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Roller-Compacted Concrete (RCC)

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51

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Preface

THE ORIGINAL CHAPTER ON ROLLER-COMPACTED concrete was authored by Kenneth L. Saucier with the U.S. Army Engineer Waterway Experiment Station and first appeared in the previous edition of *ASTM STP 169C* in 1994. Much of the content of the original work was drawn on in preparing the current edition. The most significant changes are in the sections on mixture proportioning, durability, construction, and quality control.

Definition

The American Concrete Institute (ACI) in *Cement and Concrete Terminology* (ACI 116R-99) defines roller-compacted concrete (RCC) as, "concrete compacted by roller compaction; concrete that, in its unhardened state, will support a roller while being compacted" [1]. RCC can further be defined as a stiff, extremely dry concrete that has the consistency of damp gravel. It is typically mixed using high-capacity continuous mixing or batching equipment, delivered with trucks or conveyors, and spread, in the case of mass concrete such as dams, with one or more bulldozers. For paving applications, RCC is spread with heavy-duty asphalt type pavers. Large vibratory rollers are used to externally consolidate or compact the roller-compacted concrete. Properties of fully compacted, hardened RCC are similar to those of conventionally placed concrete. However, the low-water content and absence of entrained air in most RCC affects some physical properties such as shrinkage and freeze-thaw durability.

Introduction

RCC may be considered for applications where no-slump concrete can be transported, placed, and compacted using earth- and rock-fill construction equipment or, in the case of pavements, asphalt laydown equipment. Ideal RCC projects will involve large placement areas with few interferences or discontinuities or restrictions on placement rate. Application of RCC is often considered when it is economically competitive with other construction methods. The two major applications for RCC are for mass concrete such as dams and heavy-duty pavement applications including intermodal yards, port facilities, warehouse and other industrial parking and storage areas. Other applications include overtopping protection for earth fill dams, buttressing of existing concrete dams, grade control structures in riverbeds, low permeable liners, and a variety of pavement applications.

Dams

RCC developed as a result of efforts to design and build concrete dams that could be constructed rapidly and economically. At the Rapid Construction of Concrete Dams Conference in 1970, Raphael [2] presented a paper in which he extrapolated from soil-cement applications the concept of placement and compaction of an embankment with cement-enriched granular bank or pit-run material using high-capacity earthmoving and compaction equipment. He noted that the increase in shear strength of cement-stabilized material would result in a significant reduction of the cross section when compared with a typical embankment dam and that use of continuous placement methods, similar to those used in earth dams, would generate savings in time and money as compared with traditional concrete gravity dam construction.

In 1972, Cannon [3] presented results of tests on a lean concrete using 75-mm maximum size aggregates transported by truck, spread by a front-end loader, and compacted by a vibratory roller at a Tennessee Valley Authority (TVA) project. The U.S. Corps of Engineers (USCE) soon thereafter constructed RCC field test sections at Jackson, Mississippi [4] and Lost Creek Dam in Oregon [5] in 1972 and 1973.

The 52-m-high Willow Creek Dam confirmed the economy and rapid construction possible with RCC. The structure contained 330 000 m^3 of RCC and was placed in less than five months. The in-place RCC cost averaged about \$26 per m^3 when considering all the different mixes used [6]. The U.S. Bureau of Reclamation's (USBR) 90-m high Upper Stillwater Dam, completed in 1987, contains 1.12 million m^3 of RCC placed within horizontally slip-formed, air-entrained concrete facing elements [7].

Worldwide, there are more than 280 RCC dams in 39 countries. Forty-seven of these dams are greater than 90-m high and located predominantly in Japan and China. The United States has 37 RCC dams with the highest being Olivenhain Dam in San Diego, CA. Completed in 2003; the dam is 97-m high and contains 1070 m^3 of RCC. Worldwide the highest RCC dam is Miel I in Columbia at 188 m. [8]. Figure 1 shows construction of the 40-m high C. E. Siegrist Dam in Lebanon, PA.

In addition to new dams, RCC has also been used extensively in the rehabilitation of existing dams. Applications include increasing spillway capacity for earth fill dams, grade

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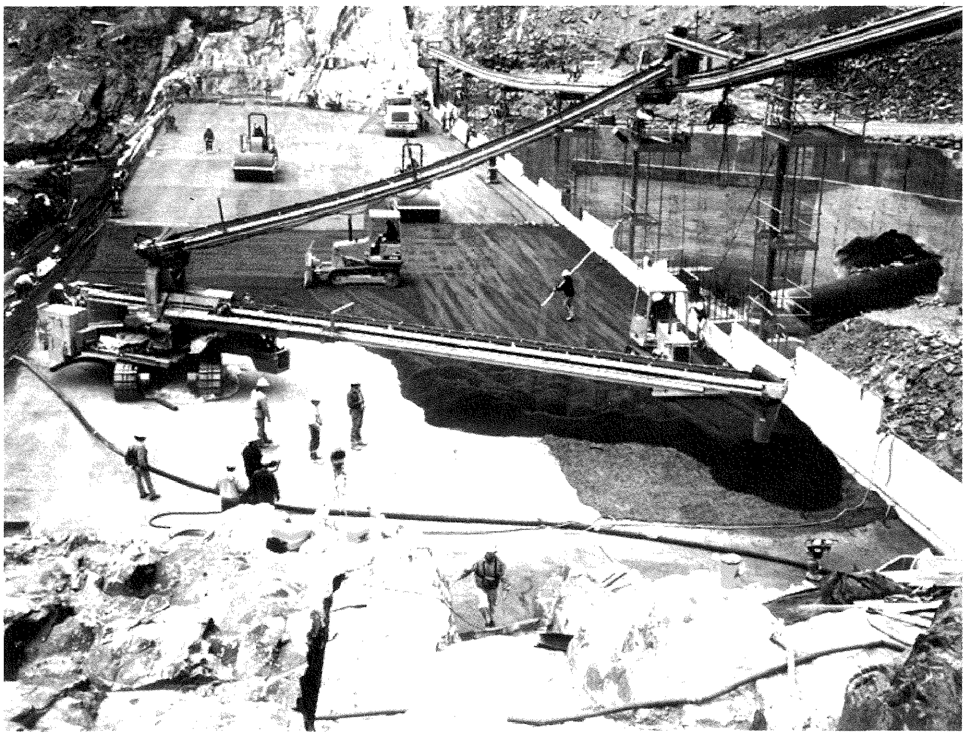

Fig. 1—Construction of C. E. Siegrist Dam, PA. Note use of conveyors to place roller-compacted concrete (photo courtesy of Gannett Fleming).

control structures in rivers, and seismic reinforcement for existing concrete dams. The Tennessee Valley Authority in 1980 was the first to use RCC as overtopping protection to rehabilitate Ocoee Dam No. 2. Since then, RCC has been used in more than 200 dam rehabilitation projects. Information on designing RCC for spillways and overtopping protection applications can be found in Ref 9.

Pavement

The use of RCC for pavements evolved from the use of soil cement and cement-treated base (CTB) material. Although equipment for batching, mixing, and transporting roller-compacted concrete is similar to CTB, RCC is designed to have the strength of conventional concrete. RCC has considerably more cementitious material than CTB, and differs from most soil cement in that it contains a well-graded coarse and fine aggregate. To enhance surface texture, the maximum size aggregate is limited to 16–19 mm. In addition, most RCC pavement projects are placed with heavy-duty asphalt type pavers. According to the Seattle office of the U.S. Corps of Engineers (USACE), the first use of RCC pavement in North America was a runway at Yakima, WA, constructed in 1942 [10]. The USACE at Vicksburg, Mississippi installed the first known RCC test pavement in the United States in 1975. This 4-m by 80-m service road proved the feasibility of RCC for use in pavement construction [11]. The first use of RCC pavement in Canada was built in 1976 at a log-sort yard at Caycuse, British Columbia. The project included 16 350 m^2 of 0.35-m-thick RCC pavement placed in a two-lift operation on a crushed-rock base. The yard size was doubled in 1979 with a second RCC application. When inspected in 1984, these pavements were in excellent condition [12].

In 1984 the Corps of Engineers constructed the first significant RCC pavement in the United States at Fort Hood, Texas. This was a large parking area for tanks and other tracked vehicles surrounding a maintenance shop. The 15 000 m^2 area of 0.25-m pavement was placed in one lift and achieved a flexural strength of 5.5 MPa. [12]. In general, RCC has been used for heavy-duty pavements such as tank hardstands, log handling yards, intermodal yards, freight depots, and other special applications. However, in the past ten years RCC has also been proven to be a cost-effective pavement for many conventional pavement applications including warehouse facilities, industrial access roads, large commercial parking areas, intersection replacements, roadway inlays, and residential streets.

Two of the largest paving projects to date have been for the auto industry. The Saturn automobile plant in Tennessee was completed in 1989. Approximately 500 000 m^2 of a 180-mm-thick pavement was placed for parking areas and access roads [13]. Approximately 830 000 m^2 of 175-mm-thick pavement was placed in 2003 for the Honda manufacturing facility in Alabama. According to the contractor on this project, RCC typically costs between \$19 and \$24 per m^2 [14].

Advantages

The primary advantage of RCC over conventional construction is in the speed of construction and cost savings. Construction cost histories of RCC and conventional concrete show that the unit cost per cubic meter of RCC is considerably less than conventionally placed concrete. Approximate costs of RCC pavement range from 20–30 % less than conventionally placed concrete [12,15,16]. The difference in percentage savings usually depends on complexity of placement and on total quantities of concrete placed. Savings associated with RCC are primarily due to reduced cement content, forming, placement, and compaction costs, as well as reduced construction times. To achieve the highest measure of cost effectiveness and achieve a high-quality product similar to what is expected of conventional concrete structures, the following design and construction objectives are desired: (1) RCC should be placed as quickly as practical after mixing; (2) operations should include as few laborers as possible; (3) design should avoid, as much as possible, multiple mixtures and other construction or forming requirements that tend to interfere with production; and (4) the design should not require complex construction procedures.

Typically, RCC needs no forms or finishing. In the case of pavements, there are no dowels, tie rods, or steel reinforcement. To minimize the treatment of cold joints, rapid placement is desired. In pavements, that may mean the use of two paving machines working in tandem. With dams and other mass placement projects, the contractor will typically run two 10-h shifts per day, six days a week. At Olivenhain Dam, a record placement rate of 224 800 m^3 per month was achieved [17]. High production rates make dam construction in one season readily achievable for even large structures. When compared to embankment or conventional concrete dams, construction time for large projects can be reduced by one to two years. Other benefits from rapid construction include reduced administration costs, reduced risk of flooding, and earlier operation of the facility. Basically, RCC construction offers economic advantages in all aspects of construction that are related to time.

Materials

Cementitious Materials

RCC can be made with any of the basic types of hydraulic cement or a combination of hydraulic cement and pozzolan. Selection of materials for chemical resistance to sulfate attack, potential alkali reactivity, and resistance to abrasion with certain aggregates should follow procedures used for conventional concrete construction.

The strength of RCC is primarily dependent on the quality and gradation of the aggregate, degree of compaction, and the proportions of cement, pozzolan, and water. The type of cementitious material has a significant effect on the rate of hydration and the rate of strength development and, therefore, significantly affects strengths at early ages.

Cement

RCC can be made using any of the basic types of portland cement given in ASTM Specification for Portland Cement (C 150) or blends of these with ground granulated blast-furnace slag as specified in ASTM Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortar (C 989). To minimize thermal cracking in mass applications, portland cements with lower heat-generation characteristics than Type I are often specified. They include Type II (moderate heat), Type IP (portland-pozzolan cement), and Type IS (portland blast-furnace slag cement). Type IV (low-heat) cement is not generally available in the United States. Before specifying a low-heat type cement, the engineer should determine its availability in the project area. Also the strength development for these lower-heat cements is usually slower than for Type I.

Pozzolans

The selection of a pozzolan suitable for RCC should be based on its conformance with ASTM Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete (C 618). Class F and Class N pozzolans are usually preferred especially for dams, since they normally contribute less heat of hydration than Class C and have greater sulfate resistance. They also help reduce expansion due to alkali-silica reactivity (ASR). For Class C pozzolans, more attention may be needed with regard to set time, sulfate resistance, ASR and free lime content. Use of pozzolans in RCC mixtures may serve one or more of the following purposes: (1) as a partial replacement for portland cement to reduce heat generation; (2) to reduce cost; and (3) as a mineral filler to provide supplemental fines for mixture workability and paste volume. The use of pozzolan will depend on required material performance as well as on its cost and availability at each project [18].

Aggregates

As with conventional concrete, aggregates for RCC should be evaluated for quality and grading. Aggregate for RCC should meet the same standards for quality and grading as required for conventional concrete construction. However, aggregates that do not meet the normal standards or requirements for conventional concrete have also been successfully used in RCC dam construction [19]. Changes from the grading or quality requirements of ASTM Specification for Concrete Aggregates (C 33) should be supported by laboratory or field test results that show that the concrete produced from the proposed materials fulfills the requirements of the project as is provided for in ASTM C 33.

Early RCC mass concrete dam projects in the United States used a 75-mm nominal maximum size of aggregate (NMSA); however, a 50-mm NMSA, preferably crushed coarse aggregate, is less prone to segregation and is becoming more widely used. Although larger sizes have been successfully used in Japan and at Tarbela Dam in Pakistan, the use of larger aggregate greatly increases the probability of segregation during transporting and spreading, and seldom significantly reduces the cost [15].

Maximum size aggregate for other applications include overtopping protection for embankment dams, which frequently use a NMSA of 25 mm, since lifts are typically thinner than for mass concrete placement [18]. For RCC pavement projects a NMSA of 16–19 mm is typically specified. In addition to minimizing the chance for segregation during handling and placement, a smaller NMSA provides a relatively smooth pavement surface texture.

Grading

The grading limits of individual coarse aggregate size fractions should comply with those used in conventional concrete. Individual size groups are normally combined to produce gradings approaching those given in Table 1. Fine aggregate gradings

TABLE 1—Ideal Coarse Aggregate Grading [15]

	Cumulative Percent Passing		
Sieve Size (mm)	4.75–75 mm	4.75–50 mm	4.75–19.0 mm
75	100		
63	88		
50	76	100	
37.5	61	81	
25.0	44	58	
19.0	33	44	100
12.5	21	28	63
9.5	14	18	41
4.75	...	...	...

TABLE 2—Fine Aggregate Grading Limits

Sieve Size	Cumulative Percent Passing [15]	Cumulative Percent Passing [ASTM C 33]
9.5 mm	100	100
4.75 mm	95–100	95–100
2.36 mm	75–95	80–100
1.18 mm	55–80	5–85
600 μm	35–60	2–60
300 μm	24–40	5–30
150 μm	12–28	0–10
75 μm	6–18	...
Fineness modulus	2.10–2.75	...

are also specified as shown in Table 2. Approximate fine aggregate contents, expressed as a percentage of the total aggregate volume, for mass RCC are given in Table 3. Typical gradation range for RCC pavements is shown in Table 4.

Some designers, however, have used locally available road base material with grading requirements similar to that contained in ASTM D 2940. However, the grading band for road base material can be quite open resulting in possible gap grading and segregation. Where close control of grading of the coarse aggregate and RCC production are desired, size separations should follow normal concrete practice, as recommended in ACI 304R.

The required amount of material passing the 75 μm may be greater for RCC than acceptable for conventional concrete. The larger percentage of fines is used to fill voids and contribute to compactibility. The additional fines are usually made up of naturally occurring non-plastic silt and fine sand, manufactured fines, or extra pozzolan. Depending on the volume of cementitious material and the NMSA, the required total minus 75-μm fines may be as much as 10 % of the total aggregate volume, with most mixtures using approximately 3–8 % [18].

Admixtures

Water-Reducing and Retarding Admixtures

The use of a water-reducing and retarding admixture or a retarding admixture as specified in the ASTM Specification for Chemical Admixtures for Concrete (C 494) may be considered for any RCC placement. Water-reducing and retarding admixtures have proven beneficial for improving and extending the workability of RCC beyond the typical 45 min to 1 h specified on most projects. The extended workability is especially beneficial during warmer weather, during RCC startup activities, longer haul distances, and for placement of thick lifts. It is also beneficial in maintaining lift surfaces in an unhardened state until the next layer or adjacent layer of RCC is placed, thereby creating a better bond. By improving the workability, RCC can be more easily mixed in conventional central plant drum mixers and transit truck mixers. Required dosages of water-reducing and retarding admixtures are normally several times as much as recommended for conventionally placed concrete.

TABLE 3—Approximate Ratio of Fine to Total Aggregate Volume [15]

Nominal Maximum Size and Type of Coarse Aggregate	Fine Aggregate Ratio, Percent of Total Aggregate Volume
75 mm, crushed	29–36
75 mm, rounded	27–34
37.5 mm, crushed	39–47
37.5 mm, rounded	35–45
19.0 mm, crushed	48–59
19.0 mm, rounded	41–45

Air-Entraining Admixtures

Air-entrainment of RCC has had only limited application to date. Most of the problem comes from the difficulty of entraining a good air-void system in such a low-paste, dry concrete. Research has indicated that air-entrainment may be limited to the more workable mixes with Vebe consistency times less than about 35 s [30,35]. Also, ASTM Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method (C 173) and Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method (C 231) determine total air content and do not differentiate between entrained and entrapped air voids. The entrapped air content in RCC mixtures will vary depending on the compactive effort applied in consolidating the material.

Minimizing frost damage in RCC has been achieved by proportioning mixtures with sufficient low-water-cementitious material ratios (w/c) so that the permeability of the paste is low. Once concrete has dried through self-desiccation, it is difficult to again become critically saturated by outside moisture. The use of proper compaction techniques that lower the entrapped air-void content, increase strength, and lower the permeability of the concrete should also improve the pavement's frost resistance [10].

Mixture Proportioning

As with conventional concrete construction, the primary considerations for mixture proportioning are durability, strength, workability, and, in the case of RCC, compactibility. Another important consideration for mass RCC is the minimization of heat rise due to the chemical reactions of the cementitious ingredients. Again, as with conventional mass concrete, factors such as use of (1) the largest nominal maximum-size of aggregate; (2) minimum amount of cementitious material; (3) pozzolans or

TABLE 4—Typical Combined Aggregate Grading Limits for RCC Pavement Mixture [20]

Sieve Size	Cumulative Percent Passing
19.0 mm	83–100
12.5 mm	72–93
9.5 mm	66–85
4.75 mm	51–69
2.36 mm	38–56
1.18 mm	28–46
600 μm	18–36
300 μm	11–27
150 μm	6–18
75 μm	2–8

blended cements; and (4) cooling procedures for the materials are evaluated on a job-specific basis.

A number of mixture-proportioning methods have been successfully used for RCC structures throughout the world, making it difficult to generalize any one procedure as being standard. Most mixture-proportioning methods are variations of two general approaches: (1) a w/cm approach with the mixture determined by solid volume; and (2) a cemented-aggregate approach with the mixture determined by either solid volume or moisture-density relationship. ACI 207.5R discusses four predominant mixture-proportioning methods:

Corps of Engineers Method–This proportioning method is based on w/cm and strength relationship. The method calculates mixture quantities from solid volume determinations, as used in proportioning most conventional concrete. The approximate water demand is based on nominal maximum size aggregate and desired modified Vebe time. A recommended fine aggregate as a percentage of the total aggregate volume is based on the nominal maximum size and nature of the course aggregate. Once the volume of each ingredient is calculated, a comparison of the mortar content to recommended values maybe made to check the proportions.

High Paste Method–This method results in mixtures that generally contain high proportions of cementitious materials, high pozzolan contents, clean and normally graded aggregates and high workability. The optimum water, fine aggregate, and coarse aggregate ratios are determined by trial batches Vebe consistencies are typically determined in accordance with ASTM Test Method for Determining the Consistency and Density of Roller-Compacted Concrete (C 1170). The major advantage of the high paste method is to provide excellent lift-joint bond strength and low joint permeability by providing sufficient cementitious paste in the mixture to enhance performance at the lift joints.

Roller-Compacted Dam Method–The roller-compacted dam (RCD) method is used primarily in Japan. The method is similar to proportioning conventional concrete in accordance with ACI 211.1 except that it incorporates the use of a consistency meter. The procedure consists of determining relationships between the consistency, termed VC value, and the water content, sand-aggregate ratio, unit weight of mortar, and compressive strength. Because of the consistency test equipment requirements and differences in the nature of RCD design and construction, this method is not widely used in proportioning RCC mixtures outside of Japan.

Maximum Density Method–This method is a geotechnical approach similar to that used for selecting soil-cement and cement stabilized base mixtures. Proportioning by this approach is also covered in Appendix 4 of ACI 211.3. Instead of determining the water content by Vebe time or visual performance, the desired water content is determined by moisture-density relationship of compacted specimens, using ASTM Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (D 1557).

Another method for proportioning nonair-entrained RCCP mixtures is referred to as the optimal paste volume method. The premise behind the method is that workability and strength requirements are treated in two independent steps. The method is based on the assumption that an optimal RCC should have just enough paste to completely fill the interstices remaining when the granular skeleton has reached its maximum density under compaction.

The procedure includes three major steps. The first step is to select an aggregate grading that contains a minimum volume of voids for a given compaction energy. The next step is to adjust the paste volume to obtain the required workability. The final step involves the selection of the w/cm ratio and the proportions of cement and pozzolanic materials to produce a paste with enough binding capacity to satisfy the strength requirements [21,22].

All of the methods include the preparation of trial mixtures to confirm that the workability, compactibility and engineering properties are suitable for the particular project. This is usually confirmed in a test section using the placing methods and equipment that are planned for use on the job. If the laboratory-proportioned mixture proves unsuitable for construction, the mixture is adjusted accordingly. Although mixture proportions are project-specific, Table 5 provides typical values for estimating RCC trial mixture proportions.

TABLE 5—Typical Values for Estimating RCC Trial Mixture Proportions [15]

	Nominal Maximum Size of Aggregate[a]					
	19.0 mm		50 mm		75 mm	
Contents	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Water content[b], kg/m^3						
a) Vebe <30 sec	150	133–181	122	107–140	107	85–128
b) Vebe >30 sec	134	110–154	119	104–125	100	97–112
Sand content, % of total aggregate volume						
a) crushed aggregate	55	49–59	43	32–49	34	29–35
b) rounded aggregate	43	38–45	41	35–45	31	27–34
Mortar content, % by volume						
a) crushed aggregate	70	63–73	55	43–67	45	39–50
b) rounded aggregate	55	53–57	51	47–59	43	39–48
Paste: mortar ratio, Vp/Vm, by volume	0.41	0.27–0.55	0.41	0.31–0.56	0.44	0.33–0.59
Entrapped air content on 37.5-mm fraction, %	1.5	0.1–4.2	1.1	0.2–4.1	1.1	0.5–3.3

[a] Quantities for use in estimating water, sand, mortar, and entrapped air content for trial RCC mixture proportioning studies.

[b] Lower range of values should be used for natural rounded aggregates and mixtures with low cementitious material or aggregate fines content.

Properties of Hardened RCC

The significant material properties of hardened RCC include compressive strength, tensile and shear strength, elastic modulus, tensile strain capacity, Poisson's ratio, volume change (thermal, drying, and autogenous), thermal coefficient of expansion, specific heat, creep, permeability, and durability. The hardened properties of RCC and conventional concrete are quite similar and differences are primarily due to differences in mixture proportions, aggregate grading, and voids content. A wide range of RCC mixtures can be proportioned, just as there is a wide range of mixtures for conventionally placed concrete. It is difficult to quantify typical values in either case. In general, RCC will have lower cement, paste, and water contents and may contain nonplastic fines to fill aggregate voids. Aggregate quality, grading, and physical properties have a major influence on the physical properties of RCC.

Compressive Strength

Compressive strength tests are conducted in the design phase to determine mixture proportion requirements, and to optimize combinations of cementitious materials, water and aggregate. The percentage of pozzolan has a significant influence on the strength development of RCC especially at early ages. The compressive strength of RCC is determined by several factors including the water to cementitious materials ratio, quality and grading of aggregate, degree of compaction, and curing. Degree of compaction has a significant influence on compressive strength. Because of its dry consistency, compaction (consolidation) of RCC requires more effort than conventional concrete. Without full compaction, increased voids will occur within the matrix of the concrete resulting in decreased strength. Delays in compaction may also result in a decrease in compressive strength. Finally, consideration must be given to the fact that most specifications accept 96–98 % of maximum density. As a result, compressive strengths of RCC compacted at less than maximum density will be reduced.

Volume Change

The two significant changes in volume experienced with RCC are due to drying shrinkage (primarily in pavements) and thermal expansion and contraction in mass concrete. Volume change associated with drying shrinkage is normally less than that in comparable conventional concrete mixtures due to the lower water content. This lower shrinkage has resulted in less cracking and revised design considerations for RCC pavements [23]. With respect to thermal considerations, heat rise that causes expansion of a massive concrete structure is due almost entirely to the chemical reactions of the cementitious material. Therefore, the use of lesser amounts of cementitious material in mass RCC construction lowers the potential for thermal cracking. For large dams a common practice is to install contraction joints in the individual lifts of the freshly placed RCC.

Permeability

The permeability of RCC is largely dependent on voids in the compacted mass, together with porosity of the mortar matrix, and therefore is almost totally controlled by mixture proportioning, placement method, and degree of compaction. Hardened RCC permeability is comparable to conventional concrete, although one researcher has indicated the permeability of RCC to be greater than conventional concrete [24]. Typical values for mass RCC range from 0.15 to 15 $\times 10^{-9}$ cm/s [18]. For higher cementitous mixtures such as those for RCC pavements, the permeability tends to be lower.

Durability

Abrasion/Erosion Resistance

Compressive strength and aggregate size, grading, and quality primarily govern abrasion/erosion resistance. Erosion tests in test flumes have indicated the excellent erosion resistance for RCC [*25*]. ASTM Test Method for Abrasion Resistance of Concrete (Underwater Method) (C 1138) has been used to evaluate the performance of RCC for use as streambank protection. Research has indicated that the abrasion resistance of RCC increased with increasing strength and maximum aggregate size. In fact, some studies indicated that aggregates contributed more to abrasion resistance than cement content [26].

Observations of various projects from heavy-duty pavements such as log sort yards to RCC spillways have also indicated excellent resistance to abrasion/erosion. However, ACI 207 on Roller Compacted Mass Concrete recommends that for overflow spillways of RCC dams subjected to frequent use, the RCC should generally be lined with high-quality concrete to prevent abrasion/erosion damage [18].

Freezing and Thawing

Because of its dry consistency, it has not been practical to entrain air in RCC mixtures. Laboratory specimens of nonair-entrained RCC tested according to ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666), Procedure A (in water) and large blocks of mass RCC material exposed to natural weathering of Treat Island, Maine [18], have typically performed very poorly. Nevertheless, there are numerous examples of good performance of nonair-entrained RCC in the field [12,18,27–29]. In Piggott's study [29] a total of 34 RCC pavement projects in the United States and Canada were visually inspected. The projects ranged in age from 3–20 years. The study concluded that except for some surface wear (fines were removed up to a depth 2 mm), the performance of the RCC was very good. The coarse aggregate at the surface remained firmly embedded in the RCC matrix. The study also noted that surface wear typically occurred within the first 2–3 years of service and then stabilized.

Similar to other no-slump, nonair-entrained concrete products such as concrete pavers and precast concrete pipe, RCC derives its durability from its high strength and low permeability. Acceptance criteria for durability tests of concrete pavers according to ASTM Specification for Solid Interlocking Concrete Paving Units (C 936) and ASTM Test Method of Sampling and Testing Brick and Structural Clay Tile (C 67) rely on a combination of minimum compressive strength and moisture absorption. ASTM C 666, which has been used to evaluate the freeze/thaw durability of RCC, is a much harsher test that relies heavily on the presence of air-entrainment for acceptability. Acceptance of RCC according to C 666 criteria usually results in mixtures of very high strength not typical or economically viable for most RCC paving projects.

With regard to air entrainment in RCC, laboratory and field applications have shown an air-entraining admixture can effectively be used to provide good freeze/thaw durability, even when subjected to ASTM C 666 testing [18,30,31]. The difficulty comes in trying to incorporate the tiny air-entrained bubbles uniformly throughout the no-slump RCC mixture. Attempts to entrain air are most effective in RCC mixtures with a Vebe consistency time less than about 35 s using clean, ASTM graded fine aggregate.

Construction

A major benefit of RCC is the cost savings that result from optimizing material selection and the speed of construction. The entire process of batching, mixing, transporting, placing, spreading, compacting, and curing is accomplished as rapidly as possible. There are no forms, reinforcing steel, or finishing. Placement and compaction of the very dry mixture is typically done using equipment and techniques similar to those used for earthwork placement, in the case of mass concrete, and asphalt placement, in the case of RCC pavement. As a result, large quantities of concrete can be placed rapidly with minimum labor and equipment.

Batching and Mixing

The batching and mixing plant requirements for a project to be constructed using RCC are essentially the same as for a project built with conventional concrete [15]. The production, stockpiling, and reclamation of aggregate from the stockpiles are done in the same way and with the same equipment as for conventional concrete. RCC can be produced in any type of plant that will provide uniform mixing of the cementitious materials, aggregates, and water. Often the size of the project and plant availability will dictate which type of mixing method to use.

Horizontal Shaft Mixers—Whether single or dual shaft, portable or permanent, continuous flow (such as a pugmill) or batch, horizontal shaft mixers provide the most intense and fastest mixing action of any mixing plants. Many pugmills are equipped with transfer or gob hoppers to temporarily store the mixed RCC between truck loadings so that the least amount of plant stoppages is required. Due to the speed and quantity of material mixed, horizontal shaft mixers are the preferred mixing method especially for large projects.

Tilt Drum Mixers—The most common central mixing plant for conventional concrete are tilt drum mixers. These mixers are generally available locally and can be used effectively to produce RCC. Because of its dry consistency, RCC batch quantities are typically less than the drum capacity and mixing times are increased.

Transit Mixers—While transit or truck mixers are the most widely available and are capable of producing a quality RCC, difficulties in getting uniform mixing and discharging the dry consistency mixture generally make this type of mixing method unsuitable except for small projects. The recent use of water-reducing and retarding admixtures to improve workability has allowed greater use of transit mixers.

Transporting

The most common methods for transporting RCC from the mixing plant to the placement area are dump trucks, conveyors, or a combination of both. Dump trucks are the most common form of transportation. Depending on weather conditions, protective covers should be provided to minimize moisture loss. In confined areas where dump trucks may be difficult to maneuver, conveyors, front-end loaders, or backhoes may be required to supply RCC to the placement area. Conveyor systems are typically used on large dam projects and where there is a concern that truck hauling may contaminate the previously placed RCC layer.

Special care must be taken during transportation and placement to avoid segregation. Mounding of the RCC during loading and unloading operations should be avoided. Conveyor systems must be designed to minimize segregation at transfer points. RCC mixtures with a 75 mm NMSA have a greater tendency to segregate when they are dumped unto a hard surface, but with care and proper procedures, these mixtures have been hauled, dumped and remixed successfully. Design of wetter consistency mixes tends to reduce segregation.

Placement

Tracked dozers are the fastest, most cost-effective method for spreading RCC. Dozers are the preferred method of placement for dams and other nonpavement applications. Typical lift thickness range from a minimum of 0.15 m (compacted thickness), to over 1 m although no general production in the United States has exceeded 0.6 m. The design of dams where lift thickness greater than 0.3 m have been used has been based on the realization that the spreading of the RCC with heavy dozers not only remixes and redistributes the concrete to overcome segregation but also provides compaction. These procedures have been established and proven by large-scale, well-controlled test section construction and testing, as well as in full-scale production of RCC for dams in Japan and at Elk Creek Dam [15].

Placement of RCC pavements is typically accomplished by the use of heavy-duty asphalt type paving machines. Conventional asphalt pavers have been used; however, they are only equipped with vibrating screeds. As a result, almost all the compaction has to be provided by the vibratory rollers. Heavy-duty asphalt pavers are equipped with tamping and vibrating screeds, which allows for much higher initial compaction from the paver resulting in less compacted effort required from the vibratory rollers. Conventional pavers provide 80–90 % of modified Proctor density, whereas heavy-duty pavers have achieved up to 95 %.

Continuous operation of the paver is critical to achieving a smooth surface without bumps. Trucks delivering RCC to the paver must be scheduled to provide a continuous supply of concrete, but spaced so that they will not be delayed at the paving machine and thus permit the mixed concrete to dry out and loss workability. The use of a transfer device is also recommended whenever practical to eliminate starting and stopping (Fig. 2).

Compaction

One of the most important steps in RCC construction is compaction. RCC is usually compacted with self-propelled vibratory steel drum rollers. Rubber-tire rollers have also used successfully especially as a final pass to remove surface cracks and tears and provide a smooth tight surface. In tight areas such as adjacent to forms, large power tamper jumping jacks are most suitable.

Compaction of RCC should be accomplished as soon as possible after it is spread, especially in hot weather. Typically, compaction should be completed within 15 min of spreading and 45 min from the time of initial mixing. Substantial reduction in strength can be expected if RCC is compacted when it is more than 30–45 min old and the mix temperature is above 21°C. These times can be increased for RCC mixtures with extended set times due to pozzolans, admixtures, or cooler temperatures [18].

Each RCC mixture will have its own characteristic behavior for compaction depending on temperature, humidity, wind, plasticity of the aggregate fines, overall grading, and the

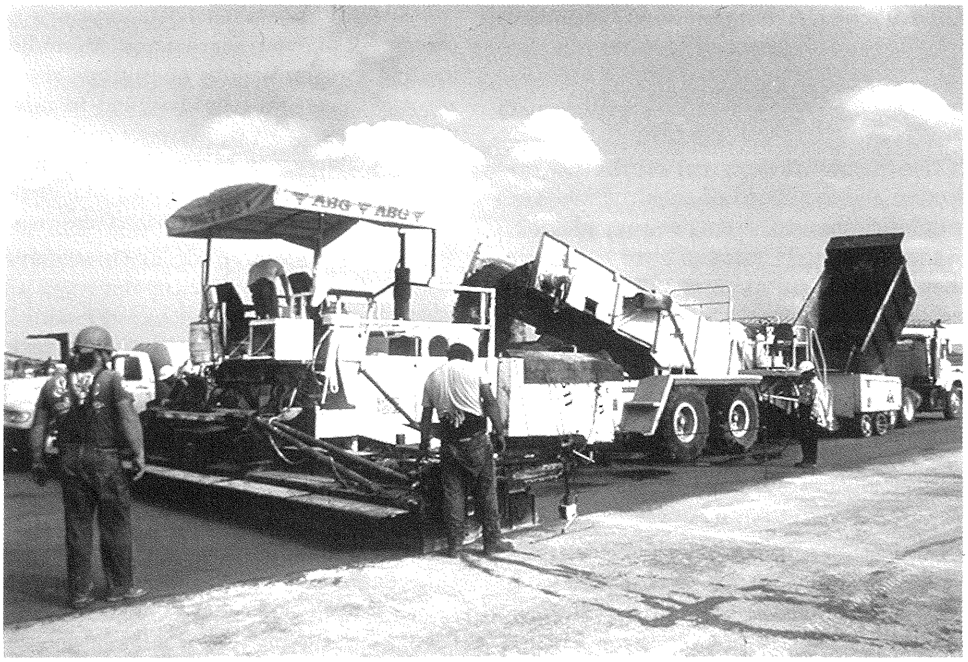

Fig. 2—RCC being placed with heavy-duty paver. Intermediate transfer device used to maintain a constant flow of material to the paver.

NMSA. Typically, four to six passes of a dual-drum 10-ton vibratory roller will achieve the desired density of at least 98 % for RCC lifts in the range of 150–300 mm. Over compaction or excessive rolling should be avoided, since it may reduce the density of the upper portion of the lift.

Curing

Because of the relatively low-water content of RCC, moist curing has been used for most projects. Water cure may be applied by water trucks equipped with fine mist spray nozzles, sprinkling systems or complete submersion. Use of open-ended hoses or coarse sprays that may erode the paste and fine aggregates from the surface should not be used.

Other methods of curing include plastic sheeting, burlap and membrane-forming curing compounds. A white pigment-curing compound conforming to ASTM Specification for Liquid Membrane-Forming Compounds for Curing Concrete (C 309) has become popular for RCC pavement projects. Because of the more open textured surface with RCC compared to conventional concrete, curing compounds are typically applied at higher application rates then for conventional concrete. The application must ensure a uniform void-free membrane exists across the entire RCC pavement surface.

Quality Control

For most RCC projects it is essential to have a quality control program that addresses the activities, procedures, and responsibilities for the specific project. The quality control program is typically the joint responsibility of the contractor, engineer, owner, or owner's representative. The extent of the inspection and testing program will depend on the nature and size of the project. It may be as simple as visual observations or as elaborate as constructing a test section and having an on-site testing lab. A thorough discussion of quality control procedures is presented in references 10, 15, 18, and 32.

Preconstruction inspection and testing typically include sampling and testing the quality of the raw materials; verifying that the type and size of the mixing plant, transportation, placing and compaction equipment meets the project requirements; and inspecting and calibrating the production and testing equipment to ensure proper operation.

Constructing a test section is also part of the preconstruction quality control program. The test section provides for evaluation of the mix design and allows the contractor to develop and demonstrate the proposed techniques for mixing, transporting, placing, compacting, jointing, and curing the RCC during production operations. The test section should be constructed sufficiently early in the contract to allow the contractor time to adjust the size of his batching, mixing, or transporting system; to modify placing, spreading, and compaction techniques; and to change any other operation that is considered essential to the success of the job.

During construction a number of quality control procedures are typically specified. Among them are regular plant calibrations, gradation tests, moisture tests, consistency and density tests, and fabrication and testing of beams and cylinders. Visual inspection for signs of segregation during placement, surface cracking or consistency changes may be indicators of construction deficiencies that need to be corrected. Another important element of inspection is to monitor the time within the various stages of construction. Most specifications require that the RCC mixture be compacted within 45–60 min of mixing and about the same time limit is used to ensure adequate bonding for placement of multiple lifts or adjacent paving lanes.

Consistency and Compactability

The Vebe or similar apparatus is used to measure the consistency or workability of many RCC mass concrete mixtures; however, it is usually not applicable for the drier RCC pavement mixtures. A modified Vebe test, conducted according to Method A of ASTM Test Methods for Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table (C

Fig. 3—Determining Vebe time according to ASTM C 1170. Note ring of mortar along side of container.

1170) is used to determine consistency and compactibility of the freshly mixed RCC. The Vebe test measures the time required for a ring of mortar to appear around the periphery of the surcharge plate (Fig. 3). This test is suitable for RCC mixes with a Vebe time between 10 and 60 s. The test can be used for overall assessment of the RCC workability, but is generally not suitable for control of the uniformity of the mix during production and placement.

The modified Proctor compaction test, ASTM D 1557, is a well-established test for soils that can also be applicable with RCC. The test is used to determine the relationship between the moisture content and dry density of a material for a specific compactive effort, and results in the establishment of a maximum dry density at optimum moisture content. This test method is more applicable for the drier RCC mixtures typically used for pavement applications.

In-Place Density

One of the most important quality control parameters to monitor is compacted density. Density measurements are taken during placing of RCC using a nuclear density gage. The in-place density in the field is compared with the theoretical maximum density or maximum density achieved from a test section or in the laboratory to determine the degree of compaction To ensure the accuracy of the nuclear gages being used, a test block is made during the early stages of the project and kept available for calibration purposes. Specifications generally require the in-place density of the RCC to achieve a minimum of 95–98 % of maximum wet density.

Preparation of Test Cylinders

The primary objective of cylinder preparation is to duplicate the compaction (consolidation) effort and consequently the in-place density of the RCC after compaction in the field. Cylindrical test specimens for determination of compressive strength of RCC cannot be fabricated using the standard procedures used for conventional concrete. As a result, several alternative methods have been developed for RCC and are being used successfully, including (1) Vebe method, ASTM Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table (C 1176), (2) vibrating hammer method, ASTM Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer (C 1435), (3) modified Proctor method, ASTM D 1557, (4) pneumatic tamper method, and (5) gyratory compaction method [33]. Each of these methods has advantages and disadvantages. The vibrating hammer (C 1435) and pneumatic tamper work for a wide range of RCC mixture consistencies. The Vebe test is used for wetter mixtures generally with Vebe times of 35 s or less [34]. Both the modified Proctor (ASTM D 1557) and gyratory compaction method are used for the drier RCC mixtures.

Closure

Over the past 30 years, roller-compacted concrete has advanced significantly as a viable construction technique. Primary applications are for dams, spillways, overtopping protection, and pavements. The main advantage of RCC over conventional construction is in the speed of construction and cost savings. Performance of RCC has been very good even under freeze-thaw conditions. Additional research and development is needed to: (1) improve surface texture, skid resistance, and joint construction methods in pavements; (2) establish standardized joint design spacing; (3) establish standardize mixture design methods; (4) develop representative freeze-thaw durability test procedures; (5) determine methods for air-entrainment, (6) improve mixing efficiency using conventional concrete mixing equipment; and (7) expand the use of admixtures including retarders and water reducers to extend working time and enhance performance.

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