# Roller-Compacted Mass Concrete

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*Roller-compacted concrete (RCC) is a concrete of no-slump consistency in its unhardened state that is transported, placed, and compacted using earth and rockfill construction equipment. This report includes the use of RCC in structures where measures should be taken to cope with the generation of heat from hydration of the cementitious materials and attendant volume change to minimize cracking. Materials mixture proportioning, properties, design considerations, construction, and quality control are covered.*

**Keywords:** admixtures; aggregates; air entrainment; compacting; compressive strength; concrete; conveying; creep properties; curing; joints (junctions); mixture proportioning; placing; shear properties; vibration; workability.







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# CHAPTER 1—INTRODUCTION

## 1.1—General

Roller-compacted concrete (RCC) is probably the most important development in concrete dam technology in the past quarter century. The use of RCC has allowed many new dams to become economically feasible due to the reduced cost realized from the rapid construction method. It also has provided design engineers with an opportunity to economically rehabilitate existing concrete dams that have problems with stability and need buttressing, and has improved embankment dams with inadequate spillway capacity by providing a means by which they can be safely overtopped.

This document summarizes the current state-of-the-art for design and construction of RCC in mass concrete applications. It is intended to guide the reader through developments in RCC technology, including materials, mixture proportioning, properties design considerations, construction, and quality control and testing. Although this report deals primarily with mass placements, RCC is also used for pavements, which are covered in ACI 325.1R.

## 1.2—What is RCC?

ACI 116 defines RCC as "concrete compacted by roller compaction; concrete that, in its unhardened state, will support a (vibratory) roller while being compacted. RCC is usually mixed using high-capacity continuous mixing or batching equipment, delivered with trucks or conveyors, and spread with one or more bulldozers in layers prior to compaction. RCC can use a broader range of materials than conventional concrete. A summary of RCC references is given in the 1994 USCOLD Annotated Bibliography.[1.1]

## 1.3—History

The rapid worldwide acceptance of RCC is a result of economics and of RCC's successful performance. During the 1960s and 1970s, there were uses of materials that can be considered RCC. These applications led to the development of RCC in engineered concrete structures. In the 1960s, a high-production no-slump mixture that could be spread with bulldozers was used at Alpe Gere Dam in Italy[1.2,1.3] and at Manicougan I in Canada.[1.4] These mixtures were consolidated with groups of large internal vibrators mounted on backhoes or bulldozers.

Fast construction of gravity dams using earthmoving equipment, including large rollers for compaction, was suggested in 1965 as a viable approach to more economical dam construction.[1.5] However, it did not receive much attention until it was presented by Raphael in 1970 for the "optimum gravity dam."[1.6] The concept considered a section similar to but with less volume than the section of an embankment dam. During the 1970s, a number of projects ranging from laboratory and design studies to test fills, field demonstrations, nonstructural uses, and emergency mass uses were accomplished and evaluated using RCC. These efforts formed a basis for the first RCC dams, which were constructed in the 1980s.

Notable contributions were made in 1972 and 1974 by Cannon, who reported studies performed by the Tennessee Valley Authority.[1.7,1.8] The U.S. Army Corps of Engineers conducted studies of RCC construction at the Waterways Experiment Station in 1973[1.9] and at Lost Creek Dam in 1974.[1.10] The early work by the U.S. Army Corps of Engineers was in anticipation of construction of "an optimum gravity dam" for Zintel Canyon Dam.[1.11] Zintel Canyon Dam construction was not funded at the time, but many of its concepts were carried over to Willow Creek Dam, which then became the first RCC dam in the U.S.

Developed initially for the core of Shihmen Dam in 1960, Lowe used what he termed "rollcrete" for massive rehabilitation efforts at Tarbela Dam in Pakistan beginning in 1974. Workers placed 460,000 yd$^3$ (350,000 m$^3$) of RCC at Tarbela Dam in 42 working days to replace rock and embankment materials for outlet tunnel repairs. Additional large volumes of RCC were used later in the 1970s to rehabilitate the auxiliary and service spillways at Tarbela Dam.[1.12]

Dunstan conducted extensive laboratory studies and field trials in the 1970s using high-paste RCC in England. Further studies were conducted in the UK under the sponsorship of the Construction Industry Research and Information Association (CIRIA) and led to more refined developments in laboratory testing of RCC and construction methods, including horizontal slipformed facing for RCC dams.[1.13,1.14, 1.15]

Beginning in the late 1970s in Japan, the design and construction philosophy referred to as roller-compacted dam (RCD) was developed for construction of Shimajigawa Dam.[1.16,1.17] In the context of this report, both RCC and the material for RCD will be considered the same. Shimajigawa Dam was completed in 1981, with approximately half of its total concrete [216,000 yd$^3$ (165,000 m$^3$)] being RCC. The RCD methods uses RCC for the interior of the dam with relatively thick [approximately 3 ft (1 m)] conventional mass-concrete zones at the upstream and downstream faces, the foundation, and the crest of the dam. Frequent joints (sometimes formed) are used with conventional waterstops and drains. Also typical of RCD are thick lifts with delays after the placement of each lift to allow the RCC to cure and, subsequently, be thoroughly cleaned prior to placing the next lift. The RCD process results in a dam with conventional concrete appearance and behavior, but it requires additional

*Fig. 1.1—Willow Creek Dam.*

*Fig. 1.2—Shimajigawa Dam.*

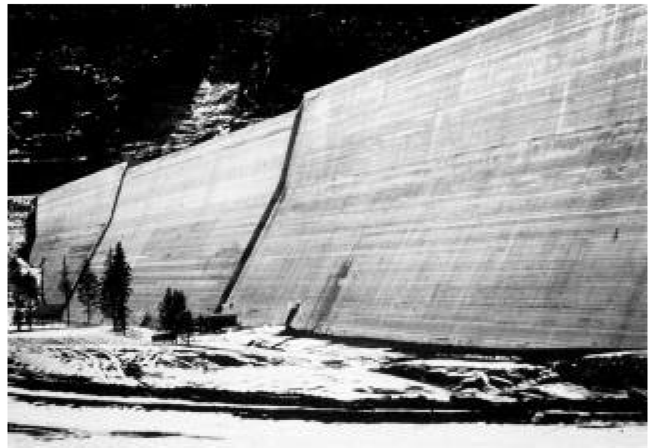

*Fig. 1.3—Upper Stillwater Dam.*

*Fig. 1.4—Wolwedans Dam.*

cost and time compared to RCC dams that have a higher percentage of RCC to total volume of concrete.

Willow Creek Dam[1.18] (Fig. 1.1), and Shimajigawa Dam[1.19] in Japan (Fig. 1.2) are the principal structures that initiated the rapid acceptance of RCC dams. They are similar from the standpoint that they both used RCC, but they are quite dissimilar with regard to design, purpose, construction details, size and cost.[1.20] Willow Creek Dam was completed in 1982 and became operational in 1983. The 433,000 $yd^3$ (331,000 $m^3$) flood control structure was the first major dam designed and constructed to be essentially all RCC. Willow Creek also incorporated the use of precast concrete panels to form the upstream facing of the dam without transverse contraction joints.[1.21]

The precast concrete facing panel concept was improved at Winchester Dam in Kentucky in 1984. Here, a PVC membrane was integrally cast behind the panels and the membrane joints were heat-welded to form an impermeable upstream barrier to prevent seepage.

In the 1980s, the U.S. Bureau of Reclamation used Dunstan's concepts of high-paste RCC for the construction of Upper Stillwater Dam (Fig. 1.3).[1.22] Notable innovations at this structure included using a steep (0.6 horizontal to 1.0 vertical) downstream slope and 3 ft (0.9 m) high, horizontally-slipformed upstream and downstream facing elements as an outer skin of conventional low-slump, air-entrained concrete. The RCC mixture consisted of 70 percent Class F pozzolan by mass of cement plus pozzolan.[1.23]

Many of the early-1980s dams successfully demonstrated the high production rates possible with RCC construction. Nearly 1.5 million $yd^3$ (1.1 million $m^3$) of RCC were placed at Upper Stillwater Dam in 11 months of construction between 1985 and 1987.[1.24] The 150 ft (46 m) high Stagecoach Dam was constructed in only 37 calendar days of essentially continuous placing; an average rate of height advance of 4.1 ft/day (1.2 m/day).[1.25] At Elk Creek Dam, RCC placing rates exceeded 12,000 $yd^3$/day (9200 $m^3$/day).[1.26]

The use of RCC for small- and medium-size dams continued in the U.S. throughout the 1980s and early 1990s, and has expanded to much larger projects all over the world. Rapid advances in RCC construction have occurred in developing nations to meet increased water and power needs. The first RCC arch gravity dams were constructed in South Africa by the Department of Water Affairs and Forestry for Knellport and Wolwedans Dams (Fig. 1.4).[1.27] Chapter 1 of *Roller-Compacted Concrete Dams*[1.28] provides further information on the history and development of the RCC Dam.

The use of RCC to rehabilitate existing concrete and embankment dams started in the U.S. in the mid-1980s and continues to flourish through the 1990s. The primary use of

RCC to upgrade concrete dams has been to buttress an existing structure to improve its seismic stability. For embankment dams, RCC has been mainly used as an overlay on the downstream slope to allow for safe overtopping during infrequent flood events. For RCC overlay applications, most of the information in this report is applicable, even though the RCC section is usually not of sufficient thickness to be considered mass concrete.[1.29,1.30]

## 1.4—Advantages and disadvantages

The advantages in RCC dam construction are extensive, but there are also some disadvantages that should be recognized. Some of the advantages are primarily realized with certain types of mixtures, structural designs, production methods, weather, or other conditions. Likewise, some disadvantages apply only to particular site conditions and designs. Each RCC project must be thoroughly evaluated based on technical merit and cost.

The main advantage is reduced cost and time for construction. Another advantage of RCC dams is that the technology can be implemented rapidly. For emergency projects such as the Kerrville Ponding Dam, RCC was used to rapidly build a new dam downstream of an embankment dam that was in imminent danger of failure due to overtopping.[1.31] RCC was also used as a means to quickly construct Concepcion Dam in Honduras after declaration of a national water supply emergency.[1.32] When compared to embankment type dams, RCC usually gains an advantage when spillway and river diversion requirements are large, where suitable foundation rock is close to the surface, and when suitable aggregates are available near the site. Another advantage is reduced cofferdam requirements because, once started, an RCC dam can be overtopped with minimal impact and the height of the RCC dam can quickly exceed the height of the cofferdam.

Although it is almost routine for efficiently designed RCC dams to be the least cost alternate when compared to other types of dams, there are conditions that may make RCC more costly. Situations where RCC may not be appropriate is when aggregate material is not reasonably available, the foundation rock is of poor quality or not close to the surface, or where foundation conditions can lead to excessive differential settlement.

# CHAPTER 2—MATERIALS AND MIXTURE PROPORTIONING FOR RCC

## 2.1—General

Mixture proportioning methods and objectives for RCC differ from those of conventional concrete. RCC must maintain a consistency that will support a vibratory roller and haul vehicles, while also being suitable for compaction by a vibratory roller or other external methods. The aggregate grading and paste content are critical parts of mixture proportioning. Specific testing procedures and evaluation methods have been developed that are unique to RCC technology.

This chapter contains discussion of materials selection criteria and considerations in determining the method of mixture proportioning for mass RCC placements. It presents several alternative methods of mixture proportioning and contains references to various projects since RCC offers considerable flexibility in this area. Requirements are usually site-specific, considering the performance criteria of the structure and are based on the designer's approach, design criteria, and desired degree of product control. Regardless of the material specifications selected or mixture-proportioning method, the testing and evaluation of laboratory trial batches are essential to verify the fresh and hardened properties of the concrete.

The cementitious material content for RCC dams has varied over a broad range from 100 lb/yd$^3$ (59 kg/m$^3$) to more than 500 lb/yd$^3$ (297 kg/m$^3$). At one end of the spectrum, the 3 in. (75 mm) nominal maximum size aggregate (NMSA), interior mixture at Willow Creek Dam contained 112 lb/yd$^3$ (60.5 kg/m$^3$) of cementitious material. The mixture containing 80 lb/yd$^3$ (47.5 kg/m$^3$) of cement plus 32 lb/yd$^3$ (19.0 kg/m$^3$) of fly ash, averaged 2623 psi (18.2 MPa) compressive strength at 1 year.[2.1] In comparison, the 2 in. (50 mm) NMSA interior mixture at Upper Stillwater Dam contained 424 lb/yd$^3$ (251.6 kg/m$^3$) of cementitious material, consisting of 134 lb/yd$^3$ (79.5 kg/m$^3$) of cement plus 290 lb/yd$^3$ (172.0 kg/m$^3$) of fly ash, and averaged 6174 psi (42.6 MPa) at 1 year.[2.2] Many RCC projects have used a cementitious materials content between 175 and 300 pcy (104 and 178 kg/m$^3$) and produced an average compressive strength between 2000 to 3000 psi (13.8 and 20.7 MPa) at an age of 90 days to 1 year. Mixture proportions for some dams are presented in Table 2.1.

An essential element in the proportioning of RCC for dams is the amount of paste. The paste volume must fill or nearly fill aggregate voids and produce a compactable, dense concrete mixture. The paste volume should also be sufficient to produce bond and watertightness at the horizontal lift joints, when the mixture is placed and compacted quickly on a reasonably fresh joint. Experience has shown that mixtures containing a low quantity of cementitious materials may require added quantities of nonplastic fines to supplement the paste fraction in filling aggregate voids.

Certain economic benefits can be achieved by reducing the processing requirements on aggregates, the normal size separations, and the separate handling, stockpiling, and batching of each size range. However, the designer must recognize that reducing or changing the normal requirements for concrete aggregates must be weighed against greater variation in the properties of the RCC that is produced, and should be accounted for by a more conservative selection of average RCC properties to be achieved.

## 2.2—Materials

A wide range of materials have been used in the production of RCC. Much of the guidance on materials provided in ACI 207.1R (Mass Concrete) may be applied to RCC. However, because some material constraints may not be necessary for RCC, the application is less demanding, more material options and subsequent performance characteristics are possible. The designer, as always, must evaluate the actual materials for the specific project and the proportions under consideration, design the structure accordingly, and provide appropriate construction specifications.

**Table 2.1—Mixture proportions of some roller-compacted concrete (RCC) dams**

| Dam/project | Mix type/ID | Year | NMSA, in. (mm) | Air, % | Water | Cement | Pozzolan | Fine aggregate | Coarse aggregate | Density, lb/yd³ (kg/m³) | AEA, oz/yd³ (cc/m³) | WRA, oz/yd³ (cc/m³) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Quantities—lb/yd³ (kg/m³) | | | | | | | |
| Camp Dyer | RCC1 | 1994 | 1.50 (38) | 3.6 | 151 (90) | 139 (82) | 137 (81) | 1264 (750) | 2265 (1344) | 3956 (2347) | 7 (4) | 4 (2) |
| Concepcion | 152C | 1990 | 3.00 (76) | 0.5 | 157 (93) | 152 (90) | 0 | 1371 (813) | 2057 (1220) | 3737 (2217) | — | — |
| Cuchillo Negro | 130C100P | 1991 | 3.00 (76) | — | 228 (135) | 130 (77) | 100 (59) | 1591 (944) | 2045 (1213) | 4094 (2429) | — | — |
| Galesville | RCC1 | 1985 | 3.00 (76) | — | 190 (113) | 89 (53) | 86 (51) | 1310 (777) | 2560 (1519) | 4235 (2513) | — | — |
| | RCC2 | 1985 | 3.00 (76) | — | 190 (113) | 110 (65) | 115 (68) | 1290 (765) | 2520 (1495) | 4225 (2507) | — | — |
| Middle Fork | 112C | 1984 | 3.00 (76) | — | 160 (95) | 112 (66) | 0 | 1152 (683) | 2138 (1268) | 3562 (2113) | — | — |
| Santa Cruz | RCCAEA | 1989 | 2.00 (51) | 2.3 | 170 (101) | 128 (76) | 127 (75) | 1227 (728) | 2301 (1365) | 3953 (2345) | 7 (4) | 3 (2) |
| Siegrist | 80C80P | 1992 | 1.50 (38) | 1 | 162 (96) | 80 (47) | 80 (47) | 1922 (1140) | 2050 (1216) | 4294 (2548) | — | — |
| | 90C70P | 1992 | 1.50 (38) | 1 | 162 (96) | 90 (53) | 70 (42) | 1923 (1141) | 2052 (1217) | 4297 (2549) | — | — |
| | 100C70P | 1992 | 1.50 (38) | 1 | 162 (96) | 100 (59) | 70 (42) | 1920 (1139) | 2048 (1215) | 4300 (2551) | — | — |
| Stacy Spillway | 210C105P | 1989 | 1.50 (38) | — | 259 (154) | 210 (125) | 105 (62) | 3500 (2076) | — | — | — | — |
| Stagecoach | 120C130P | 1988 | 2.00 (51) | — | 233 (138) | 120 (71) | 130 (77) | 1156 (686) | 2459 (1459) | 4098 (2431) | — | — |
| Upper Stillwater | RCCA85 | 1985 | 2.00 (51) | 1.5 | 159 (94) | 134 (79) | 291 (173) | 1228 (729) | 2177 (1292) | 3989 (2367) | — | 12 (7) |
| | RCCB85 | 1985 | 2.00 (51) | 1.5 | 150 (89) | 159 (94) | 349 (207) | 1171 (695) | 2178 (1292) | 4007 (2377) | — | 20 (12) |
| | RCCA | 1986 | 2.00 (51) | 1.5 | 167 (99) | 134 (79) | 292 (173) | 1149 (682) | 2218 (1316) | 3960 (2349) | — | 16 (9) |
| | RCCB | 1986 | 2.00 (51) | 1.5 | 168 (100) | 157 (93) | 347 (206) | 1149 (682) | 2131 (1264) | 3952 (2345) | — | 21 (12) |
| Urugua-I | 101C | 1988 | 3.00 (76) | — | 169 (100) | 101 (60) | 0 | 2102 (1247) | 2187 (1297) | 4559 (2705) | — | — |
| Victoria | 113C112P | 1991 | 2.00 (51) | — | 180 (107) | 113 (67) | 112 (66) | 1365 (810) | 2537 (1505) | 4307 (2555) | — | — |
| Willow Creek | 175C | 1982 | 3.00 (76) | 1.2 | 185 (110) | 175 (104) | 0 | 1108 (657) | 2794 (1658) | 4262 (2529) | — | — |
| | 175C80P | 1982 | 3.00 (76) | 1.2 | 185 (110) | 175 (104) | 80 (47) | 1087 (645) | 2739 (1625) | 4266 (2531) | — | — |
| | 80C32P | 1982 | 3.00 (76) | 1.2 | 180 (107) | 80 (47) | 32 (19) | 1123 (666) | 2833 (1681) | 4248 (2520) | — | — |
| | 315C135P | 1982 | 1.50 (38) | 1.2 | 184 (109) | 315 (187) | 135 (80) | 1390 (825) | 2086 (1238) | 4110 (2438) | — | — |
| Zintel Canyon | 125CA | 1992 | 2.50 (64) | 4.5 | 170 (101) | 125 (74) | 0 | 1519 (901) | 2288 (1357) | 4102 (2434) | 18 (11) | 18 (11) |
| | 125CNA | 1992 | 2.50 (64) | 1.4 | 188 (112) | 125 (74) | 0 | 1586 (941) | 2371 (1407) | 4270 (2533) | — | 18 (11) |
| | 300CA | 1992 | 2.50 (64) | — | 171 (101) | 300 (178) | 0 | 1348 (800) | 2388 (1417) | 4207 (2496) | 36 (21) | 42 (25) |

**2.2.1** *Cementitious materials*

**2.2.1.1** *Portland cement*—RCC can be made with any of the basic types of portland cement. For mass applications, cements with a lower heat generation than ASTM C 150, Type I are beneficial. They include ASTM C 150, Type II (moderate heat of hydration) and Type V (sulfate-resistant) and ASTM C595, Type IP (portland-pozzolan cement) and Type IS (portland-blast furnace slag cement). Strength development for these cements is usually slower than for Type I at early ages, but higher strengths than RCC produced with Type I cement are ultimately produced.

Heat generation due to hydration of the cement is typically controlled by use of lower heat of hydration cements, use of less cement, and replacement of a portion of the cement with pozzolan or a combination of these. Reduction of peak concrete temperature may be achieved by other methods, such as reduced placement temperatures. The selection of cement type should consider economics of cement procurement. For small and medium sized projects, it may not be cost effective to specify a special lower heat cement which is not locally available. Due to the high production capability of RCC, special attention may be required to ensure a continuous supply of cement to the project.

**2.2.1.2** *Pozzolans*—The selection of a pozzolan suitable for RCC should be based on its conformance with ASTM C 618. Pozzolans meeting the specifications of ASTM C 618 for Class C, Class F, and Class N have been successfully used in RCC mixtures. Class F and Class N pozzolans are usually preferred, since they normally contribute less heat of hydration than Class C and have greater sulfate resistance. For Class C pozzolans, more attention may be needed with regard to set time, sulfate resistance, and free lime content. The use of pozzolan will depend on required material performance as well as on its cost and availability at each project.

Use of a pozzolan in RCC mixtures may serve one or more of the following purposes: 1) as a partial replacement for cement to reduce heat generation; 2) as a partial replacement for cement to reduce cost; and 3) as an additive to provide supplemental fines for mixture workability and paste volume. The rate of cement replacement may vary from none to 80 percent, by mass. RCC mixtures with a higher content of cementitious material often use larger amounts of pozzolan to replace portland cement in order to reduce the internal temperature rise that would otherwise be generated and consequently reduce thermal stresses.

In RCC mixtures that have a low cement content, pozzolans have been used to ensure an adequate amount of paste for filling aggregate voids and coating aggregate particles. Pozzolan may have limited effectiveness in low-cementitious content mixtures with aggregates containing deleterious amounts of clay and friable particles. While the pozzolan enhances the paste volume of these mixtures, it may not enhance the long-term strength development be-

**Table 2.2—Combined aggregate gradings for RCC from various projects in U.S.**

| Sieve size | Willow Creek | Upper Stillwater | Christian Siegrist | Zintel Canyon | Stagecoach | Elk Creek |
|---|---|---|---|---|---|---|
| 4 in. (100 mm) | — | — | — | — | — | — |
| 3 in. (75 mm) | 100 | — | — | — | — | 100 |
| 2.5 in. (62 mm) | — | — | — | 100 | — | 96 |
| 2 in. (50 mm) | 90 | 100 | — | 98 | 100 | 86 |
| 1.5 in. (37.5 mm) | 80 | 95 | 100 | 91 | 95 | 76 |
| 1 in. (25 mm) | 62 | — | 99 | 77 | 82 | 64 |
| 0.75 in. (19 mm) | 54 | 66 | 91 | 70 | 69 | 58 |
| 3/8 in. (9.5 mm) | 42 | 45 | 60 | 50 | 52 | 51 |
| No. 4 (4.75 mm) | 30 | 35 | 49 | 39 | 40 | 41 |
| No. 8 (2.36 mm) | 23 | 26 | 38 | 25 | 32 | 34 |
| No. 16 (1.18 mm) | 17 | 21 | 23 | 18 | 25 | 31 |
| No. 30 (0.60 mm) | 13 | 17 | 14 | 15 | 15 | 21 |
| No. 50 (0.30 mm) | 9 | 10 | 10 | 12 | 10 | 15 |
| No. 100 (0.15 mm) | 7 | 2 | 6 | 11 | 8 | 10 |
| No. 200 (0.075 mm) | 5 | 0 | 5 | 9 | 5 | 7 |
| $C + P$ lb/cy | 80 + 32 | 134 + 291 | 100 + 70 | 125 + 0 | 120 + 130 | 118 + 56 |
| Total fines* | 20% | 21% | 19% | 21% | — | 21% |
| Workability | Poor | Excellent | Excellent | Excellent | Good | Excellent |

*Total fines = all materials in full mixture with particle size smaller than No. 200 sieve.

cause of insufficient availability of calcium hydroxide released from the portland cement for a pozzolanic reaction.

Class F pozzolans, especially at cool temperatures, generally delay the initial set of RCC mixtures, contributing to low early strength, but extending the working life of the freshly compacted lift joint. In high pozzolan-content RCC mixtures, the heat rise may continue for up to 60 to 90 days after placing.

**2.2.2** *Aggregates*

**2.2.2.1** *General quality issues*—The selection of aggregates and the control of aggregate properties and gradings are important factors influencing the quality and uniformity of RCC production. Aggregates similar to those used in conventional concrete have been used in RCC. However, aggregates that do not meet the normal standards or requirements for conventional concrete have also been successfully used in RCC dam construction.[2.3]

Marginal aggregates are those aggregates that do not meet traditional standards, such as ASTM C 33, regardless of the method of construction. Limits on physical requirements and on deleterious materials for aggregates to be used in RCC for a specific application should be established prior to construction, based on required concrete performance and demonstrated field and laboratory evaluations. The majority of RCC projects have been constructed with aggregates meeting all of the ASTM C 33 requirements, with the exception of an increased amount of fines passing the No. 200 (0.075 mm) sieve.

Aggregates of marginal quality have been used in RCC on some projects because they were close to the site and thereby the most economical source available. The design of the structure must accommodate any change in performance that may result. On some projects, the use of aggregates of lower physical strength has produced RCC with satisfactory creep rates, elastic moduli, and tensile strain capacity. These properties are desirable for mass-concrete applications where lower concrete strength can be tolerated. If practical, lower-quality aggregates are best used in the interior of dams where they can be encapsulated by higher-quality concrete, especially in freeze thaw areas.

A basic objective in proportioning any concrete is to incorporate the maximum amount of aggregate and minimum amount of water into the mixture, thereby reducing the cementitious material quantity, and reducing consequent volume change of the concrete. This objective is accomplished by using a well-graded aggregate with the largest maximum size which is practical for placement. The proper combination of materials should result in a mixture that achieves the desired properties with adequate paste and a minimum cementitious content. However, in RCC mixtures, the potential for segregation and the means of compaction must also be primary considerations in selecting the maximum size of aggregate. Early projects in the U.S. used a 3 in. (75 mm) nominal maximum size aggregate (NMSA); however, a 2 in. (50 mm) NMSA is less prone to segregation and is becoming more widely used.

The combined aggregate gradation should be selected to minimize segregation. The key to controlling segregation and providing a good compactable mixture is having a grading that is consistent and contains more material passing the No. 4 (4.75 mm) sieve than typical in conventional concrete of similar nominal maximum size aggregate. Table 2.2 provides typical combined aggregate gradings for various projects.

In conventional concrete, the presence of any significant quantity of flat and elongated particles is usually undesirable. However, RCC mixtures appear to be less affected by flat and elongated particles than conventional concrete mixtures. This peculiarity is because vibratory compaction equipment provides more energy than traditional consolidation methods, and because the higher mortar content in RCC mixtures tends to separate coarse aggregate particles. Field tests with amounts of 40% flat and elongated particles on any sieve with an average below approximately 30%, as determined by ASTM D 4791 with a ratio of 1:5, have shown flat and elongated particles to be no significant problem.[2.1] The U.S. Army Corps of Engineers currently has a limit of 25% on the allowable content of flat and elongated particles in any size group.

The use of manufactured aggregate (crushed stone) has been found to reduce the tendency for segregation, as compared to rounded gravels.

**2.2.2.2** *Coarse aggregate*—The selection of a nominal maximum size aggregate should be based on the need to reduce cementitious material requirements, control segregation, and facilitate compaction. Most RCC projects have used a NMSA of 1-1/2 to 3 in. (37.5 mm to 75 mm). There has typically not been enough material cost savings from using aggregate sizes larger than 3 in. (75 mm) to offset the added batching cost and cost of controlling the increased segregation problems associated with the larger aggregates. NMSA has little effect on compaction when the thickness of the placement layers is more than 3 times the NMSA, segregation is adequately controlled, and large vibratory rollers are used for compaction.

Grading of coarse aggregate usually follows ASTM C 33 size designations. Some designers, however, have used locally available aggregate road base material with grading requirements similar to that contained in ASTM D 2940. Where close control of grading of coarse aggregate and RCC production are desired, size separations should follow normal concrete practice, as recommended in ACI 304R. Cost savings can be realized by combining two or more size ranges such as ASTM C 33 size designations 357 or 467 for 2 in. to No. 4 (50 to 4.75 mm) and 1-1/2 in. to No. 4 (37.5 to 4.75 mm), respectively. However, as the size range increases, it becomes increasingly more difficult to avoid segregation of the larger particles during stockpiling and handling of this aggregate. Aggregate for RCC have used a single stockpile or been separated into as many as five aggregate sizes. Some projects simply use a coarse and a fine-aggregate stockpile.

The design engineer must weigh the potential cost savings in a reduction in number of stockpiles and separate handling and weighing facilities against the potential for increased variation in aggregate grading and its impact on uniformity of consistency, strength, on bonding, and on permeability of the resulting RCC.

RCC mixtures for overtopping protection for embankment dams frequently use a NMSA of 1 in. (25 mm) as the concrete section is thinner. Because the volume of concrete required is normally not substantial, the RCC mixture can be obtained from commercial concrete suppliers.

**2.2.2.3** *Fine aggregate*—The grading of fine aggregate strongly influences paste requirements and compactability of RCC. It also affects water and cementitious material requirements needed to fill the aggregate voids and coat the aggregate particles.

For those mixtures having a sufficient cementitious materials content and paste volume, ASTM C 33 fine-aggregate grading can be satisfactorily used. This can be determined when the mixtures are proportioned.

**2.2.2.4** *Fines*—In low-cementitious materials content mixtures, supplemental fines, material passing the No. 200 (0.075 mm) sieve, are usually required to fill all the aggregate void spaces. Depending on the volume of cementitious material and the NMSA, the required total minus No. 200 (0.075 mm) fines may be as much as 10% of the total aggregate volume, with most mixtures using approximately 3 to 8%. Characteristics of the fines and fines content will affect the relative compactability of the RCC mixture and can influence the number of passes of a vibratory roller required for full compaction of a given layer thickness. Regardless of whether it is accomplished by adding aggregate fines, cement, pozzolan, or combination of these, most compactable RCC mixtures contain approximately 8 to 12% total solids finer than the No. 200 (0.075 mm) sieve by volume, or 12 to 16% by mass. This is illustrated in Table 2.1. The fines fill aggregate void space, provide a compactable consistency, help control segregation, and decrease permeability. Including aggregate fines in low-cementitious paste mixtures allows reductions in the cementitious materials content. Excessive additions of aggregate fines after the aggregate voids are filled typically are harmful to the RCC mixture because of decreases in workability, increased water demand and subsequent strength loss.

When adding aggregate fines to a mixture, another consideration is the nature of the fines. Crusher fines and silty material are usually acceptable. However, clay fines, termed plastic fines, can cause an increase in water demand and a loss of strength, and produce a sticky mixture that is difficult to mix and compact.

**2.2.3** *Chemical admixtures*—Chemical admixtures have been effective in RCC mixtures that contain sufficient water to provide a more fluid paste. ASTM C 494, Types A (water-reducing) and D (water-reducing and retarding) are the most commonly used chemical admixtures. Water-reducing admixtures, used at very high dosages, have been shown to reduce water demand, increase strength, retard set, and promote workability in some RCC mixtures.[2.4] However, the knowledge of the effectiveness in other mixtures, typically with low-cementitious materials contents and low workability levels, is limited.[2.1,2.3] Admixtures should be evaluated with the actual RCC mixture before being used in the field.

Air-entraining admixtures are not commonly used in RCC mixtures because of the difficulty in generating the air bubbles of the proper size and distribution when the mixture has a no-slump consistency. However, air-entrained RCC has been used on a production basis in China and the U.S. in more recent projects. RCC exhibiting a fluid paste consistency has generally been necessary for air-entraining admixtures to perform.

## 2.3—Mixture proportioning considerations

A goal of mass-concrete mixture proportioning, which is also applicable to RCC mixture proportioning, is to provide a

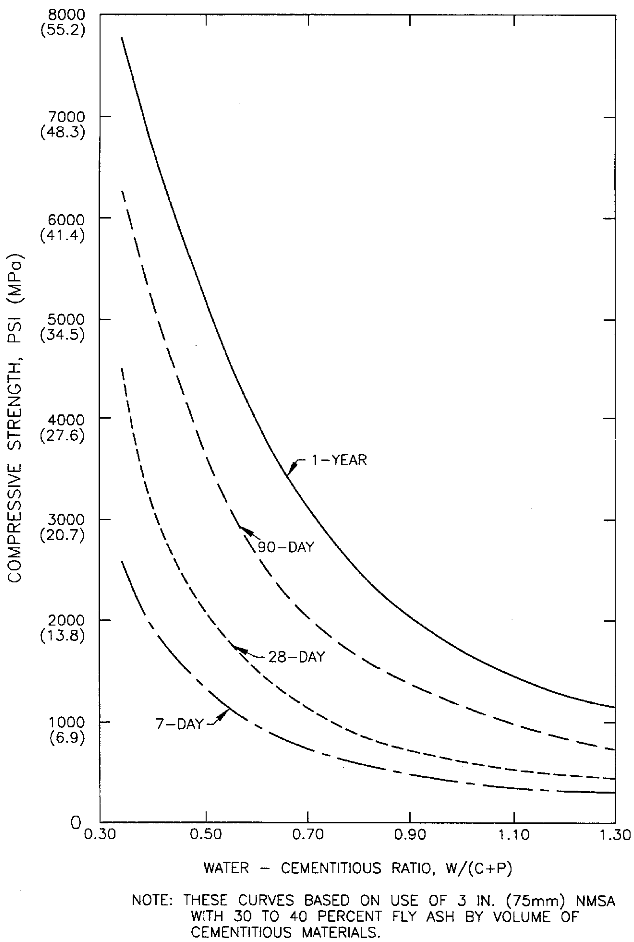


*Fig. 2.1—Compressive strength versus* w/cm *(USACE, 1992).*

maximum content of coarse aggregate and a minimum amount of cement while developing the required plastic and hardened properties at the least overall cost. Optimum RCC proportions consist of a balance between good material properties and acceptable placement methods. This includes minimizing segregation. In implementing a specific mixture-proportioning procedure, the following considerations regarding plastic and hardened properties should be addressed.

**2.3.1** *Workability*—Sufficient workability is necessary to achieve compaction or consolidation of the mixture. Sufficient workability is also necessary to provide an acceptable appearance when RCC is to be compacted against forms. Workability is most affected by the paste portion of the mixture including cement, pozzolan, aggregate fines, water, and air. When there is sufficient paste to fill aggregate voids workability of RCC mixtures is normally measured on a vibratory table with a Vebe apparatus in accordance with ASTM C 1170 (Fig. 6.1). This test produces a Vebe time for the specific mixture, and is used in a similar way as the slump test for conventional concrete. RCC mixtures with the degree of workability necessary for ease of compaction and production of uniform density from top to bottom of the lift, for bonding with previously placed lifts, and for support of compaction equipment, generally have a Vebe time of 10 to 45 sec. However, RCC mixtures have been proportioned with a wide range of workability levels. Some RCC mixtures have contained such low paste volume that workability could not be measured by the Vebe apparatus. This is particularly true of those mixtures proportioned with a very low cementitious materials content or designed more as a cement stabilized fill. Workability of these type of mixtures need to be judged by observations during placement and compaction, together with compacted density and moisture content measurements.

The water demand for a specific level of workability will be influenced by the size, shape, texture and gradation of aggregates and the volume and nature of cementitious and fine materials. Depending on the paste volume, water demand can be established by Vebe time or by the moisture-density relationship, discussed later.

**2.3.2** *Strength*—RCC strength depends upon the quality and grading of the aggregate, mixture proportions, as well as the degree of compaction. There are differing basic strength relationships for RCC, depending on whether the aggregate voids are completely filled with paste or not. The water-cement ratio (*w/c)* law, as developed by Abrams in 1918, is only valid for fully consolidated concrete mixtures. Therefore, the compressive strength of RCC is a function of the water-cementitious materials ratio (*w/cm*) only for mixtures with a Vebe time less than 45 sec, but usually in the 15 to 20 sec range. Fig. 2.1 shows this general relationship. For drier consistency (all voids not filled with paste) mixtures, compressive strength is controlled by moisture-density relationships. There is an optimum moisture content that produces a maximum dry density for a certain comparative effort. With the same aggregate, the moisture content necessary to produce maximum compressive strength is less than the moisture required to produce an RCC mixture with a Vebe time in the range of 15 sec. There is little or no change in optimum moisture content with varying cementitious contents.

If the water content is less than optimum, as determined by strength or density versus moisture curves, there are increased voids in the mixture. This condition leads to a poorly compacted mixture with a resulting loss in density and strength. In this case, the addition of water to the mixture produces higher compressive strength, while for fully consolidated mixtures, slight decreases in moisture content tend to produce a higher compressive strength.

The design strength is usually not determined by the compressive stresses in the structure, but is more dependent on the required tensile strength, shear strength, and durability. These are usually dictated by dynamic and static structural analyses, combined with an analysis of thermal stresses. Compressive strength is generally regarded as the most convenient indicator of the quality and uniformity of the concrete. Therefore, the design compressive strength is usually selected based on the level of strength necessary to satisfy compressive tensile and shear stresses plus durability under all loading conditions.

RCC mixtures should be proportioned to produce the design compressive strength plus an overdesign factor based on expected strength variation. Statistical concepts, as presented in ACI 214, can be used for this purpose. For example, if the design strength is 2500 psi (17.2 MPa) at 1 year, and the expected standard deviation is 600 psi (4.1 MPa) with no more than 2 in 10 tests allowed below the design strength, the required average strength would be equal to the design strength plus 500 or 3000 psi (3.5 or 20.7 MPa). The RCC mixture should then be proportioned for a strength of 3000 psi (20.7 MPa) at 1 year. Similar to conventional concrete, a lower standard deviation will permit a reduction in required average strength. The cost of controlling strength variation must be balanced against project needs and the savings that may be realized.

Compressive strength of RCC is usually measured by testing 6 in. (152 mm) diameter by 12 in. (304 mm) long cylinder specimens. Specimens can be prepared using a vibrating table, as described in ASTM C 1176, for high cementitious content and paste volume mixtures, or can be compacted by a tamping/vibrating hammer for drier consistency mixtures. Cylinder molds should be steel or supported by a steel sleeve if plastic or sheet metal cylinder molds are used. ASTM is currently working on a standard for casting cylinders using the tamping/vibrating hammer. These methods use the fraction of the RCC mixture that passes the 2 in. (50 mm) sieve. For mixtures containing larger NMSA, the compressive strength can be approximated for the full mixture using Fig. 227 of the *Concrete Manual*.[2.5]

**2.3.3** *Segregation*—A major goal in the proportioning of RCC mixtures is to produce a cohesive mixture while minimizing the tendency to segregate during transporting, placing, and spreading. Well-graded aggregates with a slightly higher fine aggregate content than conventional concrete are essential for NMSA greater than 1-1/2 in. (37.5 mm). If not proportioned properly, RCC mixtures tend to segregate more because of the more granular nature of the mixture. This is controlled by the aggregate grading, moisture content and adjusting fine content in lower cementitious content mixtures. Higher cementitious content mixtures are usually more cohesive and less likely to segregate.

**2.3.4** *Permeability*—Mixtures that have a paste volume of 18 to 22% by mass will provide a suitable level of impermeability, similar to conventional mass concrete in the unjointed mass of the RCC. Most concerns regarding RCC permeability are directed at lift-joint seepage. Higher cementitious content or high-workability mixtures that bond well to fresh lift joints will produce adequate water tightness. However, lower cementitious or low workability content mixtures are not likely to produce adequate water tightness without special treatment, such as use of bedding mortar between lifts. Where a seepage cutoff system is used on the upstream face, the permeability of the RCC may be of little significance except as it may relate to freeze/thaw durability of exposed surfaces.

**2.3.5** *Heat generation*—RCC mixture proportioning for massive structures must consider the heat generation of the cementitious materials. To minimize the heat of hydration, care should be taken in the selection and combination of cementing materials used. In cases where pozzolan is used, it may be worthwhile to conduct heat of hydration testing on various percentages of cement and pozzolan to identify the combination that generates the minimum heat of hydration, while providing satisfactory strength, prior to proportioning the mixture. The amount of cementitious material used in the mixture should be no more than necessary to achieve the necessary level of strength. Proportioning should incorporate those measures which normally minimize the required content of cementitious material, such as appropriate NMSA and well-graded aggregates. Further guidance in controlling heat generation can be found in ACI 207.1R, ACI 207.2R, and ACI 207.4R.

**2.3.6** *Durability*—The RCC mixture should provide the required degree of durability based on materials used, exposure conditions, and expected level of performance. RCC should be free of damaging effects of alkali-aggregate reactivity by proper evaluation and selection of materials. Recent work indicates that air-entrained RCC can be produced with adequate freeze-thaw resistance. Consideration should be given to higher cementitious material contents where air-entrained RCC can not be achieved, where RCC may be exposed to erosion by flowing water, or where protective zones of conventional concrete cannot be incorporated into the structure. RCC hydraulic surfaces have performed well where exposure has been of short duration and intermittent. Freeze-thaw resistance and erosion should not be a major concern during mixture proportioning provided that high-quality conventional concrete is used on upstream, crest and downstream faces, and on spillway surfaces.

**2.3.7** *Construction conditions*—Construction requirements and equipment should be considered during mixture proportioning. Some construction methods, placement schedules, and equipment selections are less damaging to compacted RCC than others. A higher workability mixture may result in a compacted RCC surface that tends to rut from rollers. Wheeled traffic may produce severe rutting and should be restricted from operating on the compacted surface of the last lift of the day prior to it reaching final set. Rutting of the lift surface at Elk Creek Dam and Upper Stillwater Dam was observed to be as much as 2 to 3 in. (50 to 76 mm) deep. Severe rutting is generally not desirable, as ruts may trap water or excessive mortar during joint cleanup or treatment, and may reduce bond strength along the lift joint. However, placing conditions with many obstacles requiring smaller compaction equipment benefit from mixtures having a higher level of workability.

## 2.4—Mixture proportioning methods

**2.4.1** *General*—A number of mixture proportioning methods have been successfully used for RCC structures throughout the world. These methods have differed significantly due to the location and design requirements of the structure, availability of materials, the mixing and placing equipment used, and time constraints. 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. Both approaches are intended to produce quality

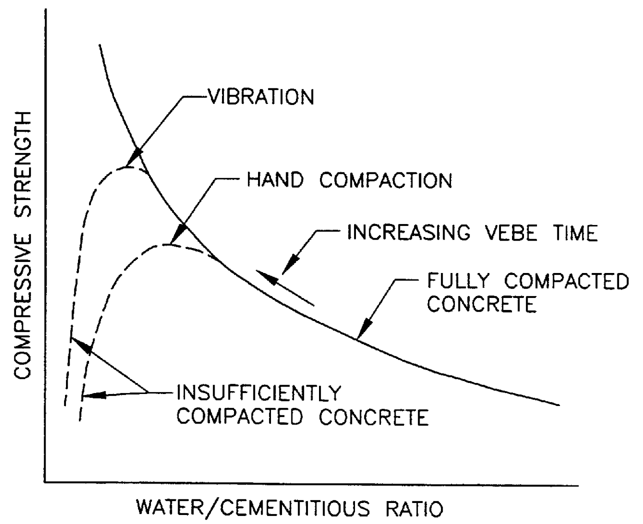


*Fig. 2.2—General relationship between compressive strength and* w/cm.

concrete suitable for roller compaction and dam construction. The basic concepts behind these approaches are covered in ACI 211.3. Mixture proportions used for some RCC dams are shown in Fig. 2.2.

RCC mixture proportions can follow the convention used in traditional concrete where the mass of each ingredient contained in a compacted unit volume of the mixture is based on saturated surface dry (SSD) aggregate condition. A practical reason for use of this standard convention is that most RCC mixing plants require that mixture constituents be so identified for input to the plant control system. For continuous mixing plants, the mixture proportions may have to be converted to percent by dry weight of aggregate.

**2.4.2** *Corps of Engineers method*[2.6,2.7]—This proportioning method is based on *w/cm* and strength relationship. Appendix 4 of ACI 211.3 contains a similar method. Both methods calculate mixture quantities from solid volume determinations, as used in proportioning most conventional concrete. The *w/cm* and equivalent cement content are established from figures based on the strength criteria using Fig. 2.1 and Fig. 2.3. The approximate water demand is based on nominal maximum size aggregate and desired modified Vebe time. A recommended fine aggregate content as a percentage of the total aggregate volume is based on the nominal maximum size and nature of the coarse aggregate. Once the volume of each ingredient is calculated, a comparison of the mortar content to recommended values can be made to check the proportions. This method also provides several unique aspects, including ideal combined coarse aggregate gradings and fine aggregate gradings limits incorporating a higher percentage of fine sizes than permitted by ASTM C 33. Because design strength for many RCC dams is based on 1 year, a target 90- or 180-day strength may be estimated using Fig. 2.1 and Fig. 2.3.

**2.4.3** *High paste method*[2.8,2.9]—This mixture proportioning method was developed by the U.S. Bureau of Reclamation for use during the design of Upper Stillwater Dam. The resulting mixtures from that testing program generally contained high proportions of cementitious materials, high pozzolan contents, clean and normally graded aggregates, and high-workability. The purpose of the Upper Stillwater Dam mixtures was 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.

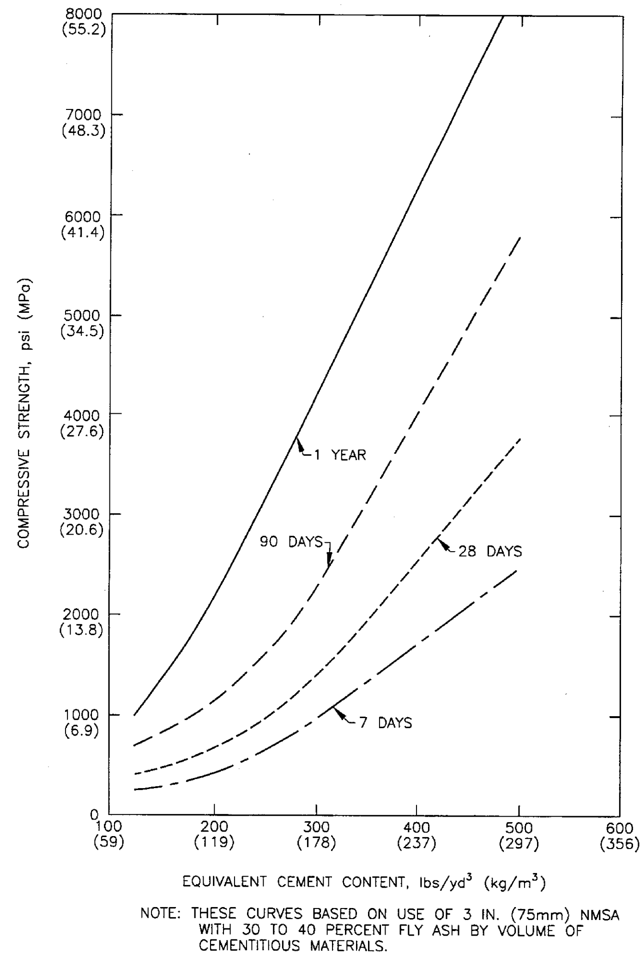


*Fig. 2.3—Equivalent cement content versus compressive strength (USACE, 1992).*

The high paste method involves determining *w/cm* and fly ash-cement ratios for the desired strength level and strength gain. The optimum water, fine aggregate, and coarse aggregate ratios are determined by trial batches, evaluating the Vebe consistency for a range of 10 to 30 sec. The required volumes and mass of aggregate, cement, pozzolan, water, and air are then calculated.

Laboratory trial mixtures are evaluated to verify acceptable workability, strength, and other required properties are provided by the mixture. Specific mixture variations may be performed to evaluate their effect on the fresh properties, such as consistency and hardened strength properties to optimize the mixture proportions. Strength specimens are fabricated using ASTM C 1176 with the vibrating table.

**2.4.4** *Roller-compacted dam method*[2.10]—The roller-compacted dam (RCD) method was developed by Japanese engineers and 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 consistency meter is similar to the Vebe apparatus in that RCC mixture is placed in a container and vibrated until mortar is observed on the surface. The device is sufficiently large to allow the full mixture, often 150 mm (6 in.) NMSA, to be evaluated rather than having to screen out the oversize particles.

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. The proper RCD mixture is the optimum combination of materials which meets the specific design criteria. 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.

**2.4.5** *Maximum density method*[2.11]—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 D 1557, Method D.

Variations of this method can also be used depending on the mixture composition and nominal maximum size of aggregate. Compaction equipment may be a standard drop hammer, some variation of this equipment better suited for larger-aggregate mixtures, or an alternate tamping/vibration method that simulates field compaction equipment and obtains similar densities.

In this method, a series of mixtures for each cementitious materials content is prepared and batched using a range of water contents. Each prepared mixture is compacted with a standard effort. The maximum density and optimum water content are determined from a plot of density versus water content for the compacted specimens at each cementitious materials content. The actual water content used is usually slightly higher (plus approximately 1%) than the optimum value determined in the laboratory, to compensate for moisture loss during transporting, placing, and spreading. RCC specimens are then made at the optimum or the designated water content for strength testing at each cementitious materials content.

Conversion of maximum density and optimum or designated water content to batch weights of ingredients on a $yd^3$ or $m^3$ basis is covered in Appendix 4 of ACI 211.3.

## 2.5—Laboratory trial mixtures

**2.5.1** *General*—It is recommended that a series of mixtures be proportioned and laboratory trial mixed to encompass the potential range of performance requirements. This practice will allow later mixture modifications or adjustments without necessarily repeating the mixture evaluation process. Final adjustments should be made based on full-sized field trial batches, preferably in a test strip or section where workability and compactability can be observed.

**2.5.2** *Visual examination*—Several characteristics can be determined by visual examination of laboratory prepared trial mixtures. Distribution of aggregate in the mixture, cohesiveness, and tendency for segregation are observable by handling the mixture on the lab floor with shovels. The texture of the mixture (harsh, unworkable, gritty, pasty, smooth) can be seen and felt with the hand. These characteristics should be recorded for each mixture.

**2.5.3** *Testing*—Laboratory tests, including temperature, consistency, unit weight, and air content, should be conducted on the fresh RCC produced from each trial mixture. In addition, specimens should be prepared for compressive strength testing at various ages, usually 7, 28, 90, 180 days, and 1 year to indicate the strength gain characteristics of each mixture. These specimens can also be used for determination of static modulus of elasticity and Poisson's ratio at selected ages. Additional specimens should also be fabricated for splitting tensile strength (ASTM C 496) or direct tensile strength at various ages to established their relationship to compressive strength, and to provide parameters for use in structural analysis.

On major projects, specimens for thermal properties, including adiabatic temperature rise, coefficient of thermal expansion, specific heat, and diffusivity, are usually cast from one or more selected RCC mixtures. Specimens for specialized tests such as creep, tensile strain capacity, and shear strength may also be cast from these mixtures. Many commercial laboratories are not equipped to conduct these tests, and special arrangements may be required with the Corps of Engineers, U.S. Bureau of Reclamation, or universities that have the equipment and facilities for this work.

## 2.6—Field adjustments

The primary purpose of laboratory mixture proportioning is to provide proportions that when batched, mixed, and placed in the field, will perform as intended. However, laboratory conditions seldom perfectly duplicate field conditions due to batching accuracies, differences in mixer size and mixing action, changes in materials and material gradings, compaction equipment, RCC curing, and time between adding water and compaction. In spite of these differences, laboratory mixture proportioning has proven to be an effective means to ensure RCC performance and to minimize field adjustments.

Field adjustments should include: 1) adjustment of aggregate percentages based on stockpile gradings of each individual size range to produce the required combined grading; 2) correction of batch weights for aggregate moisture contents; and 3) adjustment of water content for the desired consistency or degree of workability based on compactability of the mixture. Field adjustments should be done with caution to ensure the original mixture *w/cm* or other critical mixture requirements are not exceeded.

Prior to use in permanent work, it is recommended that the proposed RCC mixture be proportioned and mixed in full-size batches and placed, spread, and compacted in a test strip or section using the specified construction procedures. The test strip or section will provide valuable information on the need for minor mixture modifications and can be used to determine the compactive effort (roller passes) required for full compaction of the RCC mixture. A test strip or section can also be used to visually examine the condition of lift joints and potential for mixture segregation.

# CHAPTER 3—PROPERTIES OF HARDENED RCC

## 3.1—General

The properties of hardened RCC are similar to those of mass concrete. However, some differences between RCC and mass concrete exist, due primarily to differences in required strength, performance and voids content of the RCC mixtures. Most RCC mixtures are not air entrained and also may use aggregates not meeting the quality or grading requirements of conventional mass concrete. RCC mixtures may also use pozzolans, which affect the rate of strength gain and heat generation of the mix. Because some RCC mixtures may use lower quality aggregates and lower cementitious materials contents (than conventional concretes), the range of hardened properties of RCC is wider than the range of properties of conventional concrete.

Designers should also be aware of the potential for increased variability of hardened strength properties of RCC due to the potential for greater variations in materials and degree of compaction. Lower quality aggregates are those that may not meet the requirements for conventional concrete aggregates, either in durability or grading, or those that have been processed without washing. The use of these materials should be specified by the designer, based on required performance. The rapid placing rates common in RCC construction can place construction loads on concrete before it reaches its initial set, and early-age testing of performance may be needed for the design. The designer should maintain an awareness of the potential impact of low early-age strength on construction activities.

## 3.2—Strength

**3.2.1** *Compressive strength*—Compressive strength tests are performed in the design phase to determine mixture proportion requirements, and also to optimize combinations of cementitious materials and aggregates. Compressive strength is used to satisfy design loading requirements and also as an indicator of other properties such as durability. Tests of cores from test sections may be used to evaluate strength of RCC for design purposes, and also to evaluate the effects of compaction methods. During construction, compressive strength tests are used to confirm design properties as a tool to evaluate mixture variability, and for historical purposes. Cores may be used to further evaluate long-term performance. It is important to recognize that the compressive strength test results during construction will lag far behind production, and that quality assurance can only be achieved as the RCC is mixed, placed, and compacted.

The compressive strength of RCC is determined by the water content, cementitious content, properties of the cementitious materials the aggregate grading, and the degree of compaction. For fully compacted RCC, the influence of *w/cm* on compressive strength is valid. Pozzolan can delay the early strength development of RCC. Higher pozzolan contents cause lower early strength. However, mixtures proportioned for later age strengths, such as at 180 days or 1 year, can use significant quantities of pozzolan.

RCC mixtures with low cementitious contents may not achieve required strength levels if aggregate voids are not completely filled. For these mixtures, the addition of nonplastic fines or rock dust has been beneficial in filling voids, thus increasing the density and strength. Use of plastic (clay) fines in RCC mixtures has been shown to adversely affect strength and workability and therefore is not recommended.

Significant differences in compaction will affect the strength of RCC in both the laboratory and in core samples from in-place construction. For laboratory specimens, the energy imparted to the fresh mixture must be sufficient to achieve full compaction, or strength will not reach the required level due to increased voids. The compactive effort in the laboratory may be compared to cores during the test section phase of construction, provided that the test section has sufficient strength to be cored. The compressive strength of concrete will also decrease due to insufficient compaction, usually near the bottom of the lift when RCC has poor workability. Not only does this affect compressive strength, but also density bond strength and joint seepage. Compressive strength will also decrease due to delays in completing compaction.

Typical compressive strengths and elastic properties of RCC are given in Tables 3.1, 3.2, and 3.5. The design compressive strengths for these mixtures may vary from as low as 1000 lb/in.$^2$ (6.9 MPa) to as high as 4000 lb/in.$^2$ (27.6 MPa) at an age of 1 year. Fig. 3.1 and 3.2 show a family of compressive strength curves developed for two different aggregates using a maximum density method for mixture proportioning.

**3.2.2** *Tensile strength*—Tensile strength of RCC is required for design purposes, including dynamic loading and in the thermal analysis. The ratios of tensile-to-compressive strength for parent (unjointed) RCC mixtures have typically ranged from approximately 5 to 15%, depending on aggregate quality, strength, age, and test method. Mixtures with low cementitious materials content, or those with lower-quality or coated aggregates, or both, will have corresponding lower direct tensile strengths. The ratio of direct tensile strength to compressive strength of both RCC and conventional mass concrete will usually decrease with increasing age and compressive strength.[3.1]

The direct tensile strength of RCC is less than the splitting tensile strength of unjointed RCC. The designer should pay particular attention to use of either direct or splitting tensile strength, depending on whether the analysis requires using the strength across lift lines or parent strength, respectively. Designers should also consider anticipated construction and joint surface treatment methods in their design tensile strength assumptions. The direct tensile strength of RCC lift joints is not only dependent on the strength of the mixture, but also on the speed of construction, the lift-joint surface preparation, degree of compaction and segregation at the lift interface, and the use

**Table 3.1—Compressive strength of some RCC dams: construction control cylinders**

| Dam/project | Mix type/ID | Cement, lb/yd$^3$ (kg/m$^3$) | Pozzolan, lb/yd$^3$ (kg/m$^3$) | *w/cm* | NMSA, in. (mm) | Cylinder fabrication method | Compressive strength, psi (MPa), at test age | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 7 day | 28 day | 90 day | 180 day | 365 day |
| Camp Dyer | RCC1 | 139 (82) | 137 (81) | 0.55 | 1.5 (38.1) | VB | 880 (6.1) | 1470 (10.1) | — | — | 3680 (25.4) |
| Concepcion | 152C | 152 (90) | 0 | 1.03 | 3 (76.2) | PT | 580 (4.0) | 800 (5.5) | 1100 (7.6) | 1270 (8.8) | — |
| Galesville | RCC1 | 89 (53) | 86 (51) | 1.09 | 3 (76.2) | PT | 300 (2.1) | 580 (4.0) | 1020 (7.0) | — | 1620 (11.2) |
| | RCC2 | 110 (65) | 115 (68) | 0.84 | 3 (76.2) | PT | 420 (2.9) | 820 (5.7) | 1370 (9.4) | — | — |
| Middle Fork | 112C | 112 (66) | 0 | 1.43 | 3 (76.2) | PT | — | 1270 (8.8) | 1650 (11.4) | — | — |
| Santa Cruz | RCCAEA | 128 (76) | 127 (75) | 0.67 | 2 (50.8) | VB | 1090 (7.5) | 2730 (18.8) | 3220 (22.2) | — | 4420 (30.5) |
| Stacy Spillway | 210C105P | 210 (125) | 105 (62) | 0.82 | 1.5 (38.1) | MP | — | 2620 (18.1) | 3100 (21.4) | — | — |
| Stagecoach | 120C130P | 120 (71) | 130 (77) | 0.93 | 2 (50.8) | PT | 215 (1.5) | 350 (2.4) | — | 985 (6.8) | 1250 (8.6) |
| Upper Stillwater | RCCA85 | 134 (79) | 291 (173) | 0.37 | 2 (50.8) | VB | 1560 (10.8) | 2570 (17.7) | 3600 (24.8) | 5590 (38.5) | 6980 (48.1) |
| | RCCB85 | 159 (94) | 349 (207) | 0.30 | 2 (50.8) | VB | 2040 (14.1) | 3420 (23.6) | 4200 (29.0) | 5530 (38.1) | 7390 (51.0) |
| | RCCA | 134 (79) | 292 (173) | 0.39 | 2 (50.8) | VB | 1080 (7.4) | 1830 (12.6) | 2600 (17.9) | — | 6400 (44.1) |
| | RCCB | 157 (93) | 347 (206) | 0.33 | 2 (50.8) | VB | 1340 (9.2) | 2230 (15.4) | 3110 (21.4) | — | 6750 (46.5) |
| Urugua-I | 101C | 101 (60) | 0 | 1.67 | 3 (76.2) | PT | — | 930 (6.4) | 1170 (8.1) | — | 1390 (9.6) |
| Willow Creek | 175C | 175 (104) | 0 | 1.06 | 3 (76.2) | PT | 1000 (6.9) | 1850 (12.8) | 2650 (18.3) | — | 3780 (26.1) |
| | 175C80P | 175 (104) | 80 (47) | 0.73 | 3 (76.2) | PT | 1150 (7.9) | 2060 (14.2) | 3960 (27.3) | — | 4150 (28.6) |
| | 80C32P | 80 (47) | 32 (19) | 1.61 | 3 (76.2) | PT | 580 (4.0) | 1170 (8.1) | 1730 (11.9) | — | 2620 (18.1) |
| | 315C135P | 315 (187) | 135 (80) | 0.41 | 1.5 (38.1) | PT | 2030 (14.0) | 3410 (23.5) | 4470 (30.8) | — | 5790 (39.9) |

Note: Cylinder fabrication method: VB = Vebe (ASTM C 1176); MP = modified proctor (ASTM D 1557); and PT = pneumatic tamper.

**Table 3.2—Comparison of compressive strengths of RCC: construction control cylinders versus cores**

| Dam/project | Mix type/ID | Cement, lb/yd$^3$ (kg/m$^3$) | Pozzolan, lb/yd$^3$ (kg/m$^3$) | *w/cm* | NMSA, in. (mm) | Cylinder fabrication method | Cylinder strength, psi (MPa) | | | Core strength, psi (MPa) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 28 day | 90 day | 365 day | Age, days | Strength | Age, days | Strength |
| Elk Creek | 118C56P | 118 (70) | 56 (33) | 1.00 | 3 (76) | VB | 410 (3) | 1370 (9) | 2380 (16) | 90 | 1340 (9) | 730 | 2450 (17) |
| Galesville | RCC1 | 89 (53) | 86 (51) | 1.09 | 3 (76) | PT | 580 (4) | 1020 (7) | 1620 (11) | 425 | 2080 (14) | — | — |
| Middle Fork | 112C | 112 (66) | 0 | 1.43 | 3 (76) | PT | 1270 (9) | 1650 (11) | — | 42 | 2016 (14) | 0 | 0 |
| Stacy Spillway | 210C105P | 210 (125) | 105 (62) | 0.82 | 1.5 (38) | MP | 2620 (18) | 3100 (21) | — | 28 | 2090 (14) | 90 | 2580 (18) |
| Stagecoach | 120C130P | 120 (71) | 130 (77) | 0.93 | 2 (51) | PT | 350 (2) | — | 1250 (9) | 180 | 1960 (14) | 365 | 1920 (13) |
| Upper Stillwater | RCCA | 134 (79) | 292 (173) | 0.39 | 2 (51) | VB | 1830 (13) | 2600 (18) | 6400 (44) | 180 | 4890 (34) | 365 | 5220 (36) |
| Victoria | 113C112P | 113 (67) | 112 (66) | 0.80 | 2 (51) | — | — | — | — | 365 | 2680 (18) | — | — |
| Willow Creek | 175C | 175 (104) | 0 | 1.06 | 3 (76) | PT | 1850 (13) | 2650 (18) | 3780 (26) | 365 | 2120 (15) | — | — |
| | 175C80P | 175 (104) | 80 (47) | 0.73 | 3 (76) | PT | 2060 (14) | 3960 (27) | 4150 (29) | 365 | 2800 (19) | — | — |
| | 80C32P | 80 (47) | 32 (19) | 1.61 | 3 (76) | PT | 1170 (8) | 1730 (12) | 2620 (18) | 365 | 2250 (16) | — | — |
| | 315C135P | 315 (187) | 135 (80) | 0.41 | 1.5 (38) | PT | 3410 (24) | 4470 (31) | 5790 (40) | 365 | 3950 (27) | — | — |
| Zintel Canyon | 125CNA | 125 (74) | 0 | 1.50 | 2.5 (64) | — | — | — | — | 345 | 1510 (10) | — | — |

Note: Cylinder fabrication method: VB = Vebe (ASTM C 1176); MP = modified proctor (ASTM D 1557); and PT = pneumatic tamper.

of a bonding mixture on the lift surface. Inadequate lift-surface cleanup, poor consolidation, or both, can drastically reduce the direct tensile strength across lift lines. Various surface preparation methods are discussed in Chapter 5. With adequate attention to lift surface preparation, the direct tensile strength of RCC lift-joints average has been assumed to about 5% of the compressive strength. The splitting tensile strength of the parent (unjointed) RCC has been assumed to be approximately 10 percent of the compressive strength.

**3.2.3** *Shear strength*—Shear strength is generally the most critical hardened property for RCC gravity dams. Total shear strength is the sum of cohesion plus internal friction, mainly across generally bonded, intact, horizontal lift joints. Shear resistance of unbonded lift lines includes apparent cohesion and sliding friction resistance between the lift surfaces. The minimum shear properties occur at construction joints between the lifts of RCC. Typical shear test values for parent RCC and bonded and unbonded joints are given in Table 3.4.

The designer must determine the required shear strength across lift joints and also assume a percentage of bonded lift surface between joints for RCC construction. Past history has shown that assuming 100% bonded lift joints is generally not valid. Decreased bond (cohesion) may result from insufficient paste volume in the RCC mixture, poor cleanup, excessive rain, drying, or freezing on the lift surface, a segregation or poor consolidation near the bottom of an RCC. The bond strength of RCC lift joints may be increased by using good construction joint surface treatment methods, increasing the strength or cementitious content, or both, of the mixture, placing RCC rapidly over a fresh joint surface, or application of a supplemental bonding mixture of bedding mortar or concrete between lifts. Although difficult to quantify, the type of joint

## Table 3.3—Thermal properties of some laboratory RCC mixtures

| Dam/ project | Mix type/ID | Cement, lb/yd$^3$ (kg/m$^3$) | Pozzolan, lb/yd$^3$ (kg/m$^3$) | Aggregate type | Specific heat, btu/lb deg F (J/kg deg C) | Diffusivity, ft$^2$/hr (m$^2$/hr) | Conductivity, Btu/ft hr deg F (W/m deg K) | Coeff expansion, millionths/ deg F (millionths/ deg C) | Initial deg F (deg C) | Adiabatic temperature rise, Change in deg F (deg C): 3 day | 7 day | 28 day | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | — | | | | |
| Concep-cion | 152CL | 152 (90) | 0 | Ignimbrite | 0.25 (1047) | 0.03 (0.003) | 1.1 (1.9) | 6.2 (3.4) | 67 (19.4) | 21 (11.7) | 24 (13.3) | 25 (13.9) | — |
| Coolidge | 124C124 | 124 (74) | 124 (74) | Volcanics/ alluvial | — | — | — | — | 63 (17.2) | 23 (12.8) | 28 (15.6) | 35 (19.4) | — |
| Elk Creek | 113C28P | 113 (67) | 28 (17) | Basalt/ sandstone | — | — | — | — | 41 (5.0) | 11 (6.1) | 14 (7.8) | 20 (11.1) | IP cement |
| | 118C56P | 118 (70) | 56 (33) | Basalt/ sandstone | 0.18 (754) | — | — | — | 43 (6.2) | 17 (9.4) | 21 (11.7) | 24 (13.3) | — |
| | 94C38P | 94 (56) | 38 (23) | Basalt/ sandstone | 0.18 (754) | 0.03 (0.003) | 1 (1.7) | 3.9 (2.2) | 44 (6.7) | 13 (7.2) | 16 (8.9) | 20 (11.1) | — |
| Middle Fork | 120C | 120 (71) | — | Marlstone | — | — | — | — | 60 (15.6) | 17 (9.4) | 22 (12.2) | 27 (15.0) | — |
| Milltown Hill | 111C112 | 111 (66) | 112 (66) | Andesite/ basalt | 0.25 (1047) | 0.05 (0.005) | 1.92 (3.3) | 3.3 (1.8) | 62 (16.7) | 17 (9.4) | 22 (12.2) | 30 (16.7) | Max 32 F (18 C) at 54 |
| Santa Cruz | 1e | 112 (66) | 112 (66) | Alluvial granite | 0.26 (1089) | 0.04 (0.004) | 1.67 (2.9) | 3.0 (1.7) | 61 (16.1) | 25 (13.9) | 29 (16.1) | 33 (18.3) | AEA Type A WRA |
| Upper Stillwater | L1 | 182 (108) | 210 (125) | Quartzite/ sandstone | — | 0.06 (0.006) | — | 4.9 (2.7) | 60 (15.6) | 25 (13.9) | 34 (18.9) | 45 (25.6) | Type D WRA |
| | L2 | 121 (72) | 269 (160) | Quartzite/ sandstone | — | 0.06 (0.006) | — | 4.0 (2.2) | 47 (8.3) | 15 (8.3) | 26 (14.4) | 33 (18.3) | Type D WRA |
| | L3 | 129 (77) | 286 (170) | Quartzite/ sandstone | — | — | — | — | 45 (7.2) | 4 (2.2) | 20 (11.1) | 34 (18.9) | Type D WRA |
| | L3A | 129 (77) | 286 (170) | Quartzite/ sandstone | — | 0.06 (0.006) | — | 4.9 (2.7) | 49 (9.4) | 16 (8.9) | 28 (15.6) | 37 (20.6) | Type A WRA |
| | L5 | 156 (93) | 344 (204) | Quartzite/ sandstone | — | — | — | — | 54 (12.2) | 24 (13.3) | 36 (20.0) | 48 (26.7) | Type A WRA |
| Willow Creek | 175C | 175 (104) | 0 | Basalt | 0.22 (921) | 0.03 (0.003) | 1.05 (1.8) | 4.0 (2.2) | 55 (12.7) | 23 (12.8) | 29 (16.1) | 36 (20.0) | — |
| | 175C80P | 175 (104) | 80 (47) | Basalt | 0.22 (921) | 0.03 (0.003) | 1.05 (1.8) | 4.0 (2.2) | 52 (11.1) | 23 (12.8) | 29 (16.1) | 36 (20.0) | — |
| | 80C32P | 80 (47) | 32 (19) | Basalt | 0.22 (921) | 0.03 (0.003) | 1.05 (1.8) | 3.9 (2.2) | 53 (11.7) | 13 (7.2) | — | 22 (12.2) | — |
| | 315C135 | 315 (187) | 135 (80) | Basalt | 0.22 (921) | 0.03 (0.003) | 1.05 (1.8) | 4.0 (2.2) | 53 (11.7) | 31 (17.2) | 36 (20) | 53 (29.4) | — |
| Zintel Canyon | 100C197 | 100 (59) | 0 (0) | Basalt/ gravel | 0.23 (963) | 0.03 (0.003) | 1.09 (1.9) | 4.2 (2.3) | — | 14 (7.8) | 16 (8.9) | 19 (10.6) | — |
| | 200C197 | 200 (119) | 0 (0) | Basalt/ gravel | 0.23 (963) | 0.03 (0.003) | 1.06 (1.8) | 4.3 (2.4) | — | 14 (7.8) | 16 (8.9) | 19 (10.6) | — |

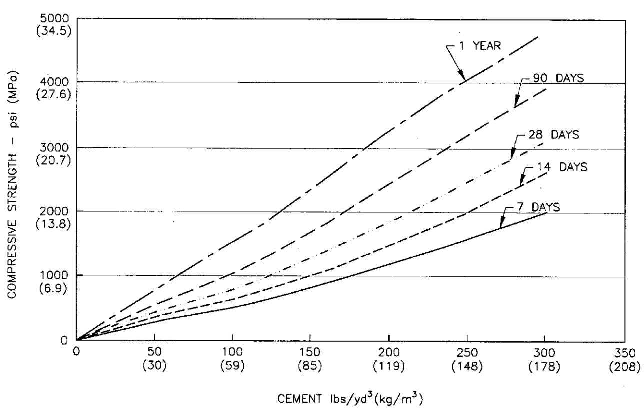


*Fig. 3.1—RCC strength curves that can be developed from tests conducted on concretes with varying proportions of cement for good quality aggregates.*

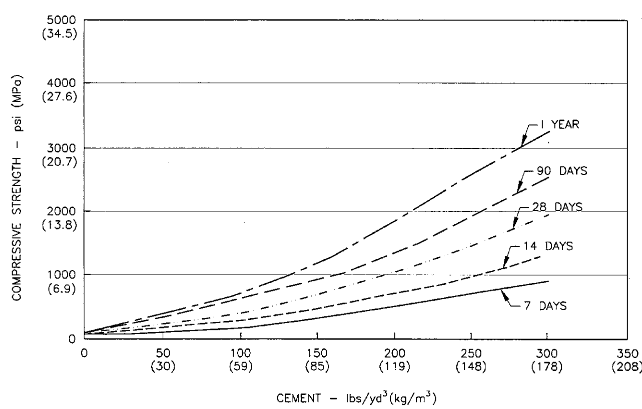


*Fig. 3.2—RCC strength curves developed for lesser quality aggregates.*

**Table 3.4—Shear performance of drilled cores of RCC dams**

| Dam/project | Mix type/ID | Cement, lb/yd$^3$ (kg/m$^3$) | Pozzolan, lb/yd$^3$ (kg/m$^3$) | *w/cm* | NMSA, in. (mm) | Joint type | Age, days | Core compressive strength, psi (MPa) | Peak cohesion, psi (kPa) | Shear $\phi$, deg | Residual shear cohesion, psi (kPa) | Residual shear $\phi$, deg | Vebe consistency, sec | Bonded joints, % | Joint maturity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cuchillo Negro | 130C100P | 130 (77) | 100 (59) | 0.99 | 3 (76.20) | B | 750 | 2530 (17) | 225 (1551) | 58 | — | — | — | — | — |
| | 130C100P | 130 (77) | 100 (59) | 0.99 | 3 (76.20) | P | 750 | 2530 (17) | 360 (2482) | 52 | — | — | — | — | — |
| | 130C100P | 130 (77) | 100 (59) | 0.99 | 3 (76.20) | NB | 750 | 2530 (17) | 100 (689) | 62 | — | — | — | — | — |
| Elk Creek | 118C56P | 118 (70) | 56 (33) | 1.00 | 3 (76.20) | P | 90 | 1340 (9) | 225 (1551) | 43 | — | — | 21 | — | — |
| | 118C56P | 118 (70) | 56 (33) | 1.00 | 3 (76.20) | B | 90 | 1340 (9) | 125 (862) | 49 | — | 49 | — | 58 | — |
| Galesville | RCC1 | 89 (53) | 86 (51) | 1.09 | 3 (76.20) | NB | 415 | 2080 (14) | 110 (758) | 67 | 80 (552) | 40 | — | 24 | 500 deg hr |
| | RCC1 | 89 (53) | 86 (51) | 1.09 | 3 (76.20) | B | 415 | 2080 (14) | 330 (2275) | 52 | 70 (483) | 43 | — | 76 | — |
| | RCC1 | 89 (53) | 86 (51) | 1.09 | 3 (76.20) | P | 415 | 2080 (14) | 380 (2620) | 33 | 95 (655) | 45 | — | — | — |
| Upper Stillwater | RCCA | 134 (79) | 292 (173) | 0.39 | 2 (50.80) | NB | 365 | 5220 (36) | 450 (3103) | 53 | 30 (207) | 49 | 17 | 80 | — |
| | RCCA | 134 (79) | 292 (173) | 0.39 | 2 (50.80) | NB | 545 | 5590 (39) | 560 (3861) | 76 | 20 (138) | 53 | 17 | — | — |
| | RCCA85 | 134 (79) | 291 (173) | 0.37 | 2 (50.80) | P | 120 | 3870 (27) | 300 (2068) | 55 | 30 (207) | 42 | 29 | 60 | — |
| | RCCA85 | 134 (79) | 291 (173) | 0.37 | 2 (50.80) | NB | 730 | 6510 (45) | 440 (3034) | 48 | 20 (138) | 46 | 29 | 60 | — |
| Victoria | 113C112P | 113 (67) | 112 (66) | 0.80 | 2 (50.80) | P | 365 | 2680 (18) | 280 (1931) | 64 | 40 (276) | 47 | 730 | — | — |
| | 113C112P | 113 (67) | 112 (66) | 0.80 | 2 (50.80) | B | 365 | 2680 (18) | 230 (1586) | 69 | 10 (69) | 44 | — | — | — |
| | 113C112P | 113 (67) | 112 (66) | 0.80 | 2 (50.80) | NB | 365 | 2680 (18) | 170 (1172) | 62 | 200 (1379) | 48 | — | — | — |
| Willow Creek | 175C | 175 (104) | 0 | 1.06 | 3 (76.20) | NB | 200 | — | 185 (1278) | 65 | — | — | — | 57 | 500 deg hr |
| | 175C80P | 175 (104) | 80 (47) | 0.73 | 3 (76.20) | NB | 200 | — | 186 (1279) | 63 | — | — | — | 54 | 500 deg hr |
| | 80C32P | 80 (47) | 32 (19) | 1.61 | 3 (76.20) | NB | 200 | — | 115 (793) | 62 | — | — | — | 58 | 500 deg hr |
| Zintel Canyon | 125CNA | 125 (74) | 0 | 1.50 | 2.5 (63.50) | NB | 345 | 1510 (10) | 85 (586) | 56 | 10 (69) | 40 | 14 | — | — |
| | 125CNA | 125 (74) | 0 | 1.50 | 2.5 (63.50) | B | 345 | 1510 (10) | 200 (1379) | 54 | 10 (69) | 40 | 14 | 65 | — |
| | 125CNA | 125 (74) | 0 | 1.50 | 2.5 (63.50) | P | 345 | 1510 (10) | 290 (1999) | 56 | 0 | 55 | 14 | — | — |

Joint type: B = bedding concrete or mortar; NB = no bedding; and P = parent concrete.

preparation, joint maturity, and moisture condition can significantly effect shear strength of bonded RCC lift joints. Thus, the shear properties can be significantly impacted by construction placing rates and ambient weather conditions that are not directly under the control of the designer.

The unconfined shear strength of an unjointed section of RCC has varied from 16 to 39% of its compressive strength. The unconfined shear strength of conventionally placed concrete, as determined by direct shear tests generally ranges from approximately 20 to 25% of its compressive strength, but a conservative value of approximately 10 percent is often used in design. The coefficient of friction within the mass has been usually taken to be 1.0 ($\phi$ = 45 deg) for RCC if no project specific tests have been conducted.

## 3.3—Elastic properties

**3.3.1** *Modulus of elasticity*—Modulus of elasticity is typically a required input parameter for most stress analysis programs. In linear-elastic numerical analysis, a low modulus of elasticity may be desirable, since it may predict lower stresses from an assumed linear stress-strain relationship versus a high modulus material. However, in brittle materials (and not modeled in linear elastic theory), ultimate failure strains used to predict stress may already be in the cracking (nonlinear) range for a low modulus material, thus not correctly predicting stress by linear-elastic behavior. Principal factors affecting the elastic properties of RCC are age, strength, paste volume, and aggregate type. Generally, for a given aggregate type, the modulus of elasticity is a function of strength. Typical moduli of elasticity for a variety of RCC mixtures are shown in Table 3.6. The modulus of elasticity in tension is typically assumed to be the same as in compression.

**3.3.2** *Poisson's ratio*—Values of Poisson's ratio for RCC, as indicated in Table 3.6, have ranged from approximately 0.17 to 0.22, with lower values occurring at earlier ages and with lower compressive-strength mixtures. In general, Poisson's ratio values for RCC are similar to values reported for conventional concrete mixtures.

## 3.4—Dynamic properties

The strength and material properties of conventional concrete have been measured for cyclic loadings and rapid strain rates to simulate dynamic loading conditions on dams during earthquakes. The ultimate compressive and tensile strength and elastic modulus generally increase under rapid dynamic loading conditions. To date, there are no known comparable test results for shear strength under similar dynamic loading conditions.

The usual increase in concrete modulus during dynamic loading is well documented by laboratory tests and the use of

**Table 3.5—Strain and creep properties of some laboratory RCC mixtures**

| Dam/project | Cement, lb/yd$^3$ (kg/m$^3$) | Pozzolan, lb/yd$^3$ (kg/m$^3$) | *w/cm* | Loading age, days | Creep coefficients: 1/*E*, $10^{-6}$/psi ($10^{-6}$/KPa) | Creep coefficients: *f*(*K*) | Compressive strength, psi (MPa) | Modulus of elasticity, $10^6$/psi (GPa) |
|---|---|---|---|---|---|---|---|---|
| Concepcion | 152 (90) | 0 | 1.20 | 7 | 1.4 (0.20) | 0.12 | 640 (4) | — |
| | 152 (90) | 0 | 1.20 | 28 | 0.73 (0.11) | 0.08 | 980 (7) | 1.40 (10) |
| | 152 (90) | 0 | 1.20 | 90 | 0.47 (0.07) | 0.03 | 1250 (9) | 2.10 (14) |
| Upper Stillwater | 182 (108) | 210 (125) | 0.47 | 28 | 1.05 (0.15) | 0.11 | 2150 (15) | 1.03 (7) |
| | 129 (77) | 286 (170) | 0.43 | 28 | 0.66 (0.10) | 0.04 | 2030 (14) | 1.49 (10) |
| | 129 (77) | 286 (170) | 0.43 | 180 | 0.57 (0.08) | 0.01 | 4170 (29) | 1.69 (12) |
| | 121 (72) | 269 (160) | 0.45 | 180 | 0.62 (0.09) | 0.02 | 3220 (22) | 1.26 (9) |
| | 182 (108) | 210 (125) | 0.47 | 365 | 0.57 (0.08) | 0.02 | 4990 (34) | 1.75 (12) |
| | 121 (72) | 269 (160) | 0.45 | 365 | 0.57 (0.08) | 0.01 | 4870 (34) | 1.63 (11) |
| | 182 (108) | 210 (125) | 0.47 | 90 | 0.84 (0.12) | 0.06 | 3410 (24) | 1.32 (9) |
| | 129 (77) | 286 (170) | 0.43 | 365 | 0.53 (0.08) | 0.02 | 5140 (35) | 1.82 (13) |
| | 182 (108) | 210 (125) | 0.47 | 180 | 0.67 (0.10) | 0.03 | 4120 (28) | 1.58 (11) |
| Willow Creek | 80 (47) | 32 (19) | 1.61 | 7 | 1.97 (0.29) | 0.20 | 580 (4) | 1.20 (8) |
| | 175 (104) | 80 (47) | 0.73 | 7 | 0.58 (0.08) | 0.08 | 1150 (8) | 2.40 (17) |
| | 80 (47) | 32 (19) | 1.61 | 28 | 1.09 (0.16) | 0.11 | 1170 (8) | 1.59 (11) |
| | 80 (47) | 32 (19) | 1.61 | 90 | 0.52 (0.08) | — | 1730 (12) | 1.91 (13) |
| | 175 (104) | 0 | 1.06 | 7 | 0.48 (0.07) | 0.08 | 1000 (7) | 2.20 (15) |
| | 175 (104) | 0 | 1.06 | 28 | 0.34 (0.05) | 0.05 | 1850 (13) | 2.67 (18) |
| Zintel Canyon | 100 (59) | 0 | 2.00 | 28 | 0.76 (0.11) | 0.08 | 630 (4) | 1.54 (11) |
| | 100 (59) | 0 | 2.00 | 90 | 0.47 (0.07) | — | 1090 (8) | 2.15 (15) |
| | 100 (59) | 0 | 2.00 | 365 | 0.39 (0.06) | — | 1550 (11) | 2.57 (18) |
| | 200 (119) | 0 | 1.00 | 7 | 0.76 (0.11) | 0.05 | 990 (7) | 1.54 (11) |
| | 200 (119) | 0 | 1.00 | 28 | 0.45 (0.07) | 0.03 | 1620 (11) | 2.39 (16) |
| | 200 (119) | 0 | 1.00 | 90 | 0.40 (0.06) | — | 2130 (15) | 2.47 (17) |
| | 200 (119) | 0 | 1.00 | 365 | 0.30 (0.04) | — | 3100 (21) | 3.28 (23) |
| | 100 (59) | 0 | 2.00 | 7 | 1.43 (0.21) | 0.09 | 280 (2) | 0.68 (5) |

dynamic or rapid load concrete modulus for dynamic analysis is accepted practice.[3.2,3.3,3.4]

A value of instantaneous concrete modulus is approximately 25% larger than the sustained modulus of elasticity and can be used for preliminary studies in the absence of actual laboratory test data. Dynamic strength values also are dependent on the rate of loading. The results from laboratory tests on conventional concrete by the Bureau of Reclamation, Raphael, and others indicate an approximate 30% increase for compressive strength, and increases of slightly greater than 50% for tensile strength, based on splitting tensile or modulus of rupture tests of mast specimens under rapid dynamic loading conditions.[3.5,3.6,3.7,3.8]

There are no published results of dynamic material properties tests for RCC. Because mature RCC (based on both cast and cored specimens) exhibits similar properties to those of conventional concrete, it is generally considered acceptable practice to assume comparable increases for compressive and tensile strength and elastic modulus for RCC mixtures under dynamic loading conditions. In the absence of definitive test data for dynamic shear strength of conventional concrete or RCC, designers must choose reasonable values for evaluating designs for earthquake loads. The choice ranges from values of static shear strength to values based on the proportional relationship between ultimate compressive strength and shear strength. Until comparable testing of RCC specimens under dynamic loading conditions has been accomplished to prove the validity of these relationships, a cautious implementation of this approach is suggested.

## 3.5—Creep

Creep is a function of the material properties and proportions in the mixture, modulus of elasticity, and compressive strength. Generally, higher-strength mixtures have a more rigid cementing matrix and lower creep, whereas low-strength mixtures or those utilizing aggregates with low modulus of elasticity will produce concretes with higher creep. Typical creep values for a variety of RCC mixtures are shown in Table 3.5. Higher creep properties are generally desirable to relieve stress and strain buildup due to foundation restraint, thermal and exterior loadings.

## 3.6—Volume change

**3.6.1** *Drying shrinkage*—Drying shrinkage is primarily governed by the water content of the mixture and, to a lesser extent, by the degree of aggregate restraint. Compared to conventional mass concrete, the volume change from drying shrinkage in RCC is similar or lower because of the reduced water content.

**3.6.2** *Autogenous volume change*—Autogenous volume change is primarily a function of the material properties and proportions in the mixture. Similar to conventional concrete,

**Table 3.6—Compressive strength and elastic properties of some laboratory RCC mixtures**

| Dam/project | Mix type/ ID | Cylinder fabrication method | NMSA, in. (mm) | *w/cm* | Compressive strength, psi (MPa) | | | | Modulus of elasticity, million psi (GPa) | | | | Poisson's ratio | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 7 day | 28 day | 90 day | 365 day | 7 day | 28 day | 90 day | 365 day | 7 day | 28 day | 90 day | 365 day |
| Concepcion | 152C | PT | 3 (76) | 1.03 | 640 (4.4) | 980 (6.8) | 1250 (8.6) | 1690 (11.7) | — | 1.10 (7.58) | 1.91 (13.17) | 3.31 (22.82) | — | 0.17 | — | — |
| Santa Cruz | 1e | VB | 2 (51) | 0.88 | 640 (4.4) | 1290 (8.9) | 2180 (15.0) | 3050 (21.0) | 1.36 (9.38) | 1.80 (12.41) | 2.26 (15.58) | 3.24 (22.34) | 0.13 | 0.14 | 0.19 | 0.21 |
| Upper Stillwater | L1 | VB | 2 (51) | 0.47 | 1360 (9.4) | 2130 (14.7) | 3510 (24.2) | 5220 (36.0) | — | 1.03 (7.10) | 1.32 (9.10) | 1.71 (11.79) | — | 0.13 | 0.14 | 0.17 |
| | L2 | VB | 2 (51) | 0.45 | 770 (5.3) | 1220 (8.4) | 2150 (14.8) | 4780 (33.0) | — | 0.82 (5.65) | — | 1.59 (10.96) | — | 0.13 | — | 0.20 |
| | L3 | VB | 2 (51) | 0.43 | 1110 (7.7) | 1620 (11.2) | 2770 (19.1) | 4960 (34.2) | — | 0.92 (6.34) | — | 1.76 (12.14) | — | 0.13 | — | 0.18 |
| Urugua-I | 101C | PT | 3 (76) | 1.67 | — | 930 (6.4) | 1170 (8.1) | 1390 (9.6) | — | 2.25 (15.51) | 3.12 (21.51) | 3.60 (24.82) | — | — | — | — |
| Willow Creek | 175C | PT | 3 (76) | 1.06 | 1000 (6.9) | 1845 (12.7) | 2650 (18.3) | 3780 (26.1) | 2.20 (15.17) | 2.67 (18.41) | 2.78 (19.17) | — | — | 0.19 | 0.18 | — |
| | 175C80P | PT | 3 (76) | 0.73 | 1150 (7.9) | 2060 (14.2) | 3960 (27.3) | 4150 (28.6) | 2.40 (16.55) | 2.91 (20.06) | 3.25 (22.41) | — | — | 0.21 | 0.21 | — |
| | 80C32P | PT | 3 (76) | 1.61 | 580 (4.0) | 1170 (8.1) | 1730 (11.9) | 2620 (18.1) | 1.20 (8.27) | 1.59 (10.96) | 1.91 (13.17) | — | — | 0.14 | 0.17 | — |
| Zintel Canyon | 100C1975 | PT | 3 (76) | 2.00 | 280 (1.9) | 630 (4.3) | 1090 (7.5) | 1550 (10.7) | 0.68 (4.69) | 1.54 (10.62) | 2.15 (14.82) | 2.57 (17.72) | — | — | 0.21 | — |
| | 200C1975 | PT | 3 (76) | 1.00 | 990 (6.8) | 1620 (11.2) | 2130 (14.7) | 3100 (21.4) | 1.54 (10.62) | 2.39 (16.48) | 2.47 (17.03) | 3.28 (22.62) | — | — | 0.20 | — |

Cylinder fabrication method: VB = Vebe (ASTM C 1176); PT = pneumatic tamper.

autogenous volume change can not be reliably predicted without laboratory testing. This is especially true for mixtures made with an unusual cement, pozzolan or aggregate.

## 3.7—Thermal properties

Thermal properties including specific heat, conductivity, coefficient of thermal expansion and adiabatic temperature rise are of primary concern for mass concrete, both conventional and roller compacted. Thermal properties are governed by the thermal properties of the mixture constituents. Although values for conventional concrete and roller-compacted concretes are similar, the actual measured values can vary significantly depending on aggregate, cement, and pozzolan type and content. For this reason, testing using the full mixture is recommended. Traditional test procedures for hardened concrete may not always be applicable to some RCC mixtures, particularly those with either lower strength or high pozzolan contents. For example, the adiabatic temperature rise of mass concrete is normally tested for approximately 28 days, with most mixtures producing little increase past that time. However, a high-pozzolan RCC mixture may have significant delay in early-age temperature rise and increased temperature rise beyond 28 days. RCC mixtures with more than approximately 30% pozzolan should be tested for heat rise and other properties at approximately 56 days.

The adiabatic temperature rise is affected by the total cementitious materials content and percentage of pozzolan in the mixture. RCC mixtures with low-cementitious materials content will have lower temperature rise than normal mass-concrete mixtures. Typically, pozzolans such as Class F pozzolan will produce an adiabatic temperature rise at 28 days of approximately one half that of cement on an equal mass basis. Also, pozzolans may reduce the rate of temperature rise at early ages. Table 3.3 shows typical adiabatic temperature rise and other thermal properties of some RCC mixtures.

## 3.8—Tensile strain capacity

Strain is induced in concrete when a restrained volume change occurs. When the volume change results in strains that exceed the tensile strain capacity of the material, a crack occurs. The threshold strain value just prior to cracking is the tensile strain capacity of the material. Tensile strains in concrete can be developed by external loads as well as by volume changes induced through drying, reduction in temperature, and autogenous shrinkage.

The major factors affecting strain capacity are the strength and age of the concrete, rate of loading, type of aggregate, aggregate shape characteristics (angular, as produced by crushing versus natural round), and the cementitious content.

As with other material properties, tensile strain capacity can vary considerably with the wide range of mixture proportions and variety of usable aggregates of RCC. Typical slow-load tensile strain capacities for RCC dam mixtures are on the order of approximately 90 to 150 millionths, but values outside of this range are possible. Each mixture should be evaluated if tensile strain capacity is used for crack analysis.

## 3.9—Permeability

The permeability of RCC is largely dependent upon 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. RCC will be relatively impervious when the mixture contains sufficient paste and mortar, an adequate fine-particle distribution that minimizes the air void system, no segregation of coarse aggregate occurs, and is fully compacted. In general, an unjointed mass of RCC proportioned with sufficient paste will have permeability values similar to conventional mass concrete. Test values typically range from 0.3 to 30 $\times 10^{-9}$ ft/min (0.15 to 15 $\times 10^{-9}$ cm/sec). High cementitious mixtures tend to have lower permeability than low cementitious mixtures.

If seepage occurs in RCC dams, it usually occurs mainly along the horizontal lift joints rather than through the compacted and unjointed mass. If seepage occurs along horizontal lift joints, it also indicates a reduction in shear and tensile strength at this location.

Leakage can be experienced through cracks and monolith joints, regardless of the permeability of the RCC. Although generally not a factor in the stability of a structure, leakage through cracks can result in an undesirable loss of water, create operational or maintenance problems, and be aesthetically undesirable. Leakage through vertical cracks can be extremely difficulty to stop or control without grouting. The best method of preventing leakage is to induce controlled cracking in the mass RCC before filling and either control leakage with embedded waterstops and drains, seal the cracks on the upstream facing, or use a membrane. With time, natural calcification will generally reduce seepage through cracks.

## 3.10—Durability

RCC, like conventional mass concrete, is subject to potential deterioration due to the effects of abrasion/erosion, freezing and thawing, and other factors such as alkali-silica reaction, and sulfate attack.

**3.10.1** *Abrasion/erosion*—Abrasion/erosion resistance is primarily governed by compressive strength and quality of the aggregate. RCC pavements at heavy-duty facilities such as log storage yards and coal storage areas have shown little wear from traffic and industrial abrasion under severe conditions. The North Fork Toutle River Debris Dam spillway showed only surface wear after being subjected to extraordinary flows of highly abrasive grit, timber and boulders. This structure was constructed with RCC containing good quality small-size aggregate and a higher cement content than normally used in mass RCC construction [500 lb/yd$^3$ (300 kg/m$^3$)]. Additional abrasion/erosion damaged the top lift of the RCC spillway.

Overflow spillways of RCC dams subjected to frequent use should generally be lined with high-quality concrete to prevent abrasion/erosion damage (Section 4.8). The spillways at both Willow Creek and Galesville Dams have exposed RCC flow surfaces. The rationale for not constructing conventional concrete lined, overflow spillways was primarily based on cost and infrequent use. However, overtopping flows experienced at Galesville Dam in 1996 and 1997 flooding resulted in an irregular hydraulic flow surface that jumped off the spillway face in some locations. Some large-scale performance tests of lean mass RCC by the U.S. Army Corps of Engineers at the Detroit Dam test flume showed good resistance to erosion. Tests with small samples at the Corps' Waterways Experiment Station also showed excellent resistance to erosion.[3.9]

Low-head structures at Ocoee No. 2 and Kerrville Dams have been subjected to overtopping without the need for maintenance or repairs. However, caution is still suggested because high-velocity flows across RCC spillways have not yet been fully evaluated. Spillways subjected to frequent high-velocity flows are still typically faced with conventional concrete. ASTM C 1138 has been used to evaluate the erosion resistance of both conventional concrete and RCC.

**3.10.2** *Freezing and thawing*—RCC mixtures do not normally have intentionally entrained air, and consequently will not have a high freeze-thaw resistance in a critically saturated moisture condition. Many examples of good field performance exist. However, RCC subjected to ASTM C 666, Procedure A, typically performs very poorly. Large blocks of the Lost Creek RCC test fill material totally deteriorated when exposed at mean tide level at Treat Island, Me. due to the combined action of salt water, major tidal fluctuations, wet-dry cycles and freezing and thawing.

Laboratory investigations and field applications have shown an air-entraining admixture can effectively establish an air-void system with good performance, even when subjected to ASTM C 666 testing. Air-entrained RCC samples showed improved freeze-thaw resistance compared to non-air-entrained RCC for Santa Cruz Dam mixtures.[3.10] Microscopic evaluation of cores from full-scale field mixtures at Zintel Canyon Dam have shown satisfactory air-void systems and excellent freeze-thaw performance. Most mixtures require a high dosage of air-entraining admixture to be effective.

## 3.11—Unit weight

The lack of entrained air and lower water content of many RCC mixtures results in a slightly higher density when compared to conventional air-entrained mass concrete made with the same aggregate. Fully compacted RCC has a low air content (generally 0.5 to 2.0%) and a low water content. More solids occupy a unit volume and the increased density is approximately 1 to 3% more than conventional concrete and routinely exceeds 150 lb/ft$^3$ (2400 kg/m$^3$).

# CHAPTER 4—DESIGN OF RCC DAMS

## 4.1—General

The use of RCC offers a wide range of economical and safe design alternatives to conventional concrete and embankment dams. Placing RCC in lifts that are compacted by vibratory rollers does not change the basic design concepts for dams, locks or other massive structures. A detailed treatment of dam design principles and formulas is not addressed in this Chapter. References and information sources for gravity dam design are contained in Section 7.6. This chapter focuses on design considerations for RCC dams.

Important considerations that must be addressed before proceeding with detailed final designs include the basic purpose of the dam and the owner's requirements for cost, schedule, appearance, watertightness, operation and maintenance. A review of these considerations should determine the selection of the proper RCC mixture, lift surface treatments, facing treatments and the basic configuration of the dam. The overall design should be kept as simple as possible to fully capture the advantages of rapid construction using RCC technology.

The information in this chapter presents the state of the art in the design of RCC dams and other massive structures. It is not purported to be the standard for design. Any organization or individual may adopt practices or design criteria which are different than the guidelines contained herein.

## 4.2—Dam section considerations

The design of an RCC structure balances the use of available materials, the selection of structural features, and the proposed methods of construction. Each must be considered in light of the other factors. For example, a dam section may require a certain shear strength for stability; however, the available materials may not be capable of providing those strengths or the specified construction method may not ensure that the lift-joint quality is sufficient to provide the required shear strength. Mix design changes, construction method changes, or a revised section may be the solution.

Sound rock foundations are considered the most suitable for conventional concrete and RCC dams. Favorable characteristics include high bearing capacity, good shear strength, low permeability and a high degree of resistance to erosion. However, some RCC dams have been constructed on low-modulus weathered rock, as well as on soil foundations.

RCC dams can be constructed with straight or curved axes, with vertical or inclined upstream faces, and with downstream faces varying from vertical to any slope, which is economically and structurally appropriate for a given site. The adopted design criteria, proposed height, and foundation characteristics strongly influence the basic dam cross section.[4.1]

The typical gravity dam section shown in Fig. 4.1 with a vertical upstream face and constant downstream slope has been used for most RCC dams located on competent rock foundations. The design of a downstream slope is generally a function of structural stability and economics. A low unit cost of RCC may make it reasonable to flatten the downstream slope, but with an attendant increase in volume. A flatter downstream slope reduces stresses in the dam and RCC strength requirements, but increases foundation excavation and preparation costs. The larger volume section may also allow use of a lower cementitious materials content and reduced adverse temperature stresses. Alternatively, if foundation strength and temperature stresses are reasonable, the use of a steeper downstream slope, in combination with a higher cementitious materials content RCC mixture, can also prove economical because of the reduced volume. For dams exposed to significant seismic loads, a straight downstream slope from the crest to the foundation, instead of a vertical face near the crest intersecting a sloped downstream face below, eliminates the potential for stress concentration cracking.

Small RCC dams on pervious or soil foundations require special design considerations. Designs should consider differential settlement, seepage, piping and erosion at the downstream toe. Foundations of this type usually require one or more special measures such as upstream and downstream aprons, grouting, cutoff walls, and drainage systems. A basic gravity dam design configuration for a low dam on a weak foundation or for dams on soil foundations is shown in Fig. 4.2.

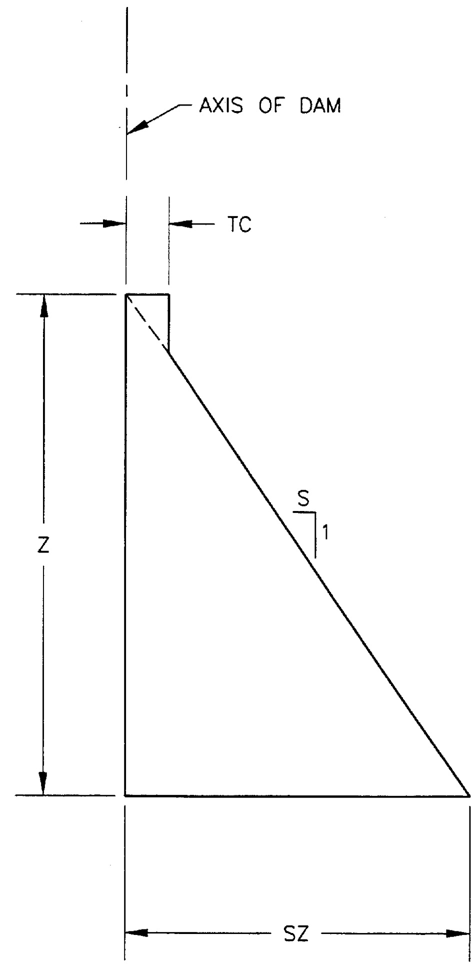


*Fig. 4.1—Typical RCC dam section.*

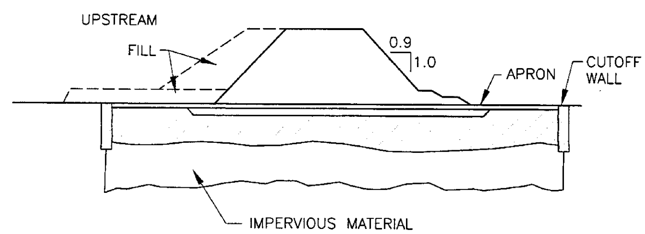


*Fig. 4.2—Typical low RCC dam section for nonrock foundation.*

## 4.3—Stability

**4.3.1** *Methods to analyze stability*—Approaches to stability analysis for RCC dams are similar to those used for conventional concrete structures, with added emphasis on tensile strength and shear properties of the horizontal lift joints. A static stress analysis is often performed for the initial design of an RCC dam. For dams in wide canyons, the two-dimensional gravity or finite element method of analysis is better suited to calculate stresses. More complex methods of analysis such as the Trial-load Twist Method and three-dimensional Finite Element Method have been used for dams located in narrow V-shaped canyons. For dams located in seismicly active areas, a dynamic stability analysis is often necessary using either a two or three-dimensional finite element method, whichever is appropriate for the canyon shape. Section 7.6 contains references from leading U.S. agencies which describe strength and stability analyses for dams, including the types of loads and loading combinations for which a RCC dam should be analyzed. Recommended safety factors to be applied for the complete range of loading conditions from static through dynamic loads are also given.

**4.3.2** *Shear-friction factor*—As in a conventional concrete gravity section, resistance to sliding within the RCC section is dependent upon the cohesion of the concrete, the compressive stress on the potential failure plane, and the coefficient of sliding friction of the concrete. The shear-friction factor (SFF) is a measure of the stability of a dam against sliding. The SFF on a horizontal plane is expressed as:

$$SFF = (cA + (W - U)\tan\phi)\ /H$$

where

$c$ = unit cohesion;
$A$ = area of cross section;
$W$ = vertical weight on cross section;
$U$ = uplift force acting on cross section;
$\phi$ = angle of sliding friction; and
$H$ = horizontal shear force.

Most design criteria require a minimum shear-friction factor of safety (SFFS) against sliding of 2 to 4 based on normal high headwater and low tailwater conditions, from 1.5 to 2 under flood conditions, and greater than 1.0 for seismic loads. The average compacted in-situ density at the time of construction is suitable for computing the vertical weight. For a complete treatment of the subject, refer to the references in Section 7.7.

Shear properties at lift surfaces are dependent on a number of factors including, mixture properties, joint preparation, time from mixing to compaction, and exposure conditions. Actual values used in final designs should be based on tests of the materials to be used or estimated from tests on RCC mixtures from other projects with similar aggregates, cementitious materials content, aggregate gradings and joint preparation. As with any dam design, the designer of RCC structures should be confident that design assumptions are realistically achievable with the construction conditions anticipated and the materials available. Joint shear strength and sample data are discussed more in Chapter 3, 5, and various references.[4.2,4.3,4.4,4.5] For initial planning and design purposes, a value of cohesion of 5 percent of the design compressive strength with a coefficient of friction of 1.0 (corresponding to a $\phi$ angle of 45 deg) is generally used.

**4.3.3** *Determining design values*—Design values for tensile and shear strength parameters at lift joints can be determined in several ways. Drilled cores can be removed from RCC test placements and tested in shear and direct tension. Individual specimens can be laboratory fabricated and similarly tested if the mixture is of a consistency and the aggregate is of a size that permits representative individual samples to be fabricated. At a number of RCC projects, joint shear tests have been performed on a series of large blocks of the total RCC mixture cut from test placements compacted with walk behind rollers. Various joint maturities and surface conditions of the actual mixture for the project are evaluated and used to confirm or modify the design and construction controls. In-situ direct shear tests have been performed at various confining loads on blocks cut from field test placements made with full production equipment and field personnel.

## 4.4—Temperature studies and control

Details of comprehensive temperature evaluations unique to RCC are discussed in "USBR Design Considerations for Roller-Compacted Concrete Dams," "Roller-Compacted Concrete," *Engineer Manual* No. 1110-2-2006, U.S. Army Corps of Engineers, and several specific references.[4.6,4.7,4.8]

Studies of the heat generation and temperature rise of massive RCC placements indicate that the sequential placement of lifts can reduce thermal cracking, due to the more consistent temperature distribution throughout the mass. Depending on the environment, the average placement rate can have a more significant effect than the lift height on maximum temperature rise. Fig. 4.3 shows the effect of placing rate and lift height on temperature rise for equal placing and ambient temperatures for a generalized situation. Because variations in placing rates, lift thicknesses, mixture proportions and other factors, such as the time of day that placing occurs, can significantly influence the temperature parameters for specific RCC placements, it is important to use the information from Fig. 4.3 with caution.

The design engineer has a variety of options to minimize thermal stresses. These include substitution of pozzolan for some of the cement, limiting placement of RCC to the time of year when cool weather is expected, placing at night, lowering the placing temperature, and jointing. When the option is available, selecting an aggregate of low elastic modulus and low coefficient of thermal expansion is helpful. Liquid nitrogen can be injected into the RCC during the mixing process to reduce its placing and peak temperature, but this can be expensive and may slow production. Ice and chilled water can help precool the mixture; however, the lower water content of RCC limits the amount of temperature reduction these measures can provide. It also adds cost and may slow production if extra mixing time is needed to melt the ice. Stockpiling aggregates in large piles during cold weather and reclaiming them in their naturally precooled condition during warm weather has been effective where sufficient stockpile area is available and the required scheduling is possible. Postcooling has not been found to be practical in most RCC construction.

The exposure of relatively thin lifts of RCC during initial hydration may contribute to an increase or decrease in peak temperatures, depending on ambient conditions and the length of exposure. Each situation must be separately and carefully evaluated. For example:

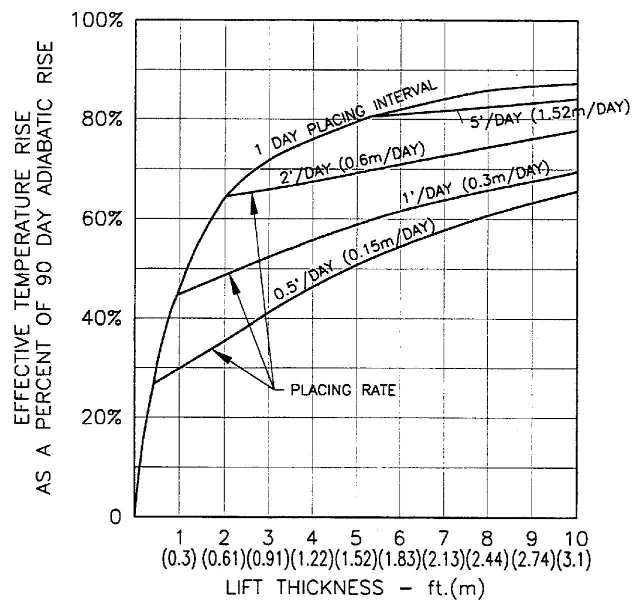


*Fig. 4.3—Generalized effect of placing rates and lift height on temperature for conventional conditions (Cannon, 1972).*

1. While placing RCC during a hot time period, the surface absorbs heat from the sun, which increases the temperature of the mixture and increases the rate at which hydration is generated. The longer the surface is exposed, the more solar energy is absorbed, which will produce a higher peak internal temperature. Faster placement in this situation will help reduce internal temperatures.

2. Placing during the cooler time of year can allow completion of a project before the heat of summer. Under these conditions, materials are naturally precooled, resulting in lower placing temperatures and, consequently, lower peak temperatures, than if placed in warmer periods. If the time interval until placement of the next lift is long, some of the early heat from hydration can be dissipated to the atmosphere. If the peak temperature does not occur before placement of the next lift, faster placing can have the detrimental effect of increasing the internal temperatures.

Various analytical methods, ranging from hand computations to more sophisticated finite element methods, are available to provide an estimate of the temperature and stress or strain distributions throughout a structure. Comprehensive, state-of-the-art analyses account for the time dependent effects of temperature, including adiabatic heat rise, ambient climatic conditions, simulated construction operations, and time variant material properties.

## 4.5—Contraction joints

The principal function of vertical contraction joints is to control cracking due to foundation restraint, foundation geometry, and thermal volume change. Contraction joints have also been used as formed construction joints that divide the dam into separate independent work areas. Depending on the mixture, climate, and approach to design, some RCC projects have included many contraction joints, while others have had no contraction joints.

The principal concerns for cracking in RCC and other gravity dams are structural stability, appearance, durability, and leakage control. Although not a factor in the stability of a structure, uncontrolled leakage through transverse cracks can result in an undesirable loss of water, create operational or maintenance problems, and be visually undesirable; leakage is extremely difficult to control.

The location and spacing of joints depends on foundation restraint, temperature change, the time period over which it occurs, the tensile strain capacity of the concrete at the time in question, creep relaxation, and the coefficient of thermal expansion of the concrete. Most recent RCC dams have included contraction joints to control transverse cracking. For many projects, joints are carefully formed to go through the entire dam to induce cracks. Other designs use partial joints to provide a weakened plane along which cracks will propagate. Waterstops and drains are usually an integral part of a complete joint design. Chapter 5 provides various methods for installing transverse joints and joint drains.

The location and spacing of joints depends on foundation restraint, temperature change, the time period over which it occurs, the tensile strain capacity of the concrete at the time in question, creep relaxation, and the coefficient of thermal expansion of the concrete. Most recent RCC dams have included contraction joints to control transverse cracking. Methods of constructing contraction joints have included: 1) inducing a discontinuity by vibrating a plate into each life after RCC placement; and 2) placement of a bond galvanized sheet metal or a plastic sheet at a joint location prior to spreading each lift.

Installation of a plate after RCC placement provides the ability to maintain better alignment of the contraction joints then trying to maintain alignment of a form placed before spreading the RCC. It is not necessary for the joints to be carefully formed or to go through the entire dam to induce cracks. Partial joints are sufficient to provide a weakened plane along which cracks will propagate. Preformed joints should be located at boundaries, such as sharp changes in foundation shape, and changes in the dam cross section.

Seepage control methods of contraction joints has varied widely. Seepage control methods for RCC dams has included: 1) a surface control joint with waterstop; 2) a surface control joint with waterstops and grout taken; 3) membrane placed over the upstream (either a membrane placed with precast concrete ponds or an exposed membrane; and 4) conventional concrete face of jointed slabs placed after the RCC.

Transverse contraction joints with surface control and waterstop have been used in numerous RCC dams. Typical details consist of a formed crack inducer in the upstream face with a waterstop in the facing concrete (as shown in Fig. 4.6) followed by crack inducement in the RCC lift by one of the methods described previously. A drain hole has also been installed along the contraction joint, ranging from approximately 1 ft (300 mm) downstream of the waterstop to the centerline of the gallery. Surficial sealing of the contraction joint has

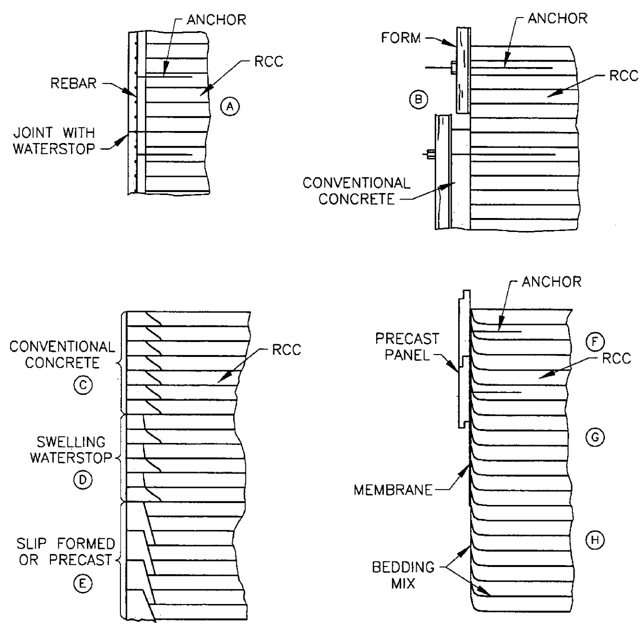


*Fig. 4.4—Upstream facing options.*

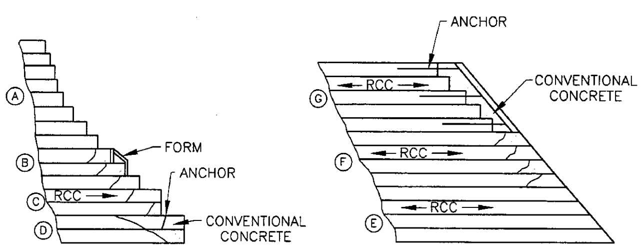


*Fig. 4.5—Downstream facing options.*

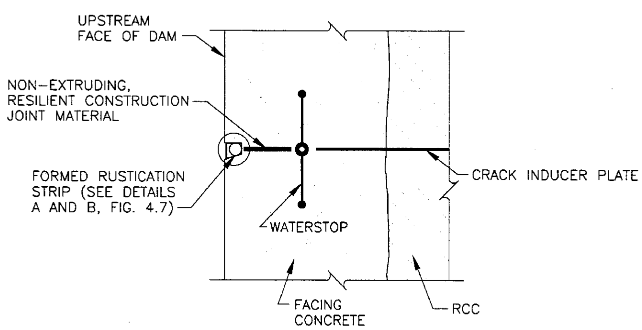


*Fig. 4.6—Contraction joint detail.*

ranged from backer rod and sealant (Fig. 4.7, Detail A) to the membrane sealant method used at New Victoria Dam (not shown in Fig. 4.7)

Contraction joint construction at gravity arch RCC dams in South Africa has used similar methods with the addition of grout tubes for postconstruction grouting of contraction joints such as at Wolwedans dam. Surficial control of seepage control through contraction joints with a precast panel and membrane, or exposed membrane and formed conventional concrete face, are shown in Fig. 4.4(f), (g), and (b), respectively. Installation of a precast panel with membrane is shown on Fig. 4.8.

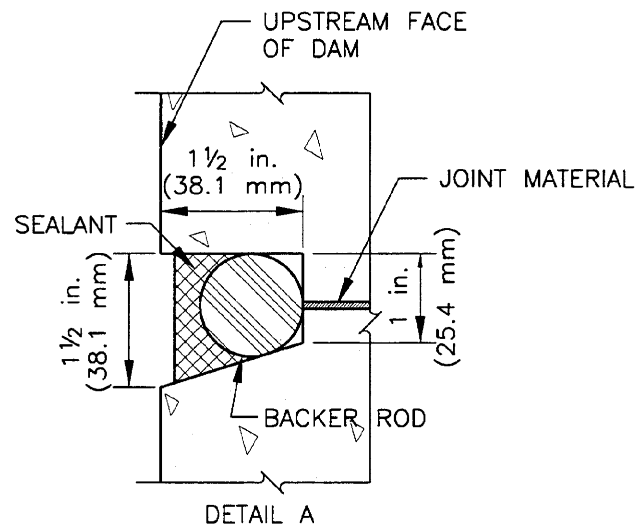


*Fig. 4.7—Contraction joint seal at upstream face.*

*Fig. 4.8—Installation of precast facing panel with attached membrane.*

## 4.6—Galleries and adits

Galleries and adits serve the same purposes in RCC dams as they do in conventional concrete dams. A foundation gallery will serve as access to the interior of the dam for drilling or redrilling foundation grout curtain and drain holes, grouting the foundation, inspections, seepage collection, access for instrumentation and other equipment, and a terminal point for drain holes drilled from the crest or into the foundation. Design requirements for RCC galleries and adits are commensurate with those of conventional concrete dams.

Generally, RCC dams less than approximately 100 ft (31 m) high have not used galleries, while higher dams generally have included galleries. Flood control structures that impound an infrequent pool are likely to not have a gallery, whereas a structure with a full-time reservoir may include a gallery.

Galleries are an obstacle to rapid and efficient placement of RCC. The presence of galleries will generally reduce RCC placement efficiency in those areas. Where galleries are necessary, the layout of the gallery should consider the effects on RCC placement operations. If possible, the gallery should be located a reasonable distance from the upstream face to allow construction equipment to operate in the area. The gallery can be stepped in a manner that, when placing the RCC adjacent to the gallery, access to placement areas is not completely blocked. The gallery construction methods (discussed in Chapter 5) should be consistent with the purpose of the gallery. A gallery that is intended to provide a means to inspect the RCC and to observe cracks should avoid methods that mask the RCC, i.e., precast concrete forms.

## 4.7—Facing design and seepage control

The upstream and downstream faces of RCC dams can be constructed by various means.[4.9,4.10] The purpose of facings may be to control the seepage of water through the RCC lift joints, provide a surface that is durable against freezing and thawing, provide a surface that is durable against spillway flows, and provide a means to construct a face steeper than the natural angle of repose of the RCC. Seepage may also be controlled by other methods.

**4.7.1** *Upstream facing*—Numerous designs have been conceived to create a water barrier at the upstream face of RCC dams to control seepage through the structure. Each has advantages and disadvantages. The following paragraphs refer to upstream facing options (a) through (h) of Fig. 4.4. The seepage control measures discussed for particular facing systems can be used for most of the other facing systems.

Fig. 4.4(a) and (b) are reinforced conventional concrete facings placed after the RCC has been placed. This is similar in concept to the concrete facing on the sloped face of a rockfill dam. Because of its typically high estimated cost and extended construction time, this facing method has not had frequent usage. However, it has been used at Stacy and Lake Alan Henry Dams.

A common method of constructing a conventional concrete face is to concurrently place the RCC with the conventional concrete facing concrete. No anchors or reinforcement other than that necessary to stabilize formwork are used to anchor the facing concrete to the RCC. [Fig. 4.4(c)]. Crack control of the facing mixture can be provided by waterstopped or sealed vertical contraction joints spaced appropriately for the mixture and exposure conditions. Typically, this is approximately every 16 to 30 ft (5 to 10 m). The thickness, or width (upstream to downstream), of a conventional concrete face varies from 1 to 3 ft (300 to 900 mm). For thicker facings, the designer should consider the effect the extra mass has on temperatures, thermal contraction of the RCC and facing, and the contraction joint spacing.

A modification of (c) uses a temporary blockout at the face for every other lift (d). The blockout is removed prior to placing the conventional facing and the next RCC lift. Added watertightness can be achieved by using a simple swelling-strip waterstop that is impregnated with chemical grout. It is placed along the lift surfaces of the facing concrete. If seepage occurs, the moisture causes the strip to swell and create a watertight pressure seal against the adjacent lift surface.

Interlocking facing elements, whether precast or slipformed, have been used to create a permanent upstream face (e). Care should be exercised to ensure proper bond or anchorage between the facing and the interior RCC. The slipformed facing method is appropriate for projects that require long continuous placement of elements, and where the rate of vertical rise of the structure is approximately 1 m or less per day, unless job tested for a higher placement rate.

Precast panels make an attractive, economical, and crack-free face, but the panel joints are not watertight (f). Watertightness has been provided with a membrane of polyvinyl chloride (PVC) or polyethylene attached to the back of each panel. A pressure connection with epoxy has been used to provide a watertight seal where the anchors penetrate the membrane. The joints between panels need to be heat-welded to produce the impermeable face. Drains can be installed in the RCC to collect seepage.

RCC has been placed directly against a conventional form that is later removed. The higher the workability of the RCC mixture, the more uniform the appearance of the formed RCC face. The appearance can be improved by placing a small amount of a bedding mixture the form to provide a better surface. Watertightness can be achieved by placing a sheet of PVC directly against the dam face together with placing a bedding concrete downstream of the membrane (g). Drains can be installed between the membrane and RCC. The use of bedding mixture between the lifts can substantially improve watertightness (h) and bond along horizontal lift joints. This practice has become the more common approach to reducing seepage at lift joints. Regardless of what facing design or seepage control measures are selected, good bond is essential at the lift joint and at the interface between the dam and the foundation.

**4.7.2** *Downstream facing*—The downstream face of the dam can be designed using any of a number of options. Typical methods are shown in Fig. 4.5. The most common approaches are the formed stair-stepped conventional concrete face and the unformed RCC surface. In Fig. 4.5(a), RCC is placed directly against reusable form panels. A small amount of bedding mortar or concrete can be used to provide a uniform formed surface. If a conventional concrete appearance or added durability is desired, conventional concrete can be used for the facing [Fig. 4.5(b)]. Larger steps can be built for a spillway, as shown in Fig. 4.5(c) and (d). Relatively smooth spillways and downstream faces have been constructed by trimming the RCC exposed face, as shown in Fig. 4.5(e), by hand or machine. An unreinforced conventional concrete facing with approximately 10 in. (250 mm) minimum width is shown in Fig. 4.5(f). The stability of this method depends on the degree of bond between the facing concrete and the RCC. Slipformed concrete with anchors and two-way reinforcement, placed after completion of the RCC, is shown in Fig. 4.5 (g), and is suitable as a flow surface.

**4.7.3** *Seepage control*—Internal seepage is generally collected by joint drains, abutment drains, and vertical drain holes located near the upstream face. Vertical drain holes, often referred to as face drains in conventional concrete construction, can be formed either during construction or drilled after construction. At Galesville Dam, 3 in. (75 mm) diameter holes on 10 ft (3 m) centers were drilled through the galleries into the foundation to varying depths. Drains channel seepage into foundation gallery gutters where the flow continues, by gravity, downstream through the adits. Without internal seepage control, uplift pressures may build with time, reducing the stability of the structure. Where no gallery is designed, drainage systems may range from piping systems to rock drains.

### 4.8—Spillways

Traditional spillway designs used for conventional concrete dams are also appropriate for RCC dams. Gated spillways that include controls, support piers, and spillway chutes constructed of reinforced concrete, can be incorporated into RCC structures. However, the practice in most current RCC dams has been to design an ogee spillway, without gates, located at the dam crest and aligned with the streambed. The economies of uncontrolled spillways and their ease of construction have made them a popular choice among RCC dam designers. Spillway discharge velocities can be controlled by increasing the crest length (space permitting), thus reducing the depth of water over the crest, or relying on stair steps to dissipate energy.

The spillway face can be either formed or unformed, depending on desired flow characteristics, aesthetic and cost considerations, weather protection and other design needs. Formed faces of small and medium height dams may consist of conventional concrete formed as 12 to 24 in. (300 to 600 mm) high steps designed to dissipate energy.[4.11] Depending on the erosion potential of the foundation materials in the area of the energy dissipation, the magnitude of the stilling basin may be significantly reduced with the use of steeped spillways. Other dams have been constructed using conventional reinforced concrete to provide a smooth sloping spillway surface that discharge into a stilling basin.

Unformed faces, having the rough textured appearance of the RCC placement, has been used for low-head spillways or spillways subject to infrequent use. The ogee crest can be effectively shaped with conventional concrete or shotcrete after RCC placement. The design may allow the spillway surface to remain untreated or it may require the loose RCC to be removed and a conventional concrete facing to be applied afterwards.

For low spillway discharge situations, the spillway and outlet may be combined. The primary spillway and outlet works at Middle Fork Dam were combined in a double-chambered tower placed against the upstream face and connected to conduits in a trench at the maximum section leading to the control structure at the toe.[4.12] The conduits were constructed before RCC placement, thus avoiding interference with RCC placing operations.

### 4.9—Outlet works

Outlet structures and conduits can provide obstacles to RCC placement. The preferred practice in placement of outlet works in RCC design is to locate the conduits in or along the rock foundation to minimize delays in RCC placement.

Conduits usually are constructed of conventional concrete prior to initiating RCC placement. Locating the intake structure upstream of the dam, and control house and the energy dissipator downstream of the toe also minimizes interference with RCC placement. The avoidance of large embedments in the dam simplifies the construction, minimizes schedule impacts and can maximize savings. The conduits are usually installed in trenches beneath the dam or along an abutment. Sometimes it may be possible or even necessary to route outlets through diversion tunnels. In situations where conditions dictate that waterways must pass through the dam, the preferred approach is to locate all the penetrations in one conventionally placed concrete block prior to starting the RCC placements. This permits proper cooling of the conventional concrete and eliminates interface problems between the RCC and conventional concrete.

## CHAPTER 5—CONSTRUCTION OF RCC DAMS

### 5.1—General

The layout, planning, and logistics for construction with RCC are somewhat different than for conventional mass-concrete construction. Instead of vertical construction with independent monolith blocks, RCC construction involves placing relatively thin lifts over a large area. Conventional mass-concrete placement usually requires a high ratio of man hours to volume placed due to labor-intensive activities, such as forming faces, joint preparation, and consolidating concrete with internal vibrators. RCC typically has a lower ratio of man hours to volume placed because of the use of mechanical equipment for spreading and compacting the mixture, less forming, and reduced joint cleanup. More labor and attention is required to provide wet curing for RCC because membrane-forming curing compounds are prohibited due of their adverse effects on lift joints.

With the rapid construction progress typical of RCC placement, when problems develop in the placing area, they should be resolved quickly. There usually are no alternate monolith blocks in RCC construction where work can progress while the problem is studied. Raising a portion of the placing area ahead of the problem area has been done, but it can later result in placing difficulties and potential planes of weakness at the perimeter of the lower area. Planning and preparation of materials, access, embedded parts, and foundation and lift cleanup, prior to start of RCC placement, are essential. It is also essential that lines of communication between the engineer and contractor be well-established so that they can quickly resolve problems and specification compliance issues that may impact the progress of the work. Interruptions and slowdowns generally cause reduced joint and RCC quality, as well as increased costs.

Impediments to placement and compaction rates can reduce the RCC quality. Equipment, fueling, formwork, and assembly of embedded items should all be scheduled and planned so that the majority of this work is accomplished off the RCC surfaces and during shift changes or scheduled downtime. All unnecessary vehicles and personnel should be kept out of placing areas and equipment paths.

### 5.2—Aggregate production and plant location

Aggregate stockpiles and the concrete plant location for RCC can be even more important than for conventional concrete. Typically, large stockpiles are provided prior to starting RCC placement. Some of the reasons for this are:

*Temperature control*: *Producing aggregate during the winter so that they are stockpiled cold for later use*—At Middle Fork and Stagecoach Dams in Colo., as well as Monksville Dam in N. J., winter stockpiling resulted in aggregates with occasional frozen zones in the stockpiles. At Burton Gorge Dam in Australia, instrumentation showed that production of RCC aggregate at night resulted in a 9 F (5 C) lower aggregate stockpile temperature than similar aggregates produced during the day.

*Rapid placement rate*—The rate of aggregate use during RCC placing may exceed the capacity of an aggregate production plant. Large aggregate stockpiles also have the benefit of more stable moisture contents, which reduce variations in RCC consistency.

The location and configuration of stockpiles, as well as the means of aggregate and withdrawal from stockpiles must be coordinated with the RCC plant location and method of feed to minimize segregation and variability. At the very high production rates possible with RCC, several loaders or a conveyor system may be required to keep the aggregate feed bins charged. The length of haul and size of turnarounds need to be considered so that transportation equipment can operate rapidly, efficiently, and safely.

Inadequate cementitious material delivery and storage has limited RCC production on some projects. A steady flow of these materials is necessary for optimum production and consistent RCC quality.

The RCC plant layout and location should be selected to minimize energy requirements and be appropriate for the terrain, whether the RCC is transported by conveyor or haul vehicles. The location should minimize overall haul distances, vertical lift, and exposure of the fresh mixture to sun and weather. The plant should be located on a raised area and graded so that spillage and wash water drain away without creating a muddy area, especially if vehicular haul is used. The plant location for dams will generally be in the future reservoir area and above the cofferdam level, or on one of the abutments. A plant location adjacent to the RCC structure minimizes transport time, which is critical to RCC quality, and reduces transport equipment needs. The plant should have a bypass or belt discharge that allows for wasting out-of-specification RCC without delivering it to the dam.

## 5.3—Proportioning and mixing

**5.3.1** *General*—The RCC method changes the production-controlling elements of mass-concrete placements from the rate of placement for conventional mass concrete to the output of the concrete plant and delivery system for RCC.

Rapid and continuous delivery of RCC is important to mass applications. The theoretical, or rated, peak capacity of the plant is invariably well-above the desired average production. As a general guide, the average sustained placing rate usually does not exceed approximately 65% of the peak or rated plant capacity when haul vehicles are used for delivery on the dam, and 75% when an all conveyor delivery system is used. These values tend to be lower on smaller projects and higher on uncomplicated, larger projects.

Mixers for RCC need to accomplish two basic functions: the mixers should thoroughly blend all ingredients, and should provide sufficient capacity for high placing rates typical in RCC. Typical placing rates are 100 $yd^3$/hr (76 $m^3$/hr) for small size projects, 250 to 500 $yd^3$/hr (190 to 380 $m^3$/hr) for medium projects, and 750 to over 1000 $yd^3$/hr (570 to over 760 $m^3$/hr) for large projects. Several individual mixers are used to provide the higher production rates. The mixer(s) should operate with little or no downtime. Scheduled maintenance must not be neglected, and repairs should be accomplished rapidly.

Variations in free moisture content of the aggregates can be particularly troublesome at plant startup. Providing too little water in the initial mixtures is particularly undesirable because initial mixtures are frequently used for covering construction joints or foundation areas where the RCC should be on the wet side for improved workability and bond. It is better to start with higher moisture content and to subsequently reduce it to the desired consistency than to start with a mixture that is too dry. RCC placed with a higher optimum moisture content is typically more dense, and has lower air voids and permeability. Care must be taken to avoid an overly wet mixture, which reduces the RCC strength. Variability in moisture content significantly affects the quality of the RCC.

Accurately introducing the specified quantities of materials into a mixer is only one part of the mixing process. Uniformly distributing and thoroughly blending materials, and discharging them in a continuous and uniform manner are also essential for providing quality RCC. Distributing and blending can be more troublesome with some RCC mixtures than with conventional concrete mixtures because of the lower unit water content in the RCC mixtures.

Both continuous mixers and drum mixers have been used to produce RCC. Continuous mixers generally provide higher output capacity than batch-type plants. Continuous pugmill mix plants that are specifically intended for RCC, and are properly operated and maintained, routinely achieve the high production rates and uniformity required for mass placements. This applies to plants that operate with volumetric controls, as well as those that operate on weight controls. Operation of drum mixers requires less power than pugmill mixers. Batch operations with drum mixers tend to cause the most difficulties or concerns in producing RCC, as described below. Traditional batch plants may be needed for batching of conventional concrete associated with the project.

**5.3.2** *Batching and drum mix methods*—RCC has been successfully produced with conventional batch type plants and drum mixers. Lower production, bulking, sensitivity to the charging sequence, slow discharge, and buildup in the mixer are common problems in RCC production when compared to batching of conventional plant and transmit mixed concrete. Equipment that is well-suited to normal high-production conventional concrete is not necessarily suitable for all RCC mixtures and the typically higher production rates required. Proper ribboning or sequencing and feed rates of the aggregates and cementitious materials, as they are fed into the mixer, are important factors in minimizing mixing time and buildup for both drum type batch operations and continuous mixers. The timing of adding water to the mixture and the angle of its introduction have been critical in drum mixers. Each plant and RCC mixture can have unique requirements that can only be determined by trial and error and experience with RCC.

Some RCC mixtures can be very harsh, and can cause buildup of fines in drum mixes. Drums should be designed or coated to resist buildup that tends to result from the high fines content of some RCC mixtures. Even with these precautions, experience has shown that substantial buildup can develop on the vanes in drum mixers. If the buildup is not removed daily, it results in a loss of mixer effectiveness.

Transit mixer trucks and mobile batch plants should be avoided, except for small volume applications with relatively high-cementitious content mixtures, and NMSA limited to approximately 1 in. (25 mm). Even with these types of mixtures, slow discharge should be anticipated.

**5.3.3** *Continuous mixing methods*—Properly designed pugmills have handled 3 in. (75 mm) and larger NMSA mixtures, but experience has shown that the amount of material larger than 2 in. (50 mm) should not exceed approximately 8%, and the maximum size should not exceed 4 in. (100 mm). Continuous drum mixers have been used successfully with 6 in. (150 mm) NMSA.

Accurate and consistent control of cement and pozzolan feed is particularly important with continuous mix plants. This is especially true at lower cementitious materials feed rates. Maintaining sufficient head in the silos using air fluffers, vane feeders, or positive-displacement cleated belt feeders, has provided accurate feed of cementitious materials. Belt scales can provide accurate measurement of cement, pozzolan and aggregate for continuous mixing plants. Daily cleanup of buildup is also necessary for the mixing boxes of pugmill type mixers.

**5.3.4** *Mixer uniformity*—Mixture uniformity should be maintained at all production rates that will be used. Continuous mixers typically work efficiently above a minimum production rate, and up to production levels that are two to three times that of the minimum rate. Variations in production requirements, such as near abutments around galleries or other confined areas, can be accommodated on large projects with multiple mixers by shutting down some of the mixers until the higher production rate is needed again. On smaller projects with one mixer, the mixer itself must be capable of uniform production at varying outputs. Mixture variability with regard to design, equipment, and experience is discussed in more detail in the references.[5.1,5.2]

The accuracy of the concrete plant and methods for control of the mixture during production should be studied for cost effectiveness and mixture strength requirements. If exacting quality control and low variability are necessary, they can be provided in RCC mixtures but at increased cost and possibly reduced placing rates. Typical coefficients of variation for RCC compression tests with reasonable weight or volume controls in mass mixtures tend to be approximately 20 to 25%, with extremes ranging from approximately 5 to 45%.

## 5.4—Transporting and placing

The process of mixing, transporting, placing, spreading, and compacting should be accomplished as rapidly as possible and with as little rehandling as possible. The time lapse between the start of mixing and completion of compaction should be considerably less than the initial set time of the mixture under the conditions in which it is used. A general rule for mixtures with little or no pozzolan is that placing (depositing), spreading, and compacting should be accomplished within 45 min of mixing, and preferably within 30 min of mixing. This limit is applicable at mixture and weather conditions of approximately 70 F (21 C) and mixtures that are nonretarded. The time can be extended for cooler weather and should be reduced in warmer weather. Low humidity, windy conditions, and multiple handling can decrease workability and reduce the allowable time for completing compaction to less than 45 min.

**5.4.1** *Equipment selection guides*—The volume of material to be placed, access to the placement area, availability of rental or lease equipment, capital cost for new equipment, and design parameters generally are controlling factors in the selection of equipment and procedures to be used for transporting RCC from the mixing location to the placing area. RCC is usually transported by vehicles, conveyors, or a combination of both. The transport system is selected based partly on the mixing system used. When a partial conveyor system is used, it typically involves transport by conveyor to a hopper on the dam, from which vehicles collect batches for final delivery to the spreading area. However, with the use of holding hoppers designed to control segregation, continuous mixers can be used with vehicle transportation, and batch mixers can be used with conveyors. Equipment and procedures currently available are capable of mixing, delivering, and placing RCC at sustained rates in excess of 1000 $yd^3$/hr (750 $m^3$/hr). This rate is significantly greater than that achieveable in the past with conventional mass concrete.

**5.4.2** *Segregation considerations*—The maximum size of the aggregate and the tendency for the mixture to segregate are major factors in selecting equipment used to transport RCC from the mixing plant to the placement area. A 1-1/2 in. (38 mm) NMSA concrete can be transported and placed in non-agitating haul units designed for aggregate hauling and earthmoving, without objectionable segregation. Conveyor systems must be designed to minimize segregation at transfer points. RCC mixtures with a 3 in. (75 mm) NMSA have a greater tendency to segregate when they are dumped onto hard surfaces, but with care and proper procedures, these mixtures have been hauled, dumped and remixed successfully. Severe segregation can occur during the transportation and placing of large NMSA, and drier consistency mixtures. Design of wetter consistency mixes also reduces the tendency of mixes to segregate. Hand labor is often required to remove or remix segregated material prior to compaction, and the amount of hand labor will depend on the degree of segregation and design requirements.

**5.4.3** *Transporting methods*—The two principal methods of transporting RCC are by conveyor and by hauling vehicles. Transport by bucket or dinky have been used, but these slows the rate of production and are more prone to cause segregation. However, if such a system is already available (or necessary) for large volumes of conventional concrete, it can also be used for the RCC.

**5.4.3.1** *Conveyors*—Transport by continuous high-speed conveyors from the concrete plant directly to the mass RCC placement in particular for dams is ideal. The overall economics, including direct and indirect costs of alternate delivery systems, as well as reliability, the final quality, and schedule, should be considered when deciding whether to use or require a conveyor delivery system. All aspects of the conveyor system should be specifically designed for RCC of the type used on the project. Conveyor systems that work well with a conventional concrete may not work well with a low-cementitious, drier, larger-aggregate, or high-fines RCC. Clogged transfers, segregation at the discharge, severe wear at transfers, segregation over rollers, slow belts, not being able to start or stop a loaded belt, drying, loss of paste, and contamination of the RCC lift surface from material dropping off the return side of belts are the most common potential problems associated with conveyor transport.

It is especially important that conveyors do not allow RCC or other material to ravel and scatter onto the compacted RCC surface along the conveyor path. This can cause a contamination area that will require extra cleaning between lifts. Because of the rapid rise of RCC dams, conveyor systems should be designed to be raised quickly. When conveyors are located above the lift surface, provision must be made for the spreading and compacting equipment operating beneath the delivery system.

As with conventional mass-concrete conveyor systems, special attention should be given to belt widths, speed, protection, maintenance, incline angles, backup systems, and spare parts. Belt scrapers should be provided to clean the return belt. These typically require frequent attention for adjustment and wear. Properly designed charging and discharge hoppers to prevent segregation at transfer points are essential. Exposure time on conveyors should be as short as practical, with 5 min being desirable and 10 min being a normal limit. Belt speeds should be approximately 10 to 30 ft/sec (3 to 9 m/sec). Covering the conveyor to protect the mixture from drying and from rain should be considered for all long sections and, preferably, for the entire system.

A well-designed conveyor system can also be capable of handling conventional concretes that may be used concurrently with the RCC. However, this may complicate the placing operation unless separate parallel conveyors for the RCC and conventional concrete are provided.

Use of a partial conveyor system with a belt feeding continuously from a pugmill mixer to a hopper on the dam is shown in Fig. 5.1. Trucks or front-end loaders are used to haul RCC from the hopper to the placing area. Partial conveyor systems from a mixing plant to the placement area provide rapid transport and allow more time for spreading and compaction. Some problems with partial conveyor systems include continual raising of the hopper, segregation at the edges of loads dumped into and out of trucks, damage to the surface caused by the hauling equipment, and insufficient room at the top of the dam for the hopper and other equipment. Conveyor systems reduce the need for multiple access roads that need to be raised with the dam, and reduce lift contamination and cleaning problems that occur with truck hauling equipment.

All conveyor delivery systems are shown in Fig. 5.2 and 5.3. The first uses embedded steel columns raised with the dam to support and raise the conveyors. Swinger conveyors reach from the columns to essentially all of the dam surface. The second application uses segmented conveyors to feed a crawler mounted conveyor traveling on the dam and reaching out to all placing areas. A detailed discussion of conveyor equipment and methods can be found in the references.[5.3] Fig. 5.4 shows conveyor delivery of conventional concrete on a separate belt parallel to the wider RCC belt.

A continuous belt conveying from the mixer to the final placement area can substantially increase placing rates and significantly reduce other equipment needs with their related labor requirements. Fig. 5.5 compares typical average production for reduced dam widths when delivery is totally by conveyor and when haul vehicles are used on the dam. Without a conveyor, productivity decreases to very low rates in narrow sections, such as at the top of a dam. Fig. 5.5 is based on a compilation of actual data at various projects and also from computed round-trip delivery times at other projects. Conveyor systems must be properly maintained and the contractor must have prompt repair capabilities for both the mechanical and electrical systems. If the conveyor system breaks down, RCC construction stops unless an alternative transport method has been planned.

**5.4.3.2** *Haul vehicles*—If vehicles are to be used for transporting RCC, a thorough preliminary study should be made of the haul road system. Problems that may prevent hauling by road include steep and rough terrain, lack of road-building material, plant location, schedule, and environmental considerations. If the concrete plant is located upstream of a dam, the method of bringing the road through or over the upstream face system must be worked out in detail. From a scheduling standpoint, construction of roads should be completed prior to start of RCC placement. Raising the roads fast enough to keep up with the rate of rise of the dam may require so much time that it becomes an inefficient system at higher elevations. To avoid slowing the mixing and placing operations, raising the haul roads during a 2 to 4 hr/day shutdown period while maintenance and other work is being performed should be considered. The roads must be kept at slopes consistent with the equipment capabilities and safety requirements.

Haul roads should transition onto the lift surface at a shallow angle if possible so that turning and damage of RCC by tires is minimized. If an immediate right-angle turn is needed

*Fig. 5.1—Partial conveyor system to hopper on dam.*

*Fig. 5.2—All-conveyor system supported on posts in dam.*

(from roads that enter directly onto the dam perpendicular to the face), significant scuffing and lift surface damage can result. The vehicles should move slowly while turning and use the largest turning radius possible or have an exit point that avoids turning. The haul road surface should be constructed with clean, free-draining rock or gravels if possible.

The last portion of the road prior to entering the lift should be surfaced with clean large aggregate or rock material that minimizes contamination of the RCC surface from contaminated truck tires. To prevent lift contamination, it may be necessary to use water sprays to wash vehicle wheels before they are allowed on the lift surface, but then excess water dripping from the truck and its tires can become a problem. To minimize adverse effects on the surface, hauling equipment should not travel in a concentrated path on the lift. Even with all the previously mentioned precautions, experience including observation and cores has shown that damaged lift surfaces should be expected where haul roads are used for vehicles traveling onto the dam.

When haul units are used to distribute RCC that is conveyed to the lift surface, a hopper to load the vehicles is generally needed at the end of the main conveyor. The objective is to allow the mixers and conveyors to operate and discharge without interruption or waiting for the haul vehicles. A rec-

*Fig. 5.3—All-conveyor system utilizing crawler placer.*

*Fig. 5.4—Conveyor delivery of conventional concrete on separate belt parallel to wider RCC belt.*

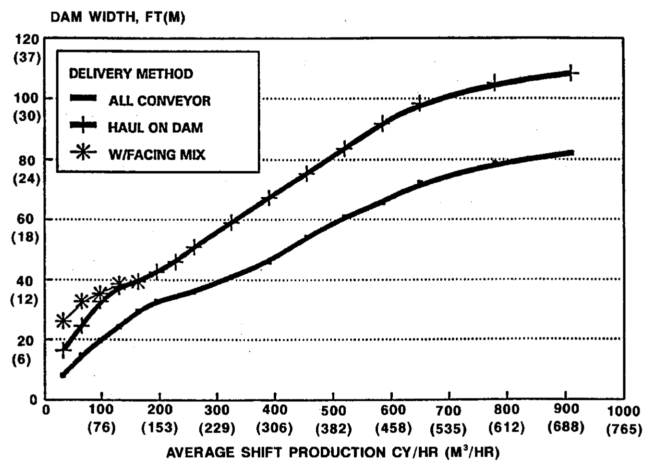


*Fig. 5.5—Effect of delivery method and dam width on production.*

ommended minimum size of the hopper is twice the size of the haul vehicle. Because of the relatively high unit weight of freshly mixed RCC compared to the loose unit weight of soil, rock, or gravel normally hauled in these vehicles, weight rather than volume normally controls the amount of material hauled per trip.

Bottom-dump trailers and scrapers minimize segregation, spreading requirements, and the distance RCC drops, but they are difficult to use in small placements near abutments in dams and other obstructions. Scrapers have better mobility than bottom dump trailers, but tend to tear the surface when making sharp turns. Scrapers and bottom dump trailers have the advantage of depositing material in the layer to be spread as they are moving.

Front end loaders have been used to deliver RCC from a central feed point on the placement to the location where it is spread. This method has production limitations not suitable for large projects, and can have problems with segregation and lift surface damage. However, where the mixture is not susceptible to segregation, where spillage can be avoided, and where tire tracking is not a problem, it may result in the most economical situation that is technically acceptable. Principal candidates for this approach are smaller dams in tight canyons where the distance for loader travel is minimal. Also, the projects should preferably have a smaller maximum-size, well-graded aggregate with a tendency for a higher paste and cementitious content. Extra cleaning, or special grout or bedding mixtures may be appropriate between lifts when they are not placed and compacted prior to the time the previous lift reaches its final set.

When the RCC is hauled to the placing location and dumped, it should generally be deposited on previously spread but uncompacted material, and pushed forward on to the compacted lift surface. This provides remixing action and minimizes clusters of coarse aggregate that otherwise would tend to occur at the lift interface. When RCC is dumped in large piles, larger aggregates tend to roll down the outside of the piles and create clusters. A general rule is to limit the height of a pile to 5 ft (1.5 m) or less. Correcting this kind of segregation is nearly impossible if the rock has already rolled onto a previously compacted lift. Where this condition occurs, the segregated large aggregate should be removed and wasted or broadcast onto the RCC layer being spread. As with conventional concrete, RCC should not be dropped freefall without chutes or trunks more than 5 ft (1.5 m).

**5.4.4** *Placing and spreading*—A preferred technique of placing RCC in a dam is to advance each lift from one abutment to the other. An exception is where the distance from abutment to abutment is shorter than the distance from the upstream to the downstream face, such as at the bottom of dams in narrow canyons. In this case, placement can be started by working in the upstream-downstream direction. Unless it is carefully controlled, placement in the upstream-downstream direction may result in segregation along lateral placement edges that cause porous zones through the structure. This can be particularly critical for RCC mixes with a tendency to segregate.

Some projects have required placing RCC in paving lanes, typically going from abutment to abutment. The problems with placing RCC in paving lanes are more serious with lower cementitious content, dryer consistency, and larger aggregate mixtures. Spreader boxes attached to dump trucks, Jersey spreaders attached to dozer equipment, and paving machines lack mobility and occupy space in narrow areas of the dam. They can be difficult to maneuver at the abutments. Paving lanes can leave segregation along the edge of the lanes with dam mixtures. The edges can also become too old to be compacted into RCC of the adjacent lane by the time the adjacent lane is placed. The edge also tends to dry out while exposed prior to placing the adjacent lane. This has resulted in concerns over poor quality and weakened or permeable planes in the dam at the interface of paving lanes. This practice should be discouraged unless the problems described can be satisfactorily addressed. Motor graders have been used on some RCC projects for spreading RCC. They are difficult to maneuver in small areas and at abutments. The tires and blade can damage compacted surfaces. There also is a tendency to overwork and rework the surface.

Tracked dozer equipment has proven to be best for spreading RCC. Tracked dozers are fast, sufficiently accurate, and contribute to uniformly compacted RCC. By careful spreading, a dozer can remix RCC and minimize segregation that occurs from dumping. Careful attention should be given to ensure that remixing is occurring and that the dozer is not simply burying segregated material. Dozers using U-shaped blades are typically modified by welding extension plates on the edges of the blades to limit segregation that can occur as RCC rolls off of the edge during spreading. Dozers should have at least hydraulic tilt capability and preferably both tilt and angle hydraulic capability. The dependability of the equipment and quality of the operator have a significant effect on controlling segregation and spreading a uniform lift thickness.

A dozer typically spreads the RCC in a 12 in., ± 2 in. thick (300 mm ± 50 mm), loose lift in a manner that allows the dozer to operate on uncompacted material. Dozers with street grousers rubber tracks, or worn tracks, are preferred so as to minimize breakdown of the aggregate or shearing of the RCC or both. Lasers surveying equipment is used on many projects for controlling the grade of grading lift surfaces.

At Elk Creek Dam,[5.4] RCC mixtures with a set retarding admixture, and a Vebe time of 15 to 25 sec, were end-dumped, in piles, on previously spread but not-yet-rolled material at least 40 ft (12 m) from the advancing face, similar to the Japanese RCD method. Dozers leveled the piles and spread the RCC forward into 6 in. (150 mm) thick layers until a full lift thickness of 24 in. (610 mm) was reached. Two double-drum 10 metric-ton vibratory rollers and three D-7 or D-8 dozers were able to spread and compact the 24 in. (0.6 m) lift thicknesses at a rate of more than 900 $yd^3$/hr (690 $m^3$/hr). The entire surface of each 6 in. (150 mm) layer was traversed by at least two passes of the dozer tracks. This dozer action produced an average density of 146.5 pcf (2347 $kg/m^3$) or approximately 98% of the optimum compaction density. Additional compaction of the roller was added only to the 24 in. (0.6 m) full thickness of the lift. If the mixture had not contained a retarder, more equipment or thinner lifts would have been needed. Typically, two rollers and one Caterpillar Model D-6 (size) dozer, with a backup dozer, can spread and roll nonretarded RCC at a rate of approximately 300 to 500 $yd^3$/hr (230 to 380 $m^3$/hr) in 12 in. (300 mm) thick lifts.

Similar results have been achieved with other RCC mixtures having a relatively plastic mix consistency. At the Nickajack Dam auxiliary spillway project,[5.5] wet consistency, air-entrained RCC was spread in two 12 in. (300 mm) thick lifts, with the second layer following as a step behind the first layer. The first layer was substantially compacted prior to placement of the second layer, and the second layer was compacted before the first reached initial set. The advancing layer was approximately 100 ft (30 m) in front of the following layer.

At Upper Stillwater Dam, end dump trucks were equipped with a spreader box that dumped and spread the RCC in approximately 14 in. (360 mm) thick loose lifts. Only a small dozer was needed for final spreading with placement rates up to 700 $yd^3$/hr (530 $m^3$/hr).[5.6]

Dozers should operate on fresh RCC that has not been compacted. All turning and crabbing should be performed on uncompacted material. Operating the dozer on a compacted surface will damage the RCC. When it is necessary for the dozer to drive onto compacted RCC, the operator should limit the movement to straight back and forth travel, or travel on rubber mats, or both, such as lengths of old conveyor belts. Track marks made prior to the mixture reaches initial set can be recompacted by the vibratory roller without significant loss of joint quality. However, damaged surfaces that are recompacted after the mixture has set or dried develop compaction planes with little or no strength, even though the RCC may have an acceptable surface appearance. Where compaction planes result, the layers will not bond together. This material can be easily removed by blowing with an air jet, even many hours later.

Spreading equipment should leave a flat or plane surface of the proper thickness before the roller compacts the lift. Depending on the workability of the mixture, ridges or steps between adjacent passes of the dozer blade can result in uneven compactive effort and variable quality in the RCC. As a general rule, having a flat surface ready to roll in the least time is more important than having an exact grade with delayed rolling.

Where conventional concrete mixtures are specified for limited areas, for example, at the upstream or downstream face, special procedures are required. If conventional concrete is used against a formed face with a dry consistency RCC mass behind it [Fig. 4.4(c) and d)], many designers believe that the conventional mixture should be placed first with the RCC immediately spread against and on top of the sloping unformed face of the conventional concrete. The conventional mixture should be proportioned to lose slump rapidly but not set rapidly. This allows the RCC to be compacted into the conventional concrete before either mixture sets. If the conventional concrete does not lose slump soon enough, the roller will sink into it with a variety of ensuing construction problems. If rolling is delayed while waiting for the conventional mixture to stiffen, the RCC can become too old for proper compaction. If the roller operator simply stays back from the conventional concrete far enough to avoid sinking into it or shoving it up, the two mixtures may not adequately compact or bond together. Conventional concrete is usually needed for appearance and possibly durability of the exposed face. The minimum amount that can be stacked against the form, approximately 2 to 6 in. (50 to 150 mm) wide, will provide a conventional concrete appearance. However, large compactors can not be operated that close to the forms. Use of smaller compactors may result in lower density RCC in this area or require placement of thinner lifts or both. If the conventional concrete zone is wider than approximately 6 in. (150 mm), the conventional concrete is usually consolidated with immersion-type vibrators while the adjacent RCC is rolled.

If the RCC has a wetter consistency, and especially if it has a delayed set, it is possible to place the conventional concrete mixture after the RCC. The facing concrete still needs to have a relatively low slump when RCC compaction is performed, but it can still be possible to immersion vibrate the interface region of the RCC and conventional concrete. Experience, coring, and internal destructive investigations have shown that a poor interface between conventional concrete and RCC often results in both sequences of conventional and RCC interface placement. Efforts are ongoing to improve the conventional concrete-RCC interface area.

The most common compacted lift thickness has been 12 in. (300 mm). The trend is to use the thickest lifts compatible with the RCC mixture and the spreading and compaction equipment to achieve the specified minimum density. In Japan, thicker lifts from approximately 1.6 to 3.2 ft (0.5 to 1.0 m) have been compacted in one lift after being spread by dozers in several layers. A 12 in. (300 mm) thickness is convenient to work with in the field.

Another factor influencing lift thickness is the maximum allowed exposure time before covering one lift with the subsequent lift. Each project should be studied to optimize the benefits of various lift thicknesses. Thicker lifts mean longer exposure times but fewer lift joints and fewer potential seepage paths. Thinner lifts result in more potential lift joints but allow the joints to be covered sooner, resulting in improved bond. Mix proportions will also affect the workability and consequently the ability to achieve uniform density, for the full lift thickness.

At the start of extremely rough foundations and where the foundation has deep holes that have not been filled with dental or leveling concrete, a front-end loader, excavator bucket or conveyor can be used to reach the placement site to deposit material. Conventional concrete can also be used to achieve a level working area to start RCC placement.

A small dozer (similar to a Caterpillar Model D-3 or a John Deere Model JD-350) is needed to start the foundation and for tight conditions. A D-3 is generally capable of spreading RCC at a rate of approximately 300 $yd^3$/hr (230 $m^3$/hr).

## 5.5—Compaction

**5.5.1** *Roller selection*—Maneuverability, compactive force per unit of drum width, drum size, vibration, frequency, amplitude, operating speed, availability, and required maintenance are all parameters to be considered in the selection of a roller. The compactive output in volume of concrete per hr obviously increases with physical size and speed of the roller. Larger-size rollers do not necessarily give the same or higher density than smaller rollers with a greater dynamic force per unit of drum width. Project size, RCC mixture workability, lift thickness, the extent of consolidation due to dozer action, and space limitations will usually dictate roller selection. Large rollers cannot operate close to vertical formwork or obstacles, so smaller, hand-guided compaction equipment is usually needed to compact RCC in these areas. If a slipformed or precast facing system that has an interior face sloping away from the RCC is used [Fig. 4.4(e)], large rollers can operate adjacent to the facing.

The dynamic force per unit of drum width or per area of impact on tampers is the primary factor that establishes effectiveness of the compaction equipment. Most experience has shown that rollers with a higher frequency and lower amplitude compact RCC better than rollers with high amplitude and lower frequency, although acceptable results have been achieved on some projects using rollers with both high frequency and amplitude. Use of rollers that have more than one setting of amplitude and frequency provides flexibility in determining the best combination for the RCC mixture being used on a project. The typical compactor is a 10 ton (10,160 kg) double- or single-drum roller with a dynamic force of at least 450 lb/in. (8 kg/mm) of drum width. These rollers are typically used for compaction of asphalt and granular materials. Larger 15 and 20 ton (15,240 and 23,320 kg) rollers with more mass and size, typically used with rockfill construction, have been used with RCC, but they usually have larger amplitudes, lower frequency, and are less suited to the aggregate gradings used in RCC. Achieving required density and a good lift-joint interface is more difficult with these larger rollers. The vibration mechanism should automatically disengage when the roller is stopped. Continued vibration in one location will cause displacement of material beneath the roller and raveling along exposed edges.

In tight areas such as adjacent to forms and next to rock outcrops, large power tamper jumping-jack compactors are most suitable. They are mobile and can provide high impact energy to produce good density. However, they usually do not leave a smooth surface and can sink when tamping RCC placed over an excessive thickness of wet bedding mixture, when tamping RCC with excess water, when compacting along an unrestrained lateral face, or along a conventional concrete mixture that has not lost its slump. Walk behind vibrating plate compactors typically used for asphalt are generally effective only for surface compaction. Jumping-jack type compactors and heavy vibrating plates can be effective in achieving the required density throughout the lift, as long as lift thickness is not excessive. They may require multiple passes. Walk-behind rollers are not very effective in most cases unless they can produce a compactive effort of approximately 350 lb of dynamic force per in. (6 kg per mm) of drum width. Four to six passes of this type roller on 6 to 12 in. (150 to 300 mm) thick lifts usually result in suitable compaction for tight areas, with densities approximately 98% of that achieved with large rollers.

At Burton Gorge Dam in Australia, 100% compaction was achieved with a small dozer in the top portion of the dam by modifying the mixture with a retarder, using a wetter RCC consistency, and rapid placing (one lift per 1 to 4 hr) and rigorously tracking the 12 in. (300 mm) thick lifts as they spread. This resulted in densities that reached the theoretical air-free density of the mixture. Thorough dozer tracking the same mixture at a drier consistency and without retarder, with mixes less than approximately 30 min old, achieved densities in the range of approximately 96% of the theoretical air free values. Roller compaction was then required to achieve a higher final density.

While compaction on a trial basis with rubber tire rollers has produced high-density RCC similar to that achieved with the vibratory roller, the degree of bond achieved at the interface of the RCC layers is questionable. Caution is advised using this equipment until its performance has been better evaluated. Rubber tire rollers have been effective in sealing, smoothing, and tightening the surface of mixtures that are susceptible to damage and that exhibit surface checking after final drum rolling.

**5.5.2** *Minimum passes and lift thickness*—The minimum number of passes for a given vibrating roller to achieve specified compaction depends primarily on the RCC mixture workability and lift thickness. Experience shows that the maximum lift thickness will be governed more by how fresh the mixture is at the time of compaction, by gradation, and by the effectiveness of the dozer while spreading than by the number of roller passes. As a general rule, the compacted thickness of any RCC lift should be at least three times the diameter of the NMSA.

The required number of roller passes should be determined or verified in the test section (Chapter 6). Some compaction specifications require the first pass to be in the static mode to initially consolidate the RCC and prevent the roller from bogging down with wetter consistency mixes. Drier mixtures may begin with the vibrating mode. The frequency and amplitude settings may have to be adjusted depending on the workability of the mixture. The most effective compaction typically occurs with a high frequency on the order of 1800 to 3200 vibrations/min, and with a low amplitude on the order of approximately 0.015 to 0.030 in. (0.4 to 0.8 mm). The transient loading and vibration result in consolidation of wetter consistency mixtures with a measurable Vebe time. The same frequency and amplitude ranges have also been very effective with compaction of drier consistency mixtures.

Typically, four to six passes of a dual-drum 10-ton (9072 kg) vibratory roller will achieve the desired density for RCC lifts in the range of 6 to 12 in. (150 to 300 mm) thick. This assumes compaction in a timely manner with appropriate equipment. Overcompaction or excessive rolling should be avoided. Excessive rolling may reduce the density in the upper portion of the lift. Compaction in thick lifts after spreading in thinner layers can be effective with some RCC mixes. This procedure requires a RCC mix with a Vebe time in the 10 to 30 sec range to achieve effective compaction by the dozer during spreading may require a retarded set RCC mixture, and may require roller passes on the top layer of the lift.

**5.5.3** *Timing and procedures*—The appearance of fully compacted RCC depends on the mixture proportions. Mixtures of the wetter consistency usually exhibit a discernible pressure wave in front of the roller. Mixtures that have more paste than necessary to fill aggregate voids and a wetter consistency will result in visible paste at the surface that may pick up on the roller drum, depending on the constituents and plasticity of the paste. If the paste content is equal to or less than the volume needed to fill all the aggregate voids, rock-to-rock aggregate contact occurs and a pressure wave may not be apparent. This can also occur if the mixture is simply too dry to develop internal pore pressure under the dynamic effect of the roller.

Compaction should be accomplished as soon as possible after the RCC is spread, especially in hot weather. Typically, compaction is specified to be completed within 15 min of spreading and 45 min from the time of initial mixing. Substantial reductions in strength values can be expected if the RCC is compacted when it is more than approximately 30 to 45 min old, and the mix temperature is approximately 70 F (21 C) or higher. These times can be increased for RCC mixtures with extended set times due to pozzolans, admixtures, or cooler temperatures.

The fresh RCC mixture surface should be spread smoothly so that the roller drum produces a consistent compactive pressure under the entire width of the drum. If the uncompacted lift surface of less workable RCC is not smooth, the drum may overcompact high spots and undercompact low spots.

Each RCC mixture will have its own characteristic behavior for compaction depending on temperature, humidity, wind, mix workability, aggregate fines content and plasticity, overall gradation, and the NMSA. Generally, RCC mixtures should compact to a uniform texture with a relatively smooth surface. In general, the material should not pick up onto the roller drum, nor should there be free surface moisture or pumping of excess water from the mixture. Minor damage from scuff marks and unavoidable dozer tears in the surface of a freshly compacted lift can usually be immediately rolled with the vibratory drum in a static mode or with a rubber tire roller. If the mixture was sufficiently fresh and moist and is rerolled prior to initial set, an acceptable condition will result. If the mixture is too old, severely damaged, or if the lift immediately below has hardened, the rerolled RCC may look acceptable but should be rerolled. Recompacted RCC that is too old or damaged can and should be easily blown off by an air hose used for general cleanup of loose debris on the lift.

## 5.6—Lift joints

**5.6.1** *Lift horizontal joint development*—Horizontal joints are inevitable in mass RCC because of its layered or lift method of construction. Each layer is the thickness of material spread. Lifts may be compacted as individual lifts, or several layers may be spread before compacting them as one lift prior to initial set of the RCC. For sliding stability, joint shear strength or water-tightness, designs usually require clean and relatively fresh joint surfaces with good bond. This is typically done by suitable large vacuum truck or air blowing with a wand. Some tests have shown sandblasting at 24 and 72 hr after placing can actually reduce bond.[5.7]

When an RCC lift is not covered with additional RCC before it reaches initial set, a cold joint is formed. A cold joint can be generally characterized by joint maturity, which is a result of the average surface temperature (AST), and time of exposure (TE). Joint maturity is expressed in deg-hr and is calculated as

$$\text{Joint maturity in deg F-hr} = (\text{AST}) \times (\text{TE})$$

For example, for 14-1/2 hr exposure at an average temperature of 70 F

$$\text{Joint maturity} = (70) \times (14\text{-}1/2 \text{ hr}) = 1015 \text{ deg F-hr}$$

Degree F-hr can not be exactly converted to deg C-hr, or vice versa, without first converting the temperature.

$$\text{Joint maturity in deg C-hr} = [(\text{AST} \times 1.8) + 32] \times \text{TE}$$

Joints are also sensitive to the quantity and characteristics of the cementitious material and the effectiveness of set-retarding admixtures. Each situation is different, but at an approximate surface temperature of 70 F (21 C), a cold joint usually begins to occur in nonretarded RCC by approximately 4 hr and most likely has developed by 6 hr. A joint that has been exposed less than 6 hr before being covered by the next lift will have adequate shear strength, but it may not be watertight unless it is clean and covered with a slumpable bedding mixture or high cementitious content RCC mixture at a maturity of 500 to 1500 deg F-hr (260 to 815 deg C-hr). After approximately 500 deg F-hr (260 deg C-hr), a bedding mixture may be necessary to achieve the required shear or tensile strength. The exact maturity limit for each project depends on the mixture and design requirements.

High dams, and those where joint shear strength is critical to stability and safety, should have design assumptions for joint shear strength confirmed with shear tests of the RCC to be used, the conditions to be encountered, and the construction controls that will be enforced. Initial design assumptions can be based on extrapolation from tests, evaluations, and successful design assumptions from previous projects. Example data are contained in Chapter 3. The issue is discussed further in Chapter 4.

Designers generally have found it prudent to require the bedding mixture (or higher paste-content RCC) after a lift has been exposed for approximately 12 to 24 hr, regardless of the surface maturity. Other designs have found it prudent to use bedding in a systematic manner for all or a portion of all lifts.

**5.6.2** *Lift-joint treatment*—Lift joints should be kept continuously moist and protected from drying or freezing prior to placing the next lift and for curing of the final surface. The surface should be clean and at or near a saturated surface dry (SSD) condition just prior to placing the next layer of RCC. Tests and experience have shown that allowing the surface to dry back to just under an SSD condition, as indicated by a change in color from dark to lighter, will greatly facilitate cleaning by air blowing, and will not reduce joint quality for most RCC. Some tests have even shown a slight increase in joint strength.[5.8] However, wetting, but not ponding, the surface after final cleaning and just prior to spreading the next layer of RCC is considered good practice.

If the surface is more than 1 to 2 days old and has become sufficiently hard, high pressure water washing may be necessary if air blowing alone does not adequately clean off damage, contamination, and laitence that may be present. Water washing can only be used after the surface has hardened. Sandblasting is generally not advised or necessary.

RCC mixtures generally do not bleed or develop laitence at the surface. An exception is very wet mixtures and some cases of dry mixtures after days of moist cure. If there is no weak laitence, coatings or deposits, or other contamination at the surface, lift-joint cleaning typically required with conventional concrete is not necessary. Although there is some debate, minor intermittent laitence that may occur in some situations is generally not removed.

If the construction joint is between 500 and 1500 deg F-hr (260 and 815 deg C-hr) old, and if it has been kept clean and moist throughout its exposure, joint treatment is not always necessary. If the surface has been contaminated by dirt, mud, or other foreign elements, the contamination should be removed. If the surface has been allowed to dry out, exceed approximately 1000 deg F-hr (550 deg C-hr) of maturity, or became damaged, it should be cleaned and may require a full or partial bedding mixture prior to placement of RCC. The 1000 deg F-hr (550 deg C-hr) used here is an example. Each project should set limits appropriate to meet the design criteria.

The practice of requiring a thin layer of highly workable mortar as a bedding over all lift surfaces is routine in Japan and was also used at Elk Creek Dam. The RCC layer is spread over the bedding while the bedding still retains its slump or workability, and the RCC is then compacted into the bedding. The bedding mortar was spread with brushes on small tractors at Elk Creek Dam, and was applied by shotcrete procedures at Zintel Canyon Dam.

Many RCC projects have used a highly sanded conventional concrete or mortar mixture for bedding with good results. The mixture should have at least a 6 in. (150 mm) slump and be significantly retarded using admixtures. The bedding layer should be thick enough to fill in irregularities without being too thick. Where concrete is used, 3/8 to 3/4 in. (9.5 to 20 mm) maximum size aggregate is desirable. The bedding concrete thickness should average the dimension of the largest aggregate particle in the mixture. Where mortar is used for bedding mixtures, the thickness is generally about 1/4 in. (6 mm). Compressive strength for bedding mixes should be greater than the RCC. Excessive thickness of bedding can result in pumping and difficulty in compacting the overlying RCC. Cores have consistently shown that the use of bedding mixtures bonds the RCC layers.

Each project should be evaluated individually for bedding mixture types and requirements. Where bedding has been used over the entire surface of every RCC layer, it has basically been to achieve better joint interfaces throughout the dam, enhance shear and tensile capacity at the lifts, and provide added protection against lift-joint seepage. On other projects, bedding mixtures have been used when and where it has been determined to be necessary to achieve the required safety factor and seepage control. The width of bedding near the upstream face should be determined by the designer.

## 5.7—Contraction joints

Contraction joints are an important part of the design of many RCC dams. Seepage control includes many methods such as: a) construction of a contraction joint by inducing a discontinuing in the dam; b) placement of an upstream impermeable membrane; c) construction of a reinforced concrete upstream face; and d) no specific measures. Contraction joint construction can have a minimal to significant impact on production and quality of RCC placement. On RCC dams with a short crest length or small volume, installation of contraction joints can slow production significantly which can reduce the benefits of fast placement of RCC. The contraction joint design feature selected should compliment the design methodology selected, as discussed in Chapter 4.

Contraction joint construction will range from relatively simple, surficial crack and seepage control, to detailed joints with water stops, drain holes and grout tubes. Surficial crack/seepage control construction includes formed control joints using chamfer strips as crack inducers. Crack inducers can be installed by placing 1-1/2 in. (37-1/2 mm) by 1 in. (25 mm) wood strips on the upstream forms. The control joints can then be sealed or treated with a backer rod and a joint sealer. A typical control joint treatment detail is shown in Fig. 4.7.

A detail of contraction joints consisting of a waterstop and drain is shown in Fig. 4.6. The waterstop is generally placed in conventional concrete at a specified distance from the upstream face of the dam, and joint filler placed upstream and downstream of the waterstop. A frame with a roll of waterstop is frequently mounted to the upstream face forms to keep the material out of the construction area. For contraction joints with drain holes, the drain holes are formed as the RCC is placed, and an outlet pipe connected to the drainage gallery.

The contraction joint through the RCC mass had been formed by either setting a crack-inducing plate braced on the RCC surface during spreading, or insertion of a plate throughout the loosely spread, uncompacted RCC. The sequence for installation of the crack inducing plate has included: a) spreading RCC to the contraction joint alignment; b) setting a vertical form plate for the joint with some external bracing to maintain the plate vertical; and c) spreading RCC on the opposite side of the vertical plate with manual labor around the plate. Plastic is usually placed around the vertical plate and the metal plate removed, leaving the plastic in place as a bond breaker.

An alternative method to induce a contraction joint through the RCC mass has included using a vertical plate on a vibrator attached to a backhoe, or using a manually operated jack hammer. The galvanized steel plate that is vibrated into place and left in the RCC as a bond breaker.

## 5.8—Forms and facings

**5.8.1** *General*—Large surface areas that are not horizontal, such as the upstream and downstream faces of dams, can be shaped to almost any desired slope or configuration, but special consideration must be given to anchorages, appearance, and technique. A few of the more common methods used to date are discussed briefly, as follows, after general comments. These and other methods depicted in Fig. 4.4 and 4.5 for facing RCC dams are discussed in Chapter 4, Design, and in the references.[5.9]

The height of overhanging sloping forms, such as for spillway surfacing or downstream face forms, restricts areas accessible to the vibratory rollers. These forms should, therefore, be limited in height or hinged at midheight to reduce the volume of concrete that must be placed under the overhang by conventional methods. Conventional jump-form anchors may not have adequate embedment depth for form support when anchored in low-strength RCC, and special anchors are typically required.

Handling and raising conventional formwork may become the limiting factor in the rate of RCC placement. Near the top of a dam, where the volume of RCC per lift is low and the form area for upstream and downstream faces is relatively large, more time may be required to set and move the forms than it takes to place the RCC.

**5.8.2** *Curb forming*—One means of forming upstream and downstream faces is using powered curbing machines to slipform conventional concrete curbs or facing elements against which the RCC placement can be initiated within approximately 8 hr. This method is more applicable to wide valleys and large projects where the rate of rise of the RCC does not exceed the rate of slipforming. At Upper Stillwater Dam, it was possible to maintain an average production rate of 2 ft (0.6 m) vertical rise per day with the curbs having enough time to develop the necessary strength.

**5.8.3** *Precast concrete forms*—Vertical and very steep faces can also be constructed with precast concrete panels or blocks. Precast concrete panels consist of relatively thin, high-quality concrete slabs with integral or external supports, or both, for erection. These panels can incorporate insulation to protect the interior concrete in extremely cold regions. They also can include a heavy-duty flexible impervious membrane attached to the rear of the panel to provide water tightness.

**5.8.4** *Uncompacted slope*—If no attempt is made to compact the edges of an RCC placement, the sides will assume a natural angle of repose of approximately 50 deg (0.8H:1.0V) with crushed aggregate and 48 deg (0.9H:1.0V) with rounded aggregate. This assumes reasonable care with spreading and compacting. Any means of containing loose concrete at the edge (for example, by forming the height of the lift, by supporting the edge by pins driven temporarily into the RCC, or by mechanical means) can be used to construct steeper faces. On some projects, the exposed face of RCC has also been trimmed after compaction and prior to development of significant RCC strength.

**5.8.5** *Formed faces*—Conventional forming can be used at the upstream or downstream face with the RCC or conventional concrete placed against the forms. When RCC is placed directly against forms, the resulting RCC surface may have relatively poor quality (unattractive and porous) unless particular attention is given to the placement and type of mixture used next to the formwork. A conventional concrete with a set retarder has been used to provide a conventional concrete appearance and to provide freeze/thaw protection for the structure. Also, use of a set-retarded conventional concrete facing has been used to effectively reduce the number of horizontal joints in the facing by vibrating subsequent lifts of upstream facing together. The sequence of placement: RCC spread first, followed by facing concrete versus stacking facing concrete, and then spreading RCC, has been performed on numerous projects. Both methods have benefits and potential problems associated with the procedures. Placement of RCC first has the benefit of more rapid construction which can improve other aspects of RCC construction. However, the lateral edge of the RCC and the quality of the RCC/concrete interface are of concern. Stacking of concrete against the form followed by RCC may be somewhat slower and special workability properties of the facing concrete are needed. Compaction of RCC on the facing concrete can cause deformation of wetter consistency RCC and the facing concrete. Experimentation is ongoing to improve the RCC/conventional concrete interface.

## 5.9—Curing and protection from weather

After RCC has been placed and compacted, the lift surface must be cured and protected just as for concrete placed by conventional methods. The surface must be maintained in a moist condition, or at least so that moisture does not escape. It should also be protected from temperature extremes until it gains sufficient strength. RCC construction should typically stop when rain exceeds about 0.1 in./hr (2 to 3 mm/hr).

When vehicles are used on the lift surface during rain, the tires may turn the surface into a soft damaged material. This situation may require waiting for the RCC to harden so that extensive cleanup can be undertaken or the entire lift surface removed.

When conveyors are used for delivery, and little or no vehicular traffic is required on the RCC, construction can continue with slight rainfall. This may require a decrease in the amount of mix water used because of the higher humidity and lack of surface drying.

Immediately after an RCC lift has been compacted, the RCC will not become damaged by light to moderate rain as long as there is no hauling or traffic on the surface. After a rain, hauling on the lift can resume only after the surface has begun to dry back naturally to a saturated surface-dry condition. A slightly sloped lift surface generally sloped down toward the upstream face of dams will aid in draining free water and speed resumption of placing operations.

Curing during construction has been accomplished with modified water trucks on larger projects, and with hand-held hoses for all size projects. Trucks should be equipped with fog nozzles that apply a fine mist that does not wash or erode the surface. They can be augmented with hand-held hoses for areas that are inaccessible to the water truck. Provision should be made for maintaining the damp surface while the trucks are fueled, maintained, and refilled with water. Care should be exercised so that the trucks do a minimum amount of turning (and disruption of) the surface. Maintaining access on and off every lift during construction can be a problem that makes trucks impractical. Water tanks and piping to transport water to the dam for distribution by sprinklers, and hand held hoses rather than water trucks, have been used successfully on numerous projects.

The final lift of RCC should be cured for an appropriate time, generally in excess of 14 days. Membrane curing compounds are not suitable because of the difficulty in achieving 100% coverage on the relatively rough surface, the probable damage to the membrane from construction activity, and the low initial moisture in the mixture. Curing compounds also do not provide beneficial surface temperature control that is associated with moist curing.

Unformed sloping surfaces such as the downstream face of a dam are difficult to compact and can be considered sacrificial and unnecessary to cure provided this has been incorporated into the design. Uncompacted exposed RCC will be subject to raveling due to weathering, which can result in an unattractive surface. While the outside several inches will be incapable of achieving any significant strength or quality, it will serve as sacrificial protection and a moisture barrier for curing of the underlying interior RCC. Where unformed sloping surfaces have been trimmed, moist curing is necessary.

Protection from temperature extremes and sudden large fluctuations should be provided in environments where it is appropriate, just as for conventionally placed concrete. The lack of contraction or frequent monolith joints or both in RCC designs adds to the concern about cracking from early or rapid temperature drops, or both, since RCC has low modulus of elasticity and high creep rates at early ages. Very few recent RCC dams have been designed without transverse contraction joints.

The hydration heat generated by the RCC mass and the continuous placing sequence can combine to allow placing in cold weather, even when ambient conditions occasionally drop below freezing, provided that the surface stays at least 2 F (1 C) above freezing until it is covered by the subsequent lift. Experience with RCC construction in freezing weather has shown that freezing water lines, pump and valves, and other problems occur at the concrete mixing plant.

## 5.10—Galleries and drainage

There are several different approaches to constructing galleries in the dam mass. One method is by conventional forming, and another is by placing gravel or fine aggregate in that part of the RCC lift where the required gallery is located, and later mining out this material to open the gallery. The interior surface resulting from the latter allows inspection of the RCC after all loose material is removed, but roughness from the fill material remains and some of it will adhere to the RCC. One method to overcome this is to use wood separators between the RCC and fill as each layer is placed. A critical aspect of any forming system is that sufficient rigidity is provided so that the RCC is fully compacted against the form. Segregation, rock pockets, and less dense RCC are typical in gallery faces when forming and bracing is insufficient or drier consistency mixes are used. Another method that has been effective is to place the RCC to the top of the gallery and then remove it with an excavator before it gains much strength. Precast concrete slabs are then generally used for the gallery roofs. Slipformed curbs were used as gallery walls at Upper Stillwater. Precast concrete sections installed as permanent gallery linings have also been used. Exposed RCC is frequently preferred in galleries so that seepage can freely drain into the gallery and to allow inspection of the interior condition of the dam. The design aspects of galleries are discussed in Chapter 4, and references.[5.3,5.10]

In constructing galleries, both the direct cost and the indirect cost due to slowed construction must be considered. Using the unformed fill method of construction adds approximately 10 to 15% to the placing time of the effected lifts, while more complex forming and precast methods may add 20 to 50%.

Gravel drains, porous concrete, and porous drain tubes have all been used to collect seepage and relieve pressure. In some cases, these techniques can be used instead of a gallery. Drain holes have also been drilled from planned RCC construction joints to galleries, and from galleries into the RCC. This drilling can start soon after the RCC is compacted and is normally done with rotary percussion drilling equipment.

# CHAPTER 6—QUALITY CONTROL OF RCC

## 6.1—General

While quality control is customarily considered to be an activity performed during RCC placement, it is also important that quality control be considered during design, planning, and the initial phases of construction of an RCC project.[6.1]

A structure should be designed with consideration of what measures will be required during construction to ensure that the required quality is attained. It is obvious that the design of projects where little quality control is anticipated should be more conservative than the design of a project where a very effective quality-control program will be implemented. For most projects, the quality control requirements are specified in the contract documents or by separate agreement with a quality control organization. The preparation of those documents should be coordinated with project designers so that the quality-control requirements are properly applied.

In addition to testing, a quality-control program should consider the various construction operations basic to RCC and how they are performed. Preparation and advance planning are a key to success of quality construction. Preconstruction meetings, preconstruction testing, and preconstruction evaluations such as test sections, are critical parts of the quality program. Once RCC placement is underway, the quality-control program should include continuous evaluations that quickly resolve quality variations.

## 6.2—Activities prior to RCC placement

**6.2.1** *General*—RCC placing rates can be significantly higher than conventional concrete. Placing rates in excess of 1000 yd$^3$/hr (590 m$^3$/hr) have been achieved on some projects in the U.S. Small structures have been constructed in only a few days or weeks. With such rapid placement rates or short-term construction periods, problems must be evaluated and solutions implemented in a short period of time. Any problems that delay RCC placing essentially delays all production. Good communications between the owner, engineer, quality control personnel, and contractor is essential and should be established in advance of the work. The most common placement delays are usually due to problems caused by:

1. Foundation preparation and cleanup;
2. Joint cleanup;
3. Hot or cold weather;
4. Equipment breakdown;
5. Insufficient materials; and
6. Weather.

**6.2.2** *Preparatory issues*—A key element in resolving potential problems in advance is to ensure that all participants understand the project requirements and procedures. Basic issues that must be considered in advance are:

*Staffing*—Sufficient laboratory and quality control personnel should be trained and available for the anticipated production operations. Shift overlaps and transitions require advance planning. All staff members must know what is acceptable and unacceptable, and they must consistently apply acceptability criteria. Many RCC projects consist of nearly continuous placement operations and staffing must be sufficient to keep all personnel fresh and not overworked.

*Facilities and equipment*—Appropriate testing facilities and equipment for the size and volume of tests that may become necessary must be available in advance of RCC-related work. Technicians should be trained in the proper use of the equipment and in the proper testing procedures. Backup equipment, such as density testing equipment, should also be available.

*Communications*—The engineer and quality control staff should meet with the contractor to review and discuss requirements and procedures for RCC material production, mixing, placement, testing, inspection, and job site safety. Adequate radio communication at the job site among key personnel of the contractor, inspection/quality control organization, and field engineer staff has been responsible for avoiding work stoppages and unnecessary removal of material.

**6.2.3** *Production issues*—Issues that relate to materials and RCC production are as follows:

*Aggregate production*—Sufficient material of acceptable grading and uniform moisture content should be tested and stockpiled prior to starting RCC. Monitoring the temperature within the stockpiles can be useful in case unusually warm or cold ambient conditions develop during RCC production.

*Mixing plant*—The mixing plant layout should provide easy access to aggregate stockpiles and methods of sampling all materials without stopping production. Sampling locations and equipment for cement, pozzolan, aggregates, and concrete should be determined to safely obtain representative materials. All equipment should be properly calibrated and calibrations documented.

*RCC placement plan*—The details of RCC placement should be documented and discussed in detail. The plan should include preparatory operations, materials supply, RCC transportation, spreading, compaction, curing, cleanup, supply, and any other operation that may impact RCC placement. The plan should include a detailed listing of equipment, pertinent characteristics, and crew composition. In many cases, this discussion serves to resolve numerous issues that may not have been extensively addressed in the contract documents.

**6.2.4** *RCC test section and test strips*—One of the primary purposes for a test section is for the contractor to demonstrate equipment and procedures to be used for mixing, handling and placing RCC and conventional concrete, and to prequalify compaction procedures and equipment. It also serves as a training and practice area for both quality control and construction personnel. It is important to recognize that, especially if the section is small or full production equipment is not available, obtaining the same quality as can be expected under full production conditions will be difficult or impractical. A separate test section is preferred over starting immediately on the permanent work because the first placement is typically at a critical section of the structure, at its base. An alternative is to place the test section in a noncritical section of the work, such as foundation replacement material, or as part of the spillway basin or discharge apron.

Typically, the test section is two to four lifts high and includes at least one lift joint requiring joint surface cleanup. The facing system should also be evaluated in the test section. Test section construction should be staged so that numerous operations are not required at the same time. For example, evaluate surface treatments on one lift surface, facing construction on another lift surface, and compaction alternatives on yet another lift surface.

The workability and density of the RCC mixture are evaluated by laboratory testing, and any mixture proportion adjustments can be fine-tuned during construction of the test section. This may include adjusting the water content, cement plus pozzolan content, or fine-coarse aggregate ratio. The test section can also be used to determine field density requirements. Coring, sawing, test trenches, and demolition of the test section with heavy equipment provides a method of evaluating lift-joint quality, a critical feature of RCC dams. Cores representative of the test section mass may be difficult to recover at early ages or with low cementitious content mixtures, or both. To increase core recovery, a number of measures have been successful. They include use of drilling fluids split core barrels, proper drill selection, and cooler installation. Use of a split inner tube core barrel has been found to minimize drilling damage, particularly at lift joints.

A major goal in test section construction is to evaluate the RCC mix performance, (i.e., mix segregation, mix proportions, and compactability). For a number of projects, it has been advantageous to evaluate mixture performance including desired moisture content separately from and in advance of test section construction. This can be done by constructing test strips; placements of approximately one equipment

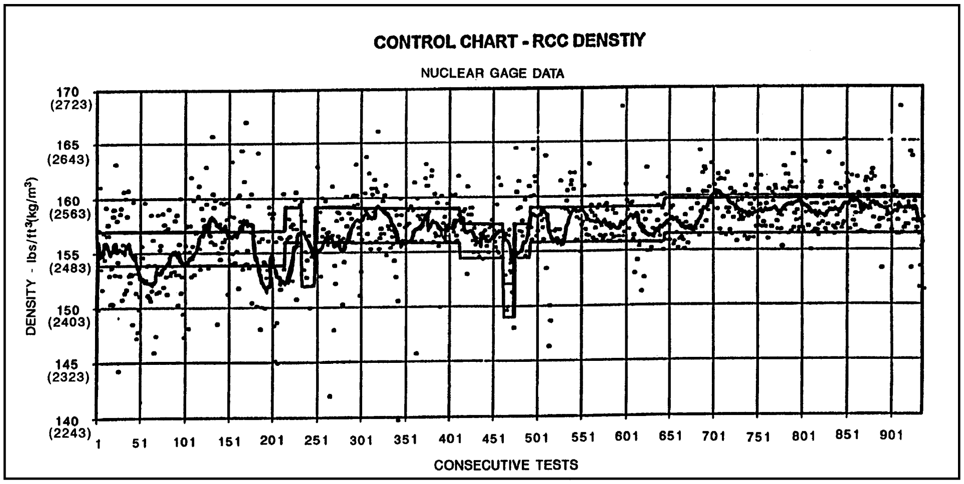


*Fig. 6.1—Typical control chart for consecutive wet density test results.*

width [approximately 10 ft (3 m)] extending 30 ft (10 m) or more in length (approximately two vibratory roller lengths) and not more than two lifts in thickness. The mix is transported from the mixing plant by loader or dump truck, leveled with the specified dozer, and compacted as specified. Field maximum density (density versus roller passes) is measured on the test placements for all the compaction equipment. This operation allows early and independent evaluation of mix handling characteristics and compaction performance and eases later test section activities by reducing test section evaluations to production and placement issues.

**6.2.5** *Determining field density/compaction requirements*—It is common to perform field density tests to establish or verify reasonable density requirements for construction and for comparison with laboratory RCC mixture properties used for design. One approach for technical specifications is to base final field density requirements for the work on density test results during placement of a control section. Later, additional density test sections may be done to establish maximum density performance for the mixture used in RCC production. The following steps illustrate a maximum density determination.

1. Select the location and dimensions of the control section (i.e., 100 ft (30 m) long and at least two roller widths wide).

2. Begin compacting the freshly placed RCC and test after every two passes until the density is no longer increasing, or the increase is less than 0.2 lb/ft$^3$ (3.0 kg/m$^3$).

3. Perform sufficient density tests to verify the maximum density, and determine the validity of specification requirements.

An example of a maximum density control section, as performed for Upper Stillwater Dam, is given in Fig. 6.1.

**6.2.6** *Checking compaction equipment*—Inspection personnel should check compaction equipment for compliance with specification requirements prior to the start of work. If there is reason to believe the equipment is not working properly, the equipment manufacturer should be consulted.

## 6.3—Activities during RCC placement

**6.3.1** *General*—Quality control during RCC placement involves two operations: inspection and testing. Inspection is the first opportunity to observe an RCC problem and institute measures to correct it. In addition to inspection activities, a comprehensive RCC testing program should monitor the aggregate properties, RCC mixture proportions, fresh concrete properties, hardened concrete properties, and in-place compaction. Examples of possible tests and test frequencies are given in Table 6.1. The frequency and extent of testing should be established according to the size of the project, the sensitivity of the design to variations in quality, and the rate of RCC production.

The goal of quality control is to identify problems before they occur or sufficiently early in the process so they can be corrected. Monitoring and reacting to the trend in performance data is preferable to reacting to an individual test result. The trend, identified by a series of tests, is more important than data provided by a single test. By continuously tracking trends, it is possible to identify detrimental changes in material performance and initiate corrective actions. Further, it is possible to modify the frequency of testing based on observed trends. For example, it is common to specify a high frequency of testing during the start of production and to later reduce the testing frequency as production stabilizes.

Tests must be performed, reported, and reviewed rapidly. The rapid placing rates and typical 20 or 24 hr/day construction timetables require careful attention and interaction between testing, inspection, and production personnel. If testing or inspection activities cause significant delays to any stage of RCC production, such as mixing, placing, compacting, or foundation cleanup, all construction may be affected and possibly stopped.

Fresh RCC properties may vary with daily, weekly, or seasonal fluctuations in ambient weather conditions. The variations generally affect water requirements, compaction characteristics during construction, and the quality of the concrete. Normally, construction activities continue throughout a variety of warm, cold, wet, or dry ambient conditions. Quality control personnel should ensure that continuous adjustments in moisture and, if appropriate, other mixture proportions are made to adapt to these conditions. Communication between shifts about these adjustments is also important.

**Table 6.1—Sample quality control test**

| Material tested | Test procedure | Test standards* | Frequency† |
|---|---|---|---|
| Cement | Physical/chemical properties | ASTM C 150 or equivalent | Manufacturer's certification or prequalified |
| Pozzolan | Physical/chemical properties | ASTM C 618 or equivalent | Manufacturer's certification or prequalified |
| Admixtures | — | ASTM C 494<br>ASTM C 260 | Manufacturer's certification |
| Aggregates | Specific gravity—absorption | ASTM C 127<br>ASTM C 128 | 1/month |
| | Grading | ASTM C 117<br>ASTM C 136 | 1/shift or 1/day |
| | Moisture content | ASTM C 566<br>ASTM C 70 | Before each shift/or as required |
| | Flat/long particles | — | 1/month or 10,000 $yd^3$ (7500 $m^3$) |
| | Plasticity of fines | — | 1/month or 10,000 $yd^3$ (7500 $m^3$) |
| RCC | Consistency and density | ASTM C 1170 | 2/shift or as required |
| | In-place density | ASTM C 1040 | 1/hr or every 250 $yd^3$ (200 $m^3$) |
| | In-place moisture (double-probe, nuclear gage only) | ASTM C 1040 | 1/hr or every 250 $yd^3$ (200 $m^3$) |
| | Oven-dry moisture | ASTM C 566 | 1/shift or every 1000 $yd^3$ (750 $m^3$) |
| | Mixture proportions—RCC mix variability | ASTM C 172, C 1078, ASTM C 1079, special | 1/week or every 5000 $yd^3$ (4000 $m^3$) |
| | Temperature | ASTM C 1064 | 1/2 hr or every 500 $yd^3$ (400 $m^3$) |
| | Compressive strength‡ | ASTM C 1176 or tamper | 1/day or every 5000 $yd^3$ (4000 $m^3$) |
| | Split tensile strength‡ | ASTM C 496 | 1/day or every 5000 $yd^3$ (4000 $m^3$) |
| | Elastic modulus‡ | ASTM C 469 | 1/day or every 5000 $yd^3$ (4000 $m^3$) |

*Other appropriate industry standards may be used.
†Frequency shown is example typical of smaller projects and/or thorough agency testing. On larger projects and those with less stringent designs, less frequent testing may be appropriate.
‡Some projects used approach of relying on control during construction to achieve required quality, making few cylinders and taking cores afterward for verification of material properties in situ.

**6.3.2** *Material testing*—All RCC materials should be checked to confirm that they meet the project specification requirements prior to use in the work.

**6.3.2.1** *Cement and pozzolan*—Cement and pozzolan are normally accepted based on manufacturer's certification. Tests may also be performed on grab samples during construction of large projects under their quality assurance program. Government agencies may prequalify sources of cement and pozzolan.

**6.3.2.2** *Admixtures*—Admixtures are normally accepted based on manufacturer's certification.

**6.3.2.3** *Aggregates*—The moisture content and grading of aggregates significantly affects the fresh and hardened properties of RCC. The grading of both sand and coarse aggregate affects workability, and the ability to effectively compact or consolidate RCC. In addition to standard gradation analyses, high-fines mixtures also require testing for Atterberg limits.

The aggregate source, whether a new on-site source or a commercial off-site source, should be inspected and approved in advance.

Sieve analyses are performed during initial processing and stockpiling of aggregates. A sieve analysis should be performed at least once per shift during production.

Varying moisture in stockpiles will result in varying workability of RCC. An increase or decrease in moisture of a few tenths of 1% can change the compacting characteristics of RCC. Samples of aggregate, as batched, should be taken and tested at least once per shift to confirm concrete plant moisture meter readings and to calculate the actual amount of water being used in the RCC mixture.

**6.3.3** *RCC testing*

**6.3.3.1** *General*—A variety of RCC quality control tests have been developed to accommodate the wide range of consistencies, mixture proportions, and aggregate gradings possible with RCC. Some tests are adapted from conventional concrete procedures, while others are adapted from soil cement or earthwork technology. There is no single set of tests that applies to all RCC mixtures and placing operations.

**6.3.3.2** *Consistency tests*—The Vebe[6.2,6.3] or similar apparatus is used to measure the consistency of many RCC

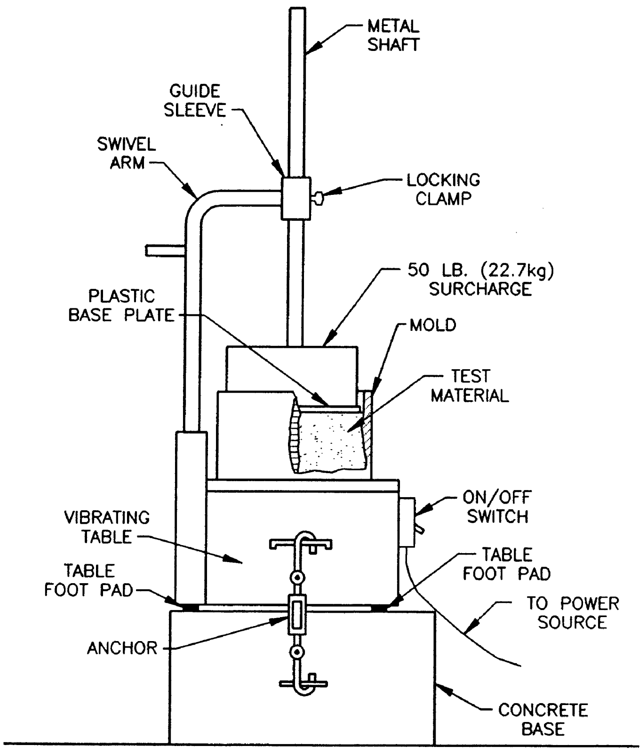


*Fig. 6.2—Vebe consistency apparatus (ASTM C 1170).*

mixtures, but does not provide a measure of consistency for the drier consistency RCC. When it is used for the wetter types of RCC mixtures, typical Vebe times are 10 to 30 sec. The Vebe test takes approximately 15 min to perform after the sample is delivered to the laboratory.

The standard Vebe apparatus for conventional no-slump concrete has been modified for RCC. Fresh RCC is placed in the 1/3 $ft^3$ (9.4 l) cylindrical steel container under a surcharge (Fig. 6.2). The sample is vibrated until it fully consolidates under the surcharge. The Vebe consistency is the time it takes to fully consolidate the sample as indicated by a ring of mortar around the periphery of the surcharge (Fig. 6.3). The density of fresh RCC is determined from the consolidated sample. ASTM C 1170 includes procedures for testing RCC with a 50 lb (22.7 kg) surcharge and without surcharge.

**6.3.3.3** *Density and air voids tests*—The maximum practically achievable density of RCC is measured from fresh samples obtained at the mixing plant or from the placement. The samples are then consolidated or compacted in a field laboratory using the Vebe procedure or one of the compaction methods discussed later.

The density test is used as a method to measure the degree of compaction or air void content. Air voids for both air-entrained and non-air-entrained RCC can be determined by compacting or consolidating the fresh RCC into a standard container and determining the air content by the pressure method.

The in-place wet density of RCC is determined indirectly with a calibrated nuclear density gage. Sand cone and balloon methods of determining density are generally not suitable because of the difficulty and time required to excavate the test hole with undisturbed sides. Two types of apparatus are com-

*Fig. 6.3—Vebe consistency test time with ring of mortar on consolidated sample.*

mercially available for the nuclear test: a single-probe (Fig. 6.4) and a double-probe (Fig. 6.5) nuclear density gage. Testing may take 5 to 15 min, depending on the number of positions that the gage is rotated (for the single probe device), the ease of driving the probe hole, and the number of depths at which densities are checked. In the U.S., the gages must be licensed by the NRC (Nuclear Regulatory Commission) and operators must receive NRC approved training.

Both the single and double-probe gage have limitations due to their design and gage geometry. The single-probe gage can usually measure up to 12 in. (300 mm) depth. The single-probe gage takes the average density of the lift from the bottom of the inserted probe to the top surface. However, the density result is weighted to the more easily compacted top of the lift than the lower portion of the lift, which is more difficult to compact, and can contain segregated material with some RCC mixtures. A 10% drop in density in the bottom 2 in. (50 mm) of the lift may only be recorded as a 1% drop in overall density with the single-probe gage.

The geometry-related problems of the single-probe gage are avoided with the double-probe gage. The density is measured horizontally from the source probe to the detector probe at the same depth. Thus, individual strata can be measured at different depths. The double-probe gage can measure up to 24 in. (600 mm) depth. Though more desirable than the sin-

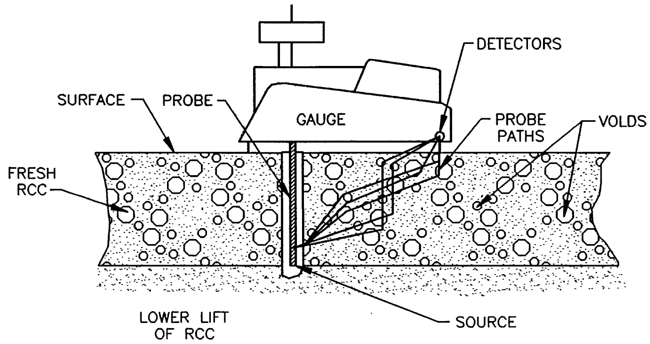


*Fig. 6.4—Single probe nuclear density gage.*

gle-probe gage, the double-probe apparatus is more costly, heavier, and more time consuming to use. A significant difficulty with the double-probe gage occurs if the two pilot holes for the probes are not properly aligned in the RCC. Due to the granular nature of RCC, driving two parallel vertical holes in the RCC is difficult, and proper seating of a double-probe gage requires more attention.

The density measured by nuclear gages is affected by the chemical composition of the concrete constituents and may not be the true density. The gage must be corrected for chemical composition error by determining the true density of fresh RCC compacted to different densities in a rigid calibrated container according to ASTM C 1040 or another acceptable standard, and comparing that density to the density indicated by the gage. When testing RCC mixtures, particularly those with a NMSA greater than 2 in. (50 mm), the probe holes must be driven into the fresh concrete quickly and not disturb the in-place density of the concrete. Voids created by driving the probe through larger size aggregate can give erroneously low density readings.

Density tests using the proposed equipment should be performed as soon as practicable, with consideration for safety and for not interfering with other placing activities. The contractor should be aware that nuclear gages must be attended or secured at all times, typically requiring personnel and a small truck at the test location. The lift may be rerolled if it fails to meet the required density, provided that it has not yet set, nor reached the time allowed prior to completion of compaction. Finish passes with the roller in static mode or with smooth rubber tired equipment may tighten up the top surface prior to testing.

**6.3.3.4** *Moisture/water content tests*—The moisture or water content is important for several reasons: 1) to determine the *w/c* or *w/cm* on projects that may use it in design or as a specification requirement; 2) to ensure the optimum or desired moisture content for workability and compaction; and (3) as use as one of the indicators of mixture uniformity. Some moisture test methods are:

1. Chemical tests (ASTM C 1079);
2. Drying tests (ASTM C 566, ASTM D 4643, and ASTM D 4959); and
3. Nuclear tests (ASTM D 3017).

Chemical and drying tests can be performed on samples obtained either before or after compaction. The samples must be representative of the actual production, particularly with

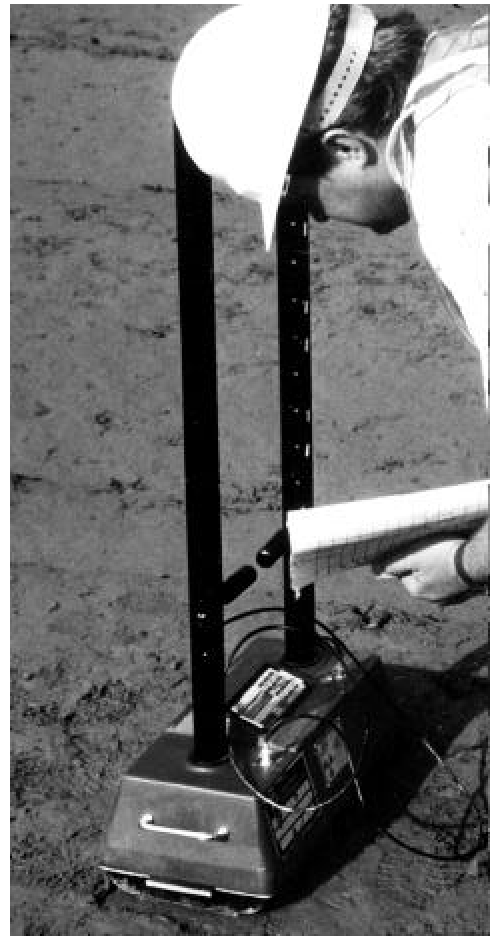

*Fig. 6.5—Double probe nuclear gage.*

respect to the mortar-aggregate ratio and the time the sample is obtained.

1. *Chemical tests*—Two chemical tests are given in ASTM C 1079. Both procedures relate the water content of the concrete to the chloride ion concentration of the test sample either by volumetric titration or calorimetric technique. The methods require calibration for individual mixtures and materials, and recalibration for new reagents. A reasonably clean and constant laboratory environment is recommended for these test procedures. These procedures have not been used to a great extent on RCC projects.

2. *Drying tests*—Drying tests include hot-plate, standard oven, or microwave oven to remove the water from a representative sample. The tests are adapted from soil and aggregate procedures. The test accuracy is affected by both evaporation and chemical hydration of cement. This, in turn, is a function of time, temperature, precipitation and humidity, mixture proportions, and materials properties (grading, absorption, and cement chemistry).

The test result is significantly affected by where and when the sample is obtained. A sample tested directly out of the mixing plant may not produce the same results as a sample tested after being spread and compacted by a roller. Consequently, the location for sampling should be specified. It has become common on some projects to test for moisture at the mixer to obtain an indication of how much water is being added or lost under construction conditions. Hot-plate and oven-dry tests performed by the Bureau of Reclamation with samples obtained and tested immediately after mixing closely compared to the as-batched moisture content. In that set of conditions, samples tested 1 hr after mixing lost approximately one third of the as-batched moisture due to evaporation and hydration. Samples obtained immediately after mixing and sealed to prevent evaporation lost approximately 6% of the as-batched moisture 1 hr after mixing. The sample size for these tests was 10 lb (4.5 kg). Microwave evaporation tests generally are limited to mortar samples due to the potential for exploding aggregate and because large samples are needed to get reasonably accurate results. Large aggregate mixtures may require samples as large as 65 lb (30 kg). The hot-plate and oven-dry tests are the most common, reliable tests used for RCC.

3. *Nuclear test*—When used to determine moisture content, the nuclear gage actually measures hydrogen content, which is in turn related to water content. The gage reading must be adjusted or calibrated for any chemical composition error, similar to the density reading. The result is affected by stratification of moisture in the lift and may change with compaction by rollers or trucks, or from surface moisture changes due to precipitation, curing, or drying.

The nuclear gage moisture content is normally determined on compacted RCC. The single-probe gage tests moisture at the surface (backscatter mode), while the double-probe gage tests moisture at depth with a direct transmission approach. Since the single-probe nuclear gage tests only the near surface moisture content, it is not reliable for determining in-place moisture content. The double-probe gage can test moisture content of RCC at depths ranging from 2 to 24 in. (50 to 600 mm). The moisture content should be computed as the average of the bottom, midpoint, and top of the lift with this gage.

**6.3.3.5** *Determining cement content*—ASTM methods C 1078 and C 1079 can be used to determine the cement and water content of freshly mixed concrete by chemical titration or calcium ion analyzer. The sample size and specifics of sample preparation have been modified to facilitate the procedure with some RCC mixtures.[6.4] The heat of neutralization test (ASTM D 5982) has also been used to determine the cement content of freshly mixed concrete, but it has resulted in problems of high variability and premature solidification of the sample with RCC on some projects. All methods should be calibrated for a given aggregate cement pozzolan, mix water, and admixture. None of these methods is effective for determining the pozzolan content of concrete, and therefore, are rarely used.

**6.3.3.6** *Evaluating RCC mixture proportions*

**6.3.3.6.1** *General*—Evaluating RCC mixture proportions has two main aspects. First is establishing that materials enter the mixer with the desired proportions. Second is evaluating the workability of the RCC and the uniformity (or variability) of the mixture proportions after it leaves the mixer or after it has been placed and compacted. An essential element of quality control is the monitoring of batch weights or proportioning weights during RCC production.

**6.3.3.6.2** *Batch-type plant records and calibration*—Modern batch-type plants with central mixer are relatively straightforward to calibrate and operate. The primary concerns with RCC are matching aggregate feed rates and storage capacities to high production rates, finding the best batching sequence for each mixture, and getting all materials uniformly blended within a reasonable mix time. The combined charging, mixing, discharge, and return time determines the maximum production rate. Mixture proportions are input from manual or computer controls. Batch weights of ingredients should be recorded on a printout for each batch.

**6.3.3.6.3** *Continuous mixing plant records and calibration*—Continuous mix plants are relatively easy to calibrate and operate. Mixture proportions are converted to a continuous feed rate in tons/hr (kg/hr). Materials used for calibration tests are accumulated over a fixed period of time rather than being measured individually for a separate batch. As with batch-type plants, materials may be individually fed into the mixer from separate bins, or they may be accumulated on a common final feed belt. This is determined by whether the mixer has, for example, one belt for all aggregate bins or multiple belts with one for each bin. Calibration with just one belt operating may not apply to the case when the plant is in full operation with all feed belts operating. Weigh belts to provide weight controls rather than volumetric control, and computer printouts, have been used on some RCC projects and are recommended for quality control of this proportioning method. As with batch-type plants, a diversion conveyor belt is recommended to sample RCC at the plant without stopping production. Proper interlocks should be provided to prevent continued plant operation if one belt stops or slows. Also, as with batch-type plants, the continuous proportioning plant should be calibrated at the minimum, average, and maximum production rates expected. During production, it may be necessary to recalibrate the plant following a shutdown or if some unusual change in the mixture is noted.

**6.3.3.6.4** *Mixture variability test*—Variability tests can be used to establish minimum mixture retention times and the effectiveness of the mixer feed procedure for both batch and continuous type mixers. These tests are also used to determine how well and uniformly the RCC is mixed after it has been delivered and spread in the placing area. ASTM C 172, Annex A1 of ASTM C 94, and Corps of Engineers Method CRD C-55 have all been used in modified form to conduct uniformity tests of fresh RCC, and to establish acceptable mixing procedures in the field.

**6.3.3.7** *Temperature*—The temperature of RCC depends on the temperature of concrete ingredients and average ambient conditions. When a maximum or minimum temperature is specified, it usually is determined just prior to or after compaction. The temperature is normally determined by thermometers or thermocouples embedded in the concrete.

**6.3.3.8** Making test specimens—6 in. diameter by 12 in. long (152 by 304 mm) cylinders and other sizes of RCC test specimens should be made using procedures suited to the consistency of the mixture, the maximum aggregate size, and the number of samples to be made before the mixture begins to dry out. Test specimens

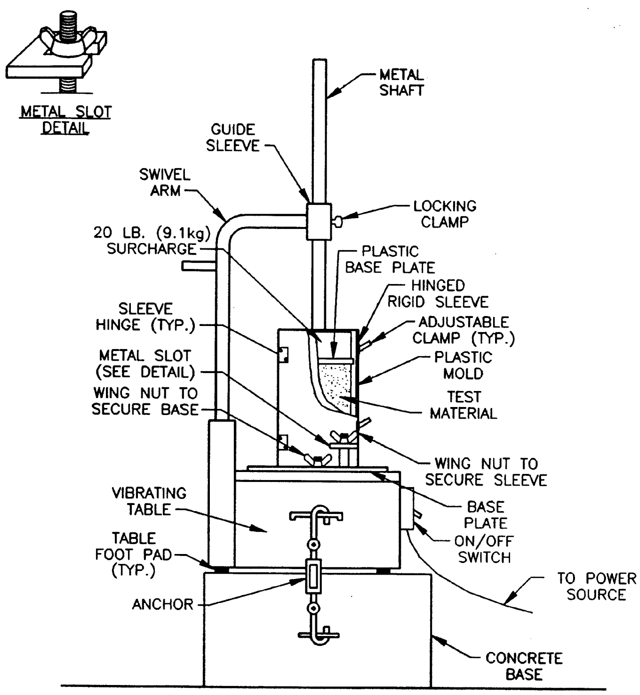


*Fig. 6.6—Device for making RCC test cylinders with modified Vebe apparatus.*

should be compacted in rigid molds or in removable liners supported during compaction by rigid molds. Higher paste content mixtures with a Vebe time less than about 30 sec are suited to consolidation by ASTM C 1176 (Fig. 6.6). This procedure uses a vibrating table similar to the Vebe apparatus and a surcharge weight such as 20 lb (9.1 kg). The RCC is consolidated in three layers. Other surcharges and modifications have also been used.

Mixtures that have Vebe times in excess of approximately 20 sec, or that do not respond at all to the Vebe test can be compacted by procedures using various models of the Hilti or Kango vibrating hammer (Fig. 6.7).[6.5] These hammers have been modified by securing a 5-1/4 in. (133 mm) diameter flat plate on the end, and have become increasingly popular for preparing test specimens. The frequency and amplitude of the vibration approximates that of a vibratory roller. It can be used for RCC of all consistencies. If mortar appears around the plate at less than maximum 15 sec per each of four lifts, the apparatus should be removed from the lift surface. This method does not have an ASTM or other industry standard designation at this time.[6.6]

The modified proctor method of compaction (ASTM D 1557) has also been used. The modified proctor method must be adjusted for use with RCC by changing the lift thickness, and aggregate size from the standard procedure.[6.7] In addition, the compaction hammer tends to fracture aggregates and is slow.

Another cylinder preparation method has consisted of compaction in three layers with a pneumatic tamper similar to an Ingersol Rand model 341 A 2M with a 5-3/4 in. (146 mm) diameter smooth faced tamping foot. This method is typically used for lower cementitious content RCC mixtures.[6.8]

Regardless of the procedure used, it should be capable of compacting the test specimens to density comparable with that achieved with the rollers in the field in a standard manner.

**6.3.3.9** *Strength testing*—RCC strength test specimens may have extremely low early-age compressive strength, which makes handling, stripping, and capping difficult. Some mixtures have compressive strengths of only 200 psi (1.4 MPa) or less at 3 days of age. A procedure that minimizes the problem of handling and storing these cylinders is to compact the specimens in thin or precut metal, or PVC liners that are supported by rigid molds during compaction. The liner then stays on the sample until immediately before it is tested.

Because of the rapid rate of RCC production and the fact that most projects use design ages of 90 days to 1 year, RCC strength tests have limited use as a quality control tool. By the time reliable results indicating a low ultimate strength are available, the project will have progressed well beyond where the questionable material was used or any action can be taken. However, the information obtained from these tests indicates the control maintained on the project and is valuable documentation of the work similar to that performed for conventional concrete dam construction.

The common practice on RCC projects is to cast a set of specimens from every 8-hr shift to one set per every three shifts of production. Compressive-strength tests are usually made at 7, 28, and 90 days. Every third set may include additional specimens for testing at other ages if required. This testing provides a good indication of the level of strength and strength gain of the RCC mixture with time.

The most accurate information on in-place strength can be obtained from cores taken after completion of the project. The number of core tests is usually limited in comparison to the normal number of cast cylinder tests made during the period of construction.

Accelerated curing (ASTM C 684) of cylinders and mortar cubes has been used in an effort to get an earlier indication of ultimate strength potential and variability. Accelerated curing appears to have more potential for success with higher cementitious content mixtures and conventional concrete aggregates, although standard procedures for RCC have not been developed.

**6.3.3.10** *Control charts*—Control charts are one of the most effective methods of tracking, displaying and interpreting quality control test data, and their use should be required by the project specifications. Many quality control tests can be directly input to computers and displayed as real-time information. Nuclear density and moisture tests can be saved in most commercial gages and tests results can be fed into a computer after each shift to give a shift moving average. Control charts should identify representative trends. A sample control chart for aggregate grading is given in Fig. 6.8. Sample control charts for RCC fresh properties are given in Fig. 6.1 and 6.9. Chapter 2 of ACI publication SP-2 contains additional information on this subject.

## 6.4—Activities after RCC placement

**6.4.1** *General*—Quality control after placement should include periodic inspections to ensure that the RCC is being continuously moist cured and properly protected from damage.

*Fig. 6.7—Making RCC test cylinders with vibrating hammer.*

**6.4.2** *Curing RCC*—Quality control records should be maintained which document the time and extent of curing, and action should be taken to correct deficiencies when observed.

**6.4.3** *Protecting RCC*—Quality control personnel should ensure that the contractor has protected the RCC surface from freezing, drying, or precipitation. When required RCC should be covered quickly with plastic or insulating mats to reduce evaporation or protect the surface from rain, dust, snow, and freezing temperatures. If rain is imminent or starting, inspectors should make sure that the contractor completes compaction of uncompacted RCC and immediately covers the RCC surfaces to prevent damage.

## CHAPTER 7—GENERAL REFERENCES AND INFORMATION SOURCES

### 7.1—General

The standards and test methods of the American Society for Testing and Materials (ASTM), the U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (USBR), and American Concrete Institute (ACI) that are applicable to

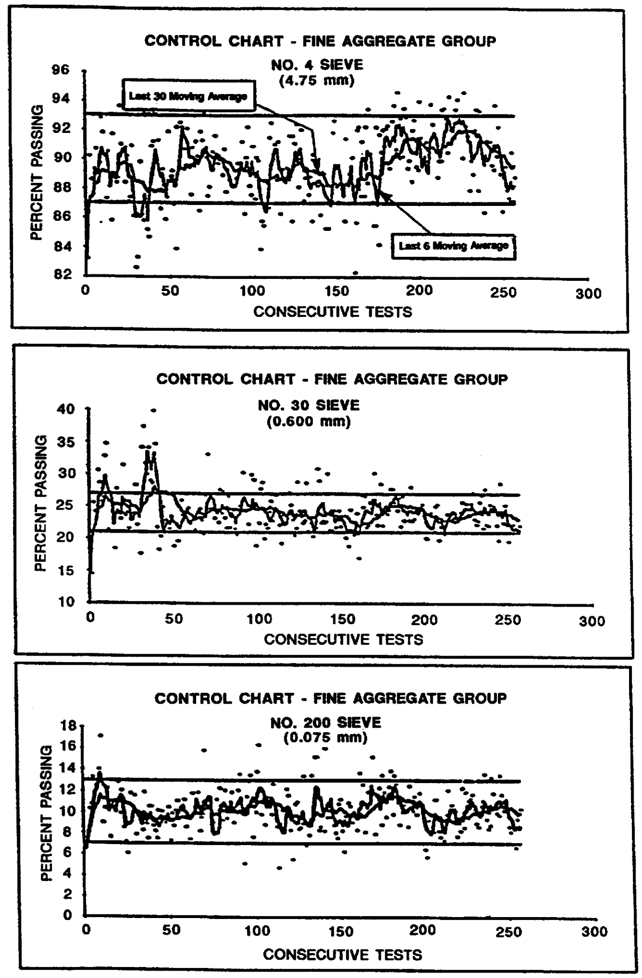


*Fig. 6.8—Typical control charts for tracking fine aggregate grading results by selected individual sieves.*

materials and properties referred to in this report are listed below with their serial designation.

### 7.2—ASTM standards

| | |
|---|---|
| C 33 | Specification for Concrete Aggregates |
| C 94 | Specification for Ready-Mixed Concrete |
| C 150 | Specification for Portland Cement |
| C 172 | Practice for Sampling Freshly Mixed Concrete |
| C 260 | Specification for Air-Entraining Admixtures for Concrete |
| C 494 | Specification for Chemical Admixtures for Concrete |
| C 512 | Test Method for Creep of Concrete in Compression |
| C 618 | Specification for Fly Ash and Raw or Calcine Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete |
| C 666 | Test Method for Resistance of Concrete to Rapid Freezing and Thawing |
| C 684 | Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens |
| C1040 | Test Methods for Density of Unhardened and Hardened Concrete In Place by Nuclear Methods. |
| C 1078 | Test Method for Determining Cement Content of Freshly Mixed Concrete |

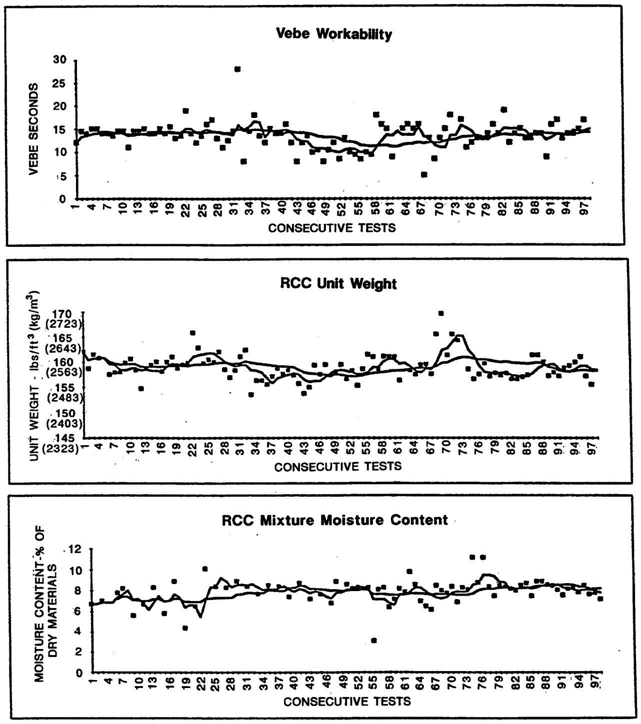


*Fig. 6.9—Typical control charts for consecutive test of Vebe; unit weight, and moisture content.*

C 1079 Testing Methods for Determining Water Content of Freshly Mixed Concrete
C 1138 Test Method for Abrasion Resistance of Concrete (Underwater Method)
C 1170 Test Methods for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
C 1176 Test Method for Casting No Slump Concrete in Cylinder Molds Using Vibratory Table
C 1557 Test Methods for Moisture-Density Relations of Soils and Soil Aggregate Mixtures Using 10 lb (4.54 kg) Rammer and 18 in. (457 mm) Drop
D 5982 Test Method for Determining Cement Content Soil-Cement (Heat of Neutralization Method)

## 7.3—U.S. Army Corps of Engineers test procedures

CRD-C 36 Method of Test for Thermal Diffusivity of Concrete
CRD-C 39 Test Method for Coefficient of Linear Thermal Expansion of Concrete
CRD-C 44 Method for Calculation of Thermal Conductivity of Concrete
CRD-C 48 Method of Test for Water Permeability of Concrete
CRD-C 53 Test Method for Consistency of No-Slump Concrete Using the Modified Vebe Apparatus
CRD-C 55 Test Method for Within—Batch Uniformity of Freshly Mixed Concrete
CRD-C 71 Test Method for Ultimate Tensile Strain Capacity of Concrete
CRD-C 89 Method of Test for Longitudinal Shear Strength, Unconfined, Single Plane

## 7.4—U.S. Bureau of Reclamation test procedures

4909 Thermal Diffusivity of Concrete
4910 Coefficient of Thermal Expansion of Concrete
4911 Temperature Rise of Concrete
4913 Water Permeability of Concrete
4914 Direct Tensile Strength, Static Modulus of Elasticity, and Poisson's Ratio of Cylindrical Concrete Specimens in Tension
4915 Direct Shear of Cylindrical Concrete Specimens

## 7.5—ACI references

116 Cement and Concrete Terminology
201.2R Guide to Durable Concrete
207.1R Mass Concrete for Dams and Other Massive Structures
207.2R Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete
207.4R Cooling and Insulating Systems for Mass Concrete
211.3R Standard Practice for Selecting Proportions for No-Slump Concrete
221R Guide for Use of Normal Weight Aggregates in Concrete
304R Guide for Measuring, Mixing, Transporting and Placing Concrete
304.4R Placing Concrete with Belt Conveyors
305R Hot Weather Concreting
306R Cold Weather Concreting
308 Standard Practice for Curing Concrete
325.1R Roller-Compacted Concrete Pavements
SP-2 Manual of Concrete Inspection

The previously mentioned publications may be obtained from the following organizations:

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

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

U.S. Army Corps of Engineers Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

U.S. Bureau of Reclamation
Denver Federal Center
Denver, CO 80225

## 7.6—Gravity dam design references

"Design Criteria for Concrete Arch and Gravity Dams," *Engineering Monograph* No. 19, U.S. Bureau of Reclamation, Denver, Feb. 1977.

"Design of Gravity Dams," U.S. Bureau of Reclamation, Denver, 1976, 553 pp.

"Earthquake Analysis and Design of Concrete Gravity Dams," *Engineer Technical Letter* (ETL) 1110-2-303, U.S. Army Corps of Engineers, Washington, D.C., Aug. 1985.

"Earthquake Design and Analysis for Corps of Engineers Projects," *Engineer Regulation* No. 1110-2-1806, U.S. Army Corps of Engineers, Washington, D.C., May 1983.

"Engineering Guidelines for Evaluation of Hydropower Projects," Federal Energy Regulatory Commission, Washington, D.C., Feb. 1993.

*Handbook of Dam Engineering*, A. R. Golze, ed., Van Nostrand Reinhold Co., New York, 1977.

"Gravity Dam Design," *Engineer Manual* No. 1110-2-2200, U.S. Army Corps of Engineers, Washington, D.C., June 1995.

Jansen, Robert B., *Advanced Dam Engineering*, Van Nostrand Reinhold Co., New York, 1988.

"Roller-Compacted Concrete," *Engineer Manual* No. 1110-2-2006, U.S. Army Corps of Engineers, Washington, D.C., Feb. 1992.

"Seismic Design Provisions for RCC Dams," *Draft* ETL 1110-2-8025, U.S. Army Corps of Engineers, Washington, D.C., May 1993.

"Sliding Stability for Concrete Structures," *Engineer Technical Letter* No. 1110-2-256, U.S. Army Corps of Engineers, Washington, D.C., June 1981.

"Standard Practice for Concrete for Civil Works Structures," *Engineer Manual* No. 1110-2-2000, U.S. Army Corps of Engineers, Washington, D.C., Feb. 1994.

"Seismic Analysis of Concrete Dams—Volume C4," *Report* 420-G-547, *Safety Assessment of Existing Dams for Earthquake Conditions*, Canadian Electrical Association, Montreal, Canada, Apr. 1990.

"Structural Design of Spillway and Outlet Works," *Engineer Manual* No. 1110-2-2400, U.S. Army Corps of Engineers, Washington, D.C., Nov. 1964.

## 7.7—References cited in text

*Chapter 1*

1.1. "Annotated Bibliography on Roller-Compacted Concrete Dams," U.S. Committee on Large Dams, Denver, Co., June 1994.

1.2. "Concrete Gravity Dam Built Like Earthfill," *Engineering News-Record*, V. 173, Dec. 24, 1964, p. 32.

1.3. Gentile, G., "Study, Preparation, and Placement of Low Cement Concrete, with Special Regard to its use in Solid Gravity Dams," Transactions, International Congress on Large Dams, R16 Q 30, International Commission on Large Dams (ICOLD), Paris, France, 1964.

1.4. Wallingford, V. M., "Proposed New Technique for Construction of Concrete Gravity Dams," *Transactions*, 10th International Congress on Large Dams, Montreal, Quebec, Canada, 1970; International Commission on Large Dams (ICOLD), Paris, V. 4, pp. 439-452.

1.5. Humphreys, T. D.; Jardine, F. M.; and Nash, J. K., "The Economic and Physical Feasibility of Soil-Cement Dams," *6th International Conference on Soil Mechanics and Foundation Engineering*, Canada, V. II, 1965.

1.6. Raphael, J. M., "The Optimum Gravity Dam," *Rapid Construction of Concrete Dams*, ASCE, New York, 1971, pp. 221-247.

1.7. Cannon, R. W., "Concrete Dam Construction Using Earth Compaction Methods," *Economical Construction of Concrete Dams*, ASCE, New York, 1972, pp. 143-152.

1.8. Cannon, R. W., "Concrete Dam Construction Using Earth Compaction Methods," *Economical Construction of Concrete Dams*, ASCE, New York, 1972, pp. 143-152.

1.9. Tynes, W. O., "Feasibility Study of No-Slump Concrete for Mass Concrete Construction," *Miscellaneous Paper* No. C-73-10, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Oct. 1973, 29 pp.

1.10. Hall, D. J., and Houghton, D. L., "Roller-Compacted Concrete Studies at Lost Creek Dam," U.S. Army Engineer District, Portland, Ore., June 1974.

1.11. Sivley, W. E., "Zintel Canyon Optimum Gravity Dam," *Transactions*, 12th International Congress on Large Dams, Mexico City, 1976; Dams, France V. 5., pp. 141-145.

1.12. Johnson, H. A. and Chao, P. C., "Rollcrete Usage at Tarbela Dam," *Concrete International*, V. 1, No. 11, Nov. 1979, pp. 20-33.

1.13. Dunstan, M. R. H., *Rolled Concrete—With Particular Reference to Its Use as Hearting Material in Concrete Dams*, The Concrete Society, London, Mar. 1978.

1.14. Dunstan, M. R. H., "Rolled Concrete for Dams— Laboratory Study of Properties of High Fly Ash Content Concrete," *CIRIA Technical Note* 105, London, May 1981, 96 pp.

1.15. Dunstan, M. R. H., "Rolled Concrete for Dams—Construction Trials Using High Fly Ash Content Concrete," *CIRIA Technical Note* 106, London, May 1981, 94 pp.

1.16. Hirose, T., and Yanagida, T., "Some Experiences Gained in Construction of Shimajigawa and Okawa Dams," *Proceedings*, CIRIA Conference on Rolled Concrete for Dams, Construction Industry Research and Information Association, London, June 1981.

1.17. Chugoku Regional Construction Bureau, *Construction of Shimajigawa Dam with Roller-Compacted Dam Concrete*, Ministry of Construction, Japan, 1981.

1.18. Schrader, E. K., and Thayer, H. J., "Willow Creek Dam—A Roller-Compacted Concrete Fill," *Transactions*, 14th International Congress on Large Dams, Rio de Janeiro, 1982; International Commission on Large Dams (ICOLD), Paris, V. 4, pp. 453-479.

1.19. *Development in Japan of Concrete Dam Construction by RCD Method*, Japan Ministry of Construction, Tokyo, 1984.

1.20. Schrader, E. K., "The First Concrete Gravity Dam Designed and Built for Roller-Compacted Construction Methods," *Concrete International*, V. 5, No. 10, Oct. 1982, pp. 16-24.

1.21. Schrader, E. K., and McKinnon, R., "Construction of Willow Creek Dam," *Concrete International*, V. 6, No. 5, May 1984, pp. 38-45.

1.22. Oliverson, J. E., and Richardson, A. T., "Upper Stillwater Dam—Design and Construction Concepts," *Concrete International*, V. 6, No. 5, May 1984, pp. 20-28.

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

1.24. McTavish, R. F., "Construction of Upper Stillwater Dam," *Roller-Compacted Concrete II*, ASCE, New York, Feb. 1988, pp. 267-276.

1.25. Arnold, T. E., and Johnson, D. L., "RCC Dam Design Concepts Versus Construction Conditions for Stagecoach Dam," *Roller-Compacted Concrete III*, ASCE, New York, Feb. 1992, pp. 291-307.

1.26. Hopman, D. R., "Lessons Learned from Elk Creek Dam," *Roller-Compacted Concrete III*, ASCE, New York, Feb. 1992, pp. 162-180.

1.27. Hollingworth, F.; Druyts, F. H. W. H; and Maartens, W. W., "Some South African Experiences in Design and Construction of Rollcrete Dams," *16th International Congress on Large Dams*, San Francisco, June 1988; International Commission on Large Dams (ICOLD), V. III, Q62, pp. 33-51.

1.28. Hansen, K. D., and Reinhardt, W. G., *Roller-Compacted Concrete Dams*, McGraw Hill, New York, 1991.

1.29. Hansen, K. D., "RCC for Rehabilitation of Dams in USA—An Overview," *Roller-Compacted Concrete III*, ASCE, New York, Feb. 1992, pp. 22-46.

1.30. McDonald, J. E., and Curtis, N. F., "Applications of Roller-Compacted Concrete in Rehabilitation and Replacement of Hydraulic Structures," *Technical Report* REMR-CS-53, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., Apr. 1997, 184 pp.

1.31. "RCC Dam Survives Texas Flood," *ENR*, Apr. 27, 1986.

1.32. Giovagnoli, M.; Schrader, E.; and Ercoli, F., "Design and Construction of Concepcion Dam," *Proceedings*, International Symposium on RCC Dams, Beijing, Nov. 1991.

<u>*Chapter 2*</u>

2.1. "Willow Creek Dam Concrete Report," U.S. Army Corps of Engineers, Walla Walla, Wash., Oct. 1984, V. 1-2.

2.2. Crow, R. et al., "Mix Design Investigation—Roller-Compacted Concrete Construction, Upper Stillwater Dam, Utah," *USBR Report* REC-ERC-84-15, June 1984.

2.3. Gaekel, L., and Schrader, E. K., "RCC Mixes and Properties Using Poor Quality Materials—Concepcion Dam," *Roller-Compacted Concrete III*, ASCE, New York, 1992.

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

2.5. *Concrete Manual*, U.S. Department of Interior, 8th Edition, 1981, p. 574.

2.6. Tatro, S. B., and Hinds, J. L., "Roller-Compacted Concrete Mix Design," *Roller-Compacted Concrete III*, ASCE, New York, 1992, pp. 323-340.

2.7. "Engineering and Design, Roller-Compacted Concrete," *Engineer Manual* No. 1110-2-2006, U.S. Army Corps of Engineers, Washington, D.C., Feb. 1992.

2.8. Dunstan, M. R. H., "A Method of Design for Mix Proportions of Roller-Compacted Concrete to Be Used in Dams," *Transactions*, 15th International Congress on Large Dams, International Commission on Large Dams (ICOLD), Paris, V. 2, pp. 713-738.

2.9. Dolen, T. P., "Mixture Proportioning Concepts and Quality Control for RCC Dams," *International Symposium on Roller-Compacted Concrete for Dams,* Beijing, Nov. 1991, pp. 440-447.

2.10. "Technical Guide to RCD Construction Method," Technical Center for National Land Development, Japan, July 1981.

2.11. Reeves, G. N., and Yates, L. B., "Simplified Design and Construction Control for Roller-Compacted Concrete," *Roller-Compacted Concrete*, New York, 1985, pp. 48-61.

<u>*Chapter 3*</u>

3.1. Schrader, E. K., "Roller-Compacted Concrete for Dams, State of the Art," *International Conference on Advances in Concrete Technology*, Athens, Greece; 2nd Edition, CANMET, Ottawa, Canada, 1994.

3.2. U.S. Bureau of Reclamation, "Design and Analysis of Auburn Dam," *Dynamic Studies*, V. 4, Denver, Colo., Apr. 1978.

3.3. Clough, R. W., and Zienkiewicz, O. C., "Finite Element Methods in Analysis and Design of Dams—Part C," *Criteria and Assumptions for Numerical Analysis of Dams*, Proceedings of International Symposium, Swansea, UK, Sept. 1975.

3.4. Lindvall, Richter and Associates, *Final Report for Investigation and Reanalysis of Big Tujunga Dam*, V. 2, Los Angeles, Calif., Oct. 1975.

3.5. "Laboratory Testing Program to Evaluate Physical Properties of Auburn Dam Design Concrete Mix for Rapid Strain Rates—Central Valley Project, California," *Memorandum* from Chief, Dam Branch to Chief, Concrete and Structural Branch, USBR, Denver, Colo., Aug. 29, 1977.

3.6. Raphael, J. M., "Tensile Strength of Concrete," ACI JOURNAL, *Proceedings* V. 81, No. 2, Mar.-Apr. 1984, pp. 158-165.

3.7. Soroushian, P.; Choi, K.-B.; and Abdulazig, A., "Dynamic Constitutive Behavior of Concrete," ACI JOURNAL, *Proceedings* V. 83, No. 2, Mar.-Apr. 1986, pp. 251-259.

3.8. Mlakar, P. F.; Vitaya-Udom, K. P.; and Cole, R. A., "Dynamic Tensile-Compressive Behavior of Concrete," ACI JOURNAL, *Proceedings* V. 82, No. 4, July-Aug. 1985, pp. 484-491.

3.9. Omoregie, F. A.; Gutschow, R. A.; and Russell, M. L., "Cement-Hardened Materials for Abrasion-Erosion in Hydraulic Structures," *Concrete International*, V. 16, No. 7, July 1994, pp. 47-50.

3.10. Dolen, T. P., "Freezing and Thawing Durability of Roller-Compacted Concrete," *Durability of Concrete*, Second CANMET/ACI International Conference, SP-126, V. M. Malhotra, ed., V. 1, American Concrete Institute, Farmington Hills, Mich., 1991, pp. 101-114.

<u>*Chapter 4*</u>

4.1. Tarbox, G. S., and Hansen, K. D., "Planning, Design, and Cost Estimates for RCC Dams," *Roller-Compacted Concrete II*, ASCE, New York, Feb. 1988, pp. 21-38.

4.2. "Roller-Compacted Concrete for Dams," *Report* AP-4715, Electric Power Research Institute (EPRI), Palo Alto, Calif., Sept. 1986.

4.3. McLean, F. G., and Pierce, J. S., "Comparison of Joint Strengths for Conventional and Roller-Compacted Concrete," *Roller-Compacted Concrete II*, ASCE, New York, Feb., 1988, pp. 151-169.

4.4. Boggs, H. L., and Richardson, A. T., "USBR Design Considerations for Roller-Compacted Concrete Dams," *Roller-Compacted Concrete*, ASCE, New York, 1985, pp. 123-140.

4.5. Tayabji, S. D., and A. S. Okamoto, "Bonding of Successive Layers of Roller-Compacted Concrete," Construction Technology Laboratories, Skokie, Ill., 1987.

4.6. Tatro, S. B., and Schrader, E. K., "Thermal Considerations for Roller-Compacted Concrete," ACI JOURNAL, *Proceedings* V. 82, No. 2, Mar.-Apr. 1985, pp. 119-128.

4.7. Ditchey, E., and Schrader, E. K., "Monksville Dam Temperature Studies," *16th International Congress on Large Dams*, San Francisco, June 1988, International Commission on Large Dams (ICOLD), V. III, Q62, pp. 379-396.

4.8. Tatro, S. B. and Schrader, E. K., "Thermal Analysis for RCC—A Practical Approach," *Roller-Compacted Concrete III*, ASCE, New York, 1992, pp. 389-406.

4.9. Schrader, E. K., "Design and Facing Options for RCC on Various Foundations," *Water Power & Dam Construction*, Sutton, Surrey, UK, Feb. 1993.

4.10. Schrader, E. K., "Watertightness and Seepage Control in Roller-Compacted Concrete Dams," *Roller-Compacted Concrete*, ASCE, New York, May 1985, pp. 11-30.

4.11. Campbell, D. B., and Johnson, P. C., "RCC Dam Incorporates Innovative Hydraulic Features," *Proceedings*, Conference on Water for Resource Development, Hydraulics Division, ASCE, Coeur d'Alene, Idaho, 1984, pp. 138-142.

4.12. Parent, W. F.; Moler, W. A.; and Southard, R. W., "Construction of Middle Fork Dam," *Roller-Compacted Concrete*, ASCE, New York, 1985, pp. 71-89.

Chapter 5

5.1. Schrader, E. K., "Design for Strength Variability: Testing and Effects on Cracking in RCC and Conventional Concretes," *Lewis Tuthill Symposium on Concrete and Concrete Construction*, SP-104, G. T. Halvorsen, ed., American Concrete Institute, Farmington Hills, Mich.,1987, pp. 1-25.

5.2. Schrader, E. K., and Namikas, D., "Performance of Roller-Compacted Concrete Dams," *16th International Congress on Large Dams*, San Francisco, June 1988, International Commission on Large Dams (ICOLD), V. III, Q62, pp. 339-364.

5.3. Schrader, E. K., "Roller-Compacted Concrete for Dams, State of the Art," *International Conference on Advances in Concrete Technology*, Athens, Greece; 2nd Edition, CANMET, Ottawa, Canada, 1994.

5.4. Hopman, D. R., and Chambers, D. R., "Construction of Elk Creek Dam," *Roller-Compacted Concrete II*, ASCE, New York, Feb. 1988, pp. 251-266.

5.5. Cannon, R. W., "An Entrained Roller-Compacted Concrete," *Concrete International*, V. 15, No. 5, May 1993, pp. 49-54.

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

5.7. Dolen, T. P., and Tayabji, S. D., "Bond Strength of Roller-Compacted Concrete," *Roller-Compacted Concrete II*, ASCE, New York, Feb. 1988, pp. 170-186.

5.8. Schrader, E. K., "Permeability and Seepage Control in Roller-Compacted Concrete Dams," *Roller-Compacted Concrete*, ASCE, New York, May 1985, pp. 11-30.

5.9. Schrader, E. K., "Design and Facing Options for RCC on Various Foundations," *Water Power & Dam Construction*, Sutton, Surrey, UK, Feb. 1993.

5.10. Jansen, R. B., *Advanced Dam Engineering for Design, Construction, and Rehabilitation*, Van Nostrand Reinhold, New York, 1989.

Chapter 6

6.1. "Guidelines for Designing and Constructing Roller-Compacted Concrete Dams," *ACER Technical Memorandum* No. 8, U.S. Bureau of Reclamation, Denver, 1987.

6.2. "Engineering and Design, Roller-Compacted Concrete," *Engineering Manual* No. 1110-2-2006, U.S. Army Corps of Engineers, Washington, D.C., Feb. 1992.

6.3. Dolen, T. P., "Mixture Proportioning Concepts and Quality Control for RCC Dams," *International Symposium on Roller-Compacted Concrete for Dams*, Beijing, Nov. 1991, pp. 440-447.

6.4. Cannon, R. W., "Compaction of Mass Concrete with Vibratory Roller," ACI JOURNAL, *Proceedings* V. 71, No. 10, Oct. 1974, pp. 506-513.

6.5. British Standard Institute, BS 1924, "Stabilized Materials for Civil Engineering Purposes."

6.6. Schrader, E. K., "Design for Strength Variability: Testing and Effects on Cracking in RCC and Conventional Concretes," *Lewis Tuthill Symposium on Concrete and Concrete Construction*, SP-104, American Concrete Institute, Farmington Hills, Mich.,1987, pp. 1-25.

6.7. Arnold, T. E.; Feldsher, T. D.; and Hansen, K. D., "RCC Test Specimen Preparation—Developments Toward Standard Method," *Roller-Compacted Concrete III*, ASCE, New York, 1992, pp. 341-357.

6.8. Schrader, E. K., "Compaction of Roller-Compacted Concrete," *Consolidation of Concrete*, SP-96, S. H. Gebler, ed., American Concrete Institute, Farmington Hills, Mich., 1987, pp. 77-101.