ACI 309.5R-00

(Reapproved 2006)

Compaction of Roller-Compacted Concrete

Reported by ACI Committee 309

Richard E. Miller, Jr.
Chairman

Neil A. Cumming	Glen A. Heimbruch	Celik H. Ozyildirim
Timothy P. Dolen	Kenneth C. Hover	Steven A. Ragan
Chiara F. Ferraris	Gary R. Mass	Donald L. Schlegel
Jerome H. Ford	Bryant Mather	Mike Thompson
Steven H. Gebler	Larry D. Olson	Brad K. Voiletta

Roller-compacted concrete (RCC) is an accepted and economical method for the construction of dams and pavements. Achieving adequate compaction is essential in the development of the desired properties in the hardened material. The compaction depends on many variables, including the materials used, mixture proportions, mixing and transporting methods, discharge and spreading practices, compaction equipment and procedures, and lift thickness. The best performance characteristics are obtained when the concrete is reasonably free of segregation, well-bonded at construction joints, and compacted at, or close to, maximum density.

Compaction equipment and procedures should be appropriate for the work. In dam or massive concrete applications, large, self-propelled, smooth, steel-drum vibratory rollers are used most commonly. The frequency and amplitude of the roller should be suited to the mixture and lift thickness required for the work. Other roller parameters, such as static mass, number of drums, diameter, ratio of frame and drum mass, speed, and drum drive influence the rate and effectiveness of the compaction equipment. Smaller equipment, and possibly thinner compacted lifts, are required for areas where access is limited.

Pavements are generally placed with paving machines that produce a smooth surface and some initial compacted density. Final density is obtained with vibratory rollers. Rubber-tired rollers can also be used where surface tearing and cracks would occur from steel-drum rolling. The rubber-tired rollers close fissures and tighten the surface.

Inspection during placement and compaction is also essential to ensure the concrete is free of segregation before compaction and receives adequate coverage by the compaction equipment. Testing is then performed on the compacted concrete on a regular basis to confirm that satisfactory density is consistently achieved. Corrective action should be taken whenever unsatisfactory results are obtained. RCC offers a rapid and economical method of construction where compaction practices and equipment are a major consideration in both design and construction.

Keywords: compaction; consolidation; dams; pavements; roller-compacted concrete.

CONTENTS

ACI 309.5R-00 became effective February 23, 2000.

CHAPTER 1—INTRODUCTION

1.1—General

Roller-compacted concrete (RCC) has become an accepted material for constructing dams and pavements, rehabilitating and modifying existing concrete dams, and providing overflow protection of embankment dams and spillways. Its production provides a rapid method of concrete construction similar in principle to soil-cement and other earthwork construction. RCC technology developed considerably in the 1980s, after early research by Cannon (1972), Dunstan (1977), Hall and Houghton (1974), and the development of the roller-compacted dam (RCD) method in Japan in the 1970s. Also, in the 1980s, RCC was developed as a heavy-duty paving material for log sorting yards, tank hardstands, railroad sorting yards, and other industrial pavements. It also found application in roadways and parking areas. Detailed information on the use of RCC in mass concrete and paving applications is contained in ACI 207.5R and ACI 325.10R, respectively.

1.2—Scope and objective

This report presents a discussion of the equipment and special construction procedures associated with the compaction of RCC. It includes characteristics of the mixture relevant to compaction and the effects of compaction on desired properties of RCC. These properties include various strength parameters, watertightness, and durability. Differentiation is made between RCC used in massive concrete work and that used in pavements. The discussion also includes provisions for measurement of compaction. This report does not cover soil-cement or cement-treated base.

The objective of this report is to summarize experience in compaction of RCC in various applications, to offer guidance in the selection of equipment and procedures for compaction, and in quality control of the work.

1.3—Description

According to ACI 116R, roller-compacted concrete is defined as "concrete compacted by roller compaction that, in its unhardened state, will support a roller while being compacted." ACI 116 further defines roller compaction as "a process for compacting concrete using a roller, often a vibrating roller."

RCC construction involves placement of a no-slump concrete mixture in horizontal lifts ranging from 150 to 600 mm (0.5 to 2 ft) thick and compaction of this mixture, normally with a smooth-drum, vibratory roller. For RCC dams, multiple lifts of concrete, generally 300 mm (1 ft) thick, are continuously placed and compacted to construct a cross section that is similar to a conventional concrete gravity dam. Another RCC placing method is to spread three or more thinner (typically approximately 230 mm [9 in.]) layers with a bull-dozer before compacting them into one thick lift with a vibratory roller. One significant difference between an RCC dam and a conventional concrete dam is the continuous placing of a horizontal lift of concrete from one abutment to the other, rather than constructing the dam in a series of separate monoliths. A horizontal construction joint is produced between each lift in the RCC dam. In paving applications, individual lanes of concrete are placed adjacent to each other to construct a pavement ranging from 150 to 250 mm (6 to 10 in.) thick. The procedure is similar to asphalt-paving techniques. In some instances, two or more lifts of RCC are quickly placed and compacted to construct a thicker, monolithic pavement section for heavy-duty use.

Several steps are required to achieve proper compaction of RCC construction: 1) A trial mixture should be developed using appropriate testing methods to determine the optimum consistency and density for each application; 2) A trial section should be constructed to validate the number of passes and establish the required moisture content and density; 3) The RCC should be placed on freshly compacted material, or, if the surface is not freshly compacted or is the start of a new lift, place a more workable mixture, or place over a bond layer of mortar; 4) For dams, roll from one abutment to the other continuously; 5) For pavements, roll immediately behind the paver and place the next lift within 1 h; 6) Roll the proper number of passes before placing the next lift; 7) Use a tamper or small compactor along edges where a roller cannot operate; and 8) Maintain a site quality-control program. The details of proper compaction and the ramifications of improper compaction are provided in the following chapters.

1.4—Terminology

The terms compaction and consolidation have both been used to describe the densification process of freshly mixed concrete or mortar. In ACI 309R, consolidation is the preferred term used for conventional concrete work. For the purposes of this document on roller-compacted concrete, however, the term compaction will be used for all types of RCC mixtures, because it more appropriately describes the method of densification.

1.5—Importance of compaction

The effect of compaction on the quality of RCC is significant. Higher density relates directly to higher strength, lower permeability, and other important properties. RCC mixtures are generally proportioned near the minimum paste content to fill voids in the aggregate, or at a water content that produces the maximum density when a compactive effort equivalent to the modified Proctor procedure (ASTM D 1557) is applied. The use of RCC in either massive structures or pavement construction needs to address the compaction of each lift because of its influence on performance. Failure to compact the concrete properly can cause potential seepage paths and reduce the stability in RCC dams or reduce the service life of RCC pavements.

In the 1980s, core sampling from RCC dams revealed instances of voids and low density in the lower one-third of lifts of RCC that had been placed and compacted in 300 mm (1 ft) lifts (Drahushak-Crow and Dolen 1988). Lower density at the bottom of lifts can be attributed to lack of compactive effort but is more commonly due to segregation of the mixture during the construction process. This segregation causes excessive voids in the RCC placed just above the previously compacted lift. Segregation is a major concern in dams due to the potential seepage path and the potential for a continuous lift of poorly bonded RCC from one abutment to the other that could affect the sliding stability. RCC dams constructed in earthquake zones can also require tensile strength across the horizontal joints to resist seismic loading. At Willow Creek Dam, seepage through a nonwatertight upstream face, and segregation at lift lines required remedial grouting (U.S. Army Corps 1984). This RCC dam was considered safe, from a sliding stability standpoint, due to its conservative downstream slope of 0.8 horizontal to 1.0 vertical. Recent innovations in South Africa (Hollingworth and Geringer 1992) and China have included the construction of RCC arch-gravity dams with very steep downstream slopes where bonding across lift joints is critical to the stability of these structures.

In pavements, flexural strength is dependent on thorough compaction at the bottom of the pavement section, while durability is dependent on the same degree of compaction at the exposed surface. Furthermore, construction joints between paving lanes are locations of weakness and are particularly susceptible to deterioration caused by freezing and thawing unless good compaction is achieved.

CHAPTER 2—MIXTURE PROPORTIONS

2.1—General

RCC mixtures should be proportioned to produce concrete that will readily and uniformly compact into a dense material with the intended properties when placed at a reasonable lift thickness. Procedures for proportioning RCC mixtures are provided in ACI 211.3R, ACI 207.5R, and ACI 325.10R.

The ability to compact RCC effectively is governed by the mixture proportioning as follows:

- Free-water content;
- Cement plus pozzolan content and cement: pozzolan ratio;
- Sand content, grading, and amount of nonplastic fines (if used);
- Nominal maximum size of aggregate;
- Air-entraining admixtures (if used); and
- Other admixtures (water-reducing, retarding or both).

For a given ratio of cement plus pozzolan, sand, fines (passing the 75µm [No. 200]) sieve, and coarse aggregate, the workability and ability to compact RCC effectively will be governed by the free-water content. As the water content increases from the optimum level, the workability increases until the mixture will no longer support the mass of a vibrating roller. As the water content decreases from the optimum level, sufficient paste is no longer available to fill voids and lubricate the particles, and compacted density is reduced.

RCC mixtures have no measurable slump, and the consistency is usually measured by Vebe consistency time in accordance with ASTM C 1170. The Vebe time is measured as the time required for a given mass of concrete to be consolidated in a cylindrically shaped mold. A Vebe time of 5 seconds (s) is similar to zero-slump concrete (no-slump concrete), and at such consistency, it is difficult to operate a roller on the surface without weaving, pumping, and sinking. For RCC mixtures used in dam work, a Vebe time of approximately 15 s is suitable for compaction in four to six passes with a dual-drum, 9 tonne (10 ton) vibratory roller. A normal range would be 15 to 20 s. At Victoria Dam Rehabilitation, the Vebe consistency of RCC ranged from approximately 15 to 20 s in the laboratory. In the field, the water content of the RCC was decreased and the Vebe consistency increased to approximately 35 to 45 s (Reynolds, Joyet, and Curtis 1993). The Vebe consistency test was not as reliable an indicator of workability at these consistency levels. Compaction was achieved by up to eight passes with a 9 tonne (10 ton) dual-drum vibratory roller at this consistency. RCC mixtures with a high consistency time, up to 180 s, have been compacted in the laboratory. RCC of this consistency required two to three times more compactive effort to achieve the equivalent percent compaction than mixtures with a lower consistency (Casias, Goldsmith, and Benavidez 1988). A Vebe time of 30 to 40 s appears to be more appropriate for RCC pavement and overtopping protection mixtures.

Lean RCC mixtures can benefit from the addition of nonplastic fines (material passing the 75 µm [No. 200] sieve) to supplement the cementitious paste volume and reduce internal voids between aggregate particles. For these mixtures, the increased fines improve handling and compactability (Schrader 1988). Lean RCC mixtures have no measurable consistency and the optimum water content for compaction is determined by visual inspection during mixing and compaction (Snider and Schrader 1988). If the moisture content is too low or there is insufficient rolling, the density at the bottom of the lifts is reduced and the bond between lifts is usually poor. This problem is easily corrected by first placing a bonding mortar or thin layer of high-slump concrete on the surface of the previously placed and compacted lift to bond the two together.

The fine aggregate content of RCC mixtures can affect compactability of RCC, though to a lesser degree than water content. RCC mixtures are less susceptible to segregation during handling and placing if the fine aggregate content is increased over that which is recommended for conventional concrete mixtures.

Fly ash (Class F or C) and water-reducing and retarding admixtures can be beneficial in the compaction of RCC mixtures. The effectiveness of these materials, however, depends on the specific mixture composition. Fly ash, when used to replace a portion of the cement, can decrease the water requirement of mixtures having a measurable consistency (ACI 207.5R). Fly ash can also be used as a mineral filler in low paste volume mixtures to increase workability and density of the RCC. At Elk Creek Dam, using water-reducing, set-controlling admixtures reduced the water content of RCC approximately 14%, and reduced the Vebe consistency from 20 to 10 s compared with mixtures without the admixture. This improved the workability of the mixture and the ease with which the RCC could be consolidated (Hopman and Chambers 1988).

Air-entraining admixtures improve both the workability of fresh RCC and resistance to freezing and thawing of hardened RCC (Dolen 1991). The dosage of air-entraining admixture may have to be increased to achieve air-entrained RCC meeting the desirable ranges of air-void parameters found in conventional air-entrained concrete. Entraining a consistent amount of air in RCC is difficult, particularly with mixtures having no measurable slump. Air-entraining admixtures should be tested for effectiveness with project materials, mixing, and placing equipment before being specified. The pressure air content of RCC can be tested using a standard air meter attached to a vibratory table with a surcharge for consolidating the sample.

2.2—Moisture-density relationship

RCC mixtures have also been proportioned using soil-compaction methods that involve establishing a relationship between dry or wet density and the moisture content of the RCC. The method is similar to that used to determine the relationship between the moisture content and density of soils and soil-aggregate mixtures (ASTM D 1557). This method can result in a mixture that has inadequate paste to completely fill voids between aggregate particles at the optimum moisture content and consequently, depends more on expulsion of voids through compactive effort. For a given compactive effort, the optimum moisture content of a mixture proportioned using this method is defined as the peak of the moisture-density curve, and is dependent on the properties of the aggregates used and the cementitious material content. Strength loss will occur in a mixture that has a moisture content below the optimum moisture content due to the presence of additional entrapped air voids. Strength loss will also occur in a mixture if the moisture content is significantly above optimum due to an increase in the water-cementitious materials ratio (*w/cm*). The strength loss above the optimum moisture content is not as dramatic as the strength loss below optimum, because more paste volume is available for bonding particles (Reeves and Yates 1985).

2.3—Coarse aggregate

The nominal maximum size aggregate (NMSA) normally affects the ease of compaction of RCC due to the tendency of large aggregate to segregate from the drier, no-slump mixture and to form rock pockets on the construction joints. For mass RCC placed in 300 mm layers, the NMSA in RCC mixtures should not exceed 75 mm (3 in.), and good placing control should be maintained. The NMSA of some RCC mixtures has been increased to 150 mm (6 in.) by placing multiple 200 mm (8 in.) layers by bulldozing and compacting the mass into a 750 mm (30 in.) lift with vibratory rollers followed by pneumatic tire rollers (Ministry of Construction, Japan 1984). The current trend is to use 37.5 to 50.0 mm (1-1/2 to 2 in.) NMSA to minimize segregation problems. In RCC pavement mixtures a 19.0 mm (3/4 in.) NMSA is recommended for producing a relatively smooth surface texture (ACI 325.10R).

In addition to NMSA, the degree to which the aggregate grading is controlled will have a significant influence on the uniformity of RCC properties, the ease of compaction, and achieving uniform density of the mixture. Where close grading control is desired, coarse aggregate should be produced and batched in separate size ranges as recommended in ACI 304R. Some facilities have cut costs in stockpiling and batching by using a single-graded aggregate or by increasing the size range of the stockpiled material. This practice, however, can increase the variation in total grading of the aggregate in stockpiles and cause difficulty in producing uniform RCC mixture during construction.

Coarse aggregate quality can also affect compaction. Aggregates of low physical strength can break down during compaction and produce variation in density. Some RCC projects have satisfactorily used aggregates of marginal quality (Parent, Moler, and Southard 1985).

CHAPTER 3—EFFECTS ON PROPERTIES

3.1—General

Proper compaction of RCC is essential to achieve the necessary properties intended for performance and design life. The degree of compaction influences strength, watertightness, and durability of RCC.

3.2—Strength

Although the strength of RCC is a function of many variables, the degree of compaction throughout its entire thickness is perhaps the most significant. For each 1% of air that can be removed from any concrete by consolidation that is not removed, the compressive strength is reduced by approximately 5%. Test results from many RCC paving projects indicate that small reductions in pavement density cause relatively large reductions in both compressive and flexural strengths (Rollings 1988). A 5% reduction in the density of cores taken from several Australian pavements resulted in an approximate reduction in compressive strength of 40%. Abrams and Jacksha (1987) reported a 2.3% decrease in RCC pavement density in Oregon that resulted in a 11% decrease in flexural strength. Rollings also noted that the performance of RCC pavements is adversely affected when adequate compaction is not achieved at the bottom of the lift. The bottom of the pavement section (where the highest stresses from loading occur) was 25% weaker in flexure tests than the top of the pavement (Rollings 1988). At Galesville Dam, Oregon, the compressive strength of cores from a mixture with a higher cement plus pozzolan content than the interior concrete had a lower compressive strength due to lower density in this outer facing zone of RCC (Drahushak-Crow and Dolen 1988).

Flexural fatigue failure occurs in pavements when the concrete cracks due to continued repetitions of loads that cause stresses less than the static flexural strength of the concrete. The U.S. Army Engineer Waterways Experiment Station conducted flexural fatigue tests on laboratory specimens compacted by external vibration to a density of approximately 98% of the theoretical air-free density. The test results indicated that both the flexural and flexural fatigue resistance of a typical RCC mixture are comparable to those of conventional concrete paving mixtures (Pittman and Ragan 1986). Tayabji and Okamoto (1987B) also found that the fatigue behavior of beams sawn from a well-compacted RCC test section was similar to that of conventional concrete.

The direct tensile strength or tensile bond strength of RCC lift joints is critical in multiple-lift pavements because it determines whether the pavement will behave as a monolithic section or as separate, partially bonded or unbonded lifts. The load-carrying capacity of a pavement consisting of partially bonded or unbonded lifts is significantly less than that of bonded lifts of equal total thickness. For the pavement to function as a monolithic section, the joint tensile strength should be at least 50% of the parent concrete tensile. The joint strength for untreated cold or construction joints is generally less than 50% of the parent (unjointed) concrete. Cores taken from RCC test pads at the Tooele Army Depot in Utah and tested for direct tensile strength, however, indicated that 60 to 90% of the parent concrete tensile strength can be achieved if the time between placement and compaction of the lifts is limited to 30 to 50 min (Hess 1988). Placing and compaction within the time limits was achieved by using two pavers in echelon. Direct shear test data from cores taken from Conley Terminal in Boston, Mass. indicated strength development along edges of longitudinal construction joints was approximately half the strength as that of interior lane locations.* The unconfined edge of an RCC pavement lane tends to be incompletely compacted, particularly when compared to the interior portions of the lane. Bond along longitudinal construction joints can be improved by complete removal of loose, uncompacted material along the edge of the lane and by use of moisture curing immediately after placing, using a bedding mortar along the joint, and better compaction techniques.

An important aspect in the analysis of concrete dams is the factor of safety against sliding. The shear-friction factor of safety, Q, is governed by the equation expression:

$$Q = \frac{CA + (\Sigma N + \Sigma U)\tan\Phi}{\Sigma V}$$

where C = the unit cohesion between lift joints; $\tan\Phi$ = the frictional resistance of the joint between lifts; and N, U, and V = the normal, uplift, and shear forces, respectively. In typical static analysis of conventional concrete dams, monolithic behavior is assumed, with full bond between lifts of concrete. These assumptions were based on extensive testing and evaluation of modern conventional concrete gravity dams (U.S. Department of the Interior 1976). Cores from RCC dams show that the assumption of 100% bond between lifts of RCC is not realistic for all cases. At Galesville Dam, Oregon, approximately 25% of the construction joints without bedding concrete were bonded, primarily due to lack of compaction. The degree of compaction directly affects the compressive and tensile strength and density of the RCC. A fully compacted lift will have significantly higher strength and bond properties than a poorly compacted lift. In poorly compacted or segregated lifts the density is generally less in the lower one-third of the lift thickness, creating a zone of porous concrete. At Upper Stillwater Dam, the cohesion of cores with voids at the lift line interface was 56% lower than cores with full consolidation at the lift line (Drahushak-Crow and Dolen 1988). Tests performed by the Portland Cement Association show a direct relationship between density and strength (Tayabji and Okamoto 1987A). Concern for stability can also arise from uncontrolled, poor compaction at the foundation. A bedding of fresh concrete, approximately 50 mm (2 in.) deep, should be placed on the foundation rock and the RCC compacted into it to ensure a bonded contact (Arnold and Johnson 1987).

Tensile stresses can develop along lift lines in RCC dams under dynamic loading conditions. Poor compaction, segregation, poor curing, or excessive time before placing the next lift tend to decrease the tensile bond between successive RCC lifts. Where tensile strength is required between lifts, either a high paste RCC mixture, or using a bedding mortar or concrete between lifts, has achieved satisfactory results (Tayabji and Okomoto 1988A).

3.3—Watertightness

Seepage water flowing through poorly compacted zones of RCC is undesirable. Seepage can saturate the concrete and result in poor resistance to freezing and thawing in severe climates (Dolen 1990). At both Willow Creek Dam and Galesville Dam in Oregon, the products of degradation of organic matter in the reservoir entered into the gallery through cracks and seepage through low-density lift lines producing low concentrations of hydrogen sulfide gas (U.S. Department of the Interior 1986). This condition required ventilation before entering the gallery and has corroded steel embedments.

Although localized seepage does not pose a threat to the safety of RCC dams, it is aesthetically unpleasing. Seepage is usually collected and returned to the stream or river channel. Watertightness can be ensured by having a mixture consistency suitable for compaction, by avoiding segregation, and by achieving uniform density of the lift from top to bottom through adequate compaction.

3.4—Durability

The resistance of RCC pavement to freezing and thawing, like that of conventional pavement, is largely dependent on the existence of a proper air-void system within the concrete.

* Tayabji, S.D., 1987, *Unpublished data on core testing at Conley Terminal*, Boston; ACI 325.10.R.

Many pavements in the northwestern U.S. and in western Canada have been constructed on non-air-entrained RCC and are performing well to date in spite of the fact that they experience numerous cycles of freezing and thawing each year. Ragan (1986) determined that samples taken from several of these pavements did, in fact, have average spacing factors that approached or were less than 0.20 mm (0.008 in.), despite the fact that no air-entraining admixtures were used. Thorough compaction was thought to be partially responsible for this phenomena. Microscopic examination of samples taken from an air-entrained RCC test section at Ft. Drum, N.Y., indicated that air bubbles entrained during the mixing of the concrete were not removed or unduly distorted as a result of the placing and compacting operations.*

Inadequate compaction of RCC pavements also increases durability concerns. Field experience shows performance and durability of RCC pavements depends, to a large extent, on the quality and tightness of the surface finish. Because of this, compaction of RCC pavement should achieve both high density, high quality, tight and even surface texture that is free of checking, rock pockets, and other defects that can initiate premature raveling at edges and joints. Ragan, Pittman, and Grogan (1990) cite numerous examples of RCC pavements that have experienced raveling and deterioration, particularly at longitudinal construction joints, due to reductions in density. They also presented test results that indicate the resistance of non-air-entrained RCC to rapid freezing and thawing can be improved as the density increases because it becomes more difficult for water to enter the concrete and critically saturate it.

Thorough compaction of RCC pavements improve their resistance to abrasion. Abrasion and surface raveling can be particularly prevalent along longitudinal and transverse joints where the relative density can be up to 10% less than that of the interior portion of the pavement. Proper compaction along the joints can be ensured by minimizing the time between placement of lanes so that compaction at the joint is completed in a timely manner.

The committee is not aware of any research that has been done that relates compacted density directly to erosion resistance. Erosion resistance generally is a function of compressive strength and indirectly proportional to compacted density.

CHAPTER 4—EQUIPMENT

4.1—General

Equipment for compaction of granular soils or asphaltic pavements is satisfactory for compacting RCC (Anderson 1986). Such equipment includes large, self-propelled, dual-drum vibratory rollers; walk-behind vibratory drum rollers; and hand-held power tampers. Larger equipment is used in open areas for high production where maneuverability is not a concern. Smaller-size vibratory rollers and hand-held equipment is used where access is limited (such as adjacent to structures) or where safety concerns limit the use of larger equipment (such as along the downstream face of dams).

RCC pavement is generally placed with a modified asphalt paving machine that provides 90 to 95% of the maximum density (Keifer 1988). Full compaction of pavement is completed with a large vibratory roller or vibratory roller used in combination with a rubber-tired roller that produces a smooth surface texture and seals the surface.

4.2—Vibratory rollers

Large, self-propelled, vibrating rollers are designed for two different purposes: compaction of granular soil and rock, and compaction of asphaltic paving mixtures. The type of compaction and lift thickness influences the design and operating characteristics of the vibratory rollers. According to Forssblad (1981A) "Vibratory rollers designed to compact large volumes of soil and rock-fill in thick layers should have an amplitude in the range of 1.5 to 2 mm (0.06 to 0.08 in.). The corresponding suitable frequency is 25 to 30 Hz (1500 to 1800 vibrations/min). For asphalt compaction, the optimum amplitude is 0.4 to 0.8 mm (0.02 to 0.03 in.) and the suitable frequency range of 33 to 50 Hz (2000 to 3000 vibrations/min). Rollers with these characteristics can, with good results, also be used for compaction of granular and stabilized bases." The frequency and amplitude of both types of vibratory rollers significantly influences effective RCC compaction. The high-amplitude and low-frequency rollers are best suited for less-workable RCC mixtures and thicker lifts. The low-amplitude and high-frequency rollers (Fig. 4.1) are better suited for more-workable (having a measurable Vebe consistency) RCC mixtures and thinner lift construction. Water content can not be used as a guide for estimating consistency for different mixtures because they can be proportioned with or without nonplastic fines that affect absorption by the aggregates.

Other parameters also influence optimal and economical compaction of RCC by vibratory rollers. These parameters include:

4.2.1 *Static mass (static linear load)*—The static linear load is the static mass of the roller divided by the total length of roller drum(s). It is approximately proportional to the effective depth effect of compaction. Equipment is selected according to the RCC lift thickness. Withrow (1988) suggests an average static linear load of 20 kg/cm (115 lb/in.) for compacted lifts up to 150 mm (6 in.) and a minimum of 27 kg/cm (150 lb/in.) for compacted lifts greater than 150 mm (6 in.).

4.2.2 *Number of vibrating drums*—The number of vibrating drums is one of the factors that establishes the number of roller passes required to effectively compact RCC. Dual-drum vibrating rollers normally compact workable RCC mixtures in approximately four to eight passes. One pass is defined as a trip from Point A to Point B for a dual-drum roller, and a trip from Point A to Point B and return to Point A for a single-drum roller.

4.2.3 *Roller speed*—Increasing the roller speed requires more roller passes for equivalent compaction. The maximum roller speed for operation and compaction is approximately 3.2 km/hr (2.0 mph).

* Cortez, E. R.; Korhonen, C. J.; Young, B. L.; and Eaton, R. A., 1992, "Laboratory and Field Evaluation of the Freeze-Thaw Resistance of Roller-Compacted Concrete Pavement, Ft. Drum, N.Y.," *ACI Committee 325 Session*, Mar., Washington, D.C.

Fig. 4.1—Compaction of mass RCC using 9 tonne (10 ton) vibratory roller. This mass RCC mixture has a Vebe consistency time of 15 s. Upper Stillwater Dam, Utah (U.S. Department of the Interior 1986).

4.2.4 *Ratio between frame and drum mass*—The ratio of frame to drum mass influences compaction. As with roller speed, there is an upper limit for the frame to drum weight ratio due to equipment operation and design requirements.

4.2.5 *Drum diameter*—The drum diameter is related to the static linear load and affects compaction characteristics of RCC. This parameter affects asphalt more so than soil and rock, and would be a greater concern for more workable RCC mixtures or paving mixtures. At Upper Stillwater Dam, larger diameter rollers had fewer problems with surface checking than the smaller diameter rollers and had less tendency to bog down in wetter mixes (Dolen, Richardson, and White 1988).

4.2.6 *Driven or nondriven drum*—Vibratory drums should be motor driven to ensure adequate drum traction whether the roller is double-drum or single-drum.

4.3—Rubber-tired rollers

Rubber-tired rollers are commonly used to eliminate thin striations or cracking caused by the vibratory roller. These cracks are perpendicular to the direction of travel. The rubber-tired roller follows the vibratory roller for surface compaction of RCC pavement. Several passes of a 9 to 18 Mg (10 to 20 ton) roller will close surface fissures and tighten the surface. Vibratory rollers with rubber-covered steel drums have also been used to tighten the surface texture.

4.4—Small compactors

Smaller-sized compaction equipment, including power tampers (jumping-jack tampers), plate vibrators, and walk-behind vibrating rollers, are normally required to supplement the large vibratory rollers. Power tampers (Fig. 4.2) should be capable of producing a minimum force per blow of at least 8.5 kN (1900 lbf). Power tampers result in deeper compaction of RCC than plate vibrators that are normally effective to only approximately 230 mm (9 in.). The power tampers, however, usually disturb the surface during operation. Plate vibrators should have a minimum mass of 75 kg (165 lb) and can be walk-along or, for mobility, can be mounted on other equipment, such as a backhoe arm for reaching difficult places. Plate vibrators (Fig. 4.3) are suitable for thinner lifts, 150 to 225 mm (6 to 9 in.) and produce a smooth finish. Small walk-behind vibrating rollers can usually be operated within a few inches of a vertical face. These rollers should have a minimum dynamic force of at least 2.6 N/mm (150 lb/in.) of drum width for each drum of a double-drum roller and 5.25 N/mm (300 lb/in.) of drum width for a single drum. The small vibrating drum roller has a higher compaction rate than power tampers or plate vibrators, but at the expense of some loss of maneuverability. To achieve density equivalent to that produced with the heavier vibratory rollers, it may be necessary to reduce or split the lift thickness when using smaller-sized compaction equipment.

Fig. 4.2—Compacting RCC at downstream facing form using power or jumping-jack tamper. Camp Dyer Diversion Dam Modification, Arizona (U.S. Department of the Interior 1992).

4.5—Paving machines

Modified asphalt paving machines (Fig. 4.4) are generally required to produce an acceptable, smooth RCC pavement for vehicular travel speeds up to 40km/hr (25 mph) (Jofre et al. 1988). These machines include a vibrating screed and one or more tamping bars that apply some initial compactive effort to the freshly laid surface. The vibrating screed consists of high-amplitude, low-frequency plates that effectively compact only the top surface so it will not be rutting by subsequent rolling. At the Portland Oregon International Airport,

Fig. 4.3—Surface compaction of RCC using vibrating-plate compactor. Camp Dyer Diversion Dam Modification, Arizona (U.S. Department of the Interior 1992).

initial compaction by paver was reported to be 94 to 95% (Rollings 1988). Paving machines travel at a speed of approximately 1 m/min (4 ft/min) (Pittman 1988) and are capable of placing RCC lifts up to 300 mm (12 in.) in thickness in a single pass (Keifer 1986).

CHAPTER 5—PLACEMENT AND COMPACTION

5.1—General

RCC construction is an extremely rapid method of construction, and preconstruction planning and coordination of all interrelated activities are critical to the success of the project. Equipment, adequate in size and number, should be available to meet production requirements. Normally, the placement rate, rather than the compaction operations, will control productivity. Backup equipment should be readily available in the event of a breakdown. All operations should be sequenced, such as access and routing for equipment; air and water support systems; foundation preparation and joint treatment; setting of forms or precast work; setting of line and grade control; placement of conventional concrete at contacts or in facings, and placement of bedding mortar. These operations should be done in a timely manner that will have the least interference with RCC placement, spreading, and compaction.

Fig. 4.4—RCC paving using modified asphalt paving machine (Portland Cement Association 1997).

5.2—Minimizing segregation

The uniformity of compaction and density throughout the work will depend on the contractor's ability to minimize segregation of the RCC mixture. Uniformity of the RCC mixture begins with proper stockpiling and handling of the graded aggregates and continues through the mixing, mixer discharge, transporting, and placement. Segregation is less likely to be a serious problem if the RCC mixture is transported from the mixing plant to placement by belt conveyor, as opposed to other methods of transporting this material, because segregation is most likely to occur when the relatively dry mixture is piled or stacked in any manner. RCC mixture should first be dumped onto freshly spread, uncompacted RCC and then spread onto the hardened or semihardened surface by a bulldozer. This spreading operation will provide some remixing of the material and will minimize the rolling of larger particles onto the joint surface that creates rock pockets. RCC should never be dumped directly on a hardened or semihardened construction joint except when using a direct conveyor placing method or when starting a new lift until there is sufficient working area for the bulldozer to operate on uncompacted RCC. Where the RCC mixture is discharged into the receiving hopper on a paving machine and is distributed and spread, remixing will also occur. Close attention should be given to the outer edges of the paving lane where segregation can occur at the ends of screw conveyors used to distribute the mixture. Rock clusters that do occur should be removed and the particles redistributed by hand if necessary.

5.3—Placement and compaction in dams and related work

The transport and placement of RCC in dams and related work should be expedient so that the mixture is as fresh as possible at the time of compaction. Placing and compaction should begin after RCC surfaces have been prepared to optimize bonding between lifts. This should include performing lift surface cleaning, maintaining surface moisture, and applying bonding mixtures, such as a fluid bedding mortar or concrete. Once placed and spread in a reasonably uniform lift thickness, the mixture should be immediately compacted by vibratory roller. Most rolling procedures begin with a static pass to even out the loosely placed RCC before operating in

Fig. 5.1—Compacting RCC with large-size and walk-behind vibrating rollers. Mixtures with a Vebe consistency of 15 s will leave a 25 mm (1 in.) depression in the fresh concrete surface. Upper Stillwater Dam, Utah (U.S. Department of the Interior 1986).

the vibrating mode. In addition, the vibratory mechanism on the roller should be disengaged before stopping or reversing direction to avoid producing a localized depression in the surface. The required number of passes should be determined before the start of construction through a test section or prequalification demonstration. This placement should correlate the number of passes to achieve the target maximum density for the mixture within a given range for consistency or moisture content. For overall performance, RCC should be compacted as soon after placing as possible. Normally, rolling should begin within 15 min after placing and 45 min after mixing. Placing should begin at one abutment and proceed across the dam to the other abutment in a continuous manner. The next lift should then be placed on the oldest RCC in the previous lift and again continue across the structure. Where required, bedding mortar should be placed immediately ahead of the RCC so that it does not dry or lose excessive moisture before being covered.

Mixtures with a Vebe consistency of approximately 15 to 20 s will normally compact in approximately four to six passes with a 9 Mg (10 ton), dual-drum roller, in most instances. At this consistency, a 300 mm (1 ft) thick loose lift of RCC will deform approximately 25 mm (1 in.) under the roller and have a noticeable pressure wave pushed in front of the leading drum (Fig. 5.1). The density of RCC will quickly increase after approximately four to six passes and then level off or drop slightly with additional passes. The drop in density is due to rebound off the top surface behind the roller, similar to that observed in fresh asphalt mixtures (Forssblad 1981B). A static pass around 1 h after initial compaction will help tighten the surface.

Mixtures that are less workable and have no measurable Vebe consistency can require more than six passes with a vibrating roller to compact. The density will continue to increase and probably level out without a distinct peak. With less workable mixtures, the roller can bounce off the surface in the final stages of compaction and fracture aggregate on the top surface. This indicates the aggregate particles are contacting each other, rather than being surrounded by paste.

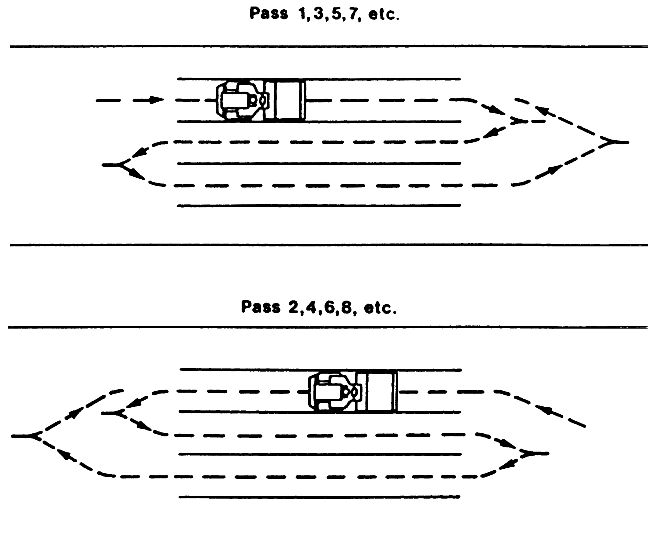

Fig. 5.2—Suggested rolling pattern for an RCC test compaction area (Forssblad 1981B).

The roller operator should establish a rolling pattern based on the width of the RCC lift and placing sequence. If loose lanes are spread, rolling should not come closer than 150 to 300 mm (6 to 12 in.) of the lane edge. This uncompacted edge should then be compacted with the RCC placed in the adjacent lane. Multiple passes in the same lane are not recommended unless the placement is only one lane wide. The operator should compact the entire width of the section as placed or follow the lift-spreading operation. A suggested rolling sequence for dam construction is shown in Fig 5.2. Normally, the rolling operation is faster than the spreading operation. If it is necessary to stop RCC placement due to plant or other equipment breakdown before completing a lift, all loose material along the lift edges should be rolled down and compacted on a slope. This edge should then be treated as a construction joint and thoroughly cleaned of all unsound material before covering with fresh RCC and resuming completion of the lift. Care should be taken in operating a roller on previously compacted RCC to avoid damaging this material.

Vibrator rollers with onboard compaction meters are now available to indicate to the operator the status of material compaction (Geistlinger 1996). Skillfully used, these meters can reduce the time needed to obtain proper compaction and make informed decisions. While they appear applicable, these meters have not been tested on RCC.

To take advantage of the potential for rapid construction of RCC, structures and conduits passing through the main cross section of dams should be minimized. Nevertheless, some areas will require smaller-sized compaction equipment for work in the following areas:

- Along the upstream and downstream facings;
- Adjacent to the dam foundation and abutments;
- Adjacent to diversion works, outlet works, and other conduits;
- Around instrumentation or other embedded items; and
- Localized compaction for repair of lift surface damaged by equipment operation.

Fig. 5.3—Compaction of RCC adjacent to slip-formed concrete facing element after approximately 6 h. Upper Stillwater Dam, Utah (U.S. Department of the Interior 1985).

Lack of restraint and safety concerns make it difficult to compact RCC along the unformed, downstream face of a dam. Ensure that the upstream facing zone is thoroughly compacted, because this zone provides the initial bond and seepage control against the water pressure. A facing constructed with cast-in-place curbing will allow roller compaction adjacent to the facing within 4 to 6 h after casting (Fig. 5.3). Wood or precast concrete forms with a conventional concrete facing can normally be compacted by a heavy vibratory roller within 300 to 900 mm (1 to 3 ft) of the form. A roller operating on a more-workable mixture will have to stay farther away from the form than a less-workable mixture. The distance the vibratory roller can operate from the form without causing the forming system to move can be determined during construction of the test section. This is especially true of precast-concrete upstream forms that depend upon a combination of interior tie rods and external braces for stability. Unformed downstream faces can not be compacted with large rollers at the extreme edge. A tamper, small roller, or a backhoe-mounted plate vibrator can be used to obtain at least a certain amount of compaction but not complete compaction along the outer edge of the face.

Large rollers can have difficulty operating along abutments due to inaccessibility. Rock outcrops and overhangs should be covered with conventional concrete or removed before placing RCC. Conventional concrete used in these areas should be consolidated with immersion vibrators and the conventional concrete/RCC interface with tampers or small rollers. This method of consolidating the conventional concrete/RCC interface, should also be used if there is an upstream or downstream facing on the dam. For covering the rock foundation, generally on a slope, extra rolling will be needed to approximately one roller length away from the foundation, because only one of the two drums of a tandem roller covers this area.

Whenever possible, diversion or outlet works conduits should be placed in the dam foundation and encased in conventional concrete before RCC construction begins. If this can not be achieved, such conduits should be located close to abutments to avoid separating the RCC working surface into two placements. Conventional concrete should be placed around the conduit to a minimum of one lift above the crown. A mat of reinforcing steel usually is placed over the conduit in traffic areas to provide additional support for placing and compacting the overlying RCC above this point. Localized embedments, such as instrumentation, are usually encased in conventional concrete and then surrounded by RCC. Care should be taken to properly identify these locations to avoid damaging during construction.

5.4—Placement and compaction of pavements

The placement and compaction of RCC pavements is normally achieved using a combination of construction equipment. A modified asphalt paving machine or similar piece of spreading equipment is used both to place RCC, and provide initial compaction using a vibrating screed that supplies vibration to the top of the pavement. Best results have been obtained with paver models that include one or more tamping bars in addition to the vibrating screed. These pavers produce a very smooth, uniform pavement surface and can compact the RCC mixture to within 5% of the final density. The increased energy applied to the surface can cause a network of fine, interconnected, superficial cracks and fissures, known as checking, directly behind the heavy-duty screed. These can be partially or totally removed during subsequent rolling operations, using either vibratory and rubber-tired rollers (Hess 1988).

Compaction of RCC pavements is typically achieved using a dual-drum, 9 Mg (10 ton) vibratory roller immediately after the RCC mixture is placed. Rolling patterns vary depending upon variables, such as subgrade support, RCC materials and mixture proportions, pavement thickness, and placing equipment that are used. A common rolling pattern involves making two static passes with the roller to within 300 mm (1 ft) of the lane edge so as to seat the concrete before vibratory rolling begins.

Visually observing the RCC surface displacement during the static rolling enables one to judge whether it has the proper consistency to achieve the specified density and maintain the smoothness tolerances during vibratory rolling. The RCC should deflect uniformly under the roller during static rolling. If the RCC is too wet, it will exhibit pumping and can shove under the roller. If it is too dry, it can shear horizontally at the surface in the direction of travel and will be unable to meet density requirements.

After static rolling is completed, four or more vibratory passes are made to achieve the specified density. Two of the vibratory passes should be made on the exterior edge of the first paving lane (such as the perimeter of the parking area or edge of the road) so that the roller wheel extends over the edge of the pavement 25 to 50 mm (1 to 2 in.). This rolling helps to confine the RCC so that lateral displacement of the concrete is minimized during additional rolling. Rolling should then be shifted to within 300 to 450 mm (12 to 18 in.) of the interior edge and make two or more additional passes. This rolling will provide an uncompacted edge that is used to set the screed height for the adjacent lane. After the adjacent lane is placed, the longitudinal joint between lanes should be compacted by centering the roller over the joint and compacting the lane edges together simultaneously. If more than approximately, a 1 h delay occurs before the adjacent lane is placed, it becomes difficult to compact the lanes together to form a monolithic pavement. In such cases, the junction of the lanes should be considered as a cold joint and should be treated as a hardened construction joint. These construction joints are typically treated by trimming the un-compacted edge of the paving lane with the blade of a motor grader, coating the exposed edge with a freshly broomed cement slurry and paving against the newly formed vertical edge. Immediately after completion of vibratory rolling a 9 to 18 Mg (10 to 20 ton) rubber-tired roller is often used to tighten pavement surface voids or fissures.

RCC in pavement should be placed and compacted while the mixture is fresh and workable, usually within 45 to 90 min from the time of mixing, depending on the climatic conditions. In warmer weather the time frame should be shorter; in cooler, humid weather the time frame can be longer. Longitudinal and transverse construction joints should be given particular attention to ensure they have the required texture, density, and smoothness. Minimizing the time between the placement and compaction of adjacent lanes, as well as following proper placing and rolling procedures, are the keys to constructing acceptable joints in pavements.

CHAPTER 6—CONSTRUCTION CONTROL

6.1—General

The quality control/quality assurance testing of RCC, relative to compaction, usually consists of consistency or moisture tests, density tests, and strength tests. The degree of compaction is generally determined as percent compaction and is the ratio of in-place compacted density to maximum density, multiplied by 100. Maximum density has been established in a variety of methods including laboratory maximum density from moisture-density relationship (ASTM D 1557) and by density tests on a test section before construction. Maximum density should be checked during construction due to minor changes that can occur in materials, mixture proportions, and compaction equipment, and whenever specific changes occur in any of these. In-place density as determined by the sand-cone method (ASTM D 1556) or the rubber balloon method (ASTM D 2167) have not been found suitable for testing RCC mixtures due to construction operations generally in progress in the immediate vicinity of the test and the squeezing of the excavated hole.

6.2—Consistency and moisture content

Consistency of RCC mixtures with adequate paste volume is measured by the Vebe test (ASTM C 1170). The Vebe apparatus (Fig. 6.1) is not portable, therefore, testing is usually done in a field laboratory that is located near the batching and mixing plant. Either plant samples or placement samples can be tested. Sampling should be done in accordance with ASTM C 172. One test should be made at the start of each shift and several times during each shift or whenever a sudden change in consistency is observed.

Fig. 6.1—Performing Vebe consistency test, ASTM C 1170. Cold Springs Dam Spillway Modification, Oregon (U.S. Department of the Interior 1995).

Moisture content testing of RCC should be done by rapid methods that can provide timely results for adjustment of RCC mixture, if required. Test methods include the microwave oven (ASTM D 4643) or calcium carbide gas pressure test method (ASTM D 4944). The most common moisture testing is done on compacted RCC using the nuclear gage (ASTM D 3017), generally used in conjunction with in-place density testing. Each of these test methods should be calibrated against oven-dry moisture tests (ASTM C 566). Nuclear moisture testing can be accomplished very quickly and is done frequently after initial compaction to smooth the surface for testing or following completion of compaction. Moisture tests obtained with a single-probe nuclear gage (by far the most common) are only surface (backscatter) results. The moisture content obtained with this gage is only an indication of the total moisture content of the full RCC lift and can be significantly affected by surface moisture changes, such as drying or precipitation. The moisture content of RCC at depths ranging from 50 to 600 mm (2 to 24 in.) can be obtained using a double-probe nuclear gauge. Aggregate moisture content tests should be made before the start of each shift and whenever change is observed to adjust batch quantities appropriately.

6.3—In-place density

In-place density of compacted RCC is nearly always determined by nuclear gage in accordance with ASTM C 1040 using either a single-probe or double-probe gage. The in-place density can be measured either in the backscatter mode (probe located at or near the top surface of the lift) or in the direct-transmission mode (probe inserted into a hole punched into the lift). The backscatter mode can be useful as a quick check test because it does not need a hole punched into the RCC. The direct transmission mode is usually specified for acceptance testing. The single-probe nuclear gage (Fig. 6.2) is most commonly used for routine RCC quality control. It is readily available at construction materials testing laboratories and is quick and easy to use. A disadvantage of the single-probe gage is that the density result is more heavily weighted by the density of the upper 150 mm (6 in.)

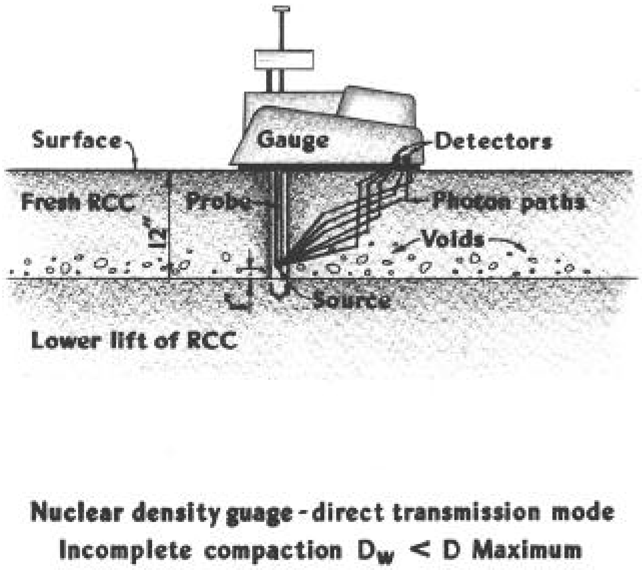

Fig. 6.2—Single-probe nuclear-density gage used to determine density and moisture content of RCC (U.S. Department of the Interior 1985).

of the lift where compaction is most easily achieved. The test result is not as sensitive to changes in density at the bottom of the lift where good compaction is not as easily achieved. The double-probe nuclear density gage (Fig. 6.3) measures across a stratum of material between two probes approximately 300 mm (12 in.) apart. The advantage of using the double-probe is that the density at any depth in the lift, especially the bottom of the lift, can be determined by direct transmission between probes. This advantage is especially beneficial where bond and watertightness of RCC at lift joints is of major importance, such as in dams.

In-place density tests should be made at random locations for each 500 m^2 (5000 ft^2) placed and compacted. In pavements, in-place nuclear density tests are usually made at a rate of approximately one test per 30 m (100 ft) of pavement.

6.4—Maximum density

The maximum density of RCC is used both for proportioning mixtures and as a basis of acceptance in the field. A soils, or geotechnical approach for proportioning RCC mixtures considers RCC as a cement-enriched aggregate compacted to its maximum density (Hansen 1992). The density of the RCC is determined for at least four different moisture contents using laboratory compaction tests made in accordance with ASTM D 1557. A moisture-density curve is plotted and the maximum wet and dry density of RCC is determined as the peak of this curve at an optimum moisture content. The maximum density can also be determined in the laboratory using samples compacted with a vibrating table (Casias, Goldsmith, and Benavidez 1988). A calculated maximum density is determined by dividing the mass of individual RCC ingredients batched (cementitious materials, water, and aggregates) by their respective densities. The theoretical maximum density is the total mass of ingredients divided by the total volume of ingredients, assuming zero air. Another

Fig. 6.3—Double-probe nuclear gage for determining density across a stratum of RCC, Elk Creek Dam Test Section, Oregon (U.S. Army Corps of Engineers 1985).

method is to determine the maximum density of RCC compacted by vibrating rollers in a preconstruction test section using either concrete cores or nuclear-density gage tests. If density tests are used as the basis of acceptance of compacted RCC, the test method for determining density should be specified.

The U.S. Bureau of Reclamation uses an average maximum density (AMD) as the basis of acceptance of compacted RCC in the field. The AMD is the average wet-density determined by nuclear gage in a 30 m (100 ft) long by two-roller-width wide field control section. The in-place density is first determined after an initial six roller passes and after every two subsequent passes with the specified vibratory roller until the maximum compacted density is achieved throughout the lift (U.S. Department of the Interior 1991). Ten additional tests are taken, after the RCC has reached its maximum density, and averaged to compute the AMD. The RCC for the remaining shift should then achieve 99% of the AMD. The object of this performance specification is to meet a target maximum density achieved by the roller in the field. This avoids comparing in-place nuclear density tests (that may be subject to chemical composition calibration errors) to laboratory compacted samples.

The U.S. Army Corps of Engineers uses an optimum compacted density value that is an average of wet-density tests made by nuclear density gage (single or double probe gage) in accordance with ASTM C 1040 on a test section compacted by 10 passes with the specified vibratory roller (1992). During construction, a cumulative optimum compacted density chart is maintained. In areas where density tests do not meet the average optimum compacted density, additional roller passes are required until the average optimum compacted density value is achieved.

On at least one paving project (Abrams and Jacksha 1987), maximum density was established by compacting the RCC mixture into a 610 mm (24 in.) square by 380 mm (15 in.) high block and measuring its unit weight. This is similar to the calibration block sample used by ASTM C 1040 for calibrating a nuclear gage.

Fig. 6.4—Compaction of RCC test specimens using electric vibrating hammer (ASTM C 1435).

The sand-cone method (ASTM D 1556) or the rubber-balloon method (ASTM D 2167) have not been found suitable for in-place RCC density testing because construction operations are generally in progress in the immediate vicinity of the test, which squeezes the excavated hole.

6.5—Strength

The compressive strength of RCC can be measured with specimens made in accordance with ASTM C 1176 using a vibrating table or using a vibrating impact hammer (Fig. 6.4), depending on the workability of the RCC mixture. The compaction hammer is an electric vibrating hammer with a 140 mm (5.5 in.) diameter plate attached to the shaft. The compaction hammers have a mass ranging from 6.5 to 9.5 kg (14.3 to 21 lb) and operate at a frequency of approximately 2000 to 2400 impacts per minute; similar to most vibratory rollers (Arnold, Felfisher, and Hansen 1992). Strength specimens can then be tested at the desired ages in accordance with ASTM C 39.

The in-place compressive strength can be determined on drilled cores in accordance with ASTM C 42. Coring is commonly done on major projects including pavements. In addition to compressive strength test specimens, the core samples enable a visual examination of interior density, distribution of aggregate, thickness of lifts, and condition of concrete at lift joints or contact with other features, and provide samples for other testing purposes. Other testing can include tensile splitting strength (ASTM C 496), tensile strength, or direct shear in unjointed and jointed specimens (ASTM D 2936 or ASTM D 5607), or Poisson's ratio and elastic modulus (ASTM C 469).

Currently, no standard procedures exist for fabricating RCC beams in the laboratory. Sawed beams from RCC pavement test sections have generally exhibited lower strengths than those of laboratory fabricated and cured specimens possibly due to the damage sustained in sawing, differences in curing, and incomplete compaction at the bottom (tension) face. Due to the difficulty in fabricating laboratory beams or sawing beams from the actual pavements, compressive strength tests are more commonly performed on RCC mixtures. The following relationship between RCC compressive and flexural strength was determined by Hess:

$$f_r = C\sqrt{f'_c}$$

where:

f_r = flexural strength determined by ASTM C 78 (third-point loading), psi;

f'_c = compressive strength determined by ASTM C 39, psi; and

C = an empirical constant between 9 and 11, depending on the RCC mixture.

6.6—Inspection of compaction operations

Visual inspection of all compaction operations is extremely important because of the rate at which RCC construction progresses. Communication should be maintained between the inspector and the contractor's supervisory personnel. Timely decisions should be made to avoid delay in the work. Inspectors should be alert to conditions that can cause segregation and should be prepared to take immediate corrective action. During placement, inspectors should monitor the appearance of the RCC mixture and its response to the action of the roller. Density and moisture tests should be completed quickly and safely to avoid interfering with the placing and compacting operation. Adjustments to the mixture should be requested, when necessary, to correct deficiencies in density or moisture content, or both, that affect workability and compaction. The inspector should also be alert to the timing of all operations so that the RCC mixture is compacted within established limits from the time of mixing and placing of bonding mortar or concrete. Special attention should be given to compaction along longitudinal joints to ensure adequate coverage and density is achieved. Rollers should be serviced regularly to prevent leakage of fluids, and to ensure that their vibratory mechanisms are in correct working order.

CHAPTER 7—REFERENCES

7.1—Referenced standards and reports

The following standards and reports were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

116R	Cement and Concrete Terminology
207.5R	Roller-Compacted Mass Concrete
211.3R	Standard Practice for Selecting Proportions for No-Slump Concrete
304R	Guide for Measuring, Mixing, Transporting, and Placing Concrete
309R	Guide for Consolidation of Concrete
325.10R	State-of-the-Art Report on Roller-Compacted Concrete Pavements

ASTM

C 39	Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 42	Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 78	Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 172	Practice for Sampling Freshly Mixed Concrete
C 469	Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C 496	Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C 566	Test Method for Total Moisture Content of Aggregate by Drying
C 1040	Test Method for Density of Unhardened and Hardened Concrete In Place by Nuclear Methods
C 1170	Test Methods for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
C 1176	Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table
C 1435	Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer
D 1556	Test Method for Density and Unit Weight of Soil In Place by the Sand-Cone Method
D 1557	Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lb/ft^3 [2700 kN-m/m^3])
D 2167	Test Method for Density and Unit Weight of Soil In Place by the Rubber Balloon Method
D 2936	Test Method for Direct Tensile Strength of Intact Rock Core Specimens
D 3017	Test Method for Water Content of Soil and Rock In Place by Nuclear Methods
D 4643	Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven Method
D 4944	Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester Method
D 5607	Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Stress The previous publications can be obtained from the following organizations:

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

ASTM
100 Barr Harbor Drive
West Conshohocken, Pa. 19428

7.2—Cited references

Abrams, J. M., and Jacksha, J. L., 1987, "An Airport Apron and a County Road," *Concrete International*, V. 9, No. 2, Feb., pp. 30-36.

Anderson, R., 1986, "Roller Compacted Concrete," *Dynapac Research Bulletin* No. 8033, Solna, Sweden, Jan.

Arnold, T. E.; Felfisher, T. B.; and Hansen, K. D., 1992, "RCC Test Specimen Preparation—Developments Toward a Standard Method," *Proceedings, Roller Compacted Concrete II*, ASCE, Feb., San Diego, Calif., pp. 341-357.

Arnold, T. E., and Johnson, D. L., 1988, "RCC Dam Design Concepts Versus Construction Conditions for Stagecoach Dam," *Proceedings, Roller Compacted Concrete II*, ASCE, Feb., San Diego, Calif., pp. 291-307.

Cannon, R. W., 1972, "Concrete Dam Construction Using Earth Compaction Methods," *Proceedings, Economical Construction of Concrete Dams*, Engineering Foundation Research Conference, May, Pacific Grove, Calif., pp. 143-152.

Casias, T. J.; Goldsmith, V. D.; and Benavidez, A. A., 1988, "Soil Laboratory Compaction Methods Applied to RCC," *Proceedings, Roller Compacted Concrete II*, ASCE, Feb., San Diego, Calif., pp. 107-122.

Dolen, T. P., 1991, "Freezing and Thawing Resistance of Roller Compacted Concrete," *Durability of Concrete—Second International Conference*, SP-56, Montreal, Canada, American Concrete Institute, Farmington Hills, Mich., pp. 101-113.

Dolen, T. P.; Richardson, A. T.; and White, W. R., 1988, "Quality Control/Inspection—Upper Stillwater Dam, Utah," *Proceedings, Roller Compacted Concrete II*, ASCE, Feb., San Diego, Calif., pp. 277-293.

Dolen, T. P., 1990, *Inspection and Observations of Freezing and Thawing Deterioration at Monksville Dam, New Jersey.*

Drahushak-Crow, R., and Dolen, T. P., 1988, "Evaluation of Cores from Two RCC Gravity Dams," *Proceedings, Roller Compacted Concrete II*, Feb., ASCE, San Diego, Calif., pp. 203-219.

Dunstan, M. R. H., 1977, "Trial of Lean Rolled Concrete at the Temar Treatment Works," *Report to the South West Water Authority*, England, June, 24 pp.

Forssblad, L., 1981A, "Vibratory Soil and Rockfill Compaction," *Dynapac Maskin AB*, Solna, Sweden.

Forssblad, L., 1981B, "Vibratory Asphalt Compaction," *Dynapac Maskin AB*, Solna, Sweden.

Geistlinger, L., 1996, "Onboard Compaction Meters Make Inroads into U.S. Market," *Roads & Bridges*, Aug., pp. 40-42.

Hall, D. J., and Houghton, D. L., 1974, "Roller Compacted Concrete Studies at Lost Creek Dam," *Report*, U.S. Army Corps of Engineers, Portland District, Oregon, June, 56 pp.

Hansen, K. D., 1992, "RCC for Rehabilitation of Dams in the USA - An Overview," *Proceedings, Roller Compacted Concrete III,* ASCE, Feb., San Diego, Calif., pp. 22-46.

Hess, J. R., 1988, "RCC Storage Pads at Tooele Army Depot, Utah," *Proceedings, Roller Compacted Concrete II,* ASCE, Feb., San Diego, Calif., pp. 394-409.

Hollingworth, F., and Geringer, J. J., 1992, "Roller Compacted Concrete Arch/Gravity Dams—South African Experience," *Roller Compacted Concrete III,* ASCE, Feb., San Diego, Calif., pp. 99-116.

Hopman, D. R., and Chambers, D. R., 1988, "Construction of Elk Creek Dam," *Roller Compacted Concrete II, Proceedings,* ASCE, Feb., San Diego, Calif., 257 pp.

Japan Ministry of Construction, 1984, "Development in Japan of Concrete Dam Construction by the RCD Method," Tokyo, Japan.

Jofre, C.; Femandez, R.; Josa, A.; and Molina, F., 1988, "Spanish Experience with RCC Pavements," *Proceedings, Roller Compacted Concrete II,* ASCE, Feb., San Diego, Calif., pp. 467-483.

Keifer, O., Jr., 1988, "Corps of Engineers Experience with RCC Pavements," *Proceedings, Roller Compacted Concrete II,* ASCE, Feb., San Diego, Calif., pp. 429-437.

Keifer, O., 1986, "Paving With Roller Compacted Concrete," *Concrete Construction,* Mar., 295 pp.

Parent, W. F.; Moler, W. A.; and Southard, R. W., 1985, "Construction of Middle Fork Dam," *Roller Compacted Concrete I, Proceedings,* ASCE, May, Denver, Colo., pp. 71-89.

Pittman, D. W., 1988, "RCC Pavement and Quality Control," *Proceedings, Roller Compacted Concrete II,* ASCE, Feb., San Diego, Calif., pp. 438-453.

Pittman, D. W., and Ragan, S. A., 1986, "A Guide for Design and Construction of Roller Compacted Concrete Pavements," *GL86,* U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., 26 pp.

Portland Cement Association, 1997, *Roller Compacted Concrete Pavement,* Portland Cement Association, Skokie, Ill.

Ragan, S. A., 1986, "Evaluation of the Frost Resistance of Roller-Compacted Concrete Pavements," *Roller-Compacted Concrete Pavements and Concrete Construction,* Transportation Research Record 1062, Transportation Research Board, Washington, D.C.

Ragan, S. A.; Pittman, D. W.; and Grogan, W. P., 1990, "An Investigation of the Frost Resistance of Air-Entrained and Non-Air-Entrained Roller-Compacted Concrete (RCC) Mixtures for Pavement Applications," *Technical Report* GL-90-18, Sept., U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss.

Reeves, G. N., and Yates, L. B., 1985, "Simplified Design and Construction Control for Roller Compacted Concrete," *Roller Compacted Concrete I, Proceedings,* ASCE, May, Denver, Colo., pp. 48-61.

Reynolds, R. D.; Joyet, R. A.; and Curtis, M. O., 1993, "Victoria Dam Rehabilitation," *Waterpower 93 Conference,* Aug., Nashville, Tenn.

Rollings, R. S., 1988, "Design of Roller Compacted Concrete Pavements," *Proceedings, Roller Compacted Concrete II,* ASCE, Feb., San Diego, Calif., pp. 454-466.

Schrader, E. K., 1988, "Comparative Limits and Advantages of RCC," *Advanced Dam Engineering for Design, Construction, and Rehabilitation,* Van Nostrand Reinhold, New York, N.Y., pp. 213-214.

Snider, S. H., and Schrader, E. K., 1988, "Monksville Dam: Design Evolution and Construction," *Roller Compacted Concrete II, Proceedings,* ASCE, Feb., San Diego, Calif., 224 pp.

Tayabji, S. D., and Okamoto, P. A., 1987A, "Bonding of Successive Layers in Roller Compacted Concrete," *CTL Report to U.S. Department of Interior,* Bureau of Reclamation, 1987A, Skokie, Ill., pp. 30-31.

Tayabji, S. D., and Okamoto, P. A., 1987B, "Engineering Properties of Roller Compacted Concrete," *Transportation Research* No. 1136, Transportation Research Board, Washington, D.C., pp. 33-45.

U.S. Army Corps of Engineers, 1984, "Willow Creek Dam, World's First All Roller Compacted Concrete Dam," *Final Concrete Report,* V. I and II, Aug., p. 91.

U.S. Army Corps of Engineers, 1985, *Elk Creek Dam Test Section,* Ore.

U.S. Army Corps of Engineers, 1992, "Roller-Compacted Concrete," *Engineer Manual EM 1110-2-2006,* Feb. 1, Department of the Army, Washington, D.C., 92 pp.

U.S. Department of the Interior, Bureau of Reclamation, 1976, "Design of Gravity Dams," Denver, Colo., 32 pp.

U.S. Department of the Interior, Bureau of Reclamation, 1985, 1986, *Upper Stillwater Dam,* Denver, Colo.

U.S. Department of the Interior, Bureau of Reclamation, 1986, Memorandum from Chief, Technical Review Staff to Chief, Division of Planning and Technical Services, Denver, Colo., Sept.

U.S. Department of Interior, Bureau of Reclamation, 1991, *Camp Dyer Diversion Dam Modifications, Specifications 1-SI-30-09170/DC-7826,* Regulatory Storage Division, Central Arizona Project, Ariz., pp. 5-11 to 5-15.

U.S. Department of the Interior, Bureau of Reclamation, 1992, *Camp Dyer Diversion Dam,* Denver, Colo.

U.S. Department of the Interior, Bureau of Reclamation, 1995, *Cold Springs Dam Spillway Modification,* Denver, Colo.

Withrow, H., 1988, "Compaction Parameters of Roller Compacted Concrete," *Proceedings, Roller Compacted Concrete II,* ASCE, Feb., San Diego, Calif., pp. 123-135.