes a "zero-slump" concrete, some method of measuring the consistency of RCC had to be developed in order to provide the same approach as that used in proportioning plain concrete. One such method utilizes the Vebe apparatus, which vibrates a cone of zero-slump concrete with a surcharge weight on top into a cylinder with a level top surface (6). The measure of the consistency of the mix is the time (in seconds) it takes to flatten the cone. Lab tests have been conducted to produce tables for RCC mix proportioning similar to those used for plain concrete (6) (see Table 1).

Another school of thought concerning the mix design for RCCP is to consider controlling the amount of water used in the concrete to provide a maximum density, much like a soil-cement moisture control procedure. The reasoning behind this is that the flexural strength increases with

Table 1. Typical mix proportions for conventional concrete and roller-compacted concrete pavement.

Ingredient	Conventional Concrete Pavement[a]	Roller-Compacted Concrete Pavement[b]
Cementitious material	15%	13%
Water	6%	4%
Coarse aggregate	49%	46%
Fine aggregate	30%	37%
Water/cement ratio	0.43	0.32

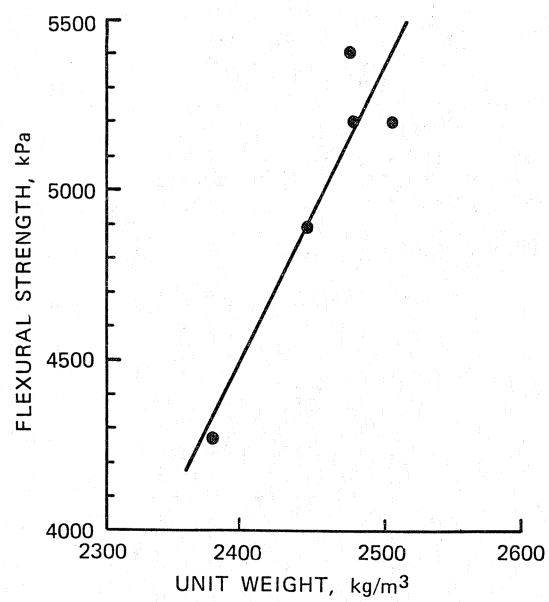
Note: Percents are given by weight.

[a]Proportions used in July 1979 at Hill AFB, Utah.

[b]Proportions used in October 1984 at Ft. Lewis, Washington.

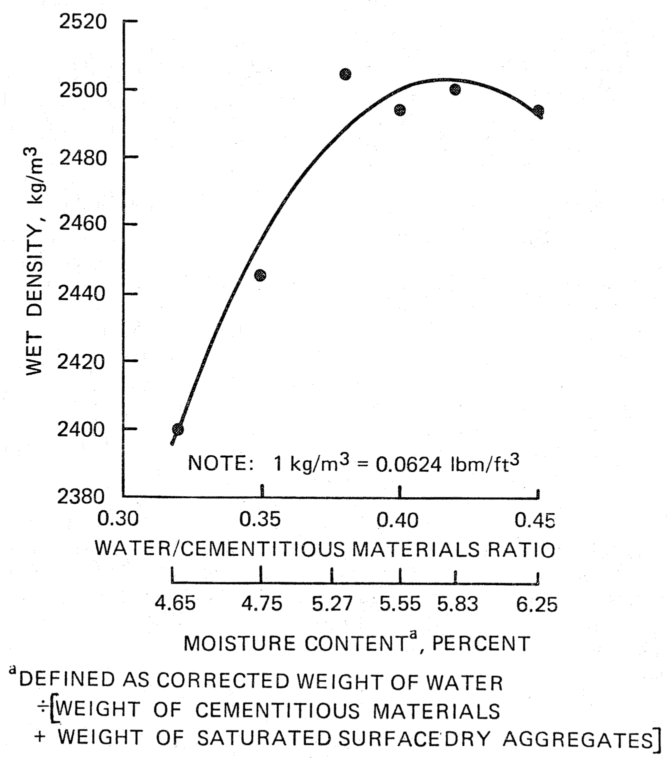
increasing density (see Figure 1), and just as in compaction of soil-cement mixtures, for a given compactive effort, density increases to a maximum at an optimum moisture content (see Figure 2). However, should RCCP mixtures react the same as CCP mixtures concerning the water/cement ratio, the flexural strength of RCCP should reduce with increasing moisture content. Experiments are currently being conducted at WES to study these relationships.

Figure 1. Relationship between flexural strength and density of roller-compacted concrete pavement (4).



NOTE: 1 kPa = 0.145 lbf/in.^{2} ; 1 kg/m^3 = 0.0624 lbm/ft^3

Figure 2. Relationship between wet density (unit weight) and water/cementitious materials ratio (moisture content).



Admixtures in RCCP may provide the same advantages of enhancing workability and retarding set time as they do in CCP. Laboratory tests have shown that these admixtures are effective in reducing the vibration time required for consolidation of RCC when used at their normal dosage rates (1). Some obvious advantages of these enhanced properties in RCCP placement are easier handling and spreading with the paver and better surface texture and smoothness after compaction. Retarding the set time at the joints would allow or at least ensure that live joints are formed. Fly ash has been used to replace portions of the cement in RCCP at Ft. Hood and in Canada, resulting in a material cost savings with the added benefit of increased workability of the concrete. Attempts to entrain air using air-entraining admixtures (AEA's) have not been very successful, according to laboratory test results from the North Pacific Division of the US Army Corps of Engineers (7). These results are by no means conclusive that AEA's may not be used successfully in RCCP, however, and the use of these and other admixtures merits future study.

Thickness Design

Thickness design for RCCP has also closely followed that for CCP. Laboratory tests on specimens cut from the Ft. Stewart and Ft. Hood test sections have shown that actual flexural strengths of beams cut from the RCCP were from 25 to 30 percent higher than the flexural strength used for thickness design taken from the design manual, Army Technical Manual 5-822-6 (8). The excellent performance of the RCCP in Canada after enduring repeated heavy loads and freeze-thaw cycles, while the CCP was badly broken, suggests that the RCCP thickness could be overdesigned. Data need to be gathered to determine flexural strength, base and/or subgrade strength, design loads, and coverage relationships to confirm the adequacy of using current rigid pavement thickness design curves for RCCP.

Joints

Much attention has been given to the matter of jointing in RCCP. While there is still much to be learned on this subject, paving experience has generated some ideas on construction of cold joints, spacing of sawed contraction joints, sawing of contraction joints, and using load-transfer devices.

A cold joint in RCCP is analogous to a construction joint in CCP. Cold joints are usually formed when there is some time delay between placing adjacent lanes, such as at the end of the day's construction. A cold joint in RCCP is formed between two adjacent lanes when the first lane has hardened to the extent that it cannot be consolidated with the fresher second lane. This hardening may take from 1 hour to several hours, depending on the properties of the mix and environmental conditions. Because of this hardening, the fresher lane tends not to bond to the hardened lane, resulting in a rough vertical crack through the thickness of the pavement.

The stiff consistency of RCCP does not lend itself to the easy application of such load-transfer devices as dowels or keyed joints, although dowels were used successfully at Ft. Stewart. However, the very good performance of RCCP cold joints in the British Columbia RCCP projects (5) suggests that some amount of load transfer develops at the joint. This could be attributed to the very rough vertical face of the RCCP at the cold joint allowing a vertical load transfer across the joint equivalent to that transferred by the aggregate interlock of contraction joints in CCP. Nondestructive testing (NDT) of the existing RCCP at Ft. Hood and Ft. Stewart should indicate the extent of any load transfer across cold and contraction joints.

Another difference in the jointing procedures of RCCP and CCP is the longitudinal spacing requirement between transverse contraction joints. While typical spacing of CCP contraction joints may range from 3.8 to 7.6 m (12.5 to 25 ft) (8), measurement of spacings between naturally forming shrinkage cracks in RCCP consistently shows distances ranging from 4.2 to 27.4 m (30 to 90 ft), with most in the 15.3- to 21.3-m (50- to 70-ft) range (9). This increased spacing is attributed to the lower water content of RCCP which reduces the shrinkage that occurs as the concrete ages. This could result in typical spacing of transverse contraction joints of approximately 15.3 m (50 ft). Larger spacings between contraction joints mean fewer necessary sawed joints, resulting in a further savings in labor costs. It should be noted at this point that the majority of RCCP placed at this time, both in the United States and Canada, has been allowed to crack naturally, with little or no obvious joint deterioration or spalling (5).

In Situ Properties

Many of the in situ properties of RCCP are similar to those for CCP. The unit weight of RCCP is typically slightly higher than that for CCP, usually ranging from 2,400 to 2,560 kg/cu m (150 to 160 pcf), depending upon the compaction effort, moisture content, and properties of the ingredients, such as the specific gravity of the aggregates. Predictably, the higher densities also result in higher flexural strengths, ranging from 4,758 to 7,033 kPa (690 to 1020 psi) in 28 days at Ft. Hood. In situ moisture contents, as measured by a nuclear density gage, typically varied from 3.5 to 4.0 percent at Ft. Hood. Although the accuracy of such devices for measuring moisture contents is questionable, the computed moisture content based on saturated surface-dry material was 3.6 percent (10). Cement content varies according to the construction procedure and mix design used. In Canada, where two-lift construction of RCCP predominated, the upper lift contained about 12 percent cementitious material by weight, while the lower lift contained about 8 percent. Most of this cementitious material consisted of about 25 percent fly ash. When a single-lift construction procedure was used, such as in Ft. Hood, the cementitious material contained in the mix was 11 percent by weight, with about one-third of this being fly ash.

Efforts have been made with limited success to fabricate cylinders and beams in the field and in the laboratory using RCC that would duplicate in situ strengths and densities taken from RCCP cores and sawed beams. It is very important to have the ability to produce samples that will be representative of in situ pavement properties, not only for proper preparation of RCCP laboratory samples for testing, but also for construction quality control and quality assurance purposes. Currently, RCCP samples are made in the field by placing fresh RCC in the beam or cylinder mold, externally vibrating the mold by placing it on a vibrating table, and putting a surcharge weight on the concrete surface. Concrete is added and consolidated until the mold is full and a grout forms at the concrete surface. This method requires subjective judgment by the person making the sample, which accounts for the inconsistent strength results obtained in the past. Much better precision is achieved in the test results of specimens prepared in the lab, although the strengths tend to be higher than the field-prepared specimens. Work is presently being done at WES to devise a means of fabricating field and laboratory specimens that accurately represent in situ RCCP properties.

The surface texture of RCCP is typically similar to that of an asphaltic concrete pavement (ACP) surface. There are small voids (less than 3 mm (1/8 in.) deep) formed where there is insufficient paste or compaction to fill in all the space between the aggregate particles at the surface. A better, tighter surface texture usually results from a mix with a higher percentage of fines and a smaller (19 mm (3/4-in.) or less) allowable maximum-size aggregate. This is reflected in the fact that the Canadians have allowed the amount of material passing the No. 200 sieve to increase to an 8 percent maximum to help provide a better surface finish.

Smoothness in RCCP is measured as the maximum vertical distance from the pavement surface to the bottom of a 3.05-m (10-ft) straightedge resting upon the pavement surface. The maximum allowable tolerance in RCCP is usually set at 10 mm in 3 m (3/8 in. in 10 ft), and most RCCP placed to date falls well within this limit. The degree of smoothness achieved with RCCP depends largely upon the skill of the spreader and roller operators and upon the consistency properties of the RCCP, which is affected by the moisture content and maximum size of aggregate. The skill of the roller operator plays a larger role in achieving smoothness in RCCP than in ACP. RCCP is usually placed in thicker lifts than ACP, which tends to magnify deviations in smoothness over those that occur in the thinner lifts that are typical of ACP.

Experience has shown that the durability of RCCP in relation to weathering resistance is very good, despite the fact that it has been difficult to entrain air in RCCP. Laboratory freeze-thaw tests (ASTM C 666) conducted on samples of RCCP from British Columbia, Canada (11), and Ft. Stewart, Georgia (12), indicate that the frost resistance of the concrete is probably not satisfactory. However, RCCP projects in Canada have shown no evidence of freeze-thaw deterioration after enduring 6 to 7 years of numerous freeze-thaw cycles per year (5). This good weathering resistance has been attributed to the high densities attained in the RCCP that inhibit saturation of the concrete by water, thus minimizing freeze-thaw problems. As mentioned earlier, freeze-thaw cycling of in situ RCCP at CRREL is currently being conducted in an attempt to model more accurately the freeze-thaw deterioration observed in the field. Visual observations of the RCCP surfaces in Canada also indicates a higher resistance to impact, abrasion, and wear than CCP surfaces, which could be due to higher compressive strengths of the RCCP.

RCCP Construction Observations/Practices

The type of equipment used in RCCP construction is virtually identical to that used in mixing, transporting, placing, and compacting ACP. Continuous mixing pug mills with capacities ranging from 590,000 to 725,000 kg (650 to 800 tons) per hour have been used successfully in Canada and at Ft. Hood, Texas, to thoroughly mix the stiff RCC. The fine and coarse aggregates are fed into the main conveyor through control gates, with the cement and/or fly ash discharged from their storage hoppers directly onto the aggregate through an adjustable vane feeder. The dry ingredients then discharge into the pug mill, where the water is added. After thorough mixing, the concrete is fed by conveyor into an awaiting heavy-duty dump truck, which is used to transport the concrete to the paver. It has been recommended that haul time between the mixing plant and the paver should not exceed 15 minutes, and the concrete should not be transported over a distance greater than 2 miles.

RCCP has been mixed with some success in a drum mixer that is either at the plant or on the transport truck. This method is best used when relatively clean aggregates are used with a minimum of fines present in the RCCP mix. Excessive fines tend to clump into balls and not mix thoroughly with the small amount of water present in the mix. However, the pulverizing action of the pug mill breaks up these balls and blends the water more thoroughly into the mix. There was also some problem with discharging the RCC from rotating drum truck mixers at Ft. Stewart. The trucks had to be tilted backwards on a ramp inclined some 30° in order to discharge the RCC into front-end loaders for placement. This problem could probably be alleviated by cleaning the interior of the drum so that a smooth surface is provided the RCC to slide against when it discharges. New truck mixers were used to mix the RCC at Ft. Stewart in September 1984, and they discharged the mix directly onto the ground with no problem.

The RCCP is placed with asphaltic concrete pavers, modified slightly to handle the RCCP. Automatic grade control devices, such as the traveling ski, are used to maintain a satisfactory grade. Manual grade control was used at Ft. Hood with good results. Some pavers have a tamping screed action which tends to place the RCCP better than vibrating screeds.

The RCCP is compacted with a heavy steel-wheel vibratory roller making three to four passes over the surface to achieve the desired density. Thirty to forty-five centimeters (12 to 18 in.) of uncompacted material is left along the edge of the lane to allow the paver to use this surface for uniform grade control when placing the adjacent lane, and to allow the joint between the two lanes to be compacted simultaneously in order to achieve a smooth, dense joint. After rolling, the in situ density is checked immediately with a nuclear density gage to ensure that adequate compaction has been achieved. A 9000-kg (10-ton) steel-wheel dual-drum vibratory roller operating at high frequency (around 2000 vibrations per minute) and amplitude at speeds from 3.2 to 4.8 km/hour (2 to 3 mph) achieved good density results at Ft. Hood, Texas. After primary compaction with the heavy roller, one or two passes with a heavy (18,000-kg (20-ton)) pneumatic-tired roller and/or a light (4,500- to 9,000-kg (5- to 10-ton)) dual-drum nonvibratory roller is used for final surface finishing.

When it is necessary to form a cold joint, such as at the end of a construction day or due to an equipment breakdown, the RCCP is rolled completely to the side or edge of the lane with the roller. Before the paving is continued, the lane is trimmed with a motor grader or by workmen with shovels in an attempt to form a smooth and clean vertical face. In Canada, two pavers working in echelon were used to minimize the number of cold joints created.

Various curing procedures have been used for RCCP. In Canada, an irrigation sprinkler system kept the pavement wet for 7 days; then an asphalt emulsion was applied for moisture retention. At Ft. Stewart, Georgia, a layer of sand was spread over the pavement surface and thoroughly dampened. At Ft. Hood, a dual curing procedure was implemented initially. First, a cotton curing mat was placed on the surface and wetted. After 24 hours, the mat was removed and a white, membrane-forming curing compound was applied to the RCCP surface. This procedure was later modified to eliminate the use of the curing mat, and the curing compound was applied immediately to the surface. Because of the low water content of RCCP, which fosters a more rapid surface drying effect, the surface of the RCCP must not be allowed to dry before the curing compound is applied to ensure that the full strength of the RCCP surface develops. Spalling occurred during the sawing of joints at Ft. Hood and may have been the result of improper curing techniques.

Quality Control/Assurance

Quality control procedures in the United States and Canada have consisted of testing the materials going into the concrete mix, checking the density of the RCCP using nuclear density gages, and checking the smoothness of the finished RCCP with a straightedge. Quality assurance procedures include taking core and beam samples from the RCCP and testing them for density, strength, and durability. As mentioned previously, proper field sample fabrication methods must be developed to aid in simplifying quality control procedures.

Conclusions and Recommendations

Roller-compacted concrete pavements provide a strong, durable pavement at less cost than conventional concrete pavement. RCCP's combine the strength of conventional concrete pavements with the ease of asphaltic concrete pavement placement. RCCP has proven its ability to perform well under adverse environmental conditions and has demonstrated expediency of construction in areas where heavy, low-speed equipment is the primary user of the pavement. Under well controlled construction procedures with the proper materials and mixture proportioning, surface smoothness adequate for high-speed traffic is attainable.

The US Army Corps of Engineers is taking the initiative in developing mix and thickness design procedures, proper construction procedures, and quality control procedures. The development of these procedures offers some unique challenges, but these are minimal in comparison to the vast potential savings involved.

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