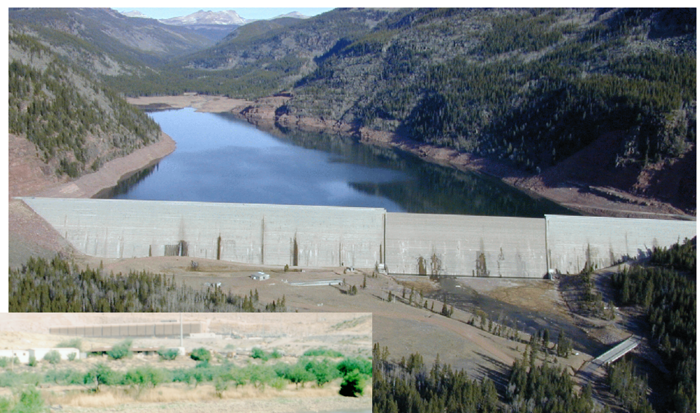
RECLAMATION
Managing Water in the West

Roller-Compacted Concrete

Design and Construction Considerations for Hydraulic Structures



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

2005

On the cover (clockwise from left): A roller-compacted concrete (RCC) buttress for Camp Dyer Diversion Dam, Arizona, a masonry gravity dam (left). Aerial view of Upper Stillwater Dam, Utah, the first RCC gravity dam constructed by the Bureau of Reclamation (top). An RCC chute that replaced the spillway at Cold Springs Dam in Oregon (bottom).

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Preface

Since the design and construction of Upper Stillwater Dam in the 1980s, the Bureau of Reclamation (Reclamation), has used roller-compacted concrete (RCC) for a wide variety of applications, including stability buttresses for masonry gravity and concrete arch dams, overtopping protection and upstream slope protection for embankment dams, new gravity dams, new spillways and spillway stilling basins, tailrace dikes, and overflow weirs.

This manual provides guidelines for the design and construction of various types of dams and hydraulic structures using RCC, based largely on the experience gained by Reclamation engineers from RCC projects completed over the past 20 years. The information provided herein is intended to illustrate the importance and versatility of RCC as both a material and a construction method, and can serve as a starting point for the design of hydraulic structures using RCC. However, this information is basic and is not intended to serve as a comprehensive design guide.

The information is organized as follows: definition of RCC and scope of the manual (chapter 1); background information, including history, philosophy, and practical uses of RCC (chapter 2); discussion of RCC materials (chapter 3); design requirements for RCC mixtures, including RCC properties and mixture proportioning procedures (chapter 4); construction methods, from batching through final testing (chapter 5); design considerations for new RCC gravity dams (chapter 6) and for RCC buttresses for concrete dam modifications (chapter 7); design applications for embankment dams, including overtopping protection, upstream slope protection, water barrier, and replacement structures (chapter 8); other design applications for RCC (chapter 9); and case histories that illustrate the design, construction, and performance of a variety of RCC projects (chapter 10). Appendices are included that contain guide specifications for RCC construction (appendix A), test procedures for RCC (appendix B), a summary of RCC costs (appendix C), and samples of adiabatic temperature rise tests of roller-compacted concrete (appendix D).

The authors of this manual (in alphabetical order) are Tim Dolen, Tom Hepler, Dan Mares, Larry Nuss, Doug Stanton, and John Trojanowski. Elizabeth Cohen and Chuck Cooper provided additional information for the case histories. Betty Chavira prepared the RCC guide specifications. John LaBoon provided peer review. The technical editor for this manual was Lelon A. Lewis.

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Chapter 1

Definition and Scope

These guidelines pertain to the design and construction of various types of dams and hydraulic structures using roller-compacted concrete (RCC), including:

- Concrete dams
- Spillways
- Downstream buttresses for existing concrete and masonry dams
- Overtopping protection for existing embankment dams
- Upstream slope protection for existing embankment dams
- Overflow weirs
- Erosion protection for stilling basins, channels, and canals
- Dikes and cofferdams
- Gravity retaining walls
- Hydraulic structure foundations

RCC can be considered as both a construction material and a construction method. RCC is generally defined as a no-slump concrete that is placed by earth-moving equipment and compacted by vibrating rollers in horizontal lifts up to 12 inches thick (Reclamation, 1987). RCC differs from soil-cement, which uses similar placing methods, because it normally contains coarse aggregates greater than ¾ inches in maximum size and develops material properties similar to those of conventional concrete. Soil-cement generally uses pit-run sand and develops lower strengths than RCC, and the mixes tend to be less consistent, primarily due to the variability in fines content (Hansen and Reinhardt, 1991).

These guidelines do not include RCC applications for structures other than those normally associated with dams and hydraulic structures. Much of these guidelines has been influenced by experience gained in the design and construction of various RCC structures by the Bureau of Reclamation (Reclamation), as well as by RCC dam construction sponsored under the Small Reclamation Projects Loan Program. Case histories of Reclamation projects are included for various structural applications:

- New gravity dams—Upper Stillwater Dam (without joints) and Clear Lake Dam (with joints)
- New spillways—Cold Springs Dam and Many Farms Dam
- Downstream buttresses—Camp Dyer Diversion Dam (straight) and Santa Cruz Dam (curved)
- Overtopping protection for embankment dams—Vesuvius Dam
- Upstream slope protection—Jackson Lake Dam
- Erosion protection—Ochoco Dam (spillway basin)
- Hydraulic structure foundation and buttress—Pueblo Dam spillway

This document is not intended to be a comprehensive guide to the design and construction of RCC hydraulic structures. It is to be used by experienced engineers, and it is the engineer's responsibility to use good engineering judgement in applying the information provided herein. Reclamation will not accept any responsibility or liability for the use of these guidelines.

1.1 References.—

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

Hansen, Kenneth D., and William G. Reinhardt, *Roller-Compacted Concrete Dams*, McGraw-Hill, Inc., 1991.

Chapter 2

Background

2.1 History of RCC development.—A steady decline in the construction of concrete gravity dams following World War II coincided with new soil mechanics technology and an increasing popularity of embankment dams. Earth and rockfill embankments could be built more cheaply than concrete dams in wide valley sites, primarily due to the greater efficiency of earth-moving equipment and embankment construction methods. The dam-building community began searching for a new type of dam that combined the efficiencies of embankment dam construction with the reduced cross-section and potential public safety advantages of concrete dams (Hansen and Reinhardt, 1991).

An early form of RCC, termed "rollcrete," was used to provide the central impervious core for an earthfill embankment cofferdam for Shihmen Dam, in Taiwan, in 1960. A concrete gravity dam was first constructed of lean concrete placed in horizontal lifts, using earth-moving equipment, at Alpe Gera Dam, in Italy, in 1964, although consolidation was by internal immersion vibration rather than by roller compaction. Vibratory rollers were first used to compact soil-cement in lifts for the Barney M. Davis reservoir dike, in Texas, in 1971. High production rates for placing roller-compacted concrete were first achieved for the tunnel repairs at Tarbela Dam, in Pakistan, in 1975 (Chao and Johnson, 1979).

RCC dam design began evolving in three different directions in the 1970s. The Army Corps of Engineers and others in the United States were developing a lean-concrete alternative with high nonplastic fines, culminating in the construction of Willow Creek Dam, in Oregon, in 1982 (USACE, 1984). Meanwhile, British engineers were developing a high-paste alternative, which combined a conventional concrete mix design with earthfill dam construction methods (Dunstan, 1978). Extensive laboratory research and field testing in England resulted in the development of a low-cement, high-pozzolan content concrete, and a laser-guided horizontal slipforming system for facing elements, which became the basis for the design of Upper Stillwater Dam, in Utah, by Reclamation in 1983. Japanese engineers took a similar approach with cast-in-place concrete facing, termed the roller-compacted dam (RCD) method, to achieve the same quality and appearance of conventional mass concrete, which resulted in placement of RCC for the main body of Shimajigawa Dam, in Japan, from 1978 to 1980 (Kokubu, 1984).

Other early, notable developments in RCC construction include the first use of precast concrete panels and an attached polyvinyl chloride (PVC) membrane to provide an impervious upstream face at Winchester Dam, in Kentucky, in 1984; and the erosion resistance of exposed RCC demonstrated by sustained overtopping of Kerrville Ponding Dam, in Texas, in 1985 (Hansen and Reinhardt, 1991). Reclamation began experimenting with the introduction of entrained air in RCC for the downstream buttresses at Santa Cruz and Camp Dyer Diversion Dams between 1988 and 1992.

2.2 Design philosophy.—Two distinct philosophies have emerged with respect to RCC mix design methods—the concrete approach and the soils (or geotechnical) approach. RCC mixtures using concrete design methods generally have a more fluid consistency and are more workable than those developed using the soils approach, although both philosophies will produce a no-slump concrete. The concrete approach considers RCC to be a true concrete, composed of sound and clean, well graded aggregates, whose strength, when fully consolidated, is inversely proportional to its water-cement ratio. The soils approach considers RCC to be a cement-enriched, processed soil, whose mix design is based on moisture-density relationships, using the principles of Proctor compaction. For a specified aggregate and cementitious materials content, an "optimum moisture content" is determined for a compactive effort corresponding to that applied by vibratory rollers in the field, to achieve a maximum dry density. Water contents above or below optimum would produce a lower dry density for a given compactive effort, and therefore a reduced compressive strength. Aggregate materials specified using the soils approach are typically pit-run, with a fines content (passing the No. 200 sieve) up to 10 percent, and with particle-to-particle contact resulting in significant voids in the mixture (Hansen and Reinhardt, 1991).

With all other factors being constant, RCC mixes using the concrete approach will typically have a wetter consistency and a higher paste content than RCC mixes using the soils approach. High-paste mixes (greater than 20 percent cementitious materials, by weight) usually provide higher bond strengths at horizontal lifts (with cohesion values typically greater than 200 lb/in^2), and reduced potential for permeability along lift lines due to excess paste, which are both very desirable characteristics for concrete dam design (Hansen and Reinhardt, 1991).

At this time, there remains no consensus procedure for RCC mixture proportioning within the dam engineering profession. Major differences still exist as to the preferred composition, consistency, and methods used for batching, mixing, transporting, placing, and compacting RCC. Many of these differences may be related to site-specific conditions. However, original mixtures compacted near optimum moisture in dams are now being specified wet of optimum about ½ to 1 percent to reduce segregation. RCC designs are strongly influenced by material availability (particularly with respect to aggregate properties), but are also influenced by local climatic conditions (such as freeze-thaw potential), size and purpose of the structure, and strength requirements (Reclamation, 1987). Massive RCC structures may employ two different mixes, with a richer mix used for external surfaces for improved durability and abrasion resistance, and a leaner mix used within the internal body where stresses are low and durability requirements are minimal. Severe freeze-thaw conditions may require the use of conventional, air-entrained concrete on exposed surfaces, or overbuilding the RCC beyond the design lines to serve as a sacrificial zone to accommodate future deterioration. A zone of conventional concrete may also be used at the upstream face to increase the watertightness of the structure, and where exposed to high velocity flow to minimize potential cavitation or abrasion damage concerns. RCC dam construction and production rates are strongly influenced by contractors' selection of equipment for batching, mixing, and transporting RCC. There is a relationship between the selected construction methodology and the RCC properties, particularly at lift lines.

Both philosophies relating to RCC mix design are being used by Reclamation on various projects, and are included in these guidelines. RCC mixes using the concrete approach have generally been used by Reclamation for RCC dam and spillway construction, whereas the soils approach has generally been used for embankment dam facings and for structure foundations.

2.3 Practical uses of RCC.—The use of high capacity placing and compaction equipment for RCC construction has resulted in the ability in many cases to place larger volumes of RCC at a lower overall cost, when compared to conventional mass concrete dams with a narrower cross section and a smaller volume. Furthermore, for dam rehabilitation projects, the cost of constructing spillways and embankment overtopping protection using layered, stepped, RCC construction techniques may be less expensive than constructing conventional, reinforced concrete overlays. The reduced overall durability of the RCC overlay can be compensated for in these cases by the addition of a "sacrificial" surface of RCC resulting from overbuilding the structure cross section.

RCC dams offer similar hydraulic advantages as for conventional concrete dams, when compared to embankment dams, in terms of spillway and outlet works designs. The smaller cross section of an RCC dam can result in a shorter and more economical outlet works conduit, and the vertical upstream face can provide a gated intake for multilevel release capability without the need for a separate intake tower and access bridge. Spillway release capacity for the passage of flood flows can be provided by allowing a portion of the RCC dam to overtop, rather than requiring the construction of a separate reinforced concrete spillway structure on one or both abutments. Overtopping studies of RCC dams resulted in the development and refinement of the stepped spillway, for which a significant portion of the energy dissipation (approaching 60 percent or more) is provided by the stepped downstream face of the dam itself, reducing the design requirements for a downstream stilling basin. The ability of RCC dams to overtop safely may also provide an important advantage during construction by improving the available diversion capacity and thereby reducing the risk of failure.

Other potential advantages of RCC dams compared to embankment dams include a smaller footprint (possibly resulting in less environmental impact), singular material construction (compared to zoned embankments or concrete-faced rockfill dams), and virtual elimination of erosion and piping concerns (when founded on competent bedrock). An RCC dam was selected for the modification of Clear Lake Dam, in California, over several embankment dam alternatives for these primary reasons.

As with conventional concrete dams, RCC dams are normally founded on firm bedrock and are therefore less likely to be selected at dam sites where the bedrock is weak or is overlain by thick deposits of soil. An embankment dam with a concrete cutoff wall was selected for New Waddell Dam, in Arizona, over an RCC dam alternative primarily due to the large depth to bedrock at the dam site.

2.4 References.—

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

Chao, P.C., and H.A. Johnson, "Rollcrete Usage at Tarbela Dam, *Concrete International: Design and Construction*, Vol. 1, No. 11, November 1979.

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

Hansen, Kenneth D., and William G. Reinhardt, *Roller-Compacted Concrete Dams*, McGraw-Hill, Inc., 1991.

Kokubu, M., *Development in Japan of Concrete Dam Construction by the RCD Method*, Technical Lecture at 52nd ICOLD Executive Meeting, Tokyo, 1984.

U.S. Army Corps of Engineers, *Willow Creek Dam Concrete Report*, Vols. 1 and 2, Walla Walla, Washington, October 1984.

Chapter 3

RCC Materials

The materials used for RCC are much the same as those used in conventional mass concrete and include water, cementitious materials (cement and pozzolan), admixtures, and fine and coarse aggregates.

All RCC materials should meet minimum quality specifications requirements before construction begins. For small structures, materials may be accepted based on the manufacturer's certification. Larger structures may require stockpiling and pretesting of materials at the point of manufacture for acceptance before shipment to the job site, to keep up with the high output necessary to maintain production.

3.1 Water.—Mix water for RCC should be free from objectionable quantities of silt, organic matter, salts, and other impurities. Specifications commonly limit the soluble sulfate content to 3,000 parts per million. Wash water is not acceptable for use in RCC. Ice used in mix water to reduce the mixture temperature of RCC should be made from water meeting these requirements.

3.2 Cementitious materials.—Cementitious materials include cement and pozzolan and should conform to ASTM (or other standard) quality requirements. In the United States, cement and pozzolan are normally accepted based on the manufacturer's certification. Grab samples should be obtained regularly during construction for chemical and physical requirements as specified by ASTM C 150 (Portland cement) and C 618 (pozzolan) (ASTM, 2004).

a. *Cement*.—Specific requirements that may affect selection of the appropriate cement for RCC include the cement type, heat-of-hydration limits, alkali content, and the design age for the concrete. Cement should meet the requirements of ASTM C 150, *Specifications for Portland Cement*. The different cement types are based on both physical requirements and chemical properties and include:

- *Type I*.—Normal strength gain and chemical resistance, not normally used in Reclamation concrete construction due to inadequate sulfate resistance

- *Type II*.—Moderate strength gain and moderate sulfate resistance, the most common cement type used for Reclamation construction

- *Type III*.—Rapid strength gain for special applications, not normally used in Reclamation concrete construction due to inadequate sulfate resistance

- *Type IV*.—Slow strength gain and low heat of hydration, not normally used due to lack of availability and increased use of Type II cement plus pozzolan as a substitute

- *Type V*.—Moderate strength gain and severe sulfate resistance, used for severe sulfate exposure conditions

- *Type I/II*.—Meets strength gain requirements for Type I and moderate sulfate resistance requirements of Type II, becoming more common in the western United States

- *Type IP*.—A preblended cement plus pozzolan, also being used as a substitute for Type I or Type II (depending on its chemical resistance)

Type II (moderate sulfate resistance) cement should be used for most RCC applications, including the optional requirements for low-alkali content and the low heat-of-hydration requirement for mass structures. Type I/II cement will not likely meet the optional low-heat requirements of a Type II cement for mass RCC. Type IP cements are also being introduced and include about 10 to 20 percent pozzolan, by mass of cement plus pozzolan premixed with the cement. This cement may be used to avoid separate batching silos at the job site. Type V cement should be used in high-sulfate durability environments, or a Type II cement plus a sulfate-resisting pozzolan may be substituted in many applications. Very severe sulfate environments will still require a Type V cement or a Type V cement plus pozzolan.

b. *Pozzolan.*—Pozzolan should meet the requirements of ASTM C 618 *Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan as a Mineral Admixture in Concrete*. ASTM C 618 classifies pozzolans in three categories:

1. *Class N*.—Raw or calcined natural pozzolan
2. *Class F*.—Coal fly ash produced from burning anthracite and bituminous coal, a low-calcium fly ash
3. *Class C*.—Coal fly ash produced from burning lignite or sub-bituminous coal, a high-calcium fly ash

Physical and chemical requirements that affect pozzolan quality include fineness (percent retained on the No. 325 sieve) and loss on ignition (LOI), which are indicators of the reactivity and unburned coal content of the ash; alkali content, an indicator of alkali-silica resistance; and R Factor, an indicator of relative sulfate resistance. Most RCC structures in the United States have used Class F pozzolan, because it reduces the cost of cementitious materials, increases the RCC mixture workability, reduces the rate of and total heat generation, and normally resists both alkali-silica reaction and sulfate attack. Some RCC mixtures have used Class C pozzolans; however, there is some concern over the potential for changes in setting time, strength development, and decreased sulfate resistance of these high-calcium fly ashes, and they must be pretested before use. Many RCC mixtures contain equal quantities of cement and pozzolan. Pozzolan is considered a cementitious material, rather than a mineral admixture, since the quality of pozzolan can significantly affect the quality of the hardened concrete.

Pozzolan reactivity influences the long term strength gain of RCC mixtures. Increases in coarse particles (higher percent retained on the No. 325 sieve) have been correlated to decreases in strength of RCC at Upper Stillwater Dam (Dolen, 2003).

3.3 Admixtures.—RCC mixtures have used both chemical water-reducing admixtures (WRAs) and air-entraining admixtures (AEAs). Admixtures should conform to ASTM specifications, including ASTM C 494, *Standard Specifications for Chemical Admixtures for Concrete*, and ASTM C 260, *Standard Specifications for Air-Entraining Admixtures for Concrete*. Admixtures are normally accepted based on manufacturer's certification. The dosage rate of WRAs and AEAs for RCC is not substantially different than for mixtures using conventional concrete quality aggregates and gradings.

a. *Chemical water-reducing admixtures*.—ASTM classifies WRAs in five types, depending on their use for water reduction (Type A) and as an accelerator (Types C and E) or retarder (Types B and D). WRAs have been used at higher dosage rates with varying success for mixtures using high percentages of silt or clay fines in aggregates. Both Type A (water reducing) and Type D (water reducing and retarding) chemical admixtures have been used in mass RCC mixtures. These admixtures increase RCC workability at a given water content, and Type B or D WRAs have set-retarding characteristics, particularly when used with Class F pozzolans. The dosage rate of WRAs may also depend on the cement to pozzolan ratio, mixture workability, and aggregate grading. Mixtures using high pozzolan contents may exhibit prolonged delay (up to 36 hr) in setting when combined with low concrete temperatures and Type B or D WRAs.

b. *Air-entraining admixtures.*—Reclamation has successfully used AEAs to increase the freezing and thawing resistance of RCC. Use of an AEA at Santa Cruz Dam increased the freeze-thaw durability of the RCC by about four times compared to the non-AEA mixture. AEAs can also increase the workability of RCC for a given water content. To be effective, AEAs should be used with RCC mixtures having a Vebe consistency of about 20 seconds or less and use clean, well graded concrete sand. AEAs are not normally effective for RCC mixtures that use high fines contents in aggregates. The total air content of RCC can be tested using a pressure air meter clamped to the Vebe vibrating table. The total air content for

RCC can be reduced about 1 percent compared to conventional concrete, due to the lower paste volume of RCC mixtures, without adversely affecting the freeze-thaw durability and workability of the mixture.

3.4 Aggregates.—The grading and quality of aggregates significantly affects the properties of fresh and hardened RCC. The grading affects the total void ratio, the mixture workability, and the ability to effectively compact or consolidate RCC. Aggregates used for RCC range from fully processed concrete aggregates meeting ASTM grading and quality requirements to minimally processed, unwashed pit-run aggregates.

Fine aggregate should generally consist of natural sand, or natural sand supplemented with crushed sand to make up for any deficiencies in the natural sand gradings. Sand particles should be predominantly cubical and free from flat and elongated particles. Coarse aggregate should generally consist of natural gravel or crushed rock, or a mixture of natural gravel and crushed rock with a minimum of 50 percent crushed rock, and uniformly blended. Crusher fines should generally not be used in the production of RCC aggregates unless approved.

Much has been made in the past decade regarding the use of lesser quality aggregates in RCC construction, particularly with respect to using “all-in” single gradings and aggregate gradings incorporating unwashed crusher fines or pit run, nonplastic fines. The purpose of including aggregate fines is to lower the void ratio of the aggregate and to reduce processing costs. Reducing the void ratio of aggregates can reduce the volume of paste required to fill the voids, thus lowering the cementitious materials content and cost. A drawback caused by including fines is caused by coatings reducing the paste-aggregate bond and clay fines that increase the water demand, thus decreasing strength. Another common cost savings practice is to use either a combined sand plus coarse aggregate grading, or one sand and one coarse aggregate. This reduces cost, but at the expense of flexibility when proportioning the sand or coarse aggregate ratios.

Aggregate physical properties tests should be completed before RCC mixture proportioning and, the aggregate source should be approved prior to beginning construction. For small jobs, locally available sources should be inspected and approved before being used in RCC. As a minimum, fine and coarse aggregate should conform to the quality and grading requirements of ASTM C 33, *Concrete Aggregates*. If additional “fines” are included in the aggregates, the specifier should document the need for such use and the physical properties requirements for the material.

a. *Aggregate grading*.—Fine aggregate should meet the grading requirements of ASTM C 33, Section 6, *Grading*, and Section 7, *Deleterious Substances*, including Table 1, *Limits for Deleterious Substances in Fine Aggregate for Concrete*. It should be noted that the percent limits for material passing the 75-µm (No. 200) sieve is a weight percentage of the sand, not of the total aggregate.

Coarse aggregate should meet the grading requirements of ASTM C 33, Section 10. *Grading* and Section 11. *Deleterious Substances*, including Tables 2 and 3. Most mass RCC mixtures will have a nominal, maximum size aggregate (NMSA) of 1½ or 2 inches. The ASTM C 33 grading requirements recommended are size numbers 4 (1½ to ¾ in.) and 67 (¾ in. to No. 4) for a 1½-inch NMSA and size numbers 3 (2 to 1 in.) and 57 (1 in. to No. 4) for a 2-inch NMSA, respectively. This normally is accomplished with two separate stockpiles. If a single stockpile is needed, a 1- or 1½-inch NMSA is suggested. This will require a size number 57 (1-in. to No. 4) or size number 467 (1½-in. to No. 4) grading. Segregation of coarse aggregate in a single stockpile can be a problem, as was observed at Ochoco Dam using a single stockpile with the number 467 grading.

Typical average gradings from four projects using ASTM C 33 aggregates and from five projects using high “fines” are shown in figure 1. The percent passing the No. 4 sieve is virtually identical for both gradings, and is about 7 percent higher than used in conventional concrete mixtures. This higher sand content is needed to reduce the segregation potential of RCC mixtures. The notable difference between the two gradings is the high percentage passing the No. 200 (75-µm) sieve. The “high-fines” grading has normally been associated with mixtures having low compressive strength requirements (less than about 2,000 lb/in^2) and/or low workability with no measurable consistency. The fines are primarily added to fill voids normally occupied by paste. However, they do not contribute to strength gain,

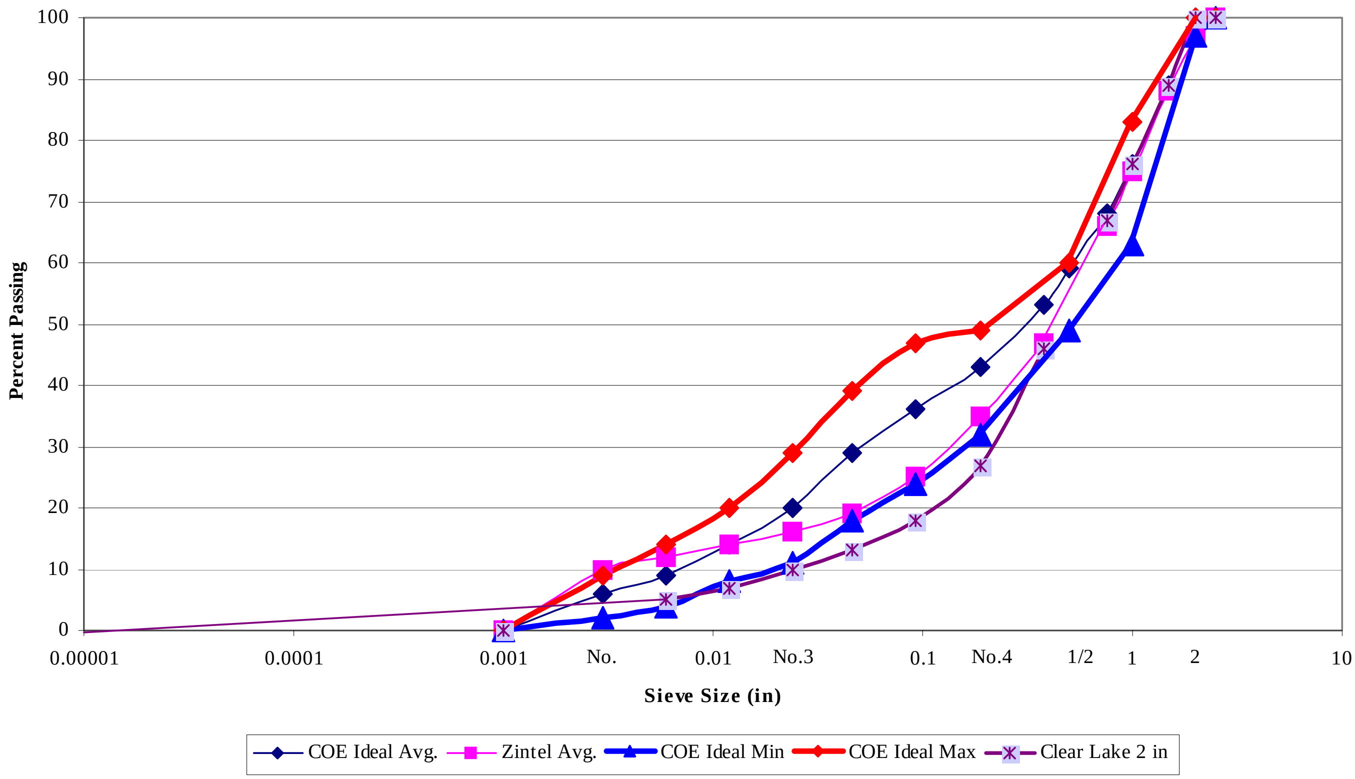

Figure 1.—Average gradation for various projects.

but may increase the density of fully compacted mixtures. Clay fines can lower strength and increase the water demand of RCC mixtures and decrease durability.

b. *Aggregate quality*.—Quality requirements for fine and coarse aggregate are given in ASTM C 33. Of particular concern is the soundness of fine and coarse aggregate, and the abrasion resistance of coarse aggregate. With RCC mixtures, poor quality aggregates may break down under the more severe mixing, transporting, placing, and compacting conditions. The breakdown of aggregates will require increased lift surface cleanup and preparation, and may decrease strength.

c. *Aggregate production, stockpiling, and testing*.—Moisture content and grading tests are initially performed during processing and stockpiling of aggregates. These tests should be performed at least once per shift during production. Final acceptance is normally based on samples as batched during RCC production. Aggregate rescreening is normally required at the batch plant for Reclamation concrete construction. The purpose of rescreening aggregate is to remove oversize and undersize particles resulting from breakdown during stockpiling and handling, to wash dust coatings or contaminants from the aggregates, and to obtain consistent moisture contents.

It is important to produce sufficient aggregates at a stable moisture condition to accommodate high RCC production rates. Since RCC mixtures have a lower water content than for conventional mass concrete, the moisture content of the aggregates may affect both the workability of the mixture and the ability to cool the mixture effectively. Varying moisture contents in stockpiles will result in varying the workability of RCC. A 10-lb/yd^3 increase or decrease in moisture can significantly change the compaction characteristics of RCC. During warm weather, overly wet stockpiles due to sprinkling will limit the available water that may be batched as ice, and thus may require more expensive cooling methods, such as liquid nitrogen injection (as used for Upper Stillwater Dam and for Camp Dyer Diversion Dam Modification).

3.5 References.—

ASTM International, *Annual Book of ASTM Standards*, West Conshohocken, Pennsylvania, 2004.

Dolen, Timothy P., *Long-Term Performance of Roller Compacted Concrete at Upper Stillwater Dam, Utah, U.S.A.*, Proceedings of the International RCC Symposium, Madrid, Spain, November, 2003.

Chapter 4

RCC Mixture Design Requirements

Proportioning RCC mixtures involves optimizing the materials based on both the performance criteria and the relative cost of the mixture. The materials and proportioning methods used has depended in part on the philosophy of considering RCC as either a concrete material modified for the placing methods, or as a cement-stabilized fill material having concrete-like properties. Though the philosophy and methods of proportioning RCC mixtures have been subject to much debate, the behavior of RCC and fundamental relationships governing the workability of fresh concrete, and the strength, elastic properties, and durability of hardened concrete has not changed. What has changed in the past decade of RCC construction is (1) the ability to economically place and compact a wider range of mixtures with soils/asphalt placing and compaction equipment in lieu of traditional concrete placing equipment, and (2) the willingness to accept nontraditional performance parameters in the end product, due in part to the substantially reduced cost of RCC over traditional concrete construction.

The mixture design requirements for RCC dams and hydraulic structures include a number of interrelated and sometimes conflicting properties. These include strength requirements for normal, unusual, and extreme loading conditions, thermal properties of mass concrete, durability requirements, and constructability issues. Strength requirements should address compressive strength, tensile strength, bond (shear and tension) strength, and associated elastic properties and creep effects. Thermal properties may particularly impact cracking of massive structures. The amount of cracking will be a function of the temperature rise generated by the mixture due to heat of hydration, the initial placing temperature of the RCC, the rate and amount of cooling experienced at the site, and elasticity/creep effects. The temperature rise of RCC is a function of both the total cementitious materials content of the mixture and the cement to pozzolan ratio. Durability requirements include the freeze-thaw resistance of the RCC, chemical resistance to alkali-silica reaction and sulfate attack, and abrasion/erosion resistance.

Constructability issues can affect the ability to achieve many design requirements. For example, the bond strength of RCC is extremely dependent on the construction process, including lift line cleanup and treatment, the rate of placement, compaction achieved, and ambient weather conditions. Projects which do not include shear or tensile bond strength requirements in the design may require little or no consideration for lift line cleanup procedures. RCC dams do not include embedded cooling pipes as used for conventional mass concrete dams, and thus the cementitious materials content and placing temperatures directly impact thermal cracking. RCC can be placed at double or triple the rates of conventional mass concrete, and the ability to effectively and economically cool (or heat) the concrete at these high placing rates is somewhat limited. Massive RCC structures should therefore include provisions for crack control by incorporating contraction joints, as described in chapter 6.

The water content of RCC mixtures is about 10 to 20 percent less than for most mass concrete mixtures, which limits the amount of ice that can be added to cool the concrete. Most RCC is not air entrained, but may be protected from freeze-thaw action with different facing schemes using conventional or precast concrete. The construction of the facing system should be designed to not interfere with the planned rate of RCC placement. Typical maximum rates of vertical rise in dams are about 2 ft/day using slipformed facing systems and 3 to 4 ft/day using precast or conventional forming systems. Long crest lengths may reduce the rate of placing formed facing systems. The minimum placing width for RCC construction is generally determined by the width of the equipment traveling and safely passing. This generally limits RCC dams to a minimum crest width of about 20 feet, and

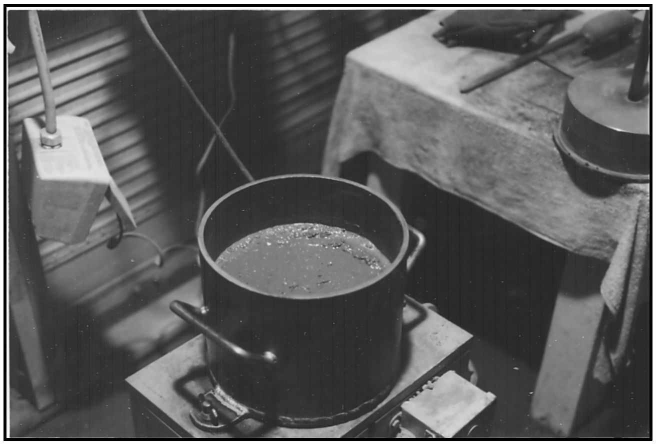

Figure 2.—Consolidated Vebe sample.

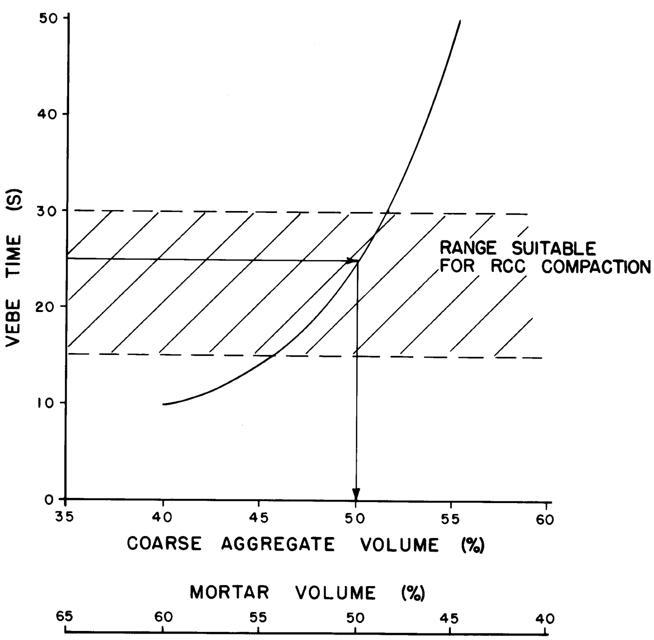

Figure 3.—Range of Vebe consistency time suitable for compaction in a 1-ft lift with a vibrating roller based on crushed aggregate.

requires a minimum width of about 8 to 10 feet for overtopping protection. Any further narrowing of the placement will slow construction and can lead to lift surface contamination from equipment moving on and off of the placement. Unformed RCC facing is normally limited to a slope of 0.8 to 1.0 (horizontal to vertical) or flatter to ensure slope stability during placement.

4.1 Properties of fresh RCC.—RCC mixtures should be proportioned to meet the design requirements for both fresh and hardened concrete properties. Properties of fresh RCC primarily affect the ability to effectively compact the full lift and thus achieve the necessary hardened properties.

a. *Vebe consistency*.—Vebe consistency is an indicator of the workability of RCC and is determined by ASTM C 1170, *Standard Test Method for Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table*. In this test, a sample of RCC is vibrated under a 50-pound surcharge until it is fully consolidated as shown in figure 2. The time required to consolidate the sample is a function of the relative workability of the RCC and is called the Vebe time. The lower the Vebe time or consistency, the easier it is to compact the sample. The typical range of consistency shown in figure 3 for RCC mixtures using the concrete approach is from about 10 to 60 seconds, with most RCC mixtures having a Vebe consistency of less than 30 seconds. RCC mixtures with a Vebe time in the range of 15 to 20 seconds will have a sufficient workability to consolidate in 12-inch lifts with approximately 4 to 8 passes of a 10-ton dual-drum vibrating roller. Segregation will also be minimized at this consistency range.

The Vebe consistency test for RCC basically replaces the slump test used for conventional and mass concrete. The Vebe consistometer, shown in figure 4, has been the most common vibrating table used for this test. A change in water content, sand content, cementitious materials, or entrained air will change the consistency as shown in figures 5 and 6. A 10-lb/yd^3 change in water content or a 5-percent change in sand content can change the Vebe time by approximately 10 to 15 seconds.

b. *Segregation potential*.—The most important property of fresh RCC is a mixture with minimum segregation. Segregation of large, coarse aggregate leads to poor bond between subsequent lifts of RCC and may result in excessive seepage between lifts. Segregation is most often caused by too dry a mixture and poor handling and placing techniques. Mixtures with a Vebe consistency less than 20 seconds generally have less segregation than those with a higher consistency. Mixtures compacted near optimum moisture in dams are now being specified wet of optimum to reduce segregation about ½ to 1 percent.

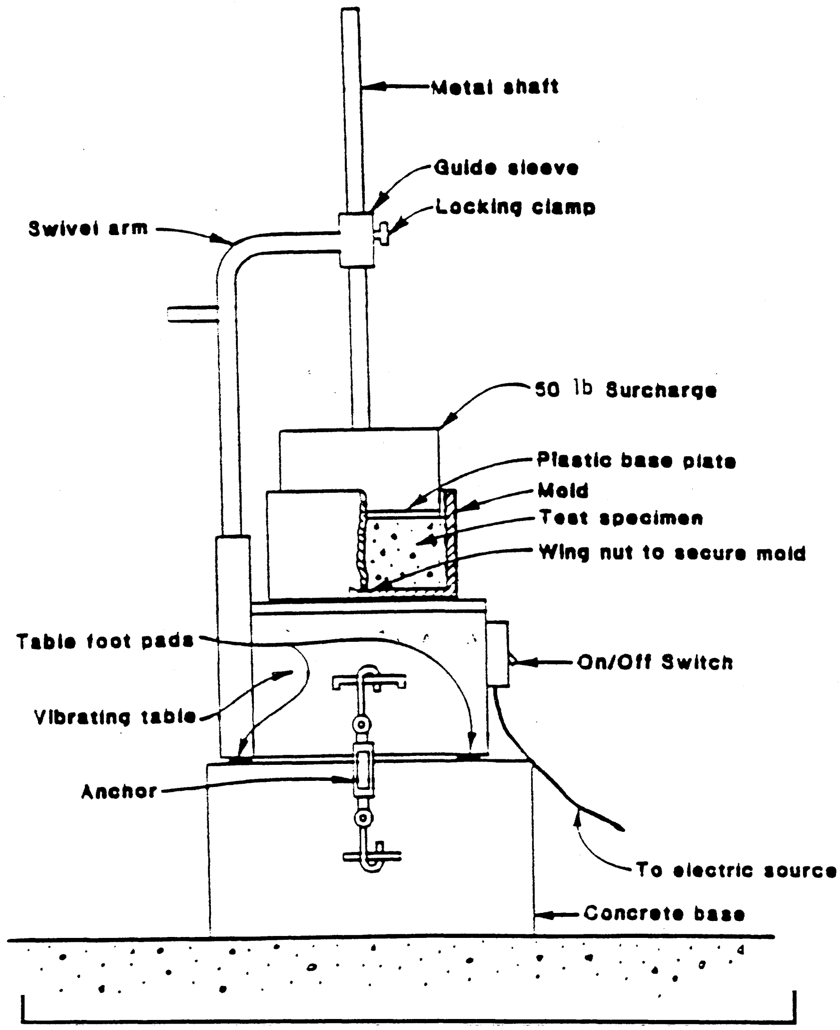

Figure 4.—Vebe equipment.

c. *Temperature*.—The placement temperature of fresh RCC will influence the mixture workability, the setting time of the RCC, and the stiffness of the lift surface, and can influence the bond potential between lifts. Lower placing temperatures, combined with a water-reducing admixture (WRA) and high pozzolan contents, can delay the initial set of fresh RCC up to 36 hours.

d. *Density*.—The density and volume of voids of fresh RCC will influence the performance of the hardened concrete. The density of the materials and the degree of consolidation govern the density of RCC. The density of RCC is normally assumed at about 150 lb/ft^3 without entrained air and with the volume of voids between 0.5 and 1.5 percent. If a lift of RCC is not fully consolidated, the percent voids along lift joints may reach 5 to 10 percent, resulting in seepage and poor bonding. Recent projects constructed by Reclamation have shown it is possible to entrain air in RCC. This slightly lowers the density to about 145 lb/ft^3, but significantly increases the freeze-thaw resistance. The water content of RCC was reduced approximately 5 percent, and the average consistency time was lowered 15 seconds for air-entrained mixtures proportioned for the proposed Milltown Hill Dam in Oregon, compared to RCC mixtures without air entrainment.

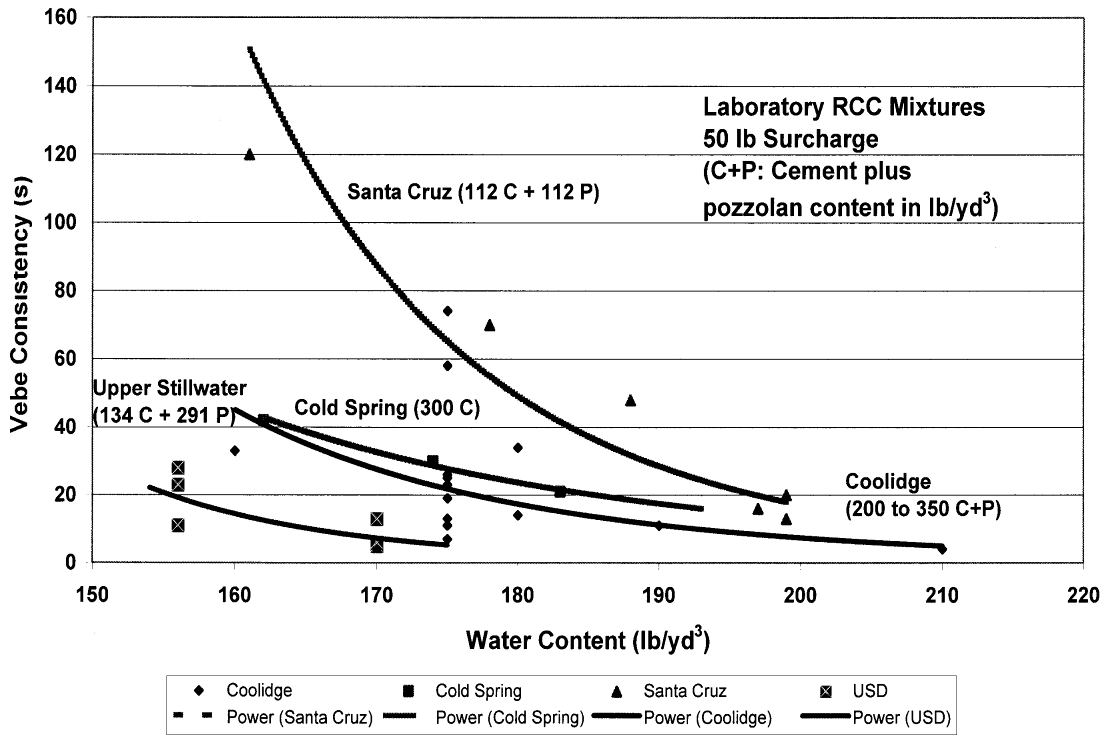

Figure 5.—Water content versus Vebe consistency.

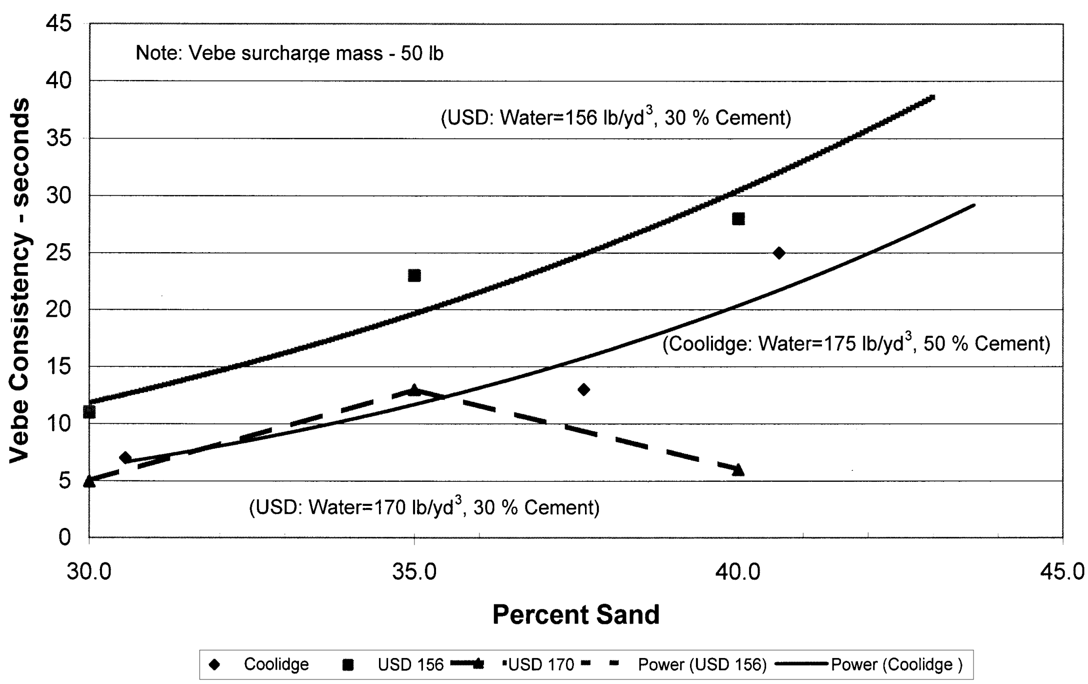

Figure 6.—Percent sand versus Vebe consistency.

4.2 Properties of hardened RCC.—RCC mixtures should be proportioned to meet strength and elastic properties for design loading conditions, to minimize thermally induced loadings causing cracking, and to meet durability requirements related to site conditions. Of primary importance in RCC mixture proportioning is the balance between providing the necessary cement plus pozzolan (C+P) content to meet design strength and durability requirements, while minimizing the C+P content to reduce the temperature rise and its associated thermal shrinkage cracking potential.

a. *Compressive strength and elastic properties*.— The design compressive strength is normally specified for most RCC structures. Though it may not be the governing design criterion, compressive strength is a good indicator of mixture composition and variability and is much easier to test for than bond strength or thermal properties. Compressive strength and elastic properties are governed by the water to cementitious material [W/(C+P)] ratio of the mixture and the degree of compaction. Compressive strength and elastic properties data are given in table 1. The relationship between compressive strength and W/(C+P) ratio is shown in figure 7. This figure is a compilation of results of laboratory or field construction control cylindrical test specimens, mostly at 1 year in test age. The results indicate RCC mixtures using ASTM graded aggregates have a higher compressive strength than comparable mixtures using “all-in” aggregate gradings with fines. Figure 8 shows the variation in compressive strength versus test age for mixtures with ASTM C 33 aggregates. The compressive strength of concrete will be reduced about 5 percent for every 1 percent of air that could be removed but is not. Some RCC mixtures cannot be effectively compacted for the full depth of the lift, leaving porous, unbonded lift lines. This is due to not having sufficient workability for compaction and particularly due to segregation of coarse aggregate during placing. The ability to detect the incomplete compaction is limited by available testing equipment. However, if the workability of the mixture is sufficient, full compaction of a 1-foot lift is easily achieved with about six passes of a dual-drum vibratory roller. A common error in RCC construction is to decrease the moisture content of the mixture in an attempt to reduce pumping of the mix and to increase the surface density, without being able to fully compact the entire lift.

b. *Cement plus pozzolan content and cement to pozzolan ratio*.—The cement plus pozzolan (C+P) content influences the ultimate strength gain of RCC. Mixtures with higher C+P contents have higher strengths for a given material and water content. The higher C+P content can increase the bond between lifts of RCC. Extremely lean RCC mixtures may meet minimum compressive strength requirements, but have little or no bond strength in either shear or tension. The rate of strength gain primarily depends on the cement to pozzolan ratio. For example, RCC mixtures from Upper Stillwater Dam with a cement to pozzolan ratio of 30:70 (by mass) achieved compressive strengths of about 1,830 and 6,400 lb/in^2 at 28 days and 1 year, respectively. The 28-day strength was less than 30 percent of the 1-year strength. RCC mixtures with 100 percent cement used for the Cold Springs Dam spillway had a compressive strength of 5,650 lb/in^2 at 28 days.

Adjusting the cement to pozzolan ratio is also done to reduce the cost of cementitious materials and for thermal heat rise considerations. Reclamation RCC mixtures have used up to 70 percent pozzolan by mass of C+P. Pozzolan is generally cheaper than cement, has good resistance to both alkali-silica reaction and sulfate attack, and utilizes an abundant mineral resource (fly ash) that would otherwise have to be disposed of in a landfill. If the design strength for loadings is required at 14 or 28 days, the pozzolan content will normally be limited to no more than 15 to 25 percent by mass of C+P. For a design age of 90 days, the pozzolan content may be increased to about 30 to 50 percent. For a design age of 180 days to 1 year, the pozzolan content has ranged from about 50 to 70 percent by mass of C+P. The spherical shape of fly ash particles increases the workability of high fly ash RCC mixtures and thus permits a reduction in water content compared to a mix without fly ash.

c. *Thermal properties*.—The influence of mixture proportions on thermal properties of RCC is primarily associated with the thermal properties of the aggregates and the C+P content. Higher C+P contents will increase the heat of hydration generated within the mass, resulting in thermal cracking as the RCC cools. Reclamation used 70 percent Class F pozzolan to reduce the temperature rise of the RCC in Upper Stillwater Dam. These mixtures had a continued temperature rise for up to 90 days. This may increase the cracking potential of dams if placed just prior to the

Table 1.—Compressive strength and elastic properties of laboratory RCC mixtures

			Compressive strength (lb/in^2)				Modulus of elasticity (10^6 lb/in^2)				Poisson's ratio			
Project	Mix	W/(C+P) ratio	7 days	28 days	90 days	1 year	7 days	28 days	90 days	1 year	7 days	28 days	90 days	1 year
Coolidge	Cool-1	0.7	850	1460	2470	3720	1.92	2.7	3.57	5.06	0.16	0.18	0.18	0.19
Coolidge	Ctwd-1	0.7	890	1860	3350	4450	1.73	2.76	3.92	4.35	0.12	0.16	0.19	0.17
Galesville		1.56	-	465	930	-	-	-	-	-	-	-	-	-
Milltown Hill	RCC-25	0.85	370	510	960	1300	-	0.68	1.39	2.03	-	0.25	0.25	0.21
Research	150	1.3	-	250	665	1120	-	-	-	-	-	-	-	-
Research	300	0.55	-	1480	2640	4540	-	-	-	-	-	-	-	-
Upper Stillwater	L1	0.47	1360	2130	3510	5220	-	1.03	1.32	1.71	-	0.13	0.14	0.17
Upper Stillwater	L2	0.45	770	1220	2150	4780	-	0.82	-	1.59	-	0.13	-	0.2
Upper Stillwater	L3	0.43	1110	1620	2770	4960	-	0.92	-	1.76	-	0.13	-	0.18
Average	All mixes	0.69	890	1220	2160	3760	-	1.49	2.55	2.75	-	0.16	0.19	0.19

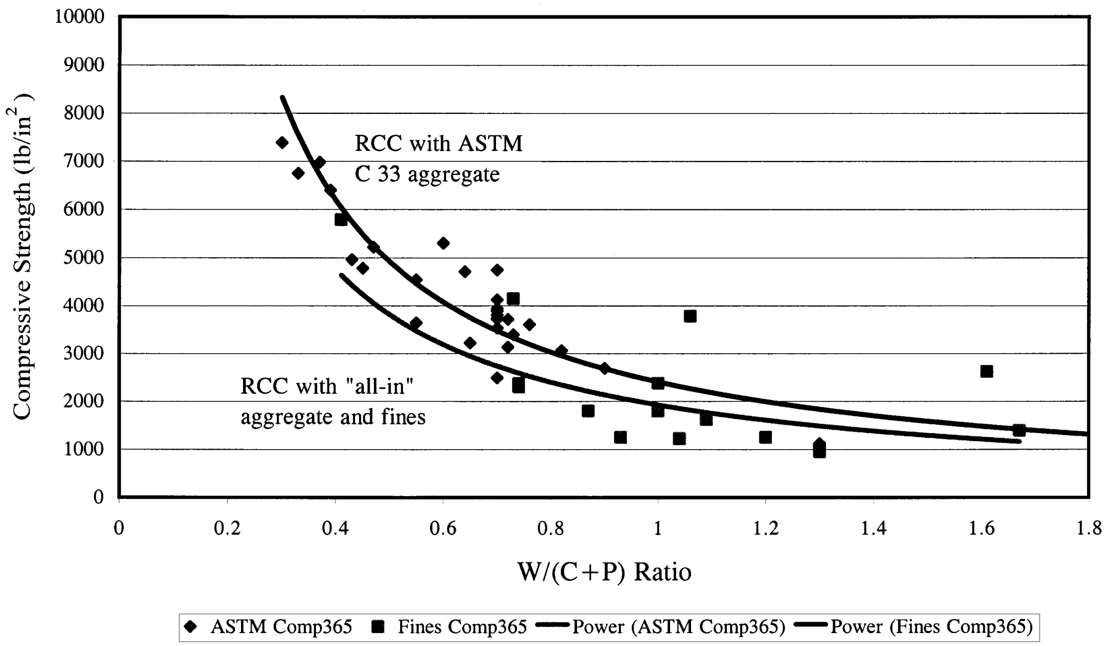

Figure 7.—RCC compressive strength vs. W/(C+P) ratio, 365 days old—ASTM C 33 aggregate vs. "all-in" aggregate with fines.

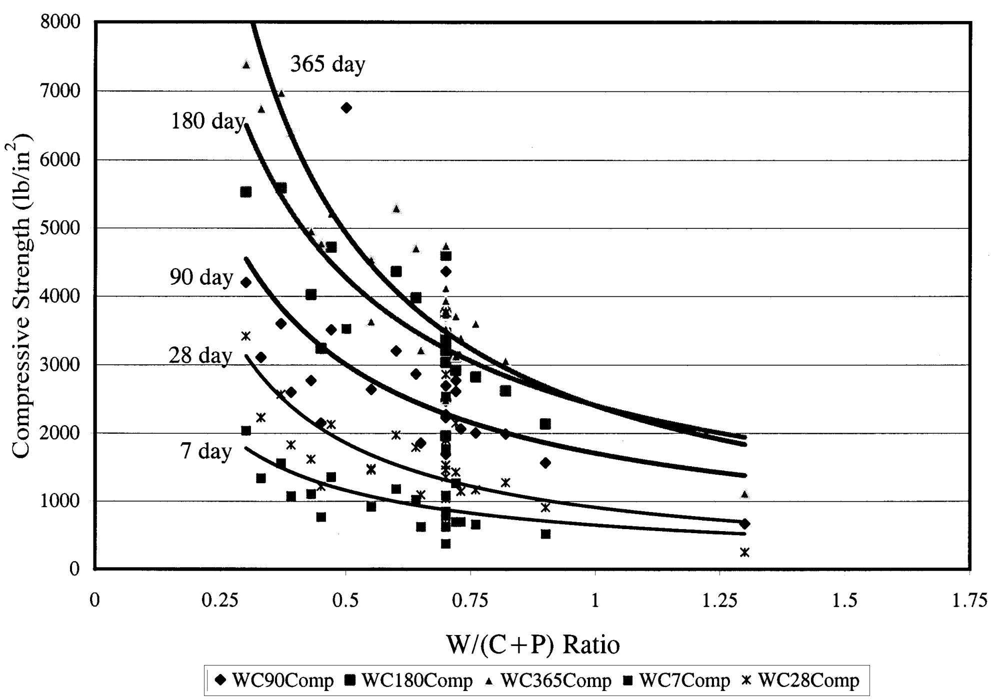

Figure 8.—Variation in compressive strength vs. W/(C+P) ratio for RCC mixtures with ASTM C 33 aggregates and test ages ranging from 7 to 365 days.

winter season, due to high temperature gradients. Sample temperature rise data for a variety of RCC mixtures is given in table 2.

d. *Durability*.—The durability of RCC is governed by the same basic principles as for conventional concrete. RCC will have only minimal resistance to freeze-thaw action unless protected from freezing or critical saturation by conventional concrete, or by using an AEA. Air-entrained RCC increases the resistance to freezing and thawing and also increases the workability of the fresh concrete. The low compressive strength of some mixtures will reduce the durability of RCC, particularly at early ages. Proper selection of cement types and using a suitable pozzolan govern durability against chemical reactions, such as sulfate attack or alkali-aggregate.

4.3 Bond between lifts.—Lift lines between concrete placements are normally the weakest planes in concrete dams. Both conventional concrete and RCC dams must generally maintain bonding at lift lines to meet required factors of safety for normal (static), unusual (flooding), and extreme (seismic) loading conditions. This requires both shear strength to resist horizontal forces and tensile strength to resist hydrostatic water pressure and vertical forces that can be seismically induced. The cohesion of the bonded lift lines and the friction between lower and upper surfaces resist horizontal forces across lift lines. For most cases, the friction resistance of unbonded lift lines is insufficient to meet required factors of safety, and true chemical bond (cohesion) between lifts is essential.

The requirements for bonding lift joints in shear and tension, and not the design compressive strength requirement, often govern the total C+P content of RCC mixtures. The W/(C+P) ratio and C+P content of the mixture affect both the ultimate shear and tensile strength capacity across lift joints and the percent of the joint surface area that is bonded. Mixtures with C+P contents lower than about 200 lb/yd^3 will have low tensile and shear strength capacity because there is insufficient volume of paste in the mixture to provide cohesion. The percent of the lift surface that is bonded may be significantly less than 50 percent, unless supplemental joint treatment, such as a layer of bonding mortar, is used. Mixtures with C+P contents greater than about 300 lb/yd^3 are generally more workable and easier to compact. These mixtures will have tensile and shear capacities similar to those of conventional concrete, and the percentage of lift joints bonded may reach 50 to 90 percent without the use of supplemental joint bonding mortar, if the previous lift surface is clean, and adequate compaction is achieved. Mixtures with C+P contents between 200 and 300 lb/yd^3 may have variable bond between lifts, depending on the consistency of the mixture, lift joint treatment, and ambient weather conditions. Placements during rain and snow should be avoided during construction, because precipitation can reduce bonding. If precipitation occurs, RCC placing should immediately be suspended and the lift surface protected.

Because it is generally necessary to maintain true "cohesion" for meeting required factors of safety, the following discussion is directed at the strength properties of **bonded** lift lines and the **percentage** of any horizontal lift surface bonded. The **percentage** of a lift surface bonded is normally determined by coring through multiple lifts of concrete and examining individual joints. The coring program may be designed to examine multiple lifts from a few locations or a few lifts from many locations, depending on the intent of the test program, thickness of the placement, drilling equipment used, and accessibility of the site. Bonded and disbonded lift lines are identified and counted. Lift lines that are mechanically broken by the coring operation are not considered "disbonded." Determining the percentage of bonded lift lines requires the examination of drilled cores to be performed carefully to eliminate those defects caused by the drilling process.

Reclamation performed shear strength testing in the 1980s to determine the bond properties of RCC. Much of the work was performed as part of the Upper Stillwater Dam design and construction process. The design of Upper Stillwater Dam required 300 lb/in^2 of cohesion and 180 lb/in^2 of direct tensile strength across lift lines to meet required factors of safety. Reclamation performed applied research specific to determining the bond strength of RCC lift joints in laboratory and field trials. Reclamation also tested cores from Galesville Dam in Oregon and Stagecoach Dam in Colorado as part of the Small Reclamation Projects Act. These dams were designed and constructed by private design firms. The knowledge gained from these test programs has been used for developing

Table 2.—Temperature rise properties of roller-compacted concretes

Feature	Mixture	C+P content (lb/yd^3)	Pozzolan (percent by mass)	Maximum aggregate size (in.)	Initial temp (°F)	Adiabatic temperature rise (°F), at age, days					Maximum temp. rise (°F) at age, days
						1	3	7	14	28	
Upper Stillwater	L-1	389	54	1.5	59.8	2.5	25.0	33.7	40.7	45.5	
	L-2	390	69	1.5	46.5	4.7	15.3	25.5	29.3	32.5	
	L-3a	415	69	1.5	44.5	2.5	3.8	20.0	29.5	34.3	
	L-3b	415	69	1.5	49.0	3.9	15.9	27.8	32.5	37.3	
	L-5	500	69	1.5	53.5	6.4	24.3	36.3	43.5	48.3	
SantaCruz	1	224	50	2.0	60.8	18.7	24.8	29.2	32.2		32.7 at 21
Pamo	RCC-3	350	65	3.0	54.0	8.9	17.3	23.5	29.9	38.6	
Middle Fork	120C	120	0	3.0	60.0	10.0	17.0	22.0	24.0	27.0	
Pueblo	RCC-8	300	60	1.5	55.0	11.0	23.5	32.0	38.0	44.0	45.0 at 31
Milltown	RCC-25	223	50	2.0	62.0	11.0	17.0	21.8	25.3	29.5	32.2 at 54
Coolidge	Cool1	249	50	2.0	63.0	16.9	22.6	27.6	32.0	34.5	34.9 at 32

L-1 to 3a used set retarding WRA (ASTM Type D)
L-3b used conventional WRA (ASTM Type A)

RCC mixture proportioning methods, quality control practices, design parameters, and construction specifications. Results of laboratory testing are summarized in table 3.

The shear strength at lift lines can be determined using a biaxial testing apparatus described by McLean and Pierce (1988) (Reclamation, 1992, Proc. No. 4915). Specimens are placed in the test apparatus so that the lift line is positioned in a fixed, horizontal plane. A normal load is applied to the specimen and a shear stress is applied across the plane of the lift line. For bonded lift lines, the shear strength of an intact lift line is determined for a number of test specimens at different normal loads. A best fit line is generated from a plot of the data to determine cohesion, c, the intercept of the line at zero normal load, and the coefficient of internal friction, tan N, representing the slope of the best fit line.

For unbonded lift lines, a similar set of tests is run varying the normal stress and determining the peak shear stress at which the specimen undergoes a large horizontal displacement. A best fit line of the data for peak shear stress versus normal stress will result in an apparent cohesion c_a or residual shear stress at the zero normal load intercept and a friction resistance, tan N_a, representing the slope of the best fit line.

The direct tensile strength of bonded lift lines is determined by Bureau of Reclamation Procedure No. 4914 (1992) using a specimen with the lift line at its midpoint. The direct tension test result represents the weakest point of the entire test specimen. The tensile strength of parent material can also be determined with a direct tension test or a splitting tension test. The splitting tension test normally gives a higher result than the direct tension test, because it stresses a fixed plane in the specimen.

Based on the tests performed by the Bureau of Reclamation and others, the following conditions are needed for achieving good bond between RCC lifts:

1. Providing sufficient paste and mortar volume and workability of the RCC mixture
2. Controlling segregation during placing
3. Providing adequate compaction with the vibrating roller
4. Providing good surface cleanup of the lift, if needed
5. Placing a bonding layer of mortar or concrete between lifts of RCC, if needed
6. Placing RCC at a high rate, thereby reducing the exposure time between lifts
7. Maintaining good construction practices for mixing, placing, compacting, and curing RCC

For items 1, 2, and 3 in the list above, providing sufficient paste and mortar volume and good workability are RCC mixture proportioning criteria. Having adequate paste and mortar provides the "glue" needed to bond layers together. Insufficient paste leads to segregation, rock pockets, and an inability to properly compact the full thickness of the RCC lift. Voids present at the bottom of a lift of RCC caused by either segregation or lack of compaction reduce the cohesion of RCC to essentially zero. This was a problem in some early RCC dams, leading to excessive seepage and lack of bond.

For items 4 and 5 in the list above, lift cleanup requirements depend on the construction placing methods, mixture proportions, and rate of placing. Lift surfaces allowed to dry must be cleaned by vacuum or air/water jetting before placing the next lift. Placing the RCC rapidly with a properly proportioned mixture required little or no cleanup at Upper Stillwater Dam, when the average vertical rate of placing approached 1 to 2 ft/day. If a lift of RCC is allowed to set and the mixture has little free paste, a bonding layer of mortar or concrete is needed to maintain cohesion. Depending on the circumstances (primarily ambient air temperatures), bonding mortar may be required on lift surfaces more than 6, 8, or 12 hours old. Research test sections placed by Reclamation and the Portland Cement Association showed that a mixture with minimum paste had little or no bond between lifts, but up to 90 percent of each lift line was bonded when bonding mortar was used. Richer mixtures had about 50 percent of each lift line bonded with no surface preparation, and 90 to 100 percent bonded with surface preparation and bonding mortar.

Table 3.—Shear bond strength properties of laboratory RCC mixtures

Project	Joint age[1] (hr)	W/(C+P) ratio	Cohesion (lb/in²)			Internal friction (tan N)			Residual cohesion (lb/in²)			Sliding friction (tan N)		
			28 days[2]	90 days	1 year	28 days	90 days	1 year	28 days	90 days	1 year	28 days	90 days	1 year
Coolidge	6-NB	0.70	205	270	510	1.08	1.52	0.93	60	50	50	1.32	0.99	1.01
Coolidge	6-NB	0.70	345	580	630	0.82	0.75	1.00	40	50	0	0.95	1.12	1.04
Galesville[3]	7-NB 7-B	1.56	- -	80140	- -	- -	0.93 1.23	- -	- -	4580	- -	- -	0.67 0.70	- -
Milltown Hill	8-NB	0.85	-	160	280	-	1.17	0.95	-	30	-	-	0.57	0.79
Research 150	8 24 72 24-B	1.30	70 (56) 40 (56) - -	1e+10	2e+11	0.93 (56) 0.87 (56) - -	1.15 1.15 0.78 1.10	1.07 0.65 1.28 1.13	35(56) 20(56) 5(56) -	6e+07	5e+07	.81(56) .65(56) .73(56) -	1.00 0.70 0.81 0.82	0.97 0.90 0.81 0.92
Research 300	8 24 72 24-B	0.55	80 265 220 -	4e+11	600 620 480 -	1.04 0.36 0.58 -	0.75 0.58 1.28 1.26	1.28 0.70 2.15 -	5e+07	4e+07	50 25 20 -	0.87 0.93 0.75 -	0.97 0.87 0.87 0.91	1.07 0.97 0.84
Upper Stillwater	24-NB	0.47	220	380	500	1.06	1.15	1.06	45	40	60	0.90	1.09	1.11
Upper Stillwater	24-NB	0.45	140	240	350	1.05	1.60	2.92	45	40	30	0.80	1.00	0.85
Upper Stillwater	24-NB	0.43	230	280	580	0.90	1.68	1.02	50	40	40	1.03	1.00	0.93
Average	NB	-	180	270	410	-	1.11	1.25	-	40	50	-	0.90	0.94
Average	B	-	-	240[4] 210[5]	-	-	1.20	-	-	45	-	-	0.81	-

[1] Joint age in hours between lifts; B—bonding layer placed on joint; NB—no bonding layer placed on joint
[2] Numbers in parentheses indicate actual age of concrete when tested in days
[3] Average cohesion for corresponding three mixtures without bonding mixture
[4] All tests performed on 6-in. diameter specimens, except Galesville Dam test specimens, which were 9-in diameter
[5] Average cohesion for three mixtures with bonding mixture

For item 6 in the list above, placing RCC rapidly allows the next lift to be placed on a joint that has not set. This allows good bonding between lifts by knitting the two layers together and allowing recompaction of the lower lift of RCC. Cores extracted from Upper Stillwater Dam following the 1986 construction season, compared to those following the 1985 season, demonstrated the effect of placing rate on bond. The 1986 construction had about a 2-ft/day rate of placement and had significantly better percent bonding than the previous year of construction. Tests from Pueblo Dam Modification mixture proportioning investigations showed a mixture with 300 lb/yd^3 of C+P had more than 90 percent bond with or without a bonding mortar when the time interval between placements was less than 8 hours.

For item 7 in the list above, all RCC construction requires good quality control and inspection practices. Because the process is so rapid, the RCC project could be completed before standard strength tests reach required design values. The RCC must be properly mixed, placed, compacted, and cured to ensure full compaction and bonding between lifts. This method of construction requires careful attention to the construction operations similar to that required for critical zones of earthwork compaction.

4.4 Field adjustments during construction.—Laboratory-proportioned RCC mixtures may require adjustment in the field, due to changes in materials, ambient temperature conditions, and the contractor's selected batching, mixing, transporting, placing, and compacting operations. The lift line bond properties will depend on the construction control during placing and on the rate of placing or time interval between lifts. Tables 4 through 7 summarize the mixture proportions and the properties of fresh and hardened RCC, based on field construction records and properties of construction control cylinders and cores.

Table 4.—Mixture proportions of RCC used in construction

Project	NMSA (in)	Air (%)	Water (lb/yd^3)	Cement (lb/yd^3)	Pozzolan (lb/yd^3)	Sand (lb/yd^3)	Coarse aggregate (lb/yd^3)	Total (lb/yd^3)
Galesville	3.0	-	190	89	86	1310	2560	4235
Research -Amc1	2.5	-	180	150	0	1367	2327	4024
Research-Amc2	2.5	-	200	150	0	1359	2315	4024
Research-Bmc1	2.5	-	180	150	150	1312	2233	4025
Research-Bmc2	2.5	-	200	150	150	1304	2221	4025
Stagecoach	2.0	-	233	120	130	1156	2459	4098
Upper Stillwater RCC-A85	2.0	1.5	159	134	291	1228	2177	3989
Upper Stillwater RCC-A86/87	2.0	1.5	166	134	291	1148	2231	3970
Upper Stillwater RCC-B85	2.0	1.5	150	159	349	1171	2178	4007
Upper Stillwater RCC-B86/87	2.0	1.5	169	155	343	1162	2128	3957
Pueblo test section	1.5	4.5	166	121	181	1293	2202	3963

Table 5.—Properties of fresh RCC mixtures used in construction

Project	Mixture	Temperature (°F)	Density (lb/ft^3)	Vebe consistency (s)	Air content (gravimetric) (%)
Galesville	RCC-1	61	156.0	NA	-
Research	RCC-150	-	151.8	-	-
Research	RCC-300	-	151.4	-	-
Stagecoach		-	150.8	(60) [1]	-
Upper Stillwater	RCC-A85	46	145.8	29	1.5
Upper Stillwater	RCC-A86/87	47	147.1	17	1.5
Upper Stillwater	RCC-B85	48	146.2	33	1.5
Upper Stillwater	RCC-B86/87	47	146.7	15	1.5
Pueblo test section	RCC-8TS	68	146.8	8	4.5

[1] Limited test data; estimated time.

Table 6.—Compressive strength and elastic properties of 6-inch diameter RCC cores used in construction

Project	Mix	W/(C+P) ratio	Test age (days)	Compressive strength (lb/in^2)	Modulus of elasticity (10^6 lb/in^2)	Poisson's ratio
Galesville	RCC 1	1.09	415	2080	3.12	0.18
Research	RCC-150	1.30	72	840	-	-
Research	RCC-300	0.55	72	1920	-	-
Stagecoach		0.93	160	1670	2.18	0.17
Stagecoach		0.93	180	1960	2.58	0.12
Stagecoach		0.93	365	1920	2.38	0.16
Upper Stillwater	RCC A85	0.37	108	3870	1.96	0.23
Upper Stillwater	RCC A85	0.37	200	4890	1.55	0.23
Upper Stillwater	RCC A85	0.37	633	6510	2.32	0.21
Upper Stillwater	RCC B-85	0.3	102	3760	_	_
Upper Stillwater	RCC A86	0.39	335	5220	2.18	0.22
Upper Stillwater	RCC B86	0.34	320	5130	2.28	0.15
Upper Stillwater	Average All RCC	0.36	322	5140	2.15	0.20

Table 7.—Bond strength properties of 6-inch diameter RCC cores used in construction

Project	Joint type [1]	Percent joint bond	Vebe time (s)	W/(C+P) ratio	Age (days)	Compressive strength (lb/in²)	Tensile strength (lb/in²)	Break bond: Cohesion (lb/in²)	Break bond: Internal friction, c (tan N)	Residual cohesion, C_a (lb/in²)	Sliding friction (tan N) a
Galesville	8-NB	24	NA	1.09	415	2,080	70	110	2.36	80	0.84
Galesville	8-B	76	NA	1.09	415	2,080	120	330	1.28	70	0.93
Galesville	P	NA	NA	1.09	415	2,080	(100)	380	0.65	95	1.00
Research Amc1	6-NB 6-B	0 96	NA	-	(85)	935	70	0 [3] (230)	-	-	-
Research Amc1	48-NB 48-B	0 75	NA	-	(85)	935	100	0 (310)	-	-	-
Research Amc2	6-NB 6-B	0 71	NA	-	(85)	740	45	0 (150)	-	-	-
Research Amc2	48-NB 48-B	8 83	NA	-	(85)	740	(90)	0 (200)	-	-	-
Research Bmc1	6-NB 6-B	42 92	NA	-	(85)	1,880	(120)	(110) (340)	-	-	-
Research Bmc1	48-NB 48-B	17 100	NA	-	(85)	1,880	20,160	0 (270)	-	-	-
Research Bmc2	6-NB 6-B	58 100	NA	-	(85)	1,920	65,135	(110) (350)	-	-	-
Research Bmc2	48-NB 48-B	67 88	NA	-	(85)	1,920	70,140	(165) (340)	-	-	-
Stagecoach	NB	65	(60)	0.93	180	1,960	105	75	2.90	40	0.93
Stagecoach	B	(100)	(60)	0.93	180	1,960	95	-	-	-	-
Stagecoach	NB	65	(60)	0.93	365	1,920	100	170	0.78	45	0.75
Stagecoach	B	(100)	(60)	0.93	365	1,920	-	360	1.54	50	1.04
Upper Stillwater RCC-A85	NB	60	29	0.37	120	3,870	140	300	1.43	30	0.90
Upper Stillwater RCC-A85	NB	60	29	0.37	730	6,510	255	440	1.11	20	1.04

Table 7.—Bond strength properties of 6-inch diameter RCC cores used in construction

Project	Joint type [1]	Percent joint bond	Vebe time (s)	W/(C+P) ratio	Age (days)	Compressive strength (lb/in^2)	Tensile strength (lb/in^2)	Break bond: Cohesion (lb/in^2)	Break bond: Internal friction, c (tan N)	Residual cohesion, C_a (lb/in^2)	Sliding friction (tan N)$_a$
Upper Stillwater RCC-A85	NB	80	29	0.37	545	5,590	225	445	1.01	20	1.07
Upper Stillwater RCC-A	NB	95	17	0.39	365	5,220	200	450	1.33	30	1.15
Upper Stillwater RCC-B85	NB	60	33	0.30	120	3,790	(165)	305	1.07	35	0.90
Upper Stillwater RCC-B	NB	95	15	0.34	365	5,130	190	370	0.81	30	1.28
Pueblo test section RCC-8TS	6-B	92	8	0.55	35 90	1,260	150 180	(430) [2]	(0.93)	(40)	(0.92)
Pueblo test section RCC-8TS	6-NB	92	8	0.55	35 90	1,260	170 170	(330) [2]	(0.99)	(30)	(1.05)
Pueblo test section RCC-8TS Lab cast specimens	6-NB 6-B 6-P	NA	8	0.55	35	1,260	155 150 175	0	0.00	0	0.00

[1] Joint age in hours between lifts; B—bonding layer placed on joint, NB—no bonding layer placed on joint, P—parent concrete
[2] Numbers in parentheses indicate approximate values based on visual examination and/or limited test data.

4.5 Mixture proportioning procedures for RCC.—RCC mixture proportioning procedures fall into two general categories; the "concrete approach"—mixtures proportioned as a mass concrete adjusted to support the construction placing and compaction equipment, and the "soils approach"—mixtures proportioned as a stabilized soil or fill material compacted to maximum density.

The "concrete approach" mixtures tend to use materials meeting conventional mass concrete specifications. Mixtures are proportioned to meet both fresh concrete needs, such as workability and segregation potential, and to meet hardened concrete properties such as bond strength (shear and tension), compressive strength, and durability. Mixtures proportioned as a stabilized soil or fill have used single or combined gradations of fines, sand, and coarse aggregate mixed with cementitious materials and water proportioned for maximum density. During placement, "stabilized soil" mixtures appear drier or less workable than the "concrete approach" mixtures, which have a noticeable plasticity or pressure wave in front of the vibrating roller. Referring to a mixture as either "wet" or "dry" may not be appropriate when comparing mixes. In actuality, the less-workable/ dry, stabilized soil mixtures may often have a higher total water content than the more-workable/wet concrete type mixtures.

a. *Mixture proportioning*.—The concrete approach to proportioning RCC mixtures generally follows classical concrete proportioning concepts incorporating both workability and strength. First and foremost, a mixture that does not have the necessary workability cannot be economically and effectively placed and compacted. Secondly, mixtures must have the required proportions to meet design strength requirements. Proportioning procedures for workability vary the water content, sand-coarse aggregate ratio, cement-pozzolan ratio, and more recently, the entrained-air content to achieve an optimum consistency for the placing conditions. The mixtures have a measurable Vebe consistency as defined by ASTM C 1170 *Standard Test Method for Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table*. After optimizing the proportions for workability, the water to cementitious materials [W/(C+P)] ratio is varied to achieve the required strength and durability properties. The cement to pozzolan ratio may also be varied to reduce the cost of cementitious materials and meet specific design strength and thermal heat rise requirements. The age when the structure must meet service requirements and the desired maximum temperature rise of the mass RCC may influence the cement to pozzolan ratio. Higher cement to pozzolan ratios will gain strength faster, but will generate more heat. Balancing the strength versus heat relationships is a part of the cementitious materials proportioning process.

b. *Steps in proportioning RCC mixtures.*—The process of proportioning RCC mixtures will depend upon the strength and temperature requirements for design, the properties of available materials, and the desired workability. A typical program may encompass a basic mix and about a dozen trial adjustments, as shown in tables 8 and 9, which illustrate the RCC trial mix program used for Coolidge Dam in Arizona. The first three mixtures varied the saturated surface dry (SSD) water content, while maintaining the other proportions of cement, pozzolan, sand, and coarse aggregate. After determining the optimum water content for workability based on a Vebe consistency, the next two mixtures varied the sand to coarse aggregate ratio. This step studied the effect of changes in sand to coarse aggregate ratio on Vebe consistency and workability/segregation potential. The next four mixtures varied the cement to pozzolan ratio to evaluate the effect of the cement to pozzolan ratio on Vebe consistency and on compressive strength development. The next two mixtures varied the C+P content about 50 lb/yd^3 above and below the initial trial mixture to show the effect of W/(C+P) ratio on strength. The remaining mixtures were used to cast additional strength and thermal property test specimens as needed from the design mixture.

Based upon the tests performed by Reclamation, the following steps for developing proportions for a typical RCC mixture with a compressive strength of about 3,000 lb/in^2 at 1 year's age are summarized below. A 2-inch NMSA and sand and coarse aggregate meeting the requirements of ASTM C 33 are assumed.

1. *Initial mixture proportions for a 2-inch NMSA basic RCC mixture*.—

1. Assume an air content of about 1 percent by volume (3.5 percent if an AEA is used).

Table 8.—RCC trial mixture proportioning program input parameters—2-inch nominal maximum size aggregate

Trial mix No.	Air[1] content (%)	Water content (lb/yd^3)	C+P[2] content (lb/yd^3)	C:P ratio[3] (by mass)	Percent sand[4, 5]	Comments
1	1	175	250	0.042361	37	First trial mix—C:P ratio for compressive strength of 2,500 lb/in^2 (17 Mpa) at 180 days age or 3,000 lb/in^2 (21 Mpa) at 1 year
2	1	160	250	0.042361	37	Reduce water—effect of water on Vebe consistency; effect of W/C+P ratio on compressive strength
3	1	190	250	0.042361	37	Increase water—effect of water on Vebe consistency; effect of W/C+P ratio on compressive strength
4	1	175	250	0.042361	30	Decrease sand—effect of sand content on Vebe consistency and segregation
5	1	175	250	0.042361	40	Increase sand—effect of sand content on Vebe consistency and segregation
6	1	175	250	1.5:1	37	Increase percent cement—effect of cement to pozzolan ratio on Vebe consistency and compressive strength gain
7	1	175	250	1:1.5	37	Increase percent pozzolan—effect of cement to pozzolan ratio on Vebe consistency and compressive strength gain
8	1	180	200	0.042361	37	Decrease C+P content—effect of W/C+P ratio on compressive strength
9	1	180	300	0.042361	37	Increase C+P content—effect of W/C+P ratio on compressive strength

[1] For air-entrained RCC, assume an air content of about 4% by volume
[2] C+P: cement plus pozzolan
[3] C:P ratio: cement to pozzolan ratio by mass
[4] The initial sand content for this mixture was selected at 37 percent due to its coarse grading.
[5] CA1:CA2 ratio: [coarse aggregate size 3] to [coarse aggregate size 57] ratio—1:1 by mass. Determined from dry-rodded density study.

2. Select an initial cement plus pozzolan (C+P) content of 250 lb/yd^3.

3. Select a cement to pozzolan © to P) ratio of 1 to 1 by mass.

4. Select an initial water content of about 175 lb/yd^3. If no pozzolan is available, increase the water content approximately 10 percent.

5. Select a sand content of about 35 percent by total volume of aggregates.

6. The remaining volume is coarse aggregate proportioned by dry-rodded density tests. Typically, the mass ratio of Size No. 3 (2 to 1 inch) to Size No. 57 (1 in to No. 4) coarse aggregate is about 1 to 1.

7. The mass and volume computations of individual ingredients are based on the known specific gravities of each material.

2. *Trial mixture adjustments*.—Keeping the initial C+P content, C to P ratio, and sand to aggregate ratio constant, perform Vebe consistency and density tests for mixtures with at least three different water contents. Select a mixture with a water content that achieves a Vebe consistency time of 15 to 20 seconds. This determines the “optimum” water content for

Table 9.—RCC mixture proportioning program—batch quantities[1] for Coolidge Dam mixture proportioning program

Trial No.	Water (lb)	Cement (lb)	Pozzolan (lb)	Sand (lb)	Coarse aggregate[2] No. 4-1 in (lb)	Coarse aggregate[2] 1-2 in (lb)	Total (lb)	W/(C+P) ratio	Vebe consistency (s)	Density (lb/ft³)	Comments
1	175	125.0	125.0	1427	1183	1184	4219	0.70	13	155.4	Basic starting mixture
2	160	125.0	125.0	1442	1196	1196	4245	0.64	33	157.4	Reduce water 15 lb/yd³
3	190	125.0	125.0	1412	1170	1171	4193	0.76	11	156.9	Increase water 15 lb/yd³
5	210	150.0	150.0	1372	1138	1138	4159	0.70	4	156.9	Increase paste volume
6	175	125.0	125.0	1157	1315	1315	4212	0.70	7	157.0	Decrease sand to 30 percent
7	175	125.0	125.0	1543	1127	1128	4223	0.70	25	156.6	Increase sand to 40 percent
8	175	250.0	0.0	1140	1194	1194	4253	0.70	58	156.2	Change C:P ratio to 1:0
9	175	157.5	62.5	1414	1198	1198	4235	0.70	74	159.0	Change C:P ratio to 75:25
10	175	62.5	157.5	1401	1187	1187	4201	0.70	11	155.1	Change C:P ratio to 25:75
11	175	150.0	100.0	1430	1185	1185	4226	0.70	26	157.1	Change C:P ratio to 60:40
12	175	100.0	150.0	1424	1181	1181	4212	0.70	23	156.6	Change C:P ratio to 40:60
13	180	150.0	150.0	1403	1163	1164	4210	0.60	14	156.4	Increase C+P 50 lb/yd³
14	180	100.0	100.0	1441	1195	1195	4210	0.90	34	157.1	Decrease C+P 50 lb/yd³
15	175	125.0	125.0	1543	1127	1128	4223	0.70	19	154.6	Repeat of mix 7

[1] Quantities in lb/yd³. Air content: approximately 1.5 percent assumed by volume.
[2] Coarse aggregate size 3 (2 to 1 inch) to coarse aggregate size 57 (1 inch to No. 4) ratio determined by dry-rodded density study

workability (although it may not necessarily be the optimum water content for maximum density). Compressive strength tests can be performed to evaluate the effect of W/C+P ratio on strength. This may be necessary for future adjustments if strengths are higher or lower than projected.

Adjust mixture water content for a Vebe consistency of about 15 seconds, if necessary, and test two additional mixtures using sand contents of 30 and 40 percent to evaluate the effect of sand content on Vebe consistency and segregation. The final trial mixture should have the water and sand content proportioned within these limits to achieve a consistency of 15 seconds with minimal segregation.

Adjust the C to P ratio while maintaining a constant water content, C+P content, and sand to aggregate ratio, to evaluate the effect on Vebe consistency and the rate of compressive strength development.

Increase or decrease the total C+P content while maintaining the water content, C to P ratio, and sand to aggregate ratio constant for two mixtures. This is done to study the effect of varying the paste volume on Vebe consistency and varying the W/(C+P) ratio on compressive strength.

Based on the compressive strength relationships from the trial mixtures, cast test specimens for thermal properties, bond strength, elastic properties, durability, and length change for the mixture that most closely meets the design strength requirements.

Typical mixtures proportioned by Reclamation using these proportioning methods are given in table 10. These mixtures represent a variety of aggregates found across the western United States. The selected mixture proportioning parameters are based on the design requirements and loading age for the structures.

4.6 References.—

Bureau of Reclamation, *Concrete Manual*, Part 2, 9th Edition, 1992.

McLean, F.G. and J.S. Pierce, *Comparison of Joint Shear Strengths for Conventional and Roller Compacted Concrete*, Roller Compacted Concrete II, Proceedings of the Second ASCE Conference on Roller Compacted Concrete, San Diego, California, February 29-March 2, 1988.

Table 10.—Roller-compacted concrete mixtures (lb/yd^3) proportioned by the Bureau of Reclamation

RCC mixture	Air (%)	Water (lb)	Cement (lb)	Pozzolan (lb)	Sand (lb)	Coarse aggregate (lb)	Total (lb)	Design strength (lb/in^2)	Test age (days)
Upper Stillwater-A	1.0	167	134	292	1149	2218 [1]	3960	4000	365
Santa Cruz [3]	2.2	170	128	127	1227	2301 [1]	3953	3000	365
Milltown Hill	1.0	189	111	111	1380	2367 [1]	4160	1800	180
Camp Dyer	3.8	152	139	137	1261	2257 [2]	3946	3000	365
Coolidge	1.5	174	123	123	1534	2238 [1]	4194	2500	180
Research 150	1.0	195	74	74	1340	2324 [2]	4010	1000	365
Research 300	1.0	165	150	150	951	2680 [2]	4096	4000	365
Cold Springs spillway	1.0	157	302	0	1593	2271 [2]	4323	4000	28
Ochoco spillway	1.0	218	434	0	1539	1881 [2]	4072	4000	28
Pueblo Dam modification	5.0	165	120	180	1287	2191 [2]	3943	3000	365

[1] 2-inch nominal maximum size aggregate
[2] 1½-inch nominal maximum size aggregate
[3] Air-entrained RCC

Chapter 5

RCC Construction Methods

5.1 General construction considerations.—The quality of the production and placement of RCC is directly related to the equipment and expertise of the contractor's construction personnel and to the project's quality control and quality assurance measures. The contractor will normally be required to develop, implement, and maintain a system of quality control, approved by the Contracting Officer, which will include concrete material properties testing, equipment calibration, quality control testing of fresh and hardened RCC, and timely communication of all test results. Federal regulations require the Government to provide quality assurance for all contract work. Quality assurance activities during a contract, which generally include construction inspection and materials testing, provide documentation that the construction is being accomplished as specified, and that the design intent is being met, but do not relieve the contractor of the responsibility for providing adequate quality control measures. Reclamation develops and implements specific inspection plans and testing procedures to verify contract performance criteria site by site. The extent of contractor quality control and Reclamation quality assurance requirements will depend upon the complexity and criticality of the project or feature. A critical feature is one whose failure could injure personnel or jeopardize the overall success of the project, and will normally require greater quality assurance measures than for a noncritical feature.

5.2 Aggregate production.—Although the designer should always identify potential local sources for sand and coarse aggregate for estimating project costs, and include information pertaining to these sources in the specifications, the contractor will generally remain responsible for the selection of the aggregate sources to be used for the work. The specifications should provide a list of tested local sources that contain, when sampled, materials meeting the quality requirements of the specifications for sand and/or coarse aggregate. Such local sources may be quarry deposits on public or private land, or commercial sources. It is desirable that a minimum of two potential sources each be identified in the specifications for sand and coarse aggregate whenever possible. Information on other local sources tested by the Government and found to not meet the specifications requirements should be made available to potential bidders upon request. Alternate sources not previously tested by the Government may also be acceptable, provided the materials meet the specifications requirements as shown by the results of independent laboratory testing and petrographic examination. In any case, the contractor shall remain responsible for the specified quality and grading of all selected sources, and final acceptance of all aggregate materials will be based on samples taken at the RCC batch plant.

Small RCC projects will normally use commercial sources to avoid the significant development and production costs of a quarry site. The contractor for Clear Lake Dam Modification selected a commercial source 40 miles away for both sand and coarse aggregate for conventional concrete and RCC, rather than attempt to produce aggregate from the basalt beds at the project site for the 18,000 yd^3 of RCC required for the work. Quarry sources, however, may be much more attractive for larger projects in order to avoid long haul distances and higher unit costs from commercial sources.

The specifications will normally require that a minimum volume of sand and coarse aggregate be available for use at the job site prior to batching RCC. Clear Lake Dam Modification required that the entire anticipated quantity of aggregates be in stockpiles at the job site before batching any RCC.

If warm weather causes the RCC to exceed the specified maximum temperature during placement, precooling of the aggregates may be required. This is performed by sprinkling water on the coarse aggregate stockpiles during the day to produce evaporative cooling.

5.3 Batching and mixing.—RCC batch plants include conventional batch plants and continuous feed plants. Conventional batch plants provide accurate, controlled delivery with recorded weights. These plants provide some added flexibility for producing other concretes needed on the job, but are generally slower than continuous plants. Continuous plants may be belt-scale feed plants or volumetric plants. Plants equipped with weigh scales on the materials feed belts provide some means of checking the concrete mixture proportions during delivery. Volumetric feed plants are more limited in providing real time mixture proportions and must be calibrated before beginning construction. Volumetric plants do not easily detect mixture proportion changes caused by equipment- or materials-related feed problems. If continuous plants are used, it is important to have the contractor's and owner's representatives agree on a method of checking plant feed and computing batched mixture quantities, preferably on a per shift basis.

Batch size shall be at least 50 percent of, but not in excess of, the rated capacity of the mixing equipment. Batched materials shall be ribbon fed into the mixer in correct proportions. The mixer should be designed and operated to ensure uniform distribution of component materials throughout the RCC mixture, and to provide RCC of uniform workability and consistency from batch to batch. Truck mixers are normally not allowed for mixing or transporting RCC. Mixers should be examined regularly for accumulations of hardened concrete and for excessive wear or damage to blades that could affect mixing results. Mixers producing unsatisfactory results must be repaired or replaced.

The RCC batching and mixing plant should be sized for the job. Typically, the average plant capacity should be able to place up to two lifts of RCC per shift or per day. This placing rate usually provides good bonding at the lift interface with the minimum lift surface treatment.

The RCC batching and mixing equipment should be sized so as not to be the controlling feature for construction progress. Small plants or inefficient delivery methods result in equipment and construction personnel downtime. These personnel cannot move to other jobs during slow progress or breakdowns. Slow progress decreases the quality of lift surface bonding and increases the time and cost for required cleanup activities. The specified batching, mixing, and delivery equipment for Clear Lake Dam Modification was required to have a peak capacity of not less than 200 yd^3/hr and a sustained average capacity of 150 yd^3/hr for the duration of the work shift.

The most important requirement for successful operation of all RCC batch plants is to maintain a continuous supply of aggregates with consistent moisture content. Constantly changing aggregate moisture makes it impossible to maintain good mixture performance and is a source of error for batch plants. The aggregates should be stockpiled well in advance of construction, so that they are well drained and have reached consistent moisture content. This ensures sufficient materials are available and the RCC mixed product is free from moisture fluctuations. Wet aggregate stockpiles also limit the batch water available for heating and cooling the mixture, although sprinkling the coarse aggregate stockpiles may be necessary during warm weather to provide evaporative cooling.

The batch plant should generally have provisions in place for efficient heating or cooling of the RCC. The low water content of RCC mixtures makes it difficult to adjust water temperature alone to heat or cool the concrete. Placing at night is often needed to reduce the mixture temperature. The addition of flake ice or liquid nitrogen to the mixture requires special provisions by the plant.

5.4 Transporting and delivering.—The RCC delivery system should be correctly sized for the placing rate. The delivery system should transport and place the RCC rapidly without excessive hauling vehicle travel on the lift surface. The delivery system should provide efficient access to all parts of the site. Designers should attempt to locate features, such as galleries, outlets, and instrumentation, where they will minimize interference with the delivery and placing process. If possible, the placement areas should be sized to allow hauling, placing, and compaction equipment to pass, and turn-around areas should be considered.

RCC delivery is usually by single batches in hauling equipment, by conveyor, or by combinations of both. A delivery system that eliminates hauling vehicles traveling on and off the lift surface is desirable to prevent lift surface contamination and deterioration. The most common method of transporting RCC to the placement is by conveyor. A conveyor system can be capable of continuous delivery of large quantities of RCC. The conveyor usually drops the concrete into dump trucks on the lift surface, which then deliver the RCC to the placement location. The transfer points on the conveyors can create problems when they become plugged, interrupting the delivery of RCC. Transfer points should be designed and maintained to avoid interruptions in delivery and minimize waste of concrete.

Methods of delivering RCC should minimize aggregate segregation. Conveyors should not allow segregation to occur at any location. The most important feature of conveyor systems is to have well designed baffles at transfer points to minimize segregation. Free falls are usually limited to 10 feet at the location where RCC is deposited, depending on the maximum size of the aggregate. RCC piles are usually limited to 3 to 4 feet in height to minimize segregation.

Surge hoppers or “gob hoppers” are necessary to provide supplemental storage of RCC and help prevent the RCC plant from stopping delivery. These may be located on the lift surface or at the batch plant. In some cases, the delivery equipment may use another waiting hauling unit as its gob hopper.

The equipment used for transporting and delivering RCC should minimize segregation, should not reduce workability or contaminate the lift surface, and should be capable of delivering RCC to the placement location within 15 minutes of mixing. Contamination of lift surfaces due to vehicles (such as trucks or scrapers) used to haul RCC from the plant to the lift surface should not be allowed. Methods of removing contamination from the tires of the haul vehicles by washing are required before reaching the lift surface, especially if bond on lifts is required.

5.5 Placing and spreading.—The common method of spreading RCC is by dozer. Laser-controlled systems for grade control have been used successfully on Upper Stillwater Dam and other projects. The RCC must be spread to the loose lift thickness required to produce a final lift thickness of 12 inches after compaction.

It is important that the RCC be transported, deposited, spread, and compacted within 45 minutes after the mix water contacts the cementitious material, or as determined prior to construction based on the anticipated temperature, humidity, and wind and sun exposure.

If some segregation occurs during spreading, the segregated aggregates are either removed or shoveled back onto the top of the spread surface prior to compaction.

5.6 Compaction of RCC.—Compaction and consolidation of RCC is important to obtain the required strength and density. When a concrete approach mix design is used, adequate compaction can be generally obtained in 6 to 8 passes with a 10-ton smooth drum vibratory roller. RCC lifts are usually compacted to a lift thickness of 12 inches. Lifts with thicknesses greater than 12 inches may not obtain adequate compaction in the lower portion of the lift and should be avoided. In areas inaccessible to the primary compaction roller, smaller equipment may be used. Smaller rollers, power tampers or plate vibrators may not be capable of compacting the full 12-inch thickness of the RCC. Lift heights of 6 inches are generally required when smaller compacting equipment is used. However, the number of lift lines in a structure should be minimized as much as possible and still provide RCC lift thicknesses that can be adequately compacted.

Good inspection and quality control are necessary to ensure the specified density. Measurement of field density is generally accomplished using a nuclear density gauge. This method allows field verification of the equipment used and the number of passes required to obtain adequate compaction, especially when smaller compacting equipment is used.

RCC should be compacted as soon as practical after the material is spread. Specifications will generally require compaction within 15 minutes of spreading and within 45 minutes of mixing. Lane edges should be compacted within 15 minutes of spreading, if an adjacent lane is not placed.

When compaction operations are interrupted prior to final compaction so that the RCC is left unworked for more than 15 minutes, is wetted by rain or allowed to dry so that the moisture content does not meet the specifications, the uncompacted RCC must be removed at the contractor’s expense.

Observation of the RCC during compaction gives an indication of the workability of mix. When RCC approaches full compaction, the concrete should exhibit slight plasticity as the roller passes over the RCC surface. Cement paste should fill all the voids as observed on the surface of the RCC. If the surface of the RCC remains stiff after additional roller passes, inadequate paste is present to fill all the aggregate voids and rock-to-rock contact will prevent further compaction. An indication of lack of workability of the RCC mix is crushing of the aggregate during compaction.

5.7 Lift surface preparation.—Depending on the design requirements, bond on lifts can be important for hydraulic structures constructed of RCC. Bond on lifts is an important design requirement when the following design objectives are identified: (1) the need to develop some tensile strength during earthquake loads, (2) the need to minimize water seepage through lift lines, (3) uplift pressures preventing RCC sections from meeting stability safety factors, and (4) sliding resistance for normal and unusual loads. Key factors that can affect bond between lifts include the time between placement of lifts, mix design, surface preparation, weather conditions, and the use of bonding mortar. To reduce the time between placements, placement rates of up to three lifts per day have been specified to improve the potential for obtaining bond on lifts.

The lift surface cleanup requirements are time dependent and affected by the RCC mix, weather, ambient temperature, and placing schedule. The surfaces of all lifts should be kept moist and free of standing or running water. Using the concrete approach and a mix with pozzolan, RCC lifts placed within 6 hours of the next lift generally require no special surface preparation on the RCC surface, because the concrete surface has not obtained its initial set. RCC will therefore obtain a good bond with the previous RCC lift if the placement is within 6 hours. The 6-hour time period is usually reduced to 4 hours if the mix contains no pozzolan, or if warm ambient temperatures exist during the time of placement.

Lift surfaces that have been cured between 6 and 48 hours or have been damaged by other activities are prepared as follows:

1. The surface shall be cleaned with vacuum equipment, air jetting, water jetting, or brushing. Water jetting or brushing should be followed by vacuuming or air jetting to completely remove laitance, standing water, and any remaining loose materials.

2. RCC that has not reached its initial set (usually within 6 hours from placement) or which is damaged by air or water jetting should be cleaned by vacuum equipment. Cleaning operations are required to be performed just prior to placing RCC or placing bonding mortar.

Lift surfaces older than 48 hours should be cleaned by high pressure water jet or by sandblasting, followed by standard cleanup requirements. A bonding mortar layer should be used in addition to preparation of the surface.

Existing concrete surfaces to receive RCC should be roughened and should be in a saturated surface dry condition. Specifications generally require that the RCC surface prior to placement of the next lift be saturated surface dry so that mix water will not be removed from subsequent lifts through absorption. Water needed for curing is discussed in the section on curing and protecting.

Bonding mortar can be specified in critical areas to improve bond on the lift surface even if the placement occurs within less than 6 hours. Bond on lifts is improved by a bonding mortar layer spread over each lift prior to the placement of the next lift, or by proportioning the RCC mix to provide a greater volume of cement paste than is required to fill the aggregate voids. Bonding mortar is usually placed in a layer ½ to ¾ inch thick just prior to the placement of the next RCC lift. The bonding mortar usually consists of 1 part cement to 2½ parts sand with enough water to bring the mortar to a broomable consistency. The maximum water to cement (W to C) ratio for bonding mortar should generally be 0.45 by weight. Bonding mortar must be covered by RCC before it is allowed to dry.

5.8 Contraction joints and crack control.—The current state of the practice for RCC design is to control temperature cracking with contraction joints. Contraction joints are installed by several methods. One method that has been used on several RCC construction projects is to create a crack or joint in the RCC by installing galvanized steel sheet metal into the compacted RCC lifts along a predetermined joint location. Figure 9 shows such an installation at Pueblo Dam. The galvanized steel sheets act as a bond breaker and crack inducer. The galvanized steel sheets have been inserted with a backhoe mounted vibratory blade or by jack hammer. Other methods include forming of the RCC and the installation of a bond breaker material, such as plastic sheeting. The type of bond breaker material used should be evaluated case by case.

5.9 Constructing galleries and drains.—The location of foundation grouting and/or drainage galleries is important in the construction of a dam. The location of the gallery can create a significant amount of interference in RCC construction and can essentially cut off the upstream area from the downstream area. If the gallery is located too close to the upstream face, it can limit the size of equipment that can be used. Several methods have been used to construct galleries or openings in RCC dams. Some methods have been developed to prevent interference with construction, such as the use of sand fill or timber blocking in lifts, which are removed after the RCC has gained sufficient strength.

Formed conventional (leveling) concrete and formed RCC are two typical methods of constructing gallery walls within an RCC dam. Precast concrete panels or formed reinforced conventional concrete have been used to construct the roof of the gallery. It is advisable to evaluate the potential stresses around openings due to construction and operating loads to determine if reinforced concrete is required. The gallery for the Santa Cruz Dam modification was formed with an inflatable form that was used to construct the reinforced shotcrete lining. The reinforced shotcrete, once it developed sufficient strength, was used to support the RCC construction. Smaller RCC dams, such as the Clear Lake Dam modification, have used a collector pipe instead of a gallery, through which drainage holes have been drilled from the dam crest.

5.10 Curing and protecting.—It is important that the RCC be continuously cured by keeping it moist for 14 days or until placement of the next lift. The required curing period may vary, depending on the mix design (cement and pozzolan content). Curing of RCC is usually accomplished with water and plastic sheets. The application of a curing compound is not an acceptable method of curing

Figure 9.—Installation of galvanized steel sheet at Pueblo Dam Modification.

RCC, because bond is usually required on lift lines. Methods and equipment used in water curing have included water trucks, stationary or portable sprinklers, perforated pipes or drip hoses, and hand held hoses with fog spray nozzles. During warm weather or when the lift placements are proceeding at a slow pace and the surface of RCC begins to dry, a fog spray should be applied to keep the surface moist until the curing period has ended or preparations begin for the next lift. Excess water should not be applied, which would change the concrete's designed W/(C+P) ratio. Any standing water on the RCC surface should be removed prior to placement of the subsequent lift. Vacuum trucks are often used to remove excess water.

The American Concrete Institute (ACI) *Manual of Concrete Practice*, "Hot Weather Concreting," ACI 305R-89, figure 2.1 (2004) provides excellent guidance on the effects of the temperature of the air and concrete, relative humidity, and wind velocity on the rate of evaporation of the surface moisture for conventional concrete. This information may be used to help anticipate potential curing requirements as temperature, humidity, and wind conditions change.

During cold weather placements, water curing is suspended if freezing temperatures are anticipated. The heat of hydration can allow RCC to be placed in cold weather if proper protection of the concrete is provided and the ambient temperature is expected to rise above freezing. The concrete temperature is verified by placing high/low thermometers underneath the insulating blankets. If the concrete temperature drops below the specified placement temperature underneath the blankets, concrete placements are suspended. When the ambient temperature is expected to drop below freezing for a prolonged time, the rock foundation also begins to draw heat out of the concrete. To maintain placement temperatures within the specified range and to keep the concrete from freezing, special measures may be required in these conditions. Measures should be considered, such as heating the aggregates and mix water, using insulating blankets or tenting and heating areas of previously placed RCC, and using conventional concrete at the foundation contacts to obtain earlier strength at locations vulnerable to freezing.

5.11 Testing and quality control.—

a. *Compressive strength*.—Compressive strength is determined by casting concrete cylinders and testing before and during the concrete placement stages, and by core drilling and testing following construction. Specifications usually require that 85 percent of all samples exceed the specified compressive strength during construction. Maintaining consistency in the batch plant during production is important to ensure that the specified compressive strength is maintained and construction variability is minimized.

Fabrication of test specimens is difficult for RCC, because it is too stiff to consolidate by rodding or internal vibrators. A standard test method for fabrication of RCC test specimens by Vebe apparatus is given in appendix B (ASTM C 1170-91). This method has been successful for almost all types of RCC mixes and has been used to consolidate 9-inch diameter by 18-inch high specimens with 3-inch maximum size aggregate (MSA). Specimens should be consolidated to their maximum density, provided this same density is achievable in the field. An alternate method for fabrication of test cylinders using a hand-held vibrating hammer is described by ASTM C 1435.

Compressive strength tests should be performed on test specimens which are representative of the mix. If a larger MSA is used (greater than 2 in.), the larger size fraction is often wet-sieved in order to compact 6- by 12- inch specimens. This usually results in a higher compressive strength than the full mass mix. If 6- by 12- inch specimens are used for mix design, the compressive strength should be increased proportionately so that the mass mix meets the design strength. It is recommended that some larger test specimens (diameter of specimen equal to three times the MSA) be cast to develop a correlation between the mass concrete mix and standard control cylinders. This also gives a better indication of the workability of the mix, because a 1.5-inch wet sieved mix has a higher unit mortar content and appears more workable than the mass concrete mix.

b. *Elastic properties.*—Elastic property testing (modulus of elasticity and Poisson's ratio) can be performed on strength specimens in compression by following the procedure in ASTM C 469 or with strain gauges. Test specimens can be obtained by casting concrete cylinders and testing before and during the concrete placement stages, and by core drilling and testing following construction.

Testing for creep parameters of RCC provides important information for large structures that will experience an increased loading almost immediately after placement due to rapid construction. The average placing rate at Galesville Dam exceeded 20 feet in height per week. When performing creep testing, it is important to test specimens that represent the actual mix design to be used in the structure.

c. *Density*.—There are two reasons to verify density. The first is to confirm the design assumptions for unit weight of the structure used in stability calculations. The second is an indirect assessment of the compaction of the lift and the compaction at the joint interface. Failure to properly compact the lower portion of the lift of RCC results in a low or no-bond situation for sliding stability and may result in significant seepage of water through the structure. An effective means of evaluating in-place density of RCC is with a nuclear gauge. It is emphasized that this method of testing is only an indirect means of evaluating compaction. Achieving the highest value for density may not necessarily result in achieving the greatest bond potential between lifts of RCC. A mix design that is wet of "optimum" from a density standpoint, will have a greater chance for developing bond, because it can be compacted closer to its maximum theoretical density. Cores obtained from Upper Stillwater Dam have shown that mixes wet of optimum had improved bond, due to reduced segregation and greater percent compaction.

A number of methods are available for density testing of both freshly mixed and hardened RCC. Care must be used when evaluating density results, due to inaccuracies of many of the test methods. It is preferable to determine the wet density of a test specimen, because this is closest to the in-place condition of the RCC. Dry density testing is not recommended unless the actual batch quantities of materials and the absorption and moisture content of aggregates are known. This is because oven drying for moisture determination often provides erratic results.

The density of fresh concrete can be determined from a vibrated sample such as the Vebe test sample. It can also be obtained from compacted test cylinders; however, the sample size produces greater variability, particularly if wet-sieving is used. After concrete has gained adequate strength, density testing of core drilling samples can be performed.

In the field, the wet density of RCC is determined with a nuclear density gauge. It is necessary to recognize that test results from the nuclear density gauge are affected by gauge geometry and calibration errors. A single probe gauge averages the density of RCC from the source at the bottom of the probe to the detector in the gauging housing. The density obtained is heavily weighted to the upper two-thirds of the lift of RCC, where compaction is easily achieved. Low density RCC at the bottom of a lift is not easily detected, even though it is the most critical area. For this reason, a double probe density gauge is normally recommended.

A nuclear density gauge should not be used for moisture determination, because it only measures the moisture at the RCC surface (for a single probe gauge) or along a 4- to 6-inch area adjacent to the probe for a double probe gauge. The moisture content reading is also affected by the presence of hydrogen in any form that could occur as a result of admixtures.

Use of a sand cone apparatus for testing density of fresh RCC is not recommended. Experience with this test has shown very poor results.

d. *Lift joint bond.*—Bond on lift joints is generally verified with core drilling and testing of concrete from RCC test sections or the actual RCC placements. Core drilling cannot be done on RCC until the concrete obtains a compressive strength of about 1,000 lb/in^2. Since the concrete continues to gain strength, bond on lift joints also continues to improve. A quality assurance program over a year after construction of an RCC structure may assist in determining the overall performance of the bonding on lift joints.

Bond strength is affected by several factors that involve mix design and construction details. These factors include compressive strength of the RCC, paste content of the mix, age of the joint if it is continuing to hydrate, degree of compaction of the RCC, and lift exposure and preparation methods.

The two primary methods of testing for bond strength are direct tension and direct shear tests. Slant shear and splitting tension tests are not recommended for bond strength evaluation, because it can be difficult to accurately locate the plane of the lift line on the test specimen.

e. *Thermal properties.*—Because of rapid construction and the lack of embedded cooling pipes in RCC structures, it is often necessary to investigate thermal properties of the mix. The adiabatic temperature rise test simulates the expected rise potential of the RCC mix. The adiabatic temperature rise depends on the cement plus pozzolan content of the mix. Because pozzolan generally generates approximately one-half the heat of cement on a pound-by-pound replacement basis, the total temperature rise may be reduced by a suitable pozzolan. It is important that the same cement and pozzolan contents be used in the test and the initial temperature is representative of the placing temperature during construction. Examples of temperature rise curves for different mixes tested by Reclamation are given in appendix D.

Other thermal properties include coefficient of thermal expansion, conductivity, diffusivity and specific heat. These properties depend upon the quantity and properties of the RCC constituents.

f. *Durability.*—The important factors in obtaining and improving durability in the concrete are concrete strength, consolidation, and air entrainment. RCC is not considered to be durable under freeze-thaw conditions unless some protection against saturation or use of air entrainment is provided. Because it is difficult to entrain air in RCC, other means of protection are generally considered. The use of a conventional, air-entrained concrete facing on the RCC is the most common method of dealing with severe freeze-thaw conditions. Other means of providing protection for the concrete include the use of precast concrete panels and adding a “sacrificial” thickness on the RCC face. This last method is not used if appearance of the structure is important.

Drying shrinkage testing may be useful to provide an indication of shrinkage potential and relative durability of RCC structures. This may be a consideration for dam facing, which is exposed to numerous cycles of wetting and drying.

Permeability testing of RCC has shown the RCC mass to be comparable to conventional concrete of similar composition. The major concern for permeability of RCC structures has been seepage on horizontal lift lines and through vertical contraction joints or cracks and not through the RCC itself.

g. *Workability*.—Material workability is measured with a Vebe test. Vebe times of 15 to 20 seconds are indications of adequate workability of the mix for compaction to the maximum theoretical density. These Vebe times also reduce segregation potential. For mixes designed with the conventional concrete approach, this test has proven effective. For drier mixes with lower paste contents designed with the soils approach, this test has greater variability. For the soils approach, the workability is verified visually.

h. *Consistency*.—The primary means of evaluating batch-to-batch consistency of RCC is with the Vebe test given in appendix B. This test indicates the batch-to-batch consistency of mixes and the working range where RCC should readily compact under a vibratory roller. For mixes designed similarly to conventional mass concrete, this test has proven to be effective. For mixes with lower paste contents, this test has greater variability. Mixes with a Vebe time in the range of 15 to 30 seconds have been found to compact readily in 4 to 8 passes with a vibratory roller.

i. *Segregation potential*.—Segregation potential was noted in several early RCC projects. Pockets of aggregates that segregated from the RCC mass can create areas of higher permeability and low strength. Segregation can be controlled by care during the depositing, transporting, and placing of RCC. Also, aggregates within the range of 1- to 2-inch maximum size aggregate can reduce the potential for segregation.

Use of an elephant trunk or tremie pipes to keep the concrete from separating as it drops from the conveyor, and maintaining the concrete piles less than 4 feet in height help reduce segregation. Small amounts of segregation that occur during a placement should be corrected by laborers removing and disposing of loose aggregates, or shoveling the aggregates to the top of the lift placement prior to compaction.

j. *Test sections*.—Test sections (or prequalification placements) are normally constructed at least 2 to 3 weeks before the commencement of RCC placement and are used as part of the quality assurance program to have the contractor demonstrate his capability to meet the specifications requirements. Test sections are generally included as a separate bid item. The primary purpose of test sections is to give the contractor an opportunity to verify the adequacy of the construction equipment used for transporting, spreading, and compacting RCC. A test section allows the contractor an opportunity to verify that he can handle the RCC without segregation, allows the adjustment of the RCC mix design, and allows the contractor’s personnel and inspectors to become familiar with the procedures and expectations for the end product.

The test section should closely simulate actual RCC placement operations, including mixing, transporting, placing, and compacting procedures. Test sections are generally 80 to 100 feet long and have a width matching the crest width of a dam or a typical lane width. The test section lift placements should also simulate the time interval between lifts expected during construction. The test section should be made accessible for coring, sawcutting, or other types of testing for at least 28 days after construction. The core is visually evaluated to determine if segregation has occurred, if compaction appears to be adequate, and to determine if bond has been achieved between lifts. This visual evaluation can be used to provide indications of the effectiveness of surface preparation and the use of bonding mortar to obtain bond on lifts. Core drilling and compressive strength testing can also be used to obtain quality control data on the material properties of in-place RCC and to verify design assumptions. The contractor may also be requested to demonstrate the installation of joints or crack inducers, forming techniques on vertical surfaces, and compaction techniques on edges of lanes or exposed surfaces. Test sections are sometimes incorporated into the final product if appropriate conditions exist.

Test sections have been very beneficial for all Reclamation RCC projects constructed to date. Test sections have allowed the opportunity to work out potential startup issues, rather than having those occur during the placement of the first lifts in the dam, which are generally the most critical to the dam's structural stability.

k. *Placement temperatures.*—The RCC placement temperature is extremely important for massive structures. If the placement temperature is too high in massive structures, the heat generation that follows could lead to thermal cracking as the structure cools, which could cause more cracking than what was estimated during design. It is recommended that a maximum placement temperature of RCC be specified, which will depend upon the anticipated temperature rise of the RCC, average site temperatures, and the contraction joint spacing. Sometimes, unanticipated delays in construction can lead to RCC placements in the colder or warmer months of the year than were originally anticipated. Specifications should address the potential for both hot and cold weather placements.

Placement temperatures of the fresh RCC are checked with a concrete thermometer to verify that the temperature is within the range specified. It is important that the placement temperature is checked periodically to ensure that the placement temperature meets the specifications. Temperatures are generally recorded at the batch plant and at the placement locations.

5.12 Reference.—

American Concrete Institute, *Manual of Concrete Practice*, 2004.

Chapter 6

Design of New RCC Dams

6.1 Site selection.—Site selection of a new RCC dam primarily focuses on economics of the site and adequacy of the foundation. The foundation issues relative to site selection are discussed in more detail in the foundation considerations section. Other site selection issues could include impacts to the local environment that would need to be evaluated by the National Environmental Policy Act (NEPA) compliance process, impacts to the local community during construction, and the haul distances for coarse aggregate and sand sources. A potentially unique problem for RCC dams, the site selection may be influenced by the cost of the development of access roads needed for construction equipment depending on the type of delivery system being considered, the steepness of the abutments, and the location of the batch plant. Other site-specific issues should be identified and evaluated during the planning process to ensure that the best dam site is selected.

6.2 Foundation considerations.—The foundation considerations for RCC dams are similar to those of conventional mass concrete gravity dams. Stability analyses are performed on the concrete structures and the foundation. Foundation stability is critical if the joints form blocks that are adversely oriented. Foundation stability analyses consider the orientation and dip angles of key joint sets, the friction angle of the joint surfaces, and the loads transferred into the foundation. Core drilling and testing may be needed if cohesion and sliding friction values used in the analysis are considered critical to the stability of the structure and foundation.

Investigations to determine the top of rock profile, depth of weathering, characteristics of rock such as jointing, spacing of joints, rock-quality designation, and material property data such as modulus of elasticity may be needed to determine the adequacy of the foundation. The strength of the foundation should be sufficient to support the structure without differential deformations or settlements that could cause undesirable cracking in the structure. Since dams are water retention structures, investigations may need to be done to determine if foundation grouting will be necessary and effective.

Foundation weathering is a key issue for foundation preparation. Generally, all weathered and more deformable rock is removed to obtain a foundation that provides a smooth deformation pattern. The design engineer would need to consider several factors for the preparation of the foundation, including the height of the dam, distribution of the loads and stresses, and how critical deformations and cracking would be to the performance of the structure.

Highly fractured and jointed rock could be a concern for foundation deformations if the fractures and joints are either open or filled with weak materials such as clay. Fault zones can also constitute critical areas requiring further investigation and treatment. In these cases, removal of weak, highly fractured foundation rock and replacement with dental or shaping concrete, and possibly consolidation grouting are typically performed.

Seepage or leakage through the foundation results in uplift pressures, which may also require removal or treatment of zones of fractured and highly jointed rock. Seepage through the foundation may be a concern in highly fractured and jointed rock, and foundation curtain grouting may be considered to reduce loss of reservoir water.

Cohesion or bond on the rock/concrete contact surface is generally necessary to improve sliding resistance on the foundation contact surface. Therefore, a clean foundation surface is required. This is usually accomplished using high pressure water jet equipment.

Abrupt corners or irregularities in the profile of the dam foundation can cause local stress concentrations that can crack the concrete. Localized excavation and shaping or dental concrete placements may need to be performed to remove any major sources of stress concentrations in the foundation.

Consideration should be given to the removal of overhangs that may make consolidation of concrete difficult. Usually, RCC lifts are limited to 12 inches to ensure proper compaction through the entire lift thickness. Leveling (conventional) concrete is considered on the foundation rock contact, when the irregularity and roughness of the rock surface make it difficult to properly compact RCC. The need for cohesion on the rock contact for sliding stability may also require leveling concrete. If leveling concrete is not used at the foundation contact, special attention must be given to ensure that segregation and rock pockets, or poor consolidation do not result in voids that can allow seepage at a critical foundation contact zone.

Bonding mortar has been used for bond and water tightness if the foundation contact is relatively flat or uniform. Bonding mortar or leveling concrete is also placed at the abutment/RCC contact as follows: (1) a layer of fluid "bedding" mortar is placed immediately ahead of fresh RCC. The interface voids are then filled and consolidated with the RCC by vibratory compaction equipment; (2) the leveling concrete is placed to a thickness of 6 inches to 1 foot just before the placement and compaction of the RCC.

During construction, water entering the foundation excavation through seeps or springs should be controlled and removed to prevent the RCC from becoming saturated with excess water. Excess water in the RCC placements will change the mix proportions and potentially prevent the RCC from obtaining the proper compaction and strength. Water content in excess of what is needed for hydration will cause a proportionate decrease in the strength of the concrete and may increase the potential for drying shrinkage. RCC is a no-slump mix, and too much water could affect the RCC's capability to support construction equipment loads, such as vibratory rollers and the other construction equipment. Excess water in the foundation will bleed up into subsequent lifts if it is not sufficiently controlled. French drains or sumps have been used to remove and control foundation water. French drains are then grouted and sumps are backfilled with concrete when no longer needed. Depending on the application and design requirements, the area of the french drains should be limited, especially if bond is required on the concrete/foundation contact.

6.3 Design considerations and methods.—The design considerations for a concrete dam composed of RCC are similar to the criteria for a conventional mass concrete dam. Since RCC dams have considerably more construction joints resulting from the lift lines, the primary difference in design would be in the assumptions and safety factors used to account for the uncertainty related to the bond on lifts.

The design of the dam and the mix design are integral. Generally, two different methods of designing the concrete mix for RCC can affect the design of an RCC dam. Reclamation generally uses the concrete approach, which consists of specifying clean concrete aggregates, cement (and pozzolan) content of about 300 lb/yd^3 and about 4 to 6 percent water content. The soils approach mix design consists of pit run aggregate material and generally requires 7 to 9 percent water content and higher cement content than the concrete approach to obtain the same strength values.

Pozzolan in the mix design is beneficial, because it tends to extend the set time and provide a plastic surface for the next lift. Pozzolan will lengthen the time when bond can be obtained between lifts without the need for additional cleanup and bonding mortar. Replacement of some of the cement with pozzolan will also reduce the total heat rise due to the heat of hydration. Pozzolan produces about half as much heat as cement during the hydration process. This reduces the maximum temperature attained in the RCC. This has the advantage of reducing thermal gradients at the exposed surfaces and minimizes surface cracking. Also, the stress-free temperature is lower. This minimizes the potential for long-term cracking in the mass of the dam and permits wider spacing of the contraction joints. Pozzolan also provides a more workable mix, which provides a better quality concrete. Pozzolan helps control or inhibit alkali-aggregate reactivity between the cement and aggregate, although usually the aggregate is tested for reactivity, and low alkali cement is used. Pozzolan is usually less expensive than cement. This may provide for some economy if a portion of the cement can be substituted with pozzolan, unless the total quantity of cement and pozzolan is small.

Bond on lift lines is a very important aspect of the design and construction of an RCC dam for both structural stability and seepage control. With the concrete approach, bond on lifts can be obtained with two methods. A bonding mortar layer can be spread over each lift prior to the placement of the next lift, or the mix can be proportioned to provide a greater volume of mortar than is required to fill the aggregate voids. For the second method, bonding mortar is required only when the lift line surface is considered a cold joint. Though a bonding mortar mix may increase the cohesive strength on the concrete lift line, some studies suggest that it may reduce the friction angle. Based on Reclamation experience, bonding mortar has provided significant benefit in terms of providing cohesion on lift lines without significant loss of friction.

a. *Shear stress and sliding stability analysis*.— Uplift is an important consideration in the stability of concrete dams and their downstream stilling basins. In addition, stability analyses may be needed on horizontal lift lines to evaluate the stability of the dam considering uplift loadings at various elevations above the foundation of an RCC dam. Drainage curtains in the foundation and internal drainage systems (in the dam) are generally incorporated into the design of concrete dams to reduce potential uplift pressures. Uplift calculations for Reclamation are based on the location of the drains, the elevation of the gallery, the presence of upstream cracking, the drain effectiveness, the width of the base, and the water surface elevations of the reservoir and tailwater.

Reclamation is transitioning from a criteria-based deterministic design approach into a risk-based design approach. Prior to adoption of the risk approach methodology, the criteria used in *Design of Gravity Dams* (Reclamation, 1976) recommended safety factors for the maximum allowable average shear stress on any plane shall be greater than 3.0 for usual (static/normal operating) loading conditions, 2.0 for unusual (flooding) loading conditions and 1.0 for extreme (seismic) loading combinations. In a foundation with intact rock, the factors of safety were 4.0 for usual conditions, 2.7 for unusual conditions, and 1.3 for extreme conditions. In a foundation with continuous joints, the factors of safety were 2.0 for usual conditions, 1.5 for unusual conditions, and 1.0 or greater for extreme conditions (Reclamation, 1976). The maximum allowable compressive stress in the foundation should be less than the compressive strength divided by the appropriate safety factors of 4.0, 2.7, and 1.3 for the usual, unusual, and extreme loading combinations, respectively.

For dam sliding stability, the shear strength and tensile strength properties of the in-place RCC are generally the main concerns. Usually, it is not the shear strength or tensile strength of the parent RCC but the strength along the lift lines and foundation that determines the stability of the dam.

The sliding factor of safety for shear friction is the measure of safety against sliding or shearing. The factor of safety should also be used to check the stability of the remainder of the partially cracked section after cracking has been included for the extreme (seismic) loading combination.

The sliding factor of safety, Q, is the ratio of resisting to driving forces as computed by:

$$Q = \frac{CA + \left(\sum N - \sum U\right)\tan\phi}{\sum V}$$

where C = unit cohesion
A = area of uncracked portion of section considered
$\sum N$ = summation of normal forces
$\sum U$ = summation of uplift forces
$\tan \phi$ = coefficient of internal friction
$\sum V$ = summation of driving or shear forces

This is a simplified approach, and finite element or other analysis could produce more accurate results. Values of cohesion and internal friction may be determined by actual tests of the foundation material and the concrete to be used in the dam. The amount of cohesion used in design can vary, depending on the design requirements based on loading combinations, RCC mix design requirements, and lift line treatment. Cores were drilled at Upper Stillwater Dam to verify bond on lifts. The coring program was performed to minimize mechanical breaks on lift lines due to the drilling process. The results of this drilling program indicated that 95 percent of the lift lines sampled were bonded. However, it should be noted that the RCC mix design and construction procedures were established with bond on lifts as a design requirement. However, not all conditions will produce 95 percent bond, even if bond on lifts is a design requirement.

Any deviation from the approved construction materials or procedures can affect the dam's overall structural stability. For example, underbatching the cement during placement of a single lift of RCC, or failure to properly prepare a single lift joint, may limit the entire dam's sliding stability. Unfortunately, the influence of a single lift joint on sliding stability is greatest near the base of the dam, placed very early in the construction. This emphasizes the need for a test section to develop the proper batching and placement procedures before placing RCC in the dam (Reclamation, 1987).

For preliminary analyses and optimization of the dam shape where actual data are not available, it is best to assume a lower concrete density of 145 lb/ft^3 for the RCC. The actual density could be less than the standard 150 lb/ft^3 usually assumed for concrete. Air entrainment, if used, will reduce the density of the concrete. Assuming a lower concrete density in the preliminary design phase could potentially save major changes in the final design.

b. *Average concrete and rock properties.*—The following concrete properties are average values recommended in the preliminary analysis of the dam. Actual properties should be determined as soon as possible in the design process.

- Specified compressive strength, f'_c = 2,000 to 4,000 lb/in^2 in 1 year
- Coefficient of thermal expansion of concrete, α = 5.6 x 10^{-6} in./in./°F
- Density (unit weight) of RCC, γ_c = 145 to 150 lb/ft^3. The unit weight of RCC can vary depending on the constituents of the mix and compaction (see table 11).
- Poisson's ratio, ν = 0.20
- Modulus of elasticity of RCC
    - Static analysis ($E_{D\ Static}$) = 2,000,000 lb/in^2
    - Dynamic analysis ($E_{D\ Dyn}$) = 3,000,000 lb/in^2
    - Laboratory test data ($E_{D\ Lab}$) = 3,000,000 lb/in^2

  Notes:

    - $E_{D\ Static}$ = b E_{Lab} to account for long-term affects of creep
    - $E_{D\ Dyn} = E_{Lab}$; the dynamic modulus of concrete is being taken as the laboratory test modulus.

- Modulus of elasticity of foundation rock
    - $E_{F\ Static}$ is typically determined using an approach based on rock mass rating.
    - Foundation modulus can have a significant effect on the dynamic response of the dam when using finite codes incorporating dam/foundation interaction. Too low a value for $E_{F\ Dyn}$ can overestimate radiation damping. A preliminary value for $E_{F\ Dyn}$ should not be less than 0.8 $E_{D\ Dyn}$.
- Damping
    - Hysteretic damping of the dam = 0.10 (= 5% viscous)
    - Hysteretic damping of the foundation = 0.10 (= 5% viscous)
    - Reservoir bottom reflection coefficient = 0.8
- Splitting tensile strength (lb/in^2)
    - Static, 1.7 $f'_c{}^{2/3}$
    - Dynamic, 2.6 $f'_c{}^{2/3}$
- Shear strength on lift lines
    - Apparent cohesion, 50 lb/in^2 (over entire surface area)
    - Friction angle, 40°

Table 11.—Summary of Reclamation projects and the RCC mix design data

Application	Year [1]	MSA (inches)	Compr. strength (lb/in^2)	Density (lb/ft^3)	Water content (lb/yd^3)	Cement + pozzolan (lb/yd^3)	Sand (lb/yd^3)	Coarse aggr. (lb/yd^3)	Air content (%)	Fines [9] (%)	Water-cement ratio [5]	RCC volume (yd^3)
Concrete approach												
Upper Stillwater Dam (new RCC gravity dam)	1987	2	4000 [2] 4000 [2]	147.0 146.2	166 150	134+291=425 159+349=508	1148 1171	2231 2178	1.0 [7]	< 1	0.39 0.34	1,471,000
Santa Cruz Dam (RCC buttress for existing arch dam)	1990	2	3000 [2]	147.4	170	131+131=262	1227	2301	2.4 [8]	< 1	0.65	38,500
Camp Dyer Diversion Dam (RCC buttress for existing gravity dam)	1992	1½	3000 [2]	147.9	151	139+137=276	1264	2265	3.5 [8]	< 1	0.55	15,400
Cold Springs Dam (RCC spillway replacement)	1996	1½	4000 [3]	156.7	152	292+0=292	1562	2224	3.0 [8]	< 1	0.52	17,800
Ochoco Dam (RCC spillway stilling basin)	1997	1½	4000 [3]	150.8	218	434+0=434	1539	1881	0.6 [7]	2	0.50	19,000
Pueblo Dam (RCC foundation and spillway modification)	2000	2	3500 [2]	145.8	143	120+180=300	1410	2150	5.2 [8]	< 1	0.48	62,800
Many Farms Dam (RCC spillway replacement)	2001	1	4000 [4]	149.9	141	280+100=380	1400	2130	3.7 [8]	< 1	0.37	6,200
Clear Lake Dam (RCC replacement dam for existing embankment dam)	2002	2	3000 [2]	147.3	185	150+160=310	1338	2145	4.0 [8]	< 1	0.60	18,000
Soils or geotechnical approach												
Jackson Lake Dam (RCC upstream slope protection for embankment dam)	1988	1½	1220 [11] 1761 [12]	149	254	400+0=400	1340	2150	No data	6.8 [6]	0.64 [10]	44,900

[1] Year project was completed
[2] Specified compressive strength at 1 year
[3] Specified compressive strength at 28 days
[4] Specified compressive strength at 90 days
[5] Water-cement ratio includes both cement and pozzolan
[6] Average values
[7] Entrapped air
[8] Entrained air
[9] Nonplastic fines with maximum percent passing 200 sieve
[10] Water-cement ratio computed from total moisture and includes absorbed water.
[11] Based on average compressive test results at 28 days
[12] Based on average compressive test results at 90 days

c. *Allowable stresses.*—The compressive strength of the RCC is usually not of concern in the analysis of concrete dams. Typical compressive stresses induced in the dam are usually many times less than the actual compressive strength of the RCC. The main concerns are long-term durability of exposed RCC, and the tensile strength and shear strength properties of the lift lines. Specified compressive strength values are used for quality control during construction and to obtain adequate long-term durability, and are in direct relationship to the modulus of elasticity desired.

Tensile stress must be evaluated for each case by considering the location, magnitude, and direction of stress and the effects of cracking on the behavior of the structure.

Tensions in RCC dams are generally not allowed for the usual or unusual loading conditions. For extreme loading conditions, some tension is allowed in the dam. Note that this differs from criteria used in mass concrete dams, where tension is allowed for unusual loads. The tensile capacity of an RCC dam will depend on the bond strength of the RCC lifts, and the overall compressive strength of the RCC. The tensile strength of the concrete/foundation contact should also be evaluated. If the tensile stresses are not considered acceptable, the section of the dam is increased generally by flattening the downstream slope.

d. *Temperature analysis.*—Temperature loads are those loads applied on a concrete dam when the concrete undergoes a temperature change and volumetric change is restrained. When the movement of any part of the structure is restrained, a drop in temperature will cause tensile stresses. Dams have restraint conditions at the foundation contact and the abutments. Temperature analyses are performed to determine the contraction joint spacing, allowable joint opening for the RCC, and recommendations for concrete placement temperatures. Temperature studies also assist in estimating internal concrete temperatures due to the heat of hydration. Finite element studies can be performed to determine the long-term internal cracking and short-term surface cracking potential based on the resulting stresses from the analysis.

The computer program DAMTEMP uses theories developed in Engineering Monograph No. 34 (Reclamation, 1981) and combines parameters such as concrete thickness, diffusivity, ambient air temperatures, reservoir temperatures and solar radiation to reproduce effective mean internal temperatures usable in a finite element model (FEM) analysis. Three sets of data are required for FEM analysis to compute thermal stresses during operating conditions, (1) stress-free temperature, (2) seasonal variations of ambient air and reservoir temperature, and (3) the coefficient of thermal expansion. Thermal properties can be obtained from laboratory testing. Estimates of air temperature at a given site are usually based on historical records. Reservoir temperatures can be obtained from historical data on existing reservoirs near the site. The stress-free temperature is the temperature of the concrete when it solidifies. In RCC construction (without artificial cooling and grouting), it is the placement temperature plus the net heat rise due to the hydration of concrete.

Modeling temperatures at the concrete/foundation rock contact is difficult using FEM for several reasons. Estimating the thermal expansion and restraint of the foundation is difficult, since the temperatures within the foundation rock tend to be stable, and cracks near the contact of the concrete and foundation rock develop which tend to relieve restraint conditions. Linear elastic finite element analysis cannot account for this relief, and large stresses are usually generated in this zone.

Lowering the placement temperature reduces the maximum temperature attained within the dam, and therefore reduces the possible surface temperature gradients. Studies using FEM analysis have been used to investigate the time of year that would be preferable for RCC placements in order to reduce the maximum temperature attained, and thereby reduce temperature stresses within the dam. Placing concrete in the spring permits the interior concrete of the dam more time to cool before the first winter and reduces the possible surface temperature gradients. However, the total heat rise may be lower for fall placements, since curing is completed before the summer heat occurs. Surface cracking is most likely during the first winter of operation, since the RCC will experience the warmest interior temperatures. The first winter can cause the highest gradients ever imposed at the surface, producing the highest restraint and contraction conditions. As time passes, the interior cools, and surface temperature gradients are lower during subsequent winters.

Controlling thermally induced horizontal cracking on the upstream face of a dam is extremely desirable. This cracking reduces the stability of the dam by permitting increases in uplift pressures and reducing the tensile capacity in an undesirable location. Temperature studies can identify the appropriate placement temperatures and direct tensile strength across horizontal joints to eliminate this potential.

Long-term internal cracking in the RCC dam near the foundation contact, due to the restraint imposed by the foundation, can be minimized by further reducing the placement temperature. RCC near the foundation to a height equal to 20 percent of the block length established by contraction joints may require a lower placement temperature than the RCC higher above the foundation surface.

Allowable concrete placement temperatures can be estimated based on the estimated heat rise due to the heat of hydration of the concrete, predicted long-term internal dam temperatures, and the maximum recommended temperature drop to eliminate cracking. Maximum recommended temperature drops are listed in Engineering Monograph No. 34 (Reclamation, 1981), reprinted in table 12. This table shows the different recommended maximum temperature drops along the dam-to-foundation contact to inhibit longitudinal cracking. The maximum allowable concrete placement temperature can then be calculated:

Placement temp. = Lowest internal temp. +
Max temp. drop - Heat of hydration

Table 12.—Temperature treatment versus block length

Block length (ft)	Treatment		
Over 200	Use longitudinal joint. Stagger longitudinal joints in adjoining blocks by a minimum of 30 ft		
	Temperature drop from maximum concrete temperature to grouting temperature (°F)		
	Foundation to H=0.2L[1]	H = 0.2L to 0.5L[1]	H > 0.5L[1]
150 to 200	25	35	40
120 to 150	30	40	45
90 to 120	35	45	No restriction
60 to 90	40	No restriction	No restriction
Up to 60	45	No restriction	No restriction

[1] H = height above foundation; L = block length

The heat rise due to the heat of hydration in mass concrete is roughly estimated to be 15 degrees for each sack of cement in the mix. The heat rise due to the heat of hydration for each sack of pozzolan in the mix is estimated to be about half of that for cement but can vary. Adiabatic temperature studies are useful in determining the potential heat rise for a given mix design.

The thickness of the dam has a significant influence on the internal temperatures. Internal stresses are calculated after a dam has reached thermal equilibrium. This can be many years, depending on the size of the dam and other factors such as mix design. The winter condition represents the most severe long-term tensile condition in the dam interior near the foundation contact. Different stress-free temperatures by elevation can be evaluated.

e. *Methods to control temperatures in RCC.*—The most common method to reduce temperature stresses in the concrete is to control the placement temperature by precooling the concrete constituents or by using ice or liquid nitrogen. Spraying water on the aggregate stockpiles during the day for evaporative cooling, and using chilled mix water are commonly employed when needed. The use of flake ice or liquid nitrogen may require special modifications to the batch plant at additional expense. Since RCC has very little mix water, the benefits of using ice may be minimal. If feasible, construction should be scheduled so that the RCC is placed during a cooler time of year. Placing exclusively at night is required in warmer climates. Water cooling is sometimes required for exposed RCC surfaces after placement. Water applied to the exposed surface also has the advantage of curing the concrete and preventing premature drying.

Minimizing the heat rise due to the heat of hydration is an important consideration in the concrete mix design. The RCC mix design usually uses a low content of total cementitious materials and the replacement of cement with a large percentage of pozzolan (up to 70%) to reduce the initial heat rise.

Cooling coils have not been used in RCC, primarily because of the cost of installing cooling tubing, but they may be considered in the future as the state of the art of RCC construction continues to advance.

f. *Risk-based design approach*.—In recent years, there has been an increasing trend toward using probabilistic design methods for water resource projects. Reclamation has developed risk-based analysis methods to quantify the likelihood of the possible outcomes that may result from the various loads that a dam can experience, and to identify the most effective way to provide public protection over the full range of loading conditions. These methods are used when evaluating and modifying existing dams and appurtenant structures and when designing new dams and/or structures. Potential failure modes are established for normal, hydrologic, and seismic loading conditions having estimated annual probabilities of occurrence, and the structure response probabilities to these various loads are estimated to produce annual probabilities of failure for each failure mode. Risk is defined as the product of the likelihood of an adverse event and the consequences of that event expressed in terms of lives lost. The annual probability of failure addresses the public's expectation that Reclamation dams should not fail by evaluating the probability of an unintended release of the reservoir. Risk addresses the expected value of life loss expressed on an annual basis and represents the major component of societal risk. Protection of human life is of primary importance to public agencies constructing, maintaining, or regulating civil works.

To ensure a responsible performance level for all of Reclamation's dams, the estimated annual probability of failure for new or existing dams should not exceed 1 chance in 10,000 (or 0.0001), and the expected value of risk should be less than 0.001. The quantification of failure probabilities and risk estimates depends on data and analysis regarding the design, construction, and maintenance of a dam, as well as the identification of loads that the dam could be subjected to over its operating life. All of this information has some level of uncertainty associated with it. When significant uncertainties or assumptions related to a lack of data result in a broad range of risk estimates, additional data or analyses may be required. Risk estimates are often developed by a team having a broad range of expertise and may use Monte Carlo computer simulations and include sensitivity studies to determine a potential range for the risk estimate. Modifications to existing dams should include estimates of risk during construction, and risk reduction estimates compared to the existing conditions.

Both risk-based (probabilistic) and criteria-based (deterministic) design methods have an important role in Reclamation's decisionmaking process. Risk assessment is a diagnostic tool used throughout the evaluation, design, and construction process to help select an appropriate course of action. Design standards and criteria are used to ensure that the selected actions are well designed and implemented (Reclamation, 2003).

6.4 Dam configuration.—The configuration of the dam may be important if the dam is not straight or does not have a uniform curvature in plan view. If the dam is designed with a change in direction in plan view, this may cause some stress concentrations at the location where the direction changes, due to temperature expansion and contraction of the RCC. Abrupt changes in alignment should be avoided, if possible. If changes in alignment are required, contraction joints at these changes in geometry are desirable.

The maneuverability of construction equipment should always be considered when laying out the dam configuration. The top of the dam should have sufficient width to accommodate construction equipment. It may be necessary for the width to be sufficient to allow equipment to pass and turn around, or an additional turn-around area on the abutment may be needed. A minimum crest width of 20 feet has been used to accommodate construction equipment.

The downstream slope of the dam generally is uniform with possibly only one change to vertical near the top of the dam. The downstream slope is determined by structural requirements and generally ranges between 0.6:1.0 and 1.0:1.0. Slopes steeper than 0.8:1.0 may need to be formed, depending on the height of the structure.

6.5 Design details.—

a. *Leakage and crack control features*.—Seepage into and through an RCC dam, if left unchecked, will cause loss of reservoir storage, reduce stability from high uplift pressure, contribute to deterioration of the downstream face, and perhaps cause leaching of cementitious material. Methods of seepage control used in RCC dams include providing a waterproof membrane at the upstream face; using a conventional concrete facing cast monolithically with each RCC lift; using a special bedding mix or joint preparation procedure between the lifts near the upstream face; providing internal vertical drains near the upstream face from the crest to a foundation gallery; and constructing impermeable RCC joints (Reclamation, 1987).

The experience with cracking and leakage at Upper Stillwater Dam has shown that contraction joints should be used in RCC dams to control cracking. Depending on the height of the dam, contraction joints should generally be placed 50 feet apart or wider and at abrupt offsets or irregularities in the foundation surface. Spacing of the contraction joints will vary from structure to structure. Crack spacing and size will vary based on the mix design, concrete strength, placement temperature and ambient temperature variations, and other factors. Contraction joints should also include seepage control features such as waterstops, membranes, and drainage. The spacing of contraction joints will depend on the results of temperature studies to determine acceptable or desired joint opening. Unlike conventional concrete dams, RCC dams have been designed with crack inducers/control notches on the upstream and downstream faces of the dam as close as 10 to 20 feet on center. This design philosophy limits the opening of the cracks, and therefore limits the amount of the leakage through the cracks.

Seepage and crack control features are generally incorporated into the facing elements. Rather than allow a dam to crack randomly, contraction joints or crack inducers are formed in dams using several different methods. The most common methods include the use of a crack inducer consisting of galvanized steel sheet metal, or forming bond breaker materials into the RCC, such as plastic sheeting. Galvanized steel sheet metal was used for the Pueblo Dam modification (fig. 10) and at Clear Lake Dam on alternating lifts. Crack inducers are also used with formed conventional concrete on the upstream face of dams to provide a reduced section that will initiate a crack at a controlled location. These controlled crack or contraction joint locations allow the use of waterstops in the upstream facing elements or concrete. PVC membranes can be used on the upstream face of the dam, or incorporated into the precast facing elements, to form a water barrier. Formed drains are often included in the joint downstream of the waterstop to intercept seepage that may bypass the waterstop and direct seepage into the drainage gallery. Collector pipes can be used when the size of the dam does not allow

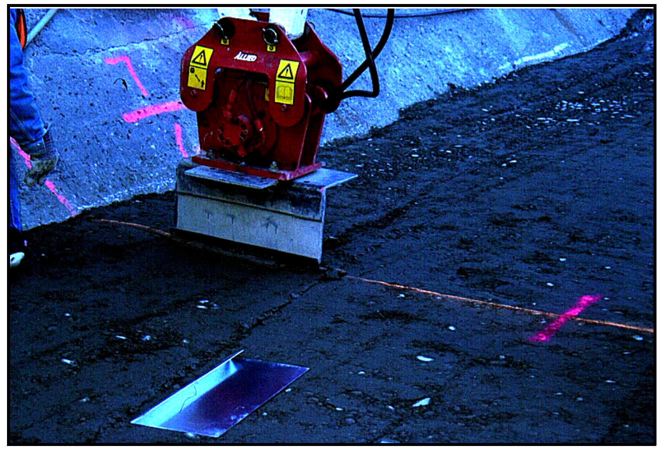

Figure 10.—Galvanized steel sheet metal installation at Pueblo Dam to create a joint with a crack inducer.

for the construction of a gallery. Even with cleanout features, the collector pipes have the potential to plug. In this case, the dam may need to be designed for full uplift pressures in the event that the collector pipes become plugged. Another method to create contraction joints, generally on the top lift of a structure, is to sawcut the RCC after it has obtained sufficient hardness and strength.

Foundation galleries are usually provided in RCC dams higher than 100 feet. These galleries may be constructed with conventional forms, horizontal slip-forming, or precast concrete panels, or by excavating preplaced, uncemented aggregates that have been placed along with the RCC. The foundation gallery is used first to construct the foundation grouting and drainage curtains, and later for maintenance of the drainage system and for internal inspection of the dam (Reclamation, 1987).

When the concrete in the dam begins to cool, the upper portion of the dam usually cools more quickly due to the reduced thickness at the top of the dam. Therefore, temperature cracking generally starts at the top of the dam. Foundation deformations and stress concentrations due to abrupt irregularities or discontinuities can also initiate cracking in a dam.

An internal drainage system consisting of vertical drill holes usually about 3 feet from the upstream face, and a gallery or horizontal collector pipe and outfall system can be incorporated into the design of the RCC dam to control seepage and divert the seepage water to a location downstream of the dam.

b. *Facing elements.*—Generally, the upstream face of an RCC dam is vertical and therefore has to be formed. The upstream face may also incorporate contraction joints and seepage control features, so that the upstream facing elements can act as an effective water barrier. Several different concepts have been used on RCC dams to provide a formed, vertical surface:

- *Precast concrete panels with a liner or membrane between panels placed on the vertical upstream face of the RCC dam*.—This is a common method of forming the upstream face and providing a continuous water barrier on the upstream face of an RCC dam. The precast concrete panels are anchored to the RCC with anchor rods. The liner or membrane is either preinstalled on the panels, or installed from rolls with the panels in place. Conventional concrete is usually used on the concrete panel/RCC interface since compaction is difficult at this location.

- *Formed conventional reinforced concrete placed on the upstream face of the formed RCC dam placements with waterstops at formed contraction joints within the conventional concrete*.—This is only considered for smaller dams because of the cost of this method, since it requires separate forming for the vertical upstream face of the RCC and then the conventional concrete overlay. Anchor bars drilled into the RCC may be required to support the reinforced concrete. The reinforcement can assist in the control of cracking and seepage. The reinforcement is stopped at the vertical contraction joints to allow for volumetric movement. Waterstops are generally used in the vertical contraction joints to accommodate the expansion and contraction of concrete. Horizontal construction joints will generally have reinforcement across the joint and may also include a waterstop. The thickness of the overlay will depend on the need to accommodate the embedded items, including reinforcement, waterstops, and anchor bars.

- *Formed conventional leveling or facing concrete*.—The conventional leveling or facing concrete is placed usually in 1-foot lifts against vertical upstream forms followed by the RCC. Contraction joints are provided at spacings of up to 50 feet, consisting of formed crack control notches with embedded ½-inch joint filler and possibly 12-inch PVC waterstops. Additional vertical crack control notches can be provided within the leveling concrete between the contraction joints to control temperature and shrinkage cracking expected in the higher-paste, exposed, conventional concrete mix. Spacing of these additional vertical crack control notches can be 10 feet. Bonding mortar can be placed on the RCC lift surfaces for a 5-foot width adjacent to the upstream face of the dam for improved bond and subsequent watertightness. In addition, bonding mortar can be used on the entire lift if it is considered a cold joint or if bond is needed on lift lines based on the structural design requirements.

  A procedure similar to this is generally the preferred approach for forming downstream facing concrete. The downstream face can be constructed as formed steps, which can be incorporated into the spillway design to assist in the energy dissipation.

- *Formed grout-enriched RCC*.—Grout-enriched RCC, sometimes referred to as GERCC, consists of placing unconsolidated RCC near the upstream and downstream forms followed by the addition of a grout mix that is vibrated into the RCC using immersion vibrators prior to RCC compaction (Forbes, 1999). The RCC lift is then compacted adjacent to and just overlapping the consolidated GERCC. Smaller compaction equipment may be necessary in the area adjacent to the forms and the GERCC. The GERCC method was developed in China in 1987, and since then, nearly all RCC dams in China have used this method. In 2002, a similar method was used at Olivenhain Dam (Reed, et al., 2003). The grout was placed before the RCC at Olivenhain Dam. The grout mix generally has a water to cement ratio of about 1 to 1 by volume (0.65 by mass excluding the water and cementitious materials in the RCC itself) and has a marsh cone viscosity of about 35 seconds. GERCC generally improves the appearance and durability of the upstream face of RCC dams and has comparable or improved compressive strength versus that of exposed and formed RCC faces. However, the upstream GERCC is not as durable as conventionally formed, air-entrained concrete in freezing and thawing environments.

- *Formed RCC with exposed liner or membrane*.—For this method, the RCC is formed and the liner or membrane is installed after the forms are removed or the RCC dam is completed. A liner or membrane would provide the primary water barrier. A richer conventional concrete mix is placed adjacent to the forms. Formed RCC can be an option, but the greatest concern with this approach is that it is extremely difficult to compact RCC on an upstream vertical face, because it is not possible to get vibratory rollers near the upstream face. The forms also have to be designed to handle the transfer of the load due to compaction and construction equipment. Compaction of RCC adjacent to the forms is typically performed with smaller compaction equipment.

- *Slipformed facing elements*.—A richer concrete mix may also be used near the upstream face with slipformed facing elements. It is very difficult to provide joints in slipformed facing elements. Because of the time required for the facing element concrete to gain strength, this method usually limits the placement of RCC to three lifts per day.

6.6 Streamflow diversion .—Streamflow diversion concepts for RCC dams are generally similar to those for conventional mass concrete dams. A major consideration in RCC construction is the placement operations and the economy in maintaining continuous placements from abutment to abutment. Therefore, the economy of diversion plans that split the construction site into two separate areas should be evaluated.

6.7 Appurtenant structures (spillways, outlet works, galleries).—Appurtenant structures, such as spillways, outlet works, and galleries, are generally incorporated into the RCC dam design in a similar manner to that of a conventional concrete dam. Avoidance of interference with the RCC construction is the primary economic consideration.

The top of the RCC dam can be utilized as an overflow spillway. This can be a major economic benefit for a concrete dam. A section of the dam is often designed with some type of overflow or ogee weir using conventional concrete, so that discharges can be optimized and can be reasonably estimated. Coefficients of discharge for the standard weir equation ($Q = CLH^{1.5}$) between 2.9 and 3.5 are fairly common in RCC dams. Steps can be incorporated into the downstream face of the dam as part of the spillway chute section to provide some energy dissipation and potentially reduce the size and cost of the stilling basin.

Conventional reinforced concrete is generally used to construct the outlet works openings through the dam. The intake and stilling basin structures are similar to those used in conventional concrete dams. When RCC is used in stilling basins, it is generally protected with conventional reinforced concrete.

Galleries are often considered a seepage control feature, since they are generally used to control internal drainage within the dam and control foundation drainage to reduce uplift pressures. The construction of galleries has presented some challenges in several projects. The key considerations with galleries or openings in the dam are to minimize impacts to the RCC placements, to ensure adequate compaction of the RCC in areas adjacent to the gallery or openings, and to provide support for the opening during construction.

6.8 Performance monitoring of completed RCC dams (instrumentation).—Reclamation establishes performance monitoring requirements for concrete dams based on an evaluation of potential failure modes, such as differential movements in the foundation and foundation rock instability including sliding, earthquake loadings, and increased loadings during a large hydrologic event. Internal erosion in soil foundations is generally not associated with concrete dams but could be a potential failure mode for other RCC applications. Reclamation establishes the monitoring needs of the facility and documents the key monitoring parameters for each failure mode and the expected behavior. Dam tenders or engineers then use this information to inspect the dam and monitor the instrumentation data. If data are found to be outside of the expected behavior, the conditions are immediately evaluated for dam safety.

Direct evidence of concrete dam foundation instability may be contraction joint offsets or cracking not associated with temperature variations. Visual inspections or data from joint meters, or measurement points could be used to detect evidence of movement. Increases or decreases in drain flows, changes in seepage flows, or changes in piezometer or observation well readings could also be indicators that the dam foundation is becoming more susceptible to sliding failure. Piezometer data are sometimes needed to assess the stability of the structure if uplift pressures increase above those estimated in design. Collimation, extensometers, or plumbline instruments are sometimes used in large structures to detect structural movements.

A thorough visual inspection of the dam and appurtenant structures is normally required following any earthquake producing strong shaking (ground acceleration estimated greater than 0.05g) at the site. All applicable data—which could include uplift pressure readings, piezometers, observation well readings, drain flow measurements, seepage measurements, extensometers, joint meters, collimation, and foundation deformation meter readings should be taken following an earthquake to identify any changes.

6.9 References.—

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Chapter 7

RCC Buttresses for Concrete Dam Modifications

RCC is frequently used for rehabilitating existing concrete dams. RCC has been used successfully to buttress concrete gravity, arch, and multiple slab or arch-buttress dams. The same economies that pertain to construction of new dams with RCC also apply to concrete dam modifications. Construction considerations may differ somewhat for rehabilitation of existing dams due to the presence of an upstream reservoir and its affect on plant layout, operations requirements, and construction scheduling. RCC is an ideal construction alternative, because large volumes of concrete can be placed in a short time, allowing the dam to resume normal operations more quickly. RCC has been used to buttress concrete dams for seismic and static structural upgrades, hydraulic overtopping, foundation erosion protection and stability, and upgrades to counteract deterioration and aging of the original structure.

7.1 Foundation considerations.—Foundation preparation for stability buttresses should follow current practice for new dam construction. As-built drawings, if available, should provide an estimate of the original excavated foundation surface. Removal of abutment overhangs should generally be by conventional mechanical methods such as, a hydraulic ram or jackhammers, rather than blasting, to prevent possible vibration damage to the existing structure. Controlled blasting was used at Gibraltar Dam in California to remove a large overhang about 65 feet downstream of the existing dam.

7.2 Stream flow diversion and foundation unwatering .—One of the first tasks for construction of a stability buttress is diversion and care of streamflow. This may be tied in with existing outlets or be a separate installation. At Santa Cruz Dam in New Mexico, a 2.5-foot diameter hole was drilled through the existing dam after the reservoir was drained, and the river was routed through this diversion outlet. The existing river outlets were removed and replaced after diversion was initiated. In many instances, extension of the existing outlet works will also serve for river diversion and reservoir releases. This may require the installation of temporary outlet pipes or flumes through the construction site that could interfere with RCC placements. Two elevated flumes were constructed for the Pueblo Dam spillway modification to bridge over the RCC construction and provide sufficient outlet capacity for required downstream releases.

Removing water downstream of existing dams may require sophisticated and/or extensive unwatering/ dewatering systems. It is essential to remove water to a couple of feet below the foundation level both for effective cleanup and for placing RCC. Upstream reservoir storage and dam foundation permeabilities will influence the quantity and duration of dewatering systems. At Santa Cruz Dam, a central dewatering well was all that was necessary for the dam foundation. Seepage through the dam and foundation was collected at this point and exited through a gravel drain. This drain was grouted after the RCC placement commenced. For Pueblo Dam's spillway, 60 well points were installed in the existing stilling basin drainage holes on 10-foot centers. Intermediate drain holes were plugged, and the well points were connected to a header system that was covered with conventional concrete. Two pumps were used to maintain the groundwater level below the stilling basin for the duration of the construction. Prior to construction, a stilling basin pump-out test was performed to estimate the quantity of water entering the spillway to help determine pumping requirements.

7.3 Design details.—Key considerations in the design of modifications that buttress an existing dam, such as the buttress design for Santa Cruz Dam and for Camp Dyer Diversion Dam in Arizona, are generally related to seepage and stress transfer at the interface of the two structures.

Seepage at the interface between the existing dam and a new buttress is addressed by providing perforated, split pipe, or flat drains to relieve any hydrostatic pressures that could develop between the two structures. The drains usually tie in to a manifold pipe or gallery system. The gallery system provides the advantages of accessibility for cleaning drains and monitoring seepage from specific locations in the gallery. It is often useful to understand the source of seepage and whether seepage is originating in lift lines, internal formed drains, foundation drains, or joints or cracks in the dam. At Camp Dyer Diversion Dam, pressure grouting of the existing masonry dam was required prior to buttress construction to improve its structural integrity and reduce reservoir seepage. A series of vertical flat drains spaced on 10-foot centers were provided at the dam/buttress contact to collect any remaining seepage.

Bond between the two structures may be an important consideration in a buttress-type modification, if the structures will need to act in unison when loads are applied. Contact surfaces should be treated as a construction joint in such cases. Consideration may also need to be given to adequate stress transfer from one structure to another. Concrete placement on a stepped surface may produce localized stress concentrations and cracking. An evaluation of the temperature load differences between the two structures may be needed to consider the temperature expansion and contraction and subsequent loadings that this may create.

Methods of concrete surface preparation include sandblasting, moderate-pressure water blasting, hydrobrooming (high pressure), and hydrodemolition (extremely high pressure). Low-strength, deteriorated concrete can be cleaned with sandblasting or moderate-pressure water blasting. The freeze-thaw deteriorated concrete at Santa Cruz Dam was cleaned to depths of about ¼ inch by 700-lb/in^2 water pressure. Any higher pressure water blasting would have removed considerably more concrete than was necessary. Higher strength concrete at Gibraltar Dam was sandblasted. The 6,000- to 7,000-lb/in^2 mass concrete at Pueblo Dam was successfully cleaned with 10,000-lb/in^2 high pressure water jets. Specifications usually specify that the aggregates be exposed or require a minimum roughness by specifying the number and amplitude of offsets per lineal foot and a method to measure the offsets. Water jetting or sand blasting a test surface before bidding can also be used to demonstrate the required surface preparation.

Multiple-arch buttress dams projecting into the RCC stability buttress may not require bond between the existing concrete and RCC. The original buttress elements of both Littlerock Dam in California and Pueblo Dam used a thick sponge-rubber bond breaker to purposely prevent bond between the two structures and allow for some differential movement.

Chapter 8

Design Applications for Embankment Dams

8.1 Overtopping protection.—In many cases where the probable maximum flood (PMF) has been updated, embankment dams have been found to be incapable of passing the design flood without overtopping. One solution has been to use the embankment dam itself as an emergency spillway by armoring the dam with a concrete cap using RCC. Figure 11 shows Vesuvius Dam following RCC placement. Depending upon the site conditions and discharge requirements, the entire length of the embankment dam can be used as an emergency spillway, or the crest of the dam can be lowered and a selected portion of the embankment can be used as a spillway. There are numerous case histories of RCC being used for overtopping protection of embankment dams. The U.S. Army Corp of Engineers has used RCC overtopping protection on embankment dams including North Fork Toutle Dam near Castle Dale, Washington (1980), Barker Dam near Houston, Texas (1988), and Butler Reservoir near Camp Gordon, Georgia (1992). Of the many dams that have overtopping protection, at least two have experienced significant flows and two others have passed smaller flood flows. The RCC structures at North Fork Toutle Dam and Ringtown Dam No. 5 were designed as service spillways and have operated frequently. North Fork Toutle Dam was designed as a debris dam with no outlet works and operated continuously for 11 months. In addition, the Brownwood Country Club Dam near Brownwood, Texas (1984) has been overtopped several times with a maximum flow depth of 1 foot. Thompson Park No. 3 Dam near Amarillo, Texas has experienced minor overtopping of 1 inch in depth.

Figure 11.—Overtopping protection at Vesuvius Dam during construction.

An RCC overlay for overtopping protection is commonly placed in 8-foot wide lanes with a 1-foot thick lift height. This accommodates normal construction equipment and provides an effective 3-foot thickness normal to the slope for a typical dam having a 2:1 (horizontal to vertical) downstream slope. Lanes wider than 8 feet may be needed to provide additional weight if required in the design for uplift pressures during overtopping.

Several key issues need to be considered in the hydraulic design for dam overtopping protection. The design head, head drop, and unit discharge will influence the design of an RCC overlay. For depths of flow of 2 feet or less, hydraulic studies have shown that stepped spillways with 1-foot high steps can significantly dissipate energy and therefore reduce the size of the stilling basin. Erosion potential of the outlet channel will need to be evaluated, and a cutoff wall to the bedrock foundation may be required if erosion damage could be extensive. If a stilling basin is determined to be necessary, the type of stilling basin will need to be selected considering economics and energy dissipation requirements based on the erosion potential and downstream consequences. Abutments generally slope toward the river channel and funnel discharges into the river channel downstream. Abutments often need to be treated with concrete armoring for overtopping protection to prevent erosion. Hydraulic model studies may be required to gain an understanding of complex three-dimensional flow conditions that may result from overtopping a concrete-capped embankment dam.

Appropriate filter and drainage capability of the embankment with an RCC overlay on the downstream face is an important consideration. The purpose of drainage is to prevent the development of excess pore pressures that could cause uplift pressures to exceed the weight of the RCC. This uplift or jacking of the overlay could create voids beneath the overlay, differential settlement of the concrete, and/or cracking in the RCC. This condition could occur as a result of static conditions due to plugging of the internal drainage system, or during flood conditions due to a high phreatic surface within the embankment or a rapid loss of tailwater due to sweepout in the stilling basin. A filter and drainage blanket with a toe drain are common features beneath an RCC overlay. Additional drainage capability can be provided by using formed holes through the RCC or by drilling holes after the RCC has been completed, if appropriate filter material is in place beneath the RCC.

Another key consideration for the use of a concrete overlay such as RCC is the settlement potential of the embankment. Settlement is a concern because of the potential for additional cracking to occur in the concrete. Cracking may occur in undesirable locations, which may affect seepage in the embankment structure and also affect the long-term durability and performance of the concrete structure. Measurement points are frequently installed on an embankment dam for settlement monitoring. If settlement on an existing embankment structure has stabilized prior to the placement of the RCC overtopping protection, this would reduce the concern for cracking due to additional settlement. However, settlement could still occur due to the additional weight of the RCC or as a result of construction loads.

8.2 Slope protection on the upstream face of dams.—A coarse-grained soil-cement, which was the equivalent of a pit-run RCC, was used successfully for upstream slope protection at Jackson Lake Dam in Wyoming (1987-1989) (fig. 12). Soil-cement was used because an acceptable riprap source was not available within Teton National Park. Because of anticipated weathering and freeze-thaw deterioration, a portion of the thickness of the concrete was considered to be sacrificial. Therefore, sufficient thickness of concrete was provided for this purpose. At Jackson Lake Dam, an 8-foot wide lane with a 9- to 10-inch lift thickness was used.

Design considerations for upstream slope protection include the potential for pore pressure buildup due to rapid reservoir drawdown. At Jackson Lake Dam, the concrete slope protection was allowed to crack randomly. The spacing of the temperature cracks appeared to be proportional to the height of the dam. The crack spacing was 40 feet at the north end of the dam and as the height of the slope protection increased, the crack spacing increased to about 100 feet. The slope protection at Jackson Lake Dam has experienced weathering due to freeze-thaw action in localized areas with undercutting observed in some lift line locations up to 12 inches in depth. The damage at Jackson Lake Dam is considered minor.

Most of Reclamation's experience with upstream slope protection has been with fine-grained soil-cement at 14 embankment dams. Minor repairs were necessary at Cheney and Merritt Dams due to damage from wind-generated wave action and freeze-thaw cycles. The damage consisted primarily of broken and displaced, unsupported cantilever slabs formed as a result of the stair-step construction and weakly bonded lift lines (fig. 13).

8.3 Water barrier.—Concrete core walls have been frequently used in embankment dams, but few case histories exist of a core wall being constructed of RCC. An early form of RCC was used to provide the central impervious core for an earthfill embankment cofferdam for Shihmen Dam in Taiwan in 1960.

Adequate foundation would be one of the key considerations for a concrete core wall within an embankment dam. The foundation would need to be the equivalent of that needed for an RCC gravity dam. Since the footprint and the volume of material required for an embankment dam is fairly large, compared to that of a concrete dam, RCC dams generally have favorable economics, if an adequate foundation exists. Construction materials availability, and the economics of an embankment dam with an RCC core wall as compared to an RCC gravity dam, would also be key factors in the selection of the preferred alternative.

If adequate impervious material were not available, an RCC core wall could be used to substitute for a soil core. The primary function of an RCC core wall would be to serve as the primary water barrier and would therefore have to be designed to be relatively impervious. Bond on lifts would be a requirement with zoned filter materials downstream in the event that seepage would occur in joints, cracks, or lift lines. The RCC core wall could require contraction joints with waterstops or membrane material to prevent seepage through joints and cracks, although temperature variations within the embankment may be minimal.

Penn Forest Dam Modification is an example of a composite design with a new RCC dam acting as the upstream water barrier and the existing embankment dam buttressing the concrete structure. Penn Forest Dam, completed in 1998, is located near Bethlehem, Pennsylvania. It was the third largest RCC dam by volume in the United States at the time of its completion, with a volume of 380,000 yd^3.

8.4 Replacement structure.—When suitable foundation and economic considerations are present, embankment dams with dam safety deficiencies have been replaced with RCC dams. The key advantage is that the abutment waterways may be incorporated into the new structure, and the overall volume of the dam can be reduced, which can reduce the construction time and cost. Typically, the top of the RCC dam can be used as a spillway, which avoids the cost of the construction of a separate spillway structure. The outlet works can be incorporated into the concrete dam or taken through one of the abutments.

Clear Lake Dam in California was modified in 2002 by the construction of an RCC dam immediately downstream of the original embankment dam, which was then breached. The original left abutment side-channel spillway was retained, and a new outlet works was provided through the RCC dam within the original outlet works channel.

Figure 12.—Upstream slope protection at Jackson Lake Dam, Wyoming.

Figure 13.—Upstream soil-cement slope protection. Damage from weakly bonded lift lines and freeze-thaw cycles.

8.5 References.—

Casias, T.J. and A.K. Howard, *Performance of Soil-Cement Dam Facings—20-Year Report*, REC-ERC-71-20, Bureau of Reclamation, 1984.

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Chapter 9

Other Design Applications

9.1 Abutment spillways.—Abutment spillways are generally constructed when a new dam, such as an embankment or concrete arch dam, cannot easily accommodate a spillway, when economics determine the ideal location for a main or auxiliary spillway to be on the dam abutment, or when a new spillway is being added to an existing dam. Abutment spillways come in many forms, as do the spillway control structures. The focus of this discussion will be on open channel type spillways having relatively long lined channels and/or stilling basins. More detailed discussion of control structures is provided in the *Overflow weir* section of this chapter.

As with all RCC construction, the selection of RCC should be based on a combination of economics and the advantages of using RCC over other materials. It may not be economical to use RCC for abutment spillways that require a relatively low volume of materials. Other considerations include space limitations, construction access, configuration, durability, and material strength.

Small volumes of RCC may not be economical to construct because of the equipment involved in the construction. RCC construction requires equipment for hauling and processing materials, batching and mixing RCC, transporting, spreading, leveling, and compacting RCC, cleaning and preparation of RCC lift surfaces, and placement of bonding mortar and leveling concrete. The equipment needed for batching and handling of three separate mixes (RCC, leveling concrete, and bonding mortar), may not be cost effective on smaller projects. Space limitations of the site or small volumes of leveling concrete or bonding mortar may make it uneconomical to batch these separate materials on site. Often these materials are batched off site at commercial facilities.

a. *Leveling and conventional concrete*.—When practical, it is desirable to eliminate the need for leveling concrete. Leveling concrete can often be eliminated when analysis indicates that high contact strength between the RCC and foundation material is not necessary. Spillways constructed from RCC are generally more massive than those constructed from structural concrete. Often anchorage to the foundation is not necessary, and sliding resistance is high enough without bond between the RCC and foundation. In these cases, leveling concrete may not be necessary.

If an acceptable flow surface can be obtained from either formed or compacted RCC surfaces, conventional concrete facing may not be necessary. Protective conventional concrete flow surfaces can be eliminated if the RCC is strong enough to resist erosion. High strength RCC can be achieved with proper mix proportioning. RCC compressive strengths of 3,000 to 4,000 lb/in^2 are not uncommon. Although the surface of the RCC may not achieve high strength, even with forming or special compaction, RCC construction typically results in excess or sacrificial material. Once this sacrificial material is eroded, the remaining RCC can have adequate strength to resist erosion. This could eliminate the need for a reinforced concrete cap or overlay, provided the flow surface will not be subject to cavitation damage.

A conventional reinforced concrete flow surface may be required in stilling basins, as it was at Pueblo Dam (fig. 14). Often there is a great deal of turbulence and high pressures associated with the operation of stilling basins. This is especially true for plunge pools. Rapid pressure fluctuations can result in “jacking” pressures which can pry apart RCC lifts or can result in high, destabilizing uplift pressures. It may be necessary to protect the RCC with a cover of reinforced concrete that includes contraction joints and waterstops. Contraction joints may also be formed in the RCC.

b. *Bonding mortar*.—Bonding mortar (fig. 15) can help improve bond or cohesion between RCC lifts in spillways, and can reduce

Figure 14.—Leveling concrete used at Pueblo Dam at the interface between the existing concrete and the RCC. Note the surface preparation to develop bond between the existing and leveling concrete.

Figure 15.—Bonding mortar used to improve sliding stability below the spillway crest.

seepage through lift lines. Bonding mortar may also be necessary when there are long delays between lift placements. However, stress and stability issues are not the same for spillways as they are for RCC dam construction. Designers should evaluate the need for bonding mortar for each design.

In some cases, bonding mortar between RCC lifts may be eliminated. Analysis may show that cohesive strength is not required on the lift surfaces. If the RCC has a high pozzolan content, it may be possible to achieve bond without bonding mortar if placement rates result in subsequent lifts being placed in 8 to 12 hours or less. However, if pozzolan is not used in the mix design, bond between lifts may not be achieved for even these high placement rates. If needed, bonding mortar can be transported to the site from a commercial off-site plant.

c. *Drainage and stability*.—Since RCC is generally placed in 1-foot lifts, there are more lift lines or construction joints than for conventional concrete. Generally, conventional concrete spillways are steel reinforced, which tends to keep the construction joints, lift lines, and cracks tight, so that very little seepage will occur. This may not be the case with RCC. Lift lines have a potential to be unbonded or weakly bonded, and settlement, movements, or temperature stress can cause some unbonded or weakly bonded lift lines to open. These openings can not only reduce sliding and overturning stability of the section, but they can also increase the potential for seepage and piping of foundation materials through the lift lines, temperature cracks, and other cracks that may open without the benefit of reinforcement. It is important to provide underdrainage and filtering where needed to prevent piping. The presence of open lift lines or cracks can also result in stagnation pressures developing behind or beneath the structure during spillway operation. Drainage can help improve the overall stability.

Seepage can occur at the upstream end of the spillway when the RCC is exposed to reservoir water either by direct contact or through the foundation. Filtered drainage of the upstream control structure may be necessary to prevent piping of foundation materials and instability of the control structure and downstream channel. Drains can typically be placed against the foundation, and consist of slotted or perforated pipe or flat drains. Drains may exit through the RCC. Drains have been successfully installed by placing the drain on top of an RCC lift, securing it in the desired position, and carefully placing and compacting RCC above it. Reclamation has placed 6-inch round drains and 12-inch flat drains in this manner. Larger drain pipes have been encased in leveling or conventional concrete prior to RCC placement. If an RCC test section is constructed, it can be used to determine a workable drain configuration.

Drains may also be placed beneath and through the spillway chute and stilling basin. Six-inch diameter cross drains placed beneath the 3-foot thick chute invert at Cold Springs Dam also served as RCC crack inducers (see case history). It is important to filter the perforated drains to prevent piping of foundation materials. The filter material also prevents plugging of the drains during RCC placement. A well graded sand and gravel envelope can serve as the filter material. These envelopes can be easily placed in the bottom corners of each side of the chute and stilling basin excavation. These areas generally have more RCC material than needed for stability, so the drainage envelope may not require separate trenching beneath the base of the structure.

Although under some conditions, the RCC spillway can be constructed without contraction joints or crack-induced joints, and simply allowed to crack, in many cases uncontrolled cracking is undesirable. Due to the potential to develop piping problems and/or high uplift pressures beneath cracked RCC, controlled cracking, drainage, and seepage control measures should be considered. Many spillways have failed due to poor design details related to these issues. In many cases, RCC spillways are no different from more conventional spillways.

d. *Hydraulic considerations.*—Spillways constructed of unlined RCC will produce a rougher flow surface than for a reinforced concrete chute. The roughness should be taken into consideration during the hydraulic computations. Stair-stepped spillway chutes are possible in both formed and unformed RCC, as well as in faced RCC. Stair-stepped chutes, like the chute shown in figure 16, result in greater energy dissipation that can reduce the size of the stilling basin. As with all spillways, the type of stilling basin, if needed, is determined by a number of factors. Types of stilling basins and methods of design are well documented elsewhere. The main difference between RCC and conventional concrete spillways is that RCC spillways are typically trapezoidal in cross section.

If velocities are high enough, cavitation damage can become an issue. This is true for longer, steeper chutes. Stair-step design can be utilized to help reduce flow velocity and aerate the flow to reduce the potential for cavitation. RCC construction lends itself well to stair-step construction. If this is not practical, other methods such as air slots may be used to reduce cavitation potential. The chute may also be lined with conventional reinforced concrete.

Figure 16.—Stepped slope downstream from the spillway crest.

Shapes beyond horizontal or simple sloped surfaces, and large radius horizontal curves are generally not practical in RCC construction. Vertical, parabolic curves and sharp, horizontal angles are generally not practical unless formed in conventional concrete. Since survey control is required on each lift placed, simple transitions are most desirable.

e. *Construction.*—Construction of abutment spillways using RCC can be more difficult than the construction of more massive RCC structures such as dams and overtopping protection. In general, the space may be more limited on the abutments. Successful construction usually includes placement of RCC in the direction of the flow, although placement normal to the flow direction can be practical for wider spillway sections, where long runs can be made and equipment has room to maneuver. RCC construction is more cost effective when long runs of RCC can be made. This reduces the amount of time the operators spend maneuvering their equipment and increases the placement rate.

It may be difficult to place RCC on steeply sloping surfaces, and horizontal placements are more desirable. Generally, the compaction equipment is the limiting factor. Reclamation has placed sloping lifts on up to about a 14-percent grade at Ochoco Dam. Sloping placements may also be made in a stair-step manner. One-foot thick horizontal lifts can be terminated at different locations as placements proceed up the slope. Obviously, because of the short RCC runs, steep slopes do not work well when placing in the direction of the flow.

Figure 17.—Tight radius corners at the upstream end of a spillway chute.

When horizontal placements are made, edge slopes of 0.8:1 (horizontal to vertical) or flatter may be practical. Generally speaking, unformed RCC chutes can be constructed with trapezoidal cross sections having 0.8:1 or flatter side slopes. Vertical sides may be possible with formed or faced RCC. For wider spillways, horizontal placements made perpendicular to the flow can produce stair-stepped chutes on relatively steep slopes.

Each piece of equipment used on the site will have limitations in terms of maneuverability and ability to access construction areas. The equipment with the largest minimum turn radius will generally dictate the sharpest horizontal bend. Since the upstream end of most chute spillways is closed off with an upstream control structure, this may be the area of greatest concern. Tight radius turns may be required at the upstream end (fig. 17). Flexibility must be provided in the design to reasonably accommodate the anticipated construction equipment. Similar problems may exist in plunge pools and stilling basins where an end sill is needed.

Spillway chutes can typically be constructed with side slope widths that are at least as wide as one lane width for the equipment being used. Higher slopes may require wider placements for safety. Since passing of equipment is not possible on a single lane placement, areas where equipment can pull off the placement must be provided. It may also be desirable to limit the pieces of equipment on a single lane placement. Although spreading and compaction equipment may be necessary, the RCC delivery system is more flexible. On multilane placements, trucks or loaders may be used to deliver RCC. On single lane placements, RCC can be delivered by a moving conveyer or by a backhoe stationed above or below the placement.

Since most abutment spillways are constructed in relatively tight construction areas, with relatively steep side slopes, contamination of the RCC lifts can be a problem. Debris falling from the side slopes above the placement, or being tracked onto the placement by construction equipment can affect a significant area of the lift surface. Measures such as gravel ramps and protective filter fabrics may be needed to minimize contamination and cleanup effort.

9.2 Overflow weirs.—Overflow weirs constructed from RCC can include spillway control structures, dam overtopping control structures, stilling basin end sills, and control sections in large canals or channels. Most weirs constructed using RCC will be relatively long and massive. It is generally not economical to construct small overflow weirs using RCC unless RCC is being used for other structures at the site.

Construction of RCC is generally in 12-inch lifts, which results in more lift lines being constructed in RCC than in conventional concrete. Therefore, there is greater potential for leakage through RCC weirs. Additionally, due to the rapid placement rates of RCC, and the low paste content, lift lines are not always bonded as well in RCC as in conventional concrete. As a result, it is sometimes necessary to face RCC weirs with conventional concrete to provide a watertight barrier. This is especially true for spillway weirs where the reservoir is stored against the crest. Excessive leakage in cold climates can also lead to freeze-thaw deterioration.

Weirs that are used only occasionally and do not have water stored against them, or weirs that are normally submerged, may be constructed using RCC without conventional concrete facing (fig. 18). For these weirs, seepage is not an issue. RCC can often be constructed at lower cost when a reasonable volume is required and no other materials are involved.

Temperature cracking can be a problem for long weirs. Vertical temperature cracks can develop at regular intervals, or where section or foundation

Figure 18.—Small RCC weir in the Cold Springs spillway chute.

Figure 19.—Conventional concrete ogee placed over RCC.

stiffness changes. These cracks can result in seepage and piping issues. Techniques for constructing contraction joints can be used to control cracking. Waterstops, grouting, and other means for controlling seepage may be necessary. Overlay concrete can be used for waterstop installation.

Construction using RCC generally will not produce smooth, controlled, finished surfaces. Weirs produced from RCC construction are generally rough, broad-crested weirs. For some weirs, this is not an issue. However, for control structures such as spillway crests, it may be desirable to have a smoother, more efficient section. RCC weirs are typically capped with conventional reinforced concrete to produce more efficient flow surfaces. Sharp crests and ogee crests are possible when conventional concrete is used (fig. 19). Surface tolerances are also smaller with conventional concrete. It is often desirable to use a minimal amount of conventional concrete, and it may be necessary to anchor the concrete to the RCC for better stability.

Concerns related to stability occur for higher weirs or weirs with high heads. Uplift pressures between lifts of RCC, coupled with weak or no bond strength on the lift lines, can result in instability. The general concern is sliding or overturning on the lift lines or at the foundation level. Since weirs are generally not much wider (upstream to downstream) than one or more equipment lanes, they can tend to be less stable than RCC dam sections. It may be necessary to provide drainage, upstream seepage barriers, or reinforcement in the form of anchor bars or rock bolts to produce the desired stability.

Weir sections can be constructed using typical RCC construction methods. Relatively short weir sections may be constructed with formed vertical faces. However, higher weirs should have 0.8:1 (horizontal to vertical) or flatter slopes if they are unformed. Generally, unformed, sloping weirs will have stair-stepped surfaces. Special compaction can smooth out the stair steps if this is desirable. When the weir is capped with conventional concrete, it is possible to shape the stepped RCC surface somewhat to minimize the use of conventional concrete. This is typically done when an ogee crest is constructed over the top of the RCC using conventional reinforced concrete. The stair steps can improve stability, but the construction joint between the RCC and conventional concrete should be cleaned with a high pressure water-air jet to remove loose material and unconsolidated RCC. It may also be necessary to install grouted anchor bars to anchor the cap to the RCC.

9.3 Erosion protection.—Reclamation has used RCC for a variety of erosion protection measures. Stilling basins, plunge pools, chute structures, and canals can all be constructed from RCC when economics are favorable. Typically, the setup of the batch plant and aggregate preparation can be a sizable investment; therefore a reasonable volume of RCC is desirable in order to make this option economically beneficial.

Stepped flow surfaces, often associated with RCC, can be utilized to dissipate hydraulic energy and prevent erosion given the right flow range, head differential and purpose of the structure. Steps can be difficult to fully compact, since compaction equipment usually cannot be positioned at the extreme limits of the placement. Thus, multiple compaction methods, height limitations, formwork with supports, innovative compaction methods, or conventional concrete should all be considered, based on the quality and durability of steps that are needed.

RCC will normally result in a rougher surface than conventional concrete, depending on the RCC mix utilized and the specific equipment used for compaction. Roughness can be an important consideration, especially when RCC is used for long chutes or canal structures. Reclamation has not specifically studied surface roughness of RCC relative to hydraulic efficiency, since Reclamation applications have not yet dictated this need. However, a rougher surface would increase hydraulic losses and reduce the hydraulic efficiency of a canal structure, compared to a conventional concrete lining.

9.4 Dikes and cofferdams.—Dikes are generally long, low structures with low heads, and are often used to supplement the main dam at a site where a low saddle area exists. In some cases, dikes may be required for freeboard purposes only, in which case no reservoir loading would normally be applied. With generally reduced loads and associated consequences in the event of failure, reduced design requirements may sometimes be considered for dikes.

Reclamation prepared final designs in 2002 for a 444-foot long, 20-foot high RCC tailrace dike at South Powerhouse on South Fork Battle Creek in California, for the Pacific Gas and Electric Company. This structure was to provide a barrier between a natural stream and a power canal. The RCC dike design featured a formed vertical face with a conventional concrete facing on the power canal side for improved durability, and an unformed 0.8:1 (horizontal to vertical) sloping face on the stream side to be buried beneath roadway fill. A minimum crest width of 10 feet for the RCC dike (for construction purposes) plus the roadway fill would provide a total roadway width of 20 feet along the dike. Design operating conditions would range from a full canal and low streamflow, with a maximum head differential of about 10 feet, to a drained canal and large (100-year) flood flow, with a maximum head differential of about 20 feet. Normal operating conditions would provide a power canal water surface about 5 feet higher than the stream. Since the structure would be partially buried and normally not subject to large differential heads, no contraction joints or special seepage control measures were included in the design, other than formed crack control notches in the exposed vertical face. In addition, a relatively low design strength (3,000 lb/in^2 at 1 year) and reduced lift bond requirements were adopted. A stepped spillway located at one end of the dike would serve as an emergency overflow for the canal, but would also allow for RCC construction equipment to turn around, thereby facilitating RCC placement. With a total RCC volume of only 15,000 yd^3, this design proved to be less economical than a mechanically stabilized earth (MSE) wall alternative and was not constructed.

Cofferdams are temporary structures used for retaining or diverting streamflow during the construction of a dam or hydraulic structure within a stream. The selection of an RCC gravity structure for use as a cofferdam would be largely based on the economics of a wide range of potential cofferdam alternatives, and should include the cost of removal of the structure when streamflow diversion is no longer required. Although RCC has not yet been used for a cofferdam on a Reclamation project, it is conceivable that an RCC test section could be utilized as a cofferdam, provided it could be constructed in the dry. The contractor often develops streamflow diversion plans for Reclamation projects, including cofferdam designs for approval by the Contracting Officer, so Reclamation does not generally design cofferdams. A very large RCC gravity structure was used as a cofferdam for construction of Three Gorges Dam in China. An RCC cofferdam was selected for Three Gorges Dam due in part to the large height requirement, limited space, and long construction period for the main RCC dam.

9.5 Gravity retaining walls.—Reclamation has not yet used RCC to construct large gravity retaining walls. The primary considerations for the use of RCC in large gravity retaining wall construction is the economics over conventional concrete construction. Gravity retaining walls were used on the Stacy Dam spillway, which is located on the Colorado River near San Angelo, Texas. The RCC was used to provide the interior mass of the gravity structures in combination with conventional reinforced concrete on the exposed surfaces.

9.6 Hydraulic structure foundations.—RCC may be used to provide a firm foundation for a reinforced concrete hydraulic structure in cases where a suitable structure foundation does not already exist. In order for RCC to be an economical alternative, the required RCC volume would have to be sufficiently large to warrant its use over conventional mass concrete. An evaluation should be made to determine whether anchor bars and/or underdrains would be necessary for foundation stability. Long-term temperature variations should be minimal in cases for which the hydraulic structure foundation would be normally submerged.

Chapter 10

Performance of Completed Projects

The state-of-the-practice of design and construction of RCC structures has continued to advance with each completed facility. The following Reclamation case histories summarize unique aspects of each facility and the lessons learned. Each case history includes background information, design considerations, concrete mix design, construction details, and conclusions. A summary of RCC mix design data for each of these projects is provided in table 10.

10.1 Upper Stillwater Dam (new RCC gravity dam).—

a. *Background*.—Upper Stillwater Dam, pictured in figure 20, was the first Bureau of Reclamation concrete gravity dam constructed with RCC, and at the time of its construction was the biggest RCC dam in the world. Upper Stillwater Dam is located on Rock Creek in eastern Utah, about 120 miles east of Salt Lake City, Utah. The dam has a maximum structural height of 292 feet, a hydraulic height of 185 feet, a crest length of 2,650 feet at elevation 8177.5, and a total concrete volume of 1,620,000 yd^3. The dam has a crest width of about 29 feet, a maximum base width of about 180 feet, and 4.5-foot high concrete parapet walls on both sides of the crest to elevation 8182. The upstream face is vertical, while the downstream face has a 0.32:1 (horizontal to vertical) slope from the crest to elevation 8100, and a 0.60:1 (horizontal to vertical) slope from elevation 8100 to the downstream toe of the dam. The reservoir has a surface area of 314 acres and a total capacity of 32,009 acre-feet at the top of active conservation capacity, elevation 8172. The reservoir is used to divert water through Stillwater Tunnel, and provides water storage for irrigation, municipal and industrial use, and recreation as part of the Bonneville Unit of the Central Utah Project. The reservoir generally fills quickly each spring, and remains full through the summer months, before being drawn down in the fall. In 1994, the dam's care, operation and maintenance responsibilities were transferred from the Bureau of Reclamation to the Central Utah Water Conservancy District, Orem, Utah.

Figure 20.—Aerial view of Upper Stillwater Dam, showing downstream face and seepage from cracks.

The upstream and downstream faces of the dam consist of slipformed concrete, while the interior mass of the dam consists of RCC, placed and compacted in 1-foot lifts using earthmoving equipment and a vibratory roller. The dam was constructed continuously from abutment to abutment without contraction joints or artificial cooling, which resulted in the development of thermally induced vertical cracks at several locations and leakage into the gallery and downstream face. Supplemental grouting was performed using both cement grout and polyurethane chemical grout, but was only partially successful, as significant leakage persisted at several cracks.

The dam is founded on relatively flat-lying Precambrian sandstone and quartzite. A thin continuous argillite interbed, termed Unit L, is contained in the lower sandstone unit, and underlies most of the dam. Sliding movements on this layer of about ½-inch in 1988 (during first filling) exacerbated the vertical cracking in some locations. Since the argillite layer does not daylight downstream, the movements were limited to closure of open joints in the rock mass and ended abruptly once the reservoir was filled. The downstream rock mass provides significant passive resistance against further movements. Washing of silty sand joint and bedding plane fillings into the foundation drains and gallery resulted in regrouting of most of the dam foundation. Grouting and drain remediation programs were performed in 1988-1989 and again in 1992-1993 to address the seepage and sand migration concerns. Minor washing of sand into the foundation drains continues. Some of this sand is washing through the cracks in the RCC from the backfill placed at the upstream face.

The outlet works is used to divert flows up to 285 ft^3/s from Rock Creek into Stillwater Tunnel, via Upper Stillwater Pipeline, and consists of a drop inlet intake structure at elevation 8010, a 72-inch diameter steel pipe and butterfly valve, two 54-inch diameter sleeve valves with upstream butterfly valves, and a 90-inch diameter precast concrete pipe. A small branch from the main pipe with a 16-inch diameter butterfly valve and a 14-inch diameter jet-flow gate provides downstream releases up to 29 ft^3/s to Rock Creek to meet minimum streamflow requirements.

The spillway, located in the central portion of the dam, consists of an uncontrolled overflow concrete ogee crest and a slipformed concrete stair-stepped chute with a hydraulic jump basin for energy dissipation. The spillway crest is at elevation 8172 and the crest length is 600 feet. The walls at each end of the spillway crest are streamlined to provide a smooth approach to the crest to avoid pulling air under the flow. The capacity of the spillway at reservoir elevation 8182.0 is 75,000 ft^3/s. Water flowing over the crest travels down 99 steps built in the spillway chute surface, which dissipates much of the hydraulic energy before the flow reaches the stilling basin. The 600-foot wide by 30-foot long stilling basin at the dam's toe stills the spillway discharges. The stilling basin floor, at elevation 7970.0, is constructed of unreinforced RCC.

b. *Design considerations.*—The final designs for Upper Stillwater Dam were performed in the early 1980s using currently acceptable analytical methods, and construction of the dam between 1983 and 1987 was generally consistent with current practices for RCC. The dam has performed well under a full range of reservoir operating conditions for over 15 years, despite the sliding movements during initial filling and continuing crack seepage. The sliding movements in the foundation have stabilized (resisted by the downstream passive rock mass) and the vast majority of foundation drain holes remain open to depths necessary to ensure foundation stability. Instrumented performance and visual observations to date indicate satisfactory conditions with respect to dam safety.

The dam was constructed without either contraction joints or internal mass concrete cooling. Temperature control for the dam's mass concrete consisted of placing the RCC at a temperature below 50 °F and by replacing cement with fly ash to reduce the heat produced during hydration.

The mix design requirements for the RCC included bond on lifts; compressive strength of 3,000 lb/in^2 at 1 year, tensile strength across lift lines of 180 lb/in^2, and 300 lb/in^2 shear strength. In addition, the mix design took into consideration the need for reducing thermal heat generation; durability of the concrete; and workability of the mix, so that adequate compaction could be obtained.

During the dam's construction, the spillway design was modified to pass a revised PMF (probable maximum flood), which required increasing the maximum spillway flow capacity from 15,000 ft^3/s to 75,000 ft^3/s. This was accomplished by increasing the hydraulic head on the crest from 3.5 to 10.0 feet. Modifications included adding 2 feet to the dam's height and allowing the maximum flood surcharge water surface to be the top of the parapets at elevation 8182.0.

c. *Concrete mix design.*—The specifications included concrete mix designs for leveling concrete, slipformed concrete, and RCC. Leveling concrete (a 2-inch slump concrete) with a design compressive strength of 4,000 lb/in^2 after 1 year, was used between the RCC and the foundation, abutments, and conduits. Slipformed concrete was used to form both the upstream and downstream faces. The design strength for the slipformed facing concrete was 4,000 lb/in^2 at 28 days, which was primarily to support the two-lift-per-day placement rate. The RCC used was a high fly ash, low water content concrete. RCC specifications called for 31 percent cement to 69 percent fly ash per cubic yard, with a water-to-cement, plus fly ash, ratio of 0.43. The fly ash in the RCC decreased the unit water content of the mixture, greatly increased the mix workability, provided long-term strength gain, and reduced hydration temperatures. The RCC mix was designed to yield a tensile strength of 180 lb/in^2, which resulted in a mix with a compressive strength of 4,000 lb/in^2 after 1 year.

Laboratory mix design studies were performed, followed by construction of an RCC test section near the dam site in 1981. A concrete coring program was performed on the test section to verify mix design assumptions. The results of these investigations were incorporated into the design and specifications. Two different RCC mixes were used in Upper Stillwater Dam. Mix RCC-A contained 425 lb of cement and flyash. Mix RCC-B contained 508 lb of cement and pozzolan and was used in a 14-foot wide lane placed against the upstream face of the dam. Since the upstream portions of the dam were more critical in obtaining the maximum density, a richer mix was used.

d. *Construction.*—Tyger Construction Company was awarded the contract for construction of the dam in December 1983. The total contract bid was $60,603,625. The bid price for RCC mix A was $10.40/yd^3 which did not include the cost of cement or pozzolan.

Extensive foundation treatment was required prior to placement of the RCC. The majority of the intensely fractured rock and rock with joint in-fillings was excavated and several fault zones crossing the foundation were excavated, filled with dental concrete, and then grouted below the dental concrete. Prior to placing leveling concrete, the entire foundation was consolidated by blanket grouting in 30-foot deep holes generally spaced 20 feet apart. Finally, leveling concrete was placed over the entire foundation, prior to any RCC placement, to form a good bond with the foundation rock and provide a level surface for the first RCC lift. A high-slump concrete was placed between the rock and the RCC, after the RCC was in place, on each abutment. Consolidation grouting of the abutments was completed after the dam was topped out.

The dam is located in the Uintah Mountains at an elevation of over 8,000 feet. The climate conditions at the dam allowed for an RCC construction season of only 5 months between May and October. RCC placements commenced in 1985, and the dam was completed in August of 1987 with over 1,620,000 yd^3 of concrete placed, including over 1,470,000 yd^3 of RCC.

The construction sequence required placing both upstream and downstream slipformed elements first, raising the outside faces 2 feet. Two feet of RCC was then placed and compacted in 1-foot thick layers continuously from abutment to abutment between the elements. A conveyor belt system was used to deliver the RCC to the placement. Two tremie tubes 30-inches in diameter were used at the end of the conveyor system to discharge the RCC into either of two haul trucks waiting beneath the tremie tubes. The RCC was deposited and spread by 16-yd^3 rock trucks. The end-dump trucks were equipped with a controlled gate to dump and spread the RCC in about 16-inch thick layers. A D-4 Dozer was used to fine spread the RCC. A laser system was used on the dozer to control the elevations of the placement within the specified tolerances. RCC was compacted to 1-foot thick lifts using a double drum, 15.6-ton vibrating roller in the interior mass of the dam. About four to six passes were needed to obtain adequate compaction of the RCC. RCC was generally placed between 8:00 pm and 12:00 noon to meet the RCC placement temperature requirements of between 40 and 50 °F.

For surface cleanup, a vacuum truck and a self-powered broom were used. For curing, a water truck with fogging nozzles was used. Peak production rates were about 800 yd^3 in a 1-hour period and about 10,000 yd^3 in 16-hour period. Both the upstream and downstream faces of the dam were constructed by extruding concrete using a conventional, horizontal slipform paver and a side-hung mold. The slipform paver traveled at about 4 to 8 linear feet per minute. The slipformed element/RCC sequence was then repeated until the dam was completed from the leveling concrete on the foundation to the conventional concrete slab at the dam's crest. The downstream slipform mold was equipped with a removable blockout, allowing it to transition from the sloping downstream face to the stair-stepped spillway face without stopping.

A single 6-foot wide gallery, with the gallery centerline located 20 feet from the upstream face of the dam, runs lengthwise through the dam from one abutment to the other. The purpose of the gallery is for observation of the condition of concrete within the dam, and to facilitate foundation drainage and grouting. The invert of the gallery is at two different elevations, elevation 7992 through most of the dam (lower gallery) and elevation 8042 at the left abutment (upper gallery). The gallery walls were constructed with elements similar to the elements used on the upstream face of the dam. The roof was formed by a 3-foot radius, half round corrugated metal pipe (CMP), covered with leveling concrete. A mat of reinforcing steel is embedded both above and below the gallery. Concrete-lined tunnels, referred to as abutment adits, extend 155 feet into the left abutment and 110 feet into the right abutment. These adits extend the gallery system to establish the grout curtain and drainage curtain in the abutments. The adits are located in the argillite material just above the argillite-sandstone contact.

After the RCC placements were completed, a single-row grout curtain was constructed from the gallery and abutment adits. Holes were drilled as deep as 150 feet into the foundation rock, inclined from vertical by 5 degrees upstream and by 30 degrees toward the nearer abutment. Downstream of the grout curtain, a drainage curtain was constructed from the gallery and abutment adits by drilling holes at 10-foot centers at least 75 feet below the dam. A gutter system in the gallery collects water from the foundation drains, and three 12-inch diameter steel pipes carry water from the gutter to below the water surface in the spillway stilling basin.

Following placement of the dam concrete, the spaces remaining between the sides of the excavation and the upstream and downstream faces of the dam were backfilled approximately to elevation 8000 with crushed sandstone waste from the production of aggregate for concrete.

e. *Conclusions.*—Due to the extreme climate conditions at the site, temperature loads on the dam are very severe. During the first winter after the dam's completion, the interior temperature of the dam was still high relative to the cold outside temperatures, and the entire dam was subjected to the ambient air temperatures on both exterior faces of the dam. This caused the exterior of the dam to cool much more rapidly than the interior of the dam, which initiated cracking at the crest of the dam. Some of the cracks extended in the upstream-downstream direction throughout the dam width and into the gallery. This type of cracking was expected and is not detrimental to the structural performance of the dam, but it is a continuing maintenance concern due to the resultant seepage. With a minimum reservoir pool now insulating the upstream face of the dam and with a cooler interior of the dam, the potential for additional cracking caused by temperature differentials has been considerably reduced in the years following the first winter. In addition to concrete cooling, reservoir loading and foundation deformation have contributed to crack development in the dam.

The most significant issue associated with continued operation of Upper Stillwater Dam is the continuing seepage through vertical cracks into the foundation gallery and from the downstream face. Total seepage from the dam is 9 ft^3/s. The cracks tend to widen during the winter months due to the colder concrete temperatures, which offsets the reduction in reservoir head due to the lower operating levels. Crack seepage is especially persistent at stations 25+20, 41+10, and 42+85. This seepage has significantly affected seepage measurement readings within the gallery, and at the two downstream seepage measurement locations. Seepage measurement weirs are replaced as necessary to maintain adequate capacities. Chemical grouting of the vertical cracks was initially successful. A gradual degradation of the chemical grout has occurred, resulting in a resumption of crack leakage back to pregrout levels. Various permanent seepage control methods have been investigated to seal cracks and reduce leakage. Internal stainless steel waterstops were installed in 2005 at the three locations where leakage is the most significant. Several of the cracks were also grouted with a hydrophobic single component water-activated polyurethane resin.

The more workable RCC mix designs resulted in excellent compaction at the lift lines and resulted in good bond strength. Tensile and shear strengths exceeded the design requirements of 180 and 300 lb/in^2 at 1 year, respectively. The 70-percent fly ash content was the highest fly ash content mix design for a concrete dam in the United States, producing long-term compressive strength exceeding 4,000 lb/in^2.

f. *References.—*

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McTavish, Robert F., *Construction of Upper Stillwater Dam*, ASCE Specialty Conference Proceedings—Roller Compacted Concrete II, San Diego, California, March 1988.

10.2 Camp Dyer Diversion Dam modification (RCC buttress for masonry gravity dam).—

a. *Background*.—Camp Dyer Diversion Dam is located on the Agua Fria River, approximately 35 miles northwest of Phoenix, Arizona, and less than 1 mile downstream from New Waddell Dam. The dam is owned and operated by the Maricopa Water District (MWD), and impounds a small reservoir for diversion of irrigation releases from New Waddell Dam to Beardsley Canal. The dam was completed in 1926 as a masonry and concrete gravity structure, having a 613-foot crest length and a maximum structural height of 75 feet. A smaller concrete gravity dike to the west has a 263-foot crest length and a maximum structural height of 25 feet. Irrigation releases to Beardsley Canal are regulated by five slide gates within a canal headworks structure at the left abutment of the dam. MWD had sealed two sluice gates within the canal headworks structure and a low-level diversion outlet through the dam. Outlet releases to the Agua Fria River from New Waddell Dam which exceed the 600-ft^3/s canal capacity

Figure 21.— Heavy equipment safely passing on 20-foot-wide lift (Camp Dyer Diversion Dam).

would overtop the dam and dike crest. Spillway releases from New Waddell Dam would enter the river below the dam.

b. *Design considerations.*—The construction of New Waddell Dam by the Bureau of Reclamation approximately midway between the original Waddell Dam and Camp Dyer Diversion Dam significantly reduced the storage capacity of the lower lake. In 1988, Reclamation agreed to increase the height of Camp Dyer Diversion Dam by 3.9 feet, to elevation 1445.0, to maintain the original storage capacity of the lower lake for potential peaking power development by MWD. The modified structure was to meet all Reclamation criteria for static and dynamic stability to help ensure continued diversion releases to Beardsley Canal and sufficient tailwater for operation of the river outlet works for New Waddell Dam. Stability analyses of the maximum section of the existing gravity dam under normal (full) reservoir and tailwater loads, assuming zero cohesion at the foundation contact, indicated that an internal friction angle of at least 45 degrees would be required for a sliding factor of safety greater than 1.0. The construction of a concrete buttress on the downstream face was recommended to increase the dead load and sliding resistance of the modified structure to provide a sliding factor of safety greater than 3.0 for normal loads and greater than 1.0 for the maximum credible earthquake. RCC was selected over conventional concrete for its relative economy and ease of construction. A buttress width of 20 feet with an 0.8:1 horizontal to vertical downstream slope was selected to accommodate two lanes of construction traffic on the RCC lifts for both the dam and dike sections (fig.21).

Figure 22.— RCC delivery from conveyor belt to front end loader on lift, near waiting dozer and vibratory roller (Camp Dyer Diversion Dam).

A conventional concrete block having a vertical downstream face was added to the narrow river channel at the maximum section of the dam below elevation 1390.1 to facilitate construction and reduce the overall concrete volume. The RCC buttresses were capped by a conventional, reinforced-concrete apron and ogee overflow crest to elevation 1445.0. At the request of MWD, an upstream wall was added along the dam and dike crest to retain normal reservoir levels and prevent potential sedimentation and algal development within the shallow approach apron. Although the conventional concrete had joints every 25 feet, no joints were specified for the RCC. The downstream face of each overflow crest and RCC buttress was stepped for optimum energy dissipation of the maximum 2-foot deep overtopping flow. The hard rhyolite bedrock at the downstream toe was sufficiently erosion resistant to not require a concrete apron or terminal structure. Pressure grouting of the existing masonry dam was required prior to buttress construction to improve its structural integrity and reduce reservoir seepage. Any remaining seepage would be collected by a series of vertical flat drains spaced on 10-foot centers at the dam/buttress contact. An abandoned 4- by 6-foot diversion outlet through the dam near the maximum section (invert elevation 1406.7) was to be extended through the dam buttress for possible future use by MWD. A $3 million contract was awarded to Commercial Contractors, Inc. in September 1991 for construction of the RCC buttresses and associated work.

c. *Concrete mix design.*—Reclamation specified all concrete mix proportions, with 275 pounds of cementitious materials per cubic yard of RCC, split evenly between cement and pozzolan, for the design compressive strength of 3,000 lb/in^2 at 1 year. A water content of about 150 lb/yd^3 produced an average "Vebe" time (per ASTM C 1170) of 13 seconds, to achieve the desired consistency. Concrete sand and coarse aggregate (1½-inch maximum size) were processed from alluvial materials along the Agua Fria River, located on Government property within 2 miles downstream from the damsite. Improved workability and durability of the exposed RCC was achieved by the addition of an air-entraining agent at a dosage rate of 2 to 3 times the dosage rate of conventional concrete having similar mix proportions, for a total air content at the placement of about 3.5 percent. Bonding mortar consisting of cement, sand, water, and admixtures was required on all lift surfaces greater than 8 hours old, to ensure adequate bond. Leveling concrete was a lean (2,500-lb/in^2) mixture from a commercial batch plant. RCC placement temperatures were limited to 75 °F, which required the use of ice and liquid nitrogen for the final placements in May 1992.

d. *Construction.*—The subcontractor, Granite Construction used an 8-yd^3 Johnson batch plant with a rated capacity of 150 yd^3/hr for RCC production. Fresh RCC was delivered by 10-wheel end dump trucks to a hopper, which fed a conveyor belt and radial stacker at the placement (fig. 22). The RCC was transported on the fill by either a front-end loader or end dump trucks, spread by a tracked D4 dozer, and compacted in 1-foot lifts by at least 6 passes of a 10-ton, dual-drum vibrating roller. Leveling concrete was placed by bucket or front-end loader to an average 1-foot width at the sloping rock abutments and at the contacts with the existing dam and dike immediately prior to RCC placement, and consolidated by internal vibration, to ensure adequate bond and compaction at the contacts. Lift surfaces were cleaned with a power broom of all laitance, coatings, and loose materials (fig. 23), followed by air-jetting and washing. The stepped downstream face was constructed using standard 1-foot curb forms, staked to the preceding lifts using steel pins and custom brackets, with external bracing as required. Flat strap tiebacks were utilized on the upper lifts of the dike buttress to support the forms. RCC was hand shoveled against the forms to minimize segregation and rock pockets, and compacted by a power tamper and plate vibrator. Surface repairs were generally not required following form removal. The first four lifts in the dike buttress served as the "prequalification placement" to demonstrate the contractor's proposed equipment and construction procedures. In-place, wet-density measurements were taken of each RCC lift using a single-probe nuclear density gauge, and were compared with the computed average maximum density (AMD) of the control section, initially established by the prequalification placement. RCC placements for the dike buttress were completed in February and March, with RCC placements for the dam buttress completed in April and May (fig. 24). A total RCC volume of 15,400 yd^3 was required for the dam and dike, at a unit bid price of $45.60 (excluding cement).

Figure 23.— Power broom for cleaning RCC lift surface (Camp Dyer Diversion Dam).

Figure 24.—Completed Camp Dyer Diversion Dam and Dike, from right abutment (flow left to right).

e. *Conclusions.*—Only Reclamation's third RCC project, this was the first to utilize exposed RCC at a formed face and is believed to be the first application of flat drains for internal drainage of a concrete dam (later to be utilized for modifications to Theodore Roosevelt Dam). Some innovative forming techniques were also employed for the downstream face and 6- by 8-foot diversion outlet blockout through the RCC buttress. Liquid nitrogen injection was successfully used for cooling RCC to meet placement temperature requirements. The incorporation of the prequalification placement into the final dike structure produced a cost savings without a detrimental effect to the project.

f. *References.*—

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10.3 Santa Cruz Dam modification (curved gravity RCC buttress).—

a. *Background*.—Santa Cruz Dam is a cyclopean concrete arch dam located about 25 miles north of Santa Fe, New Mexico on the Santa Cruz River. The dam was completed in 1929 and is 150 feet high. The curved axis of the dam has a radius of 300 feet and a crest length of 500 feet.

b. *Design considerations.*—The dam had some safety of dams concerns related to the maximum credible earthquake (MCE) and probable maximum flood (PMF). The dam was also experiencing severe concrete deterioration due to freeze-thaw. The New Mexico Interstate Stream Commission contracted with the Bureau of Reclamation to design the dam modifications to accommodate the MCE and PMF loading conditions and to replace the outlet works to improve reliability.

The dam modification (fig. 25) was completed in 1990. To address the seismic concerns related to the MCE, an RCC buttress was constructed on the downstream face of the dam. To address the

Figure 25.—Downstream face of Santa Cruz Dam under construction.

concerns related to the PMF, the entire dam was to be capable of accommodating overtopping and acting as a spillway. The portion of the dam with the 75-foot wide uncontrolled ogee crest was designed to pass 3,200 ft^3/s, which is approximately the 25-year flood. The stilling basin was designed assuming 75 percent energy dissipation as a result of the 2-foot high formed conventional concrete steps, which were incorporated into the downstream face of the RCC buttress.

c. *Concrete mix design.*—The requirements for compressive strength were based on the MCE loading condition. The design requirements for the RCC were a compressive strength of 3,000 lb/in^2 at 1 year, cohesion between new and old concrete of 50 lb/in^2 at 1 year, and freeze-thaw durability of 500 cycles. The design requirements were a compressive strength of 4,000 lb/in^2 at 28 days for conventional structural concrete, a compressive strength of 4,000 lb/in^2 at 1 year for facing/leveling concrete, and freeze-thaw durability of 500 cycles. Analyses were performed to determine the physical properties of the RCC and conventional concrete. Based on concrete testing, the cement and pozzolan content was increased to 255 lb/yd^3 from the initial mix proportion of 224 lb/yd^3. The mix proportioning investigation results and the material properties are shown on table 11.

Santa Cruz Dam modification was the first to use an air-entraining admixture to improve the freeze-thaw durability of the RCC. Laboratory and field cast specimens were tested for freeze-thaw durability and subjected to petrographic examination to evaluate the effects of air-entraining admixture in RCC. The air-entraining admixture improved the freeze-thaw durability by over 450 percent. Air entraining also improved the workability of the RCC, which allowed the reduction in the unit water content and a lowering of the net water to cement plus pozzolan ratio.

d. *Construction* .—Twin Mountain Construction Co., which is a Kiewit subsidiary, was awarded the contract with a total bid of $7.1 million. The bid price for RCC was $45.74 per cubic yard, which did not include the cost of cement. The RCC was placed in two phases. The pugmill was capable of producing 400 tons of RCC per hour. The batch plant was capable of producing both conventional concrete and RCC. In phase I, both the RCC and conventional concrete were produced on site. For phase II, the RCC was produced on site and the conventional concrete was produced by a local producer. The RCC was delivered to the placement location by a 380-foot conveyor. A Rotec swinger or a front end loader was used to deposit the RCC in its final location. A dozer was used to spread the RCC, and a vibratory roller compacted the RCC. The RCC was compacted to a 1-foot lift height. Leveling concrete was used around the perimeter of the RCC placement, so that adequate bond would be obtained with the existing dam concrete surface and the foundation rock. A minimum of six roller passes was required for compaction. Between phase I and phase II, the outlet works jet flow gates, butterfly valves, and 42-inch outlet pipes were installed. The access house and gallery also needed to be completed before the RCC for phase II could begin. When the placements became 15 to 25 feet wide, a crane with a 2-yd^3 bucket was used to place concrete. During construction, the lift placement rate was an average of four lifts per day. The steps for the spillway were formed by 4-foot wide by 2-foot high forms, which were anchored to the RCC with a two-tie and angle bracket. A total of 38,500 yds^3 of RCC was placed.

The original design for the gallery for the Santa Cruz Dam modification included an 8-foot radius, multiplate, corrugated metal pipe to form and provide support for the RCC. This forming system would need internal support. The contractor submitted a value engineering proposal, which was approved that used an inflatable form (Air-O-Form), which would provide the inner surface of a reinforced shotcrete shell. The inflatable form was inflated to the desired size using ¾-inch banding. The form was used in 60-foot long sections. The reinforced shotcrete, once it developed sufficient strength, was used to support the RCC construction. This forming system worked very well in this application because of the uneven and curved surface of the downstream face of the existing dam.

e. *Conclusions.*—Santa Cruz Dam modification was the first to use an air-entraining admixture to improve the freeze-thaw durability of the RCC, and the first use by Reclamation of RCC for a curved configuration against an arch dam. A unique inflatable form was used to provide internal support for construction of a gallery through the modified dam.

f. *References.—*

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10.4 Cold Springs Dam modification (new abutment spillway).—

a. *Background*.—Cold Springs Dam is an earth and gravel zoned embankment, operated by the Hermiston Irrigation District and administered by Reclamation. The dam was constructed between 1906 and 1908, and can store 38,330 acre-feet of water at the top of active conservation, elevation 621.5. This water is used for irrigation deliveries to northeastern Oregon. It has a structural height of 100 feet, a hydraulic height of 81.5 feet, and a crest length of 3,450 feet.

The original dam configuration included a side-channel spillway located on the right abutment. It had a 6-inch thick, lightly reinforced concrete liner, which was founded mostly on soil. The original spillway crest was 330 feet long at elevation 621.50. It was designed to pass approximately 6,000 ft^3/s of flow, which is much less than the required outflow to pass the PMF, which was a Reclamation requirement at the time of the modification. An 18-inch high concrete weir was added to the crest to provide downstream protection for up to a 200-year flood. The weir restricted the spillway discharge capacity, and would have caused overtopping during the PMF. Unauthorized storage to elevation 623.0 was also possible with the weir in place.

The original spillway discharge chute ended at a rock outcrop on the right abutment approximately 400 feet downstream and to the right of the toe of the embankment dam. A stilling basin was not provided, and flows from the spillway discharged down a steep slope that is underlain with basalt bedrock. A downstream cutoff to rock was provided to prevent head cutting. Flows entered the original stream channel (Cold Springs Wash) a short distance downstream from the slope.

The original spillway was found to have two potential failure modes. The first failure mode is caused by excessive uplift pressures beneath the original 6-inch thick chute slab. It was determined that a spillway discharge of approximately 300 ft^3/s could result in an uplift failure. This is primarily due to the lack of an underdrain system, coupled with a weak, lightly reinforced concrete liner.

The second failure mode was due to inadequate spillway capacity. Flood analyses for Reclamation’s Dam Safety studies indicated that the original spillway lacked sufficient capacity to pass the June general storm PMF, and the dam would be overtopped. Flows exceeding 6,600 ft^3/s would overtop the right inlet wall, and flows exceeding 9,000 ft^3/s would overtop the downstream chute walls. These conditions would lead to failure of the spillway.

A modification design was completed in 1994. Construction of the modification was completed in 1996. The modifications to the dam included an almost complete replacement of the original structure with a wider, more stable RCC structure. The modified spillway included improvements such as a shorter, more efficient crest and side channel, which discharge into a wider chute.

b. *Design considerations.*—RCC was used in the modified spillway to provide a more stable structure and help reduce construction cost. Comparing RCC to a reinforced concrete side-channel and chute, the two materials would be similar in cost if the structural concrete were only about 1 foot thick. However, it was believed that a

Figure 26.—Tight turn radius at the upstream end.

1-foot thick concrete chute would be unstable for the anticipated design flows. The design discharge for the side-channel spillway was 28,074 ft^3/s. High velocities (up to 45 ft/s) and the potential for high uplift pressures made the massive RCC construction more desirable.

The 3-foot thick RCC invert slab provides mass for increased stability. The 1.5:1 (horizontal to vertical) side slopes and 10-foot wide side slope lifts were configured to accommodate construction equipment. This results in an RCC thickness of approximately 5 feet normal to the slope.

High uplift pressures could develop beneath the original spillway, causing instability. An underdrain system beneath the crest, side channel, and discharge chute increases stability by relieving uplift pressures and reducing the potential for piping of foundation materials. The underdrain system consists of transverse perforated collector drains beneath the crest, and longitudinal perforated drains beneath the side channel and chute slabs. Nonperforated cross drains tie the collector drains together. The 6-inch perforated pipes are encased in an envelope of select filter material, which is wrapped in a geotextile filter fabric. This configuration was expected to require little or no maintenance. The design helps prevent piping of fine-grained foundation material in the foundation. Cross drains consisting of nonperforated pipe will provide alternate (redundant) flow paths if partial blockage does occur. The RCC lift lines were not expected to be completely watertight, and were expected to provide additional pressure relief. However, excessive seepage through the RCC, which could lead to piping of foundation material, would need to be avoided.

Crack control was considered in the design. The drainage system included 6-inch diameter HDPE transverse drains at an approximate spacing of 100 feet along the centerline of the chute. These drains reduced the cross sectional area of the 3-foot thick RCC invert slab sufficiently to induce cracking where they were installed.

Freeze-thaw and erosion resistance were required. This meant that unprotected RCC surfaces would be designed with relatively high strength. Anticipated high costs for forming or specially compacting the exposed RCC surfaces resulted in a sacrificial zone of RCC about 6 to 12 inches thick, where in-place densities could be lower than in the RCC mass.

Since the spillway was a side channel design, the upstream end was closed by wrap-around RCC (fig. 26). The original design was a typical rectangular section with sharp, angular corners. The specifications allowed for a radius to be formed in the corners. While the relatively sharp radius in each of the two corners would slow the construction, forming rounded corners was not believed to be as significant as attempting to form sharp, angular corners.

c. *Concrete mix design.*—Local materials were not available for the RCC construction. An extensive study of local sites indicated that a blended or pit-run mix was not practical. Therefore, materials would need to be imported from other sources. The mix was designed with conventional concrete sand and aggregates having a low fines content.

The mix was designed to provide a compressive strength of 4,000 lb/in^2 at 28 days for freeze-thaw durability and erosion resistance. There were no structural strength requirements except at the section below the spillway crest, which required 25 lb/in^2 of cohesive strength for sliding resistance during a full reservoir load. A ¼-inch thick bonding mortar was required between each 1-foot lift below the spillway crest and between each lift in the spillway invert.

Designers provided the contractor with the option of eliminating pozzolan from the mix. This was based on the limited space onsite for the batch plant. The contractor decided to use the no-pozzolan mix. The mix is provided in table 10 and table 11.

d. *Construction.*—The 18,000 yd^3 of RCC was placed in nearly horizontal layers of approximately 1-foot thickness having a maximum sloping grade of 2.5 percent. A commercial concrete aggregate was combined with approximately 300 pounds of cement per cubic yard.

The lack of pozzolan in the mix created some unique problems. The RCC hardened more rapidly than it would have if pozzolan were added. Each lift was hard by the time the next lift above was placed. Often laitance would form on the top of the lift prior to placing the next lift. The specified cleanup of the day-old lifts could not adequately remove all contaminants from the hardened surface. The hardened lifts did not bond well to subsequent lifts unless bonding mortar was used. With typical mixes, the lifts will bond well after 12 hours if 60 percent or more of the cement is replaced with pozzolan. However, this is too long if the cementitious materials do not include pozzolan.

Construction equipment included dump trucks, a backhoe with an oversized bucket, a dozer, a dual drum vibratory roller, and a small walk-behind roller for consolidating the edges of the placement. RCC was hauled to the site in the dump trucks, where it was deposited in temporary piles. The RCC was then placed in front of the dozer blade with the backhoe (fig. 27). It was spread in uniform layers by the dozer and compacted by the roller.

The 10-foot wide, 1½:1 (horizontal to vertical) chute side slopes were unformed. The dozer blade was retrofitted with side extensions that were in front of and normal to the face of the blade. The extensions helped confine the RCC to the specified placement width. A tamping plate was fitted below the right side blade extension. This plate had been set up to vibrate the RCC during the spreading process, but it was found to be more effective to fix this plate rigidly at a 45 degree angle from horizontal. As material was spread in front of and below the bottom of the blade the plate confined the material along the exposed edge of the chute. The resulting chute side slopes had steps consisting of horizontal benches and 1-foot high sloping faces (fig. 28). These sloping faces were fairly well compacted.

Figure 27.—Placing RCC with a backhoe.

Figure 28.—Completed RCC chute (Cold Springs Dam).

e. *Conclusions.*—Cleanup at 12 hours or more needs to have the same requirement as for conventional mass concrete, if pozzolan is not used in the RCC mix.

Unless the subsequent lift is placed immediately, bonding mortar needs to be applied to lifts, if bond is expected.

RCC can be placed over 6-inch diameter HDPE without protection, if care is taken to avoid damage.

Sharp turns are difficult to construct in RCC, but can be done if they are allowed to be rounded.

Compaction of the exposed sloping face is difficult unless it is done after compacting the horizontal lift. However, if a lower density material is acceptable on the surface, it can be done with an extension on the dozer blade.

f. *References.—*

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10.5 Ochoco Dam (spillway basin) .—

a. *Background*.—Ochoco Dam is located in central Oregon, 5 miles upstream of the city of Prineville, which has a population of approximately 5,000 people. The dam was originally constructed around 1920 and has undergone several modifications since then.

The spillway was modified in 1996 to address dam safety deficiencies, one of which was the lack of an energy-dissipating structure (stilling basin) (fig. 29). The spillway prior to modifications was a concrete, uncontrolled overflow structure, located just off of the left abutment of the dam with a 627-foot long, trapezoidal-shaped chute that tapers from 64 to 50 feet wide. The crescent-shaped spillway ogee crest had a length of 275 feet. Spillway flows discharge into an unprotected channel, which directs the flow back into Ochoco Creek. Subsurface field explorations near the downstream area of the dam revealed an artesian aquifer with approximately 70 feet of head beneath a confining clay layer. Large releases from the spillway without an energy-dissipating structure would cause erosion of the overlying confining layer. If this occurred, exposure of the aquifer would initiate piping of foundation material from the dam, resulting in dam failure. As a measure to address and reduce this potential, a stilling basin utilizing RCC was constructed in the fall of 1996. The stilling basin is a three-staged plunge pool type structure, which changes the flow direction approximately 45 degrees. The summary focuses on the RCC stilling basin added at the end of the existing chute.

b. *Design considerations.*—Unusual or unique conditions that were present at the site included:

- *Nonuniform foundation conditions*.—Ideally, a uniform foundation for the stilling basin was desirable. However, in this case the foundation for the left side slope and most of the floor was bedrock (John Day), whereas most of the right side wall was founded on newly compacted backfill.

- *A steep adjacent hillside*.—The left side of the stilling basin area consisted of a steep hillside, which dictated making the left RCC basin side slope as steep as possible.

- *An artesian aquifer*.—The underlying aquifer limited the depth of excavation that could be safely accommodated.

All conventional-type stilling basins were eliminated from consideration due to these constraints. In order to address these constraints, the size, shape, and configuration for the RCC stilling basin was arrived at by utilizing a scaled-down hydraulic model built at the Reclamation Water Resources Research Laboratory in Denver, Colorado.

A concern regarding a nonuniform foundation was that excessive or significant cracking would develop in areas of potentially highly dynamic flow conditions. Drains were placed under the structure to relieve uplift pressure and to pick up seepage through any future cracking of the RCC. The right side wall of the structure placed on the new backfill has not displayed any significant cracking after several seasons of operation, one of which included significant spillway discharges.

RCC was to be placed against the earth or rock foundation, and it was expected to have a zone adjacent to the RCC that would not be well compacted. Due to the steep hillside, engineers anticipated that the area of contact between the RCC and foundation would be “contaminated” due to the safety aspect of keeping away from the steep inner RCC slope.

The foundation for the RCC stilling basin can be divided geologically into two categories. The entire left side, most of the floor, and a small part of the right side was founded on the bedrock formation, identified as John Day. Most of the right side was founded on compacted backfill above the John Day. The downstream end of the floor for about the last 50 feet encountered soft alluvium, which was overexcavated and replaced with gravel material.

Configuration, slopes, and dimensions of the RCC stilling basin were simplified for ease of construction. Minimal conventional concrete was incorporated into the basin design to minimize costs. The pools drain freely after the spillway flows subside for public safety as well as to minimize freeze-thaw damage to the RCC.

c. *RCC materials.*—The contractor attempted to produce sand and coarse aggregates for the RCC from onsite material. Significant difficulties were encountered due to high clay content in the native materials. Eventually, the contractor abandoned his operations and began to purchase materials from quarries within 6 miles from the site. Eventually, several different sources were used for both sand and gravel. Since RCC operations are very fast moving and, in this case, were continuous around the clock, continually adjusting the mix proportions and/or getting inconsistent strengths was a common battle.

Cores were taken after completion and tested in Reclamation's Denver Office. Based on visual observations of the core, some areas showed excellent bond strength, while others showed minimal or no bond strength between lifts.

d. *Construction.*—Some of the difficulties encountered during construction were:

- Surveyors were subcontracted and used very little throughout excavation and placement of RCC. This resulted in shutting down RCC placement to make additional excavation and also resulted in difficulties in obtaining required slopes and configuration.

- Changing aggregates throughout the RCC placement resulted in inconsistent strengths and difficulties of recognizing when adjusting the mix was necessary.

Figure 29.—Aerial view of Ochoco spillway.

- *Batch plant for RCC mixing*.—The contractor chose a relatively low-end mixing plant, which did not meet specifications requirements. The plant was eventually approved, as the alternative would have been to delay the construction until the following year, which would have caused significant risk to the downstream residents and significant cost.

e. *Conclusions.*—The spillway modifications were started in July of 1996 and completed in March of 1997. Placement of approximately 19,000 yds^3 of RCC in the stilling basin took 3 weeks (placement on a 24-hour basis). Since some significant survey problems were encountered, the work was delayed. If things had gone perfectly, the RCC could have been placed in about 2 weeks.

f. *References.*—

Bureau of Reclamation, *Final Construction Report, Ochoco Dam Spillway, Crooked River Project, Oregon*, 1996-1997.

Stanton, Doug, "Ochoco Dam Spillway Modification Designs," *USCOLD Newsletter*, United States Committee on Large Dams, No. 111, March 1997.

10.6 Pueblo Dam modification (foundation stabilization).—

a. *Background*.—Pueblo Dam is located on the Arkansas River 6 miles west of Pueblo, Colorado, and serves as the terminal storage feature for the Fryingpan-Arkansas Project. The dam and reservoir provide storage for irrigation water supply, municipal and industrial water supply, flood control, and recreation. Construction was started in 1970 and completed in 1975. The reservoir contains 349,940 acre-feet at top of exclusive flood control pool, reservoir water surface elevation 4898.7.

The dam is a composite concrete and earthfill structure approximately 10,230 feet long at crest elevation 4925. The concrete section has a structural height of approximately 245 feet to the lowest point in the foundation, and a hydraulic height of 187 feet. The earthfill portions consist of the left and right abutment embankments totaling 8,480 feet in length.

1. *Concrete dam*.—The central concrete dam consists of 23 massive-head buttresses (fig. 30). This section of the dam has a maximum structural height of approximately 245 feet, but the top of dam is typically about 166 feet above the foundation. The concrete section has a crest length of 1,750 feet at elevation 4921, which includes a 550-foot long overflow spillway section and 1,200 feet of nonoverflow section. The top of the nonoverflow section contains upstream and downstream parapets to elevation 4925.25. The nonoverflow section includes 16 buttress sections spaced on 75-foot centers, and is supported on the downstream side by 18-foot wide concrete buttresses. The overflow section has 7 buttress sections, spaced on 78.5-foot centers, and supported on the downstream side by 21.5-foot wide concrete buttresses.

2. *Embankment dam*.—The embankment sections wrap around the left and right ends of the nonoverflow section of the concrete dam. These are zoned embankments, about 3,630 and 4,850 feet long, respectively, and include a 30-foot wide crest at elevation 4925. The left and right embankments have 3: l (horizontal to vertical) upstream slopes and 2.5: l downstream slopes. The upstream faces of the left and right embankment sections have a 3-foot protective layer of riprap over a 24-inch layer of bedding material. The downstream faces consist of zone 2 material, containing sand, gravel, and cobbles that were compacted in 12-inch deep layers. Each embankment section is cambered by up to 1.5 feet at the concrete section. The left embankment includes a stability berm that was completed in 1982. In 1998, filtered drains were installed downstream from the left abutment. They consist of a system of geotextile-filtered 4-foot deep trenches backfilled with gravel. These are located in the area of a “wet spot” or seepage exit area.

3. *Spillway*.—The spillway, within the central concrete section, consists of a 550-foot wide uncontrolled ogee crest at elevation 4898.7, downstream training walls, flip bucket energy dissipator, and a 550-foot wide plunge pool at the downstream toe of the dam. The original plunge pool was 80 feet long (upstream to downstream) at invert elevation 4710, which is approximately 31.5 feet below the spillway outlet channel, and excavated 45 feet below the buttress dam foundation. The original design discharge capacity of the spillway was 91,500 ft^3/s at the design maximum reservoir water surface elevation 4919. The spillway had never spilled prior to modification.

b. *Design considerations* .—Potential dam safety deficiencies were identified during the 1997 risk analysis and refined in later studies. Several recommendations for actions were made in the 1997 report, and actions were taken on those recommendations.

Because of the potential for sliding failure of the spillway foundation, modifications were completed in 1998. The modifications included filling in the stilling basin with an RCC “plug” to the downstream sill, elevation 4730, and constructing a 45-foot thick (horizontal dimension) RCC “toe block” against the upstream stilling basin apron. The new plunge pool is approximately 70 feet long with an invert at elevation 4730. The exposed RCC surfaces would be capped using reinforced concrete. Impact blocks would be constructed at the top of the plug to improve stilling basin hydraulics.

Reclamation assumed that a cohesion of 290 lb/in^2 (based on 85 percent of the surface being bonded) and friction angle of 45 degrees were possible on the RCC lift lines, based on the proposed RCC mix design. The Consulting Review Board (CRB) suggested that a safety factor of 3.0 be applied to cohesion. A design value of 95 lb/in^2 was considered appropriate using this safety factor. In most cases, Reclamation opted for a slightly more conservative cohesion value of 90 lb/in^2. The CRB also suggested a safety factor of 1.5 be applied to the friction angle. A value of 30 degrees was used. Safety factors for the potential foundation sliding surfaces, reinforced by RCC and rock bolts, were based on the CRB recommendations.

The RCC placements in the stilling basin were large (fig. 31). The original plunge pool was approximately 550 feet wide and 120 feet long in the upstream/ downstream direction. The RCC placed in the plunge pool would provide passive resistance against potential for sliding of the foundation. The large RCC placement would crack as it contracted during cooling. The RCC mass with open cracks would be weaker and more compressible when resisting foundation movements. Uncontrolled cracks in the RCC would also reflect through the protective, reinforced concrete overlay slab. Dynamic pressures induced from flows over the spillway could enter these cracks and cause damage. Therefore, cracking was controlled by installing contraction joints in the RCC, predicting RCC temperatures and joint opening with thermal analyses, and grouting the contraction joints after they opened.

High strength rock bolts were used to reduce potential tensile stresses that could develop in the toe block RCC. These rock bolts also provided additional active resistance across the assumed foundation failure surface.

c. *Concrete mix design* .—The design requirement for the RCC was a compressive strength of 3,500 lb/in^2 at 1 year. The initial RCC mix was based on concrete testing of materials from the local area. The cement and pozzolan content was 300 lb/yd^3 for the initial mix proportion of the RCC. The cementitious materials were comprised of 60 percent pozzolan and 40 percent cement. The water/cementitious materials ratio was 0.48. The average RCC mixture for construction is shown on table 11.

Figure 30.—Concrete portion of Pueblo Dam.

Figure 31.—RCC construction in the stilling basin at Pueblo Dam.

The starting mix proportions for the bonding mortar are:

Ingredient	Quantity
Water	410 lb/yd^3
Cement	915 lb/yd^3
Sand	2515 lb/yd^3
Admixture	Manufacturer's recommended dosage

d. *Construction.*—Some of the main concerns during construction included quality of RCC lift lines in the stilling basin area, compaction of the RCC in the toe block, finish tolerances of the sloping portion of the conventional concrete overlay, and the rockbolts placed through the apron.

The rock bolts were double corrosion protected, and consisted of 1 d -inch diameter high strength bars, grouted into polyethylene sheaths. Some rock bolts did not meet specification requirements, and the bars pulled out of the sheaths due to manufacturing problems and had to be replaced.

A February 18, 1999 site visit with RCC consultants raised concern related to RCC lift line bond strength. Testing was done after construction for evaluating lift line integrity. The designers evaluated the results from these reports. It is believed that some damage occurred below the lift lines when construction traffic was allowed on the compacted lift surface approximately 1 day after placement. A weak, somewhat porous zone within 2 inches below the lift surface was identified in the cores taken from the RCC in the stilling basin. It was concluded that the lift lines and the zones beneath the lift lines provide acceptable strength.

Some RCC lifts were placed the same day as the previous lift and were considered to be 12 hours or less in age, some were placed a day later, while others were placed 2 or more days later. Interestingly, the results of the 1-year shear tests indicate that a failure surface through the hydrostone surrounding the test specimen, where the hydrostone possibly contributed a significant portion of the measured shear strength, was most likely to develop in the 1-day old lift surfaces. These are surfaces where RCC was placed on the previous lift approximately 1 day later. The cause of this problem is not certain, but one theory is that the construction traffic on the previously placed lift line affected the lift surface. The curing may not have been adequate on 1-day old lifts to prevent damage from construction traffic, and yet the material was too brittle to absorb the deformation. The lift surfaces were also suspected of being too dry when the subsequent lift was placed due to windy conditions at the site. The rounded aggregates used in the RCC mix may also have contributed to the problem.

Although the use of front-end loaders was not excluded in the specifications, it is suspected that their use at Pueblo Dam contributed to the damage below the RCC lift surfaces. Front-end loaders were used to haul RCC from the south end of the stilling basin, where the batch plant was located, to the RCC placement. Intense traffic patterns developed along the lift surfaces in the RCC plug (below elevation 4728). The front-end loaders also have a sharp turning radius, and they were required to turn both at the south end, where they picked up their load of RCC, and at the placement, where they distributed their load in front of the dozer that was used for spreading. At both ends, this equipment was required to turn around. The lugged tires on the front-end loaders tended to damage the previously rolled RCC surface. Evidence that this may have occurred was revealed during a site visit to evaluate joint preparation for the overlay concrete. A variable surface was observed that could be related to construction traffic patterns.

Because of the low cement content compared to the pozzolan (approximately 120 lb of cement to 180 lb of pozzolan), the RCC would not gain adequate strength after 1 day to resist penetration by the lugged tires. The windy, dry conditions at the site tended to dry unprotected lift surfaces, and may have also contributed to the problems. Damage to the surface of partially cured RCC can result in loss of strength in partially hydrated cement paste and can loosen the compacted surface. Compaction of the lift above may not supply adequate energy to recompact the damaged lift below. RCC that is less than 12 hours old is still relatively plastic, and the hydration process has not advanced very far. After 2 or more days, the RCC may have developed adequate strength to prevent significant penetration of the lugged tires into the surface. Placement of bonding mortar on this surface (as required by the specifications) may have been enough to heal the minor surface damage that occurred after 2 days. Equipment other than front-end loaders was also used during construction. This equipment included dozers, vacuum trucks, transient mixers, dump trucks, cranes, and other vehicles used for construction. This equipment may have traveled on the surface during the critical time period within the first 48 hours, and could have damaged lift surfaces that were more than 1 day old when subsequent placements were made. However, cleanup efforts were more vigorous for older lift surfaces, so damaged RCC would more likely be removed on the older lift surfaces. Additionally, the type of tires and turning radius of this equipment was not as likely to result in damage as extensive as the damage produced by front-end loaders, which were most active on the day of a subsequent placement. The timing of the front-end loader traffic may explain why damage appeared to be deeper below the 24-hour lifts than the 2- or 3-day old lifts.

Exposed RCC surfaces were to be water cured and protected from drying. However, due to the length of time to place a lift, the lift surfaces may not have been adequately protected initially while a placement was ongoing due to the availability of the construction crew. The surface may have been dry when it was covered. The dry, windy weather at the site may have contributed to problems associated with surface drying. However, with 2 or more days between subsequent placement, the crews had time to apply additional water to the drying RCC surface. This may partially explain why older lifts seemed to experience fewer problems during testing.

A great deal of discussion has been centered around the use of rounded, coarse aggregates, instead of crushed aggregates at Pueblo Dam. A similar mix and construction conditions were used at Upper Stillwater Dam in Utah. However, the problems associated with a porous zone below the lift lines was not observed at Upper Stillwater Dam. One significant difference may be that crushed aggregate was used at Upper Stillwater. Two factors may come into play when round aggregates are used. First, round aggregate is smooth and may more easily separate from the paste during rolling. The lack of surface friction between the aggregates and the paste can also result in more damage from equipment travel. Another difference is that the Vebe times, which indicate the workability of the RCC, were similar for round aggregates at Pueblo and crushed aggregates at Upper Stillwater. However, because of the differences in the aggregates, the paste or fines content of both mixes could be significantly different. Therefore, the RCC mix used at Pueblo was probably dryer, with less paste than the mix at Upper Stillwater. The lower paste content could contribute to lower bond strengths between the paste and aggregate, and without adequate paste, any surface damage would be more pronounced.

e. *References.—*

Bureau of Reclamation, Technical Memorandum No. UB-8312-5, *Postconstruction RCC Shear Strength for Pueblo Dam, Fryingpan-Arkansas Project, Colorado*, 2001.

Bureau of Reclamation, *Design Summary—Pueblo Dam Modifications, Fryingpan-Arkansas Project, Colorado*, 2001.

Bureau of Reclamation, *Report of Findings, Pueblo Dam Modification, Fryingpan-Arkansas Project, Colorado*, 2002.

10.7 Vesuvius Dam (overtopping protection for embankment dam).—

a. *Background*.—Vesuvius Dam (fig. 32) is an embankment dam owned and operated by the U.S. Department of Agriculture, U.S. Forest Service. The dam is located in the Wayne National Forest in southern Ohio. The Forest Service built the dam in 1937 as a Civilian Conservation Corps project. The dam has a crest elevation of 614.0, is approximately 51 feet high at the centerline, and approximately 425 feet long at the crest. The spillway is an uncontrolled ogee side channel spillway, with a crest elevation of 603.0 and a crest length of 125 feet, located on the left abutment. The spillway design discharge capacity is 6,800 ft^3/s at reservoir water surface elevation 609.5. The outlet works consists of a 48-inch diameter reinforced-concrete-encased CMP, controlled by a 4- by 4-foot slide gate located upstream of the axis of the dam. The dam is classified by Forest Service standards as a high hazard dam, so the Forest Service indicated that Vesuvius Dam must safely pass the PMF, having a peak flow of 30,500 ft^3/s. This produced a hydrologic dam deficiency due to overtopping the dam for up to 7 hours by maximum depths of approximately 5.5 feet.

b. *Design considerations.—*The selected modification alternative was to armor the crest and downstream face of the dam with RCC and to allow the embankment dam to be overtopped without breach or failure. The modification also included rehabilitating the side channel spillway from the spillway crest through the spillway outlet channel with conventional concrete, and inspecting the outlet works for possible remedial work. The side channel spillway carries a significant proportion of flow. The existing spillway stilling basin is not designed for the maximum flows, so damage is expected at the stilling basin and in the downstream reinforced concrete channel.

One specific concern was the connection between the RCC and the existing spillway. A conventional concrete slab was constructed in this area to prevent construction and RCC loadings within 12 feet of the existing counterforted retaining walls.

Figure 32.—A view of Vesuvius Dam, Ohio, showing RCC armoring of the crest and downstream face.

There is a park with picnic shelters at the toe of the dam. To preserve the park-like setting, the RCC and the overtopping protection slab were covered by topsoil. During a PMF, the topsoil will wash away, leaving the erosion-resistant surface of the RCC and overtopping protection slab.

The dam foundation is composed of fine-grained alluvium and nearly horizontally bedded and interbedded sandstone, siltstone, and shale. The alluvial foundation consists of lean clay and sandy lean clay with lesser amounts of clayey sand and silty sand. Most materials encountered are considered impermeable or having a very low permeability. Permeabilities were higher in isolated locations. The sandstone is moderately hard, and fine to medium grained with fracture spacing ranging 0.1 to 1.2 feet and few to numerous shale partings. The embankment materials were similar to those found in the foundation alluvium.

Based on available geologic data, foundation grouting was not needed prior to RCC placement. The drainage for the RCC was designed to prevent uplift of the RCC slab both on the face of the dam and in the stilling basin. The design includes a sand filter and a gravel drain under the RCC, and three rows of a 6-inch diameter perforated PVC drain pipe, two on the face of the dam and one in the stilling basin. The PVC drains exit into the spillway and outlet works channels.

c. *Concrete mix design.*—The design requirements for the RCC and all cast-in-place concrete included a compressive strength of 4,000 lb/in^2 at 28 days. The initial RCC mix was based on concrete testing of materials from the local area. The cement content was estimated to be 350 lb/yd^3 for the initial mix proportion of the RCC. The specifications allowed the use of pozzolan, which could be substituted for 20 percent, by weight, of total cementitious materials. The initial mix proportions for the RCC included 194 lb/yd^3 of water, 1,700 lb/yd^3 of sand, 1,750 lb/yd^3 of coarse aggregate, and an air content of 4 percent. The sand and gravel in the drain and RCC sand and coarse aggregate were designed using ASTM C33 standards, with a maximum aggregate size of 1 inch. The sand was based on ASTM C 33, fine aggregate, with a maximum of 3 percent passing No. 200 sieve. The gravel was based on ASTM C 33, size No. 57. The properties of the drain and RCC sand and gravel were designed to be similar. The starting mix proportions for the bonding mortar were: 410 lb/yd^3 of water, 915 lb/yd^3 of cement, and 2,515 lb/yd^3 of sand.

During construction, the contractor proposed using aggregate conforming to Ohio Department of Transportation (DOT) Specifications 441 for the RCC instead of the specified aggregates, primarily due to the savings in cost. This also allowed the use of one aggregate stockpile instead of two. The U.S. Forest Service agreed to this change, as long as the RCC mix met the strength requirements. The Ohio DOT aggregate allowed a larger amount of fines (11 to 14 percent) in the mix. The cement content was also increased by 50 lb/yd^3 to meet the compressive strength requirements. Because of the high fines content, the mix became a soils approach rather than a concrete approach mix design. The specifications allowed the use of 20 percent of pozzolan. The contractor elected not to use pozzolan in the RCC mix. Air entrainment was also specified but was not used. The RCC mix proportions actually used consisted of 1-inch maximum size aggregate with 400 lb/yd^3 of cement, 194 lb/yd^3 of water, and 3,456 lb/yd^3 of aggregate.

d. *Construction.*—Reclamation designed the modification. The contract was awarded to T.C., Inc. of Indianapolis, Indiana, with a total bid of $3,702,866.80. Gears, Inc of Crested Butte, Colorado was the RCC subcontractor. The bid price for RCC was $94.65 per cubic yard for 9,500 yd^3 of RCC.

An Aran 200-t/hr continuous batching and mixing plant produced the RCC. Articulated, off-road trucks delivered the RCC to the placement location. A D5 dozer was used to spread the RCC. The RCC was compacted by 6 passes of a single drum, 5,000-pound vibratory roller, four static passes and two with the vibrator engaged. The RCC was compacted to a 1-foot lift height after a minimum of 6 roller passes. The upper third of the steps were unformed 1 foot high with a 1:1 compacted slope on the exposed face. The remaining edges on the lifts were compacted using a roller on a 2.5:1 (horizontal to vertical) slope.

Four test cylinders were obtained each day and were tested for compressive strengths at 7, 14, and 28 days. Vebe tests were not effective for this mix, because they did not produce sufficient paste. The Ohio DOT 411 gradation allowed 3 to 13 percent passing the No. 200 sieve, which resulted in a high variation in fine content. Moisture tests were performed on the stockpiles.

A test section was constructed from October 17 to 20, 2001. The test section was part of the stilling basin and was 100 feet long by 8 feet wide. RCC placements were started on November 29, 2001 and were completed in 4 weeks. The production averaged about 400 cubic yards of RCC per day. Cement contents averaged 10.5 percent (400 lb/yd^3). The nuclear density gauge measured moisture content, which varied from 6.0 to 8.0 percent. The optimum moisture content was estimated at 7.1 percent. The nuclear density gauge also measured the density of the RCC to be about 151.5 lb/ft^3.

10.8 Many Farms Dam (emergency spillway).—

a. *Background*.—Many Farms Dam is located on the Navajo Indian Reservation in northeast Arizona, approximately 1 mile east of the town of Many Farms. The reservoir is owned and operated by the Navajo Indian Tribe (Tribe) for irrigation and recreation. The dam embankment, outlet works, and spillway all underwent major dam safety modifications from 1999 to 2001. This case history addresses modifications pertaining to the spillway structure.

The original spillway was located on the reservoir rim, about 1 mile south of the main embankment. The spillway consisted of a 100-foot long, unlined cut through a small dike and was founded on alluvial deposits. The sill was at approximately elevation 5313.1 and had a discharge capacity of about 2,850 ft^3/s with a reservoir water surface at elevation 5318.0. The spillway was inadequately sized to pass the PMF and more frequent flood events. Overtopping of the dam embankment would have occurred for flood events greater than 36 percent of the PMF.

b. *Design considerations.*—Agreements between the Bureau of Indian Affairs and Tribe included design requirements for the spillway modifications:

- A new spillway to be located north of the main embankment at Dike BC, so that the spillway discharges would enter Chinle Wash downstream of the dam access road bridge and canal flume
- Spillway discharges to be limited to 11,000 ft^3/s based on the safe channel capacity at Rock Point, Arizona
- The original spillway crest elevation of 5313.1 feet to be maintained
- Spillway structures to be low maintenance and provide protection from vandalism

The new spillway was designed to pass the PMF having a peak inflow of 105,000 ft^3/s and a 24-hour volume of 27,000 acre-feet, with a maximum water surface elevation of 5324.9 feet. The crest of the RCC overtopping protection was set at elevation 5313.1. The small dike in the area of the original spillway crest was extended to close off the original spillway and was raised to accommodate the new maximum water surface. The downstream spillway discharge channel was designed to convey the discharges away from the toe of Dike BC. The floor of the apron and channel were set at approximately the existing ground level. Due to the type of soil in the region and the flow velocities, some erosion would occur between the discharge channel and Chinle Wash. This erosion would not affect the spillway structure; however, it may result in the need for some repairs after flood events.

The RCC overtopping protection was designed to act as a gravity overlay and was not intended to carry normal structural loads. The overtopping protection would experience flow velocities up to 38 ft/s during the PMF.

The RCC forming the downstream stilling basin and apron is installed on zone 2 filter material, which ties into the Dike BC toe drain. A geotextile was provided beneath this RCC to prevent mixing of the zone 2 and RCC as the RCC was spread and compacted. A geotextile was also required beneath the RCC, where there is no zone 2 filter material to act as a filter. The stilling basin will induce a hydraulic jump and reduce the velocities exiting the discharge channel for events less than a 1,000-year flood. To accommodate the period at which this jump will sweep out as flows increase, 12-inch wide flat drains were required to supplement the filter material and toe drain to reduce uplift pressures beneath the stilling basin slab. A filter blanket would bisect the spillway sidewalls and provide drainage beneath the sidewalls.

In 1999, the specifications were modified to accommodate a two-season construction period, driven by funding issues. While the specifications were being modified, several portions of the original 1993 spillway design were changed. Following additional exploratory drilling in the area of Dike BC in 1998, it was decided that the toe drain cutoff and basin portion of the spillway should be extended downward to be founded on bedrock. This modification resulted in excavation down to about elevation 5284.1, and lowering of the stilling basin floor from elevation 5293.10 to elevation 5290.10. This reduced the RCC volume and provided for more stilling action for larger flows.

In the original 1993 design, the face of the RCC steps was required to be vertically formed. Largely as a result of the RCC construction of the stilling basins at Ochoco Dam and Pueblo Dam, the designs were modified to allow the contractor to compact the exposed RCC face to any slope between vertical and 1:1.

The design was modified to include the use of leveling concrete between the RCC and any sloping foundation. This material was added to the design, since it had been found to work well for RCC placements for Pueblo Dam modifications.

The original design called for one saw cut in the top lift of the RCC along the spillway centerline as a crack-inducing measure. A second saw cut was added to cross the spillway at the break in slope of the apron. Two additional saw cuts were to be provided in the apron about 69 feet on either side of and parallel to the spillway centerline from the downstream end of the stilling basin to the downstream end of the RCC.

c. *Concrete mix design.*—During the design revision, Reclamation's materials laboratory recommended increasing the design strength of the RCC from 3,000 lb/in^2 to 4,000 lb/in^2 at 90 days. This recommendation was intended to increase the durability of the RCC, and was based on RCC placements at other sites, where this strength was easily attained. The RCC mix design is summarized in table 11.

d. *Construction.*—The new RCC spillway structure was constructed between September 18 and December 1, 2000. The excavation for the spillway began following construction of the embankment portion of Dike BC and installation of the downstream toe drain. The contractor utilized a Caterpillar D6 dozer and a 330 excavator to excavate and shape the spillway channel for placement of the RCC. The excavation was completed on September 21, 2000.

The contractor elected to erect a concrete batch plant immediately downstream of the spillway apron. The contractor began mobilizing the plant on August 4, 2000, including hauling and stockpiling concrete aggregates, cement, and flyash. The plant was tested and calibrated, and was approved for use on September 28, 2000. Several test batches of RCC were produced to ascertain the quality of the mix design, and placement of the roller-compacted concrete test section was initiated. The test section consisted of the first four upstream lifts leading into the spillway. A laser level was used to control line and grade of the placement. Clean gravel ramps were placed upstream of each side of the spillway for access to the placement and for cleaning of equipment prior to its use on the RCC. Leveling concrete was batched at the onsite batch plant and transported to the placement in a transit truck. The transit trucks either tailgated the leveling concrete directly onto the geotextile fabric or, where access was limited, discharged into the bucket of a Caterpillar 966 loader, which transported the concrete to the placement, where laborers shoveled it into place. Immediately following the placement of the leveling concrete, RCC was batched directly into a 10-wheel end dump truck and transported to the upstream side of the dike, where it was off loaded into a holding bin. A Caterpillar 966 front-end loader then picked up the RCC and transported it to the placement. The RCC was placed in approximately 14- to 16-inch lifts and spread using the Caterpillar D3 dozer (fig. 33). Once the lift was spread, a Caterpillar 634C smooth double-drum vibratory roller was used to compact the material, resulting in a completed lift thickness of 12 inches.

A laborer remained onsite to spray the surface of the RCC to maintain a water cure. The following day, laborers using brooms and shovels cleaned larger debris from the surface of the RCC, then used a power washer at 3,000 lb/in^2 and a jet vacuum to clean the surface for the next placement. Leveling concrete was placed on the sloped, fabric-covered surface to a width of 2 inches from top to bottom to minimize the amount of leveling concrete bleeding to the surface during compaction. Laborers spread a ¼- to ½-inch thick layer of bonding mortar on the cleaned surface using concrete rakes, in preparation for the next RCC lift. Reclamation's Farmington Construction Office core drilled the test section. Following a 14-day period to collect and analyze data on the test section, and for the placement to cure, the contractor resumed the RCC placement on October 16, 2000. The placement began with the bottom lift of the stilling basin downstream of the dike with the same procedures, lift thickness, and equipment used on the test section. A combination of four vibratory passes followed by two static passes were used to obtain the required compaction for the majority of RCC placements. The contractor utilized a Caterpillar 302.5 excavator with a shop-fabricated vibrating plate to accomplish the edge compaction (fig. 34). The vibrating plate was constructed with a 45-degree angle, which allowed for compaction of the outside 1 foot of the top surface of the lift and the outside sloping face. In an effort to speed up production, the contractor set up a 100-foot long telescoping Telebelt conveyor system with an Augermax hopper fed by front-end loaders.

The contractor used several methods to cure the RCC, including water, a wax-based curing compound, a moist sand cover, and plastic covering. Flat drains were installed in the stilling basin floor and up the downstream side of the spillway. The contractor saw-cut the completed spillway to the lines shown on the drawings in an effort to control cracking. The groin areas on both sides of the spillway were excavated using a Caterpillar 350 excavator; then geotextile fabric was placed in the trench by laborers and overlain by Zone 4A rock placed by a Caterpillar excavator or front-end loader. The RCC placement operations for the spillway were completed on December 1, 2000 (fig. 35). The total project cost was $12,795,228. The RCC has performed satisfactorily; however, the spillway has not yet operated.

Figure 33.—View of spillway stilling basin placement operations at Many Farms Dam.

Figure 34.—View of Caterpillar 302.5 excavator equipped with vibrating, angled plate used to compact the top and outside edges of a compacted RCC lift along the left spillway wing wall at Many Farms Dam.

e. *References.—*

Bureau of Reclamation, *Hydraulic and Structural Design for Modification of the Outlet Works—Many*

Figure 35.—View of the completed spillway located in Dike BC of Many Farms Dam. Note safety fencing has been installed along with sand backfill of the stilling basin.

Farms Dam Modifications, Technical Memorandum No. NMF-FDES-3110-1, 2001.

Bureau of Reclamation, *Many Farms Dam Modification— Final Construction Report*, Farmington Construction Office, Farmington, New Mexico, 2001.

10.9 Jackson Lake Dam (upstream slope protection for embankment dam).—

a. *Background*.—Jackson Lake Dam is a composite concrete gravity dam and embankment dam located about 25 miles north of Jackson, Wyoming on the Snake River (fig. 36). The dam was completed in 1914. The dam is 65 feet high and has a total length of 4,920 feet. The dam was modified from 1987 to 1989 to address safety of dams concerns related to the maximum credible earthquake.

Reclamation was unable to locate a viable riprap source for the upstream slope protection of the north embankment. A coarse-grained soil-cement was evaluated as the most economical approach for upstream slope protection. Soil-cement slope protection has been used on 13 Reclamation embankment dams. This was the first time that Reclamation used a coarse-grained soil-cement.

Based on the development of RCC technology at the time, it was determined that a coarse-grained soil-cement mixture could be placed in 12-inch compacted lifts. The fine-grained soil-cement mixtures applied to other Reclamation slope protection projects required a maximum compacted lift thicknesses of 6 inches to obtain the desired inplace densities. It was estimated that the thicker lift placements would reduce the construction time.

b. *Concrete mix design.*—A type II cement was proposed at Jackson Lake due to the potential for reactive aggregates. The cement content was increased to 400 lb/yd^3 from the initial mix proportion of 224 lb/yd^3.

There were no specific design requirements for the compressive strength of the soil-cement. Test cylinders were made using the impact method and tested at 7, 28, and 90 days. Test results indicated that the soil-cement had an average compressive strength of 1,760 lb/in^2 at 1 year. The soil-cement mixture was tested for density by the impact method, for moisture by the hot plate method, and for cement content by the heat of neutralization method. Sand cone inplace densities and nuclear densities were taken after compaction was completed. The cement content ranged from 12.2 to 7.7 percent. Cement content averaged 10.5 percent, with moisture content ranging between 5.5 and 8.6 percent. The average of the field test data mix proportioning investigation results are shown on table 11.

c. *Construction.*—A request-for-proposal contract was used for the safety of dams modification. National Projects, Inc. was the prime contractor for the stage II work, which included the soil-cement upstream slope protection. National Projects, Inc. was awarded the contract with a total bid of $40 million. The bid price for coarse-grained soil-cement was $14.00 per cubic yard for the first 27,000 yd^3 and $11.00 per cubic yard over 27,000 yd^3. The cost of cement was not included in the soil-cement bid price. The prime contractor used two subcontractors on the soil-cement. The soil-cement was produced by Judd Brothers Construction Co. and was placed by Peltz Construction Co.

The subcontractor placed a test section strip from July 26 to July 30, 1988 between stations 50+50 and 55+00. Based on the results of the test section, it was determined that the soil-cement would be placed in 9-inch to 10-inch lifts, and have an initial mix design with a cement content of 9 percent and a moisture content of 8.5 percent by dry weight. Both the cement and moisture content were adjusted during construction.

The soil-cement placements began on August 8, 1988. The contractor worked six 10-hour shifts per week. Production averaged about 1,000 cubic yards per shift. The soil-cement was batched and mixed using the Aran continuous mixing pugmill batch plant. The soil-cement was delivered to the placement location by end-dump trucks. An ABG Titan 280 paving machine with a duo-tamp, high density screed was used to spread the soil-cement. The soil-cement was compacted by six passes of an Ingersol Rand SD100 steel drum vibratory roller, three with the vibrator engaged and three static passes. A cement slurry bonding agent was used between lifts to obtain bond on lifts. Ramps were constructed over the previously placed soil-cement to provide access as the placement progressed up the embankment slope. The coarse-grained soil-cement slope protection was completed in October of 1988. A total of 44,900 yd^3 of coarse-grained soil-cement was placed.

Figure 36.—Aerial view of Jackson Lake Dam under construction looking north.

10.10 Clear Lake Dam modification (RCC gravity dam with joints).—

a. *Background*.—Clear Lake Dam is located on the Lost River in northern California, and is owned and operated by the Bureau of Reclamation. The dam provides irrigation water to the Langell Valley and Horsefly Irrigation Districts, and controls drainage onto reclaimed lands adjacent to the Lost River within the Tule Lake and Klamath Irrigation Districts. The reservoir serves as part of the Clear Lake National Wildlife Refuge and provides critical habitat for two endangered species of fish, the Lost River sucker and the Shortnose sucker. The original zoned earth and rockfill dam was constructed between 1908 and 1910, and was raised 3 feet in 1938. The dam embankment had a structural height of 42 feet, a total crest length of 840 feet, and a crest width of 20 feet at elevation 4552.0. The outlet works consisted of an intake tower containing two 4-foot by 4-foot 9-inch slide gates for flow regulation, a downstream cast-in-place concrete conduit, and an excavated outlet channel. A side-channel spillway having a 357-foot long overflow crest at elevation 4543.0 was provided on the left abutment for flood releases to the Lost River.

b. *Design considerations.*—Dam safety investigations performed by Reclamation in 1998 and 1999 indicated that the original Clear Lake Dam had inadequate defensive measures against internal erosion and piping, and the risk of dam failure warranted corrective action. Congress approved the modification report for Clear Lake Dam in June 2001. The approved corrective action consisted of constructing an RCC gravity structure immediately downstream of the existing embankment dam. This modification would retain the existing left abutment spillway and unlined channel for passage of the PMF. A new outlet works would be provided through the RCC dam at the location of the existing outlet works channel. The existing embankment dam would be utilized to maintain reservoir levels during the modification work, and then be breached. An RCC dam was selected over zoned earthfill and concrete-faced rockfill alternatives due to the smaller footprint and smaller volume of construction materials. The RCC dam alternative offered better technical performance, better constructability, less hydrologic risk during construction, and less disturbance of downstream wetlands than the other alternatives.

Final designs for the RCC dam were based on a straight gravity dam section founded on bedrock, with a dam axis (upstream face) located about 80 and 170 feet downstream from the original embankment crest centerline on the left and right abutment, respectively. The RCC dam cross section assumes a 20-foot crest width, matching the crest width of the existing embankment dam to serve as an access road and to facilitate RCC construction. The dam crest was set above the 100-year flood level at elevation 4544.0, or 1 foot above the spillway crest elevation. The upstream face is vertical for the entire height of the dam along the dam axis. The downstream face is vertical between elevations 4544.0 and 4530.0, and below elevation 4506.0, and has a slope of b:1 between elevations 4530.0 and 4506.0. A 4-foot high concrete parapet wall located on the upstream edge of the dam crest provides flood protection to elevation 4548.0, which is 0.8 feet above the maximum water surface resulting from passage of the PMF. The RCC dam has a crest length of 564 feet between the left end of the dam above the spillway channel and the excavated bedrock surface on the right abutment. An additional RCC wing section extends about 90 feet upstream from the left end of the RCC dam to the existing spillway bridge abutment. The dam crest includes a reinforced concrete sidewalk and parapet wall along the upstream edge, and a beam-type guardrail along the downstream edge. The final RCC lift surface has a 1-percent slope downstream for drainage. The total volume of RCC in the dam is 18,000 yd^3.

The RCC dam is founded on a hard lower basalt unit across the valley floor, and on an upper basalt unit underlain by tuff beneath the left and right abutment sections and left abutment wing section. Although some seepage was expected to occur around the right abutment, no foundation grouting was specified, to help preserve the downstream wetlands. Rockfill from the original dam was to be placed along the downstream toe to about elevation 4515, matching the original ground surface and providing a downstream buttress. Compacted backfill was to be placed along the upstream face to elevation 4515 to buttress the upstream channel alluvium.

A reinforced concrete outlet works conduit was designed for the left abutment within the existing outlet works channel. The outlet works conduit was 9 feet wide and 7.5 feet high and located within an excavated trench to elevation 4519, above which RCC was placed. The upstream intake structure consisted of two 72- by 72-inch slide gates in tandem with an invert at elevation 4510, and an additional 12- by 12-inch slide gate for a low-flow bypass. Four 6- by 15.75-foot openings were provided upstream of the gates to contain eight stainless steel fish screen panels to prevent migration of endangered sucker fish from the lake during normal operational releases up to 120 ft^3/s. Outlet releases exit a flared transition structure and downstream apron before entering the existing channel near the confluence with the spillway outlet channel.

Finite element methods were used for static and dynamic analyses of the left abutment and maximum sections of the RCC dam. The RCC gravity sections were conservatively designed for sliding stability along potentially unbonded lift lines, using an apparent cohesion of 50 lb/in^2 and a friction angle of 40 degrees. Dynamic stability was evaluated for ground motions having a 10,000-year return period for the site. Thermally induced stresses were expected to be minimal for the RCC dam due to the moderate climate of the site, specified RCC placement temperatures between 45 and 65 degrees, and design provisions for contraction joints.

c. *Concrete mix design.*—Reclamation materials laboratory personnel prepared final mix designs for RCC. A total cementitious materials content of 310 lb/yd^3 (with 52 percent pozzolan) and a water-to-cementitious materials ratio of 0.60, with a 4 percent air content, was used for the RCC to provide the design compressive strength of 3,000 lb/in^2 at 1 year. Rogue Aggregates supplied concrete aggregates from their Farmer's Pit near Merrill, Oregon, for a haul distance of over 40 miles. The fine and coarse aggregates consisted of crushed basalt, with a 2-inch maximum size and 39 percent sand.

d. *Construction.*—Specifications for Clear Lake Dam modification were issued April 26, 2001, and bids were opened on June 19, 2001 for the firm-fixed-price contract. The low bidder was ASI Civil Constructors of Carlsbad, California, for a total bid price of $5,991,250. Contract award was made to ASI on July 10, and Notice-to-Proceed was received by the contractor on August 10. This established a contract completion date of September 2, 2002, based on a 300-day contract duration plus a winter exclusion period from December 1, 2001 through February 28, 2002. The contractor was allowed to work during the winter exclusion period at their discretion. The outlet works conduit and lower portion of the intake structure were completed by April 3 to allow commencement of irrigation releases. The contractor's compulsory mixer for RCC was irreparably damaged during transportation to the site, delaying the start of the contractor's

RCC placing operations for the dam until May 30, 2002. An RCC test section was completed on April 25.

The RCC was placed and compacted in 1-foot thick, horizontal lifts between the abutments, with the placement of conventional leveling concrete just prior to RCC placement: (1) at the formed upstream face, to improve watertightness, (2) on the dam abutments, to improve the contact between the RCC and the sloping bedrock surfaces, and (3) on selected portions of the dam foundation, to facilitate the initial RCC lift placements. The downstream b:1 sloping face was constructed of compacted RCC by forming 2-foot high steps with 16-inch setbacks every other lift. Large dual-drum vibratory rollers performed compaction, with smaller power tampers used near the abutment contacts and downstream forms. RCC lift surfaces were cleaned for the development of bond strength by vacuuming, air jetting, air-water jetting, high pressure water jetting, and sand blasting, depending upon the age and condition of the lift surface. Bonding mortar was spread on all RCC lift surfaces within 5 feet of the upstream edge and within 2 feet of the downstream edge, immediately ahead of the RCC placement, to improve bond and watertightness at both faces. Additional bonding mortar was used on cold joints more than 6 hours old, and on construction joints more than 12 hours old.

Contraction joints were provided within the RCC dam at maximum 50-foot intervals, and at abrupt changes in the foundation surface, for crack control. Steel crack-inducer plates measuring 10-inches high and 24-inches long were installed in alternating lifts of RCC along transverse lines between the upstream and downstream faces immediately following lift compaction. In addition, formed vertical crack control notches extended from the dam crest to the foundation at both the upstream and downstream faces at the contraction joint locations. Sealant, ½-inch joint filler, and a 12-inch PVC waterstop were provided behind the upstream crack control notch at each contraction joint for seepage control (fig. 37).

Construction of the RCC dam occurred in two shifts, with joint surface preparation and form work construction performed during the day shift, and with all RCC placements performed at night to help meet the placement temperature requirements. Although the specified minimum RCC placement rate was two lifts per day for a single shift, the 43 lifts of RCC required 34 shifts to place between May 30 and August 7, 2002, for an average of only 530 yd^3 per shift. The maximum RCC placement temperature was increased to 75 degrees, and the maximum contraction joint spacing was reduced from 60 to 50 feet to facilitate construction during the warmer summer months. Chilled water and ice were used in the RCC mix, and aggregate stockpiles were kept sprayed with water to help meet the placement temperature requirements.

Figure 37.—Clear Lake Dam—Contraction joint detail in formed upstream face showing chamfer strip for sealant, ½-inch joint filler, and PVC waterstop within leveling concrete (from test section).

Internal drainage for the RCC dam was provided by vertical holes drilled from the completed dam crest at 10-foot centers and extending into the dam foundation approximately 20 feet. The 43 drain holes to the right of the outlet works intercepted a horizontal 18-inch diameter PVC collector pipe embedded within the RCC above elevation 4516 and 3 feet from the upstream face, with a single outfall pipe on the right abutment. The 7 drain holes to the left of the outlet works intercepted a sloping 18-inch diameter PVC collector pipe installed on the dam foundation, with a single outfall pipe into the outlet works channel. All drain

Figure 38.—Clear Lake Dam—Completed RCC gravity dam during first filling. New outlet works intake tower with control house and jib crane shown near left abutment. Original outlet works intake tower shown to left, on alignment of original embankment dam.

holes and pipes are accessible for cleaning: (1) the drilled drain holes from the dam crest, through removable galvanized plugs, (2) the outfall pipes from the downstream face, (3) the horizontal collector pipe from within the outlet works conduit, through a threaded cleanout plug, and (4) the sloping collector pipe from either the outfall pipe or drain holes.

Following completion of the RCC dam, the upstream embankment dam was breached to elevation 4525 between August 19 and October 15, 2002 (fig. 38). The existing spillway bridge girders were relocated 100 feet downstream by two large cranes to new bridge abutments in line with the RCC dam crest. First filling began on October 15, and all work was substantially completed by November 13, 2002 (fig. 39).

e. *Conclusions.*—Dam safety investigations indicated that Clear Lake Dam had inadequate defensive measures against internal erosion and piping. An RCC gravity structure was constructed immediately downstream of the existing embankment dam, retaining the existing left abutment spillway and providing a new outlet works at the location of the existing outlet channel. Significant design features for the RCC dam include an internal drainage system and waterstopped contraction joints, with an upstream face of conventional leveling concrete and exposed RCC in the dam crest and downstream face. The bid price for RCC was $103.50 per cubic yard, plus cementitious materials for the 18,000-yd^3 volume. Project costs were most impacted by the remoteness of the site and by the 40-mile haul distance for concrete aggregates.

f. *References.—*

Bureau of Reclamation, *Technical Report of Construction—Clear Lake Dam Modification—Klamath Project*, *Oregon-California*, Mid-Pacific Construction Office, Willows, California, 2003.

Hepler, Thomas E., "Preserving a Refuge—The Replacement of Clear Lake Dam Using Roller-Compacted Concrete," *Dams—Innovations for Sustainable Water Resources, Proceedings of the 22nd Annual USSD Conference*, San Diego, California, June 24-28, 2002.

Additional References

American Concrete Institute, *Roller Compacted Mass Concrete*, ACI Committee 207, Report ACI 207.5R-89, Detroit, Michigan, 1989.

American Concrete Institute, *Building Code Requirements for Structural Concrete* (ACI 318-95) and *Commentary* (ACI 318R-95), Detroit, Michigan, 1995.

American Society of Civil Engineers, "Roller Compacted Concrete II," *Proceedings of the ASCE Conference*, San Diego, California, February 29 to March 2, 1988.

Dolen, T.P., and Shiraz D. Tayabji, *Bond Strength of Roller-Compacted Concrete*, ASCE Proceedings, 1988.

Hansen, Kenneth D., *Roller-Compacted Concrete Dams in the USA: 1995*, Presented at the International Symposium on Roller Compacted Concrete Dams, Santander, Spain, October 2, 1995.

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Richardson, Alan T., *Current Design and Construction Practice for RCC Dams*, Bureau of Reclamation, 1991.

U.S. Army Corps of Engineers, *Roller-Compacted Concrete Dams*, Engineering Manual, EM 1110-2-2006, Washington DC, 2000.

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Appendix A

Guide Specifications (CSI Format)

SECTION 03702 **ROLLER-COMPACTED CONCRETE**
GUIDE SPECIFICATION DEPARTMENT OF THE INTERIOR – BUREAU OF RECLAMATION
REVISIONS Reference Standards Checked/Updated: 9/30/05 Content Revisions: 9/30/05
NOTES (1) Consult the structural designer and material specialist for selection of mix design, performance criteria, RCC mixing and placing equipment. (2) This section includes leveling concrete, bonding mortar, and crack inducers. Waterstops, drains, sealants, bond breakers, and joint materials are specified elsewhere. (3) This guide assumes Government (owner) will perform quality control testing. If Contractor will be responsible for quality control testing, include Section 01454 - Contractor Quality Control, and consult materials specialist for input to articles entitled ABatch Plant Quality Testing@ and AField Quality Testing@.

SECTION 03702 - ROLLER-COMPACTED CONCRETE

PART 1 GENERAL

1.01 MEASUREMENT AND PAYMENT

A. Roller-Compacted Concrete Test Section:

1. Payment: Lump sum price offered in the schedule.

B. Roller-Compacted Concrete:

1. Measurement: Volume, measured to lines, grades and dimensions shown on drawings or as directed by the COR.

a. Does not include volume of RCC in test section.

2. Payment: Cubic yard price offered in schedule.

C. [1]Cement for Roller-Compacted Concrete:

1. Measurement: Weight of cement used in RCC.

a. [2][Includes weight of cement in bonding mortar for foundation treatment.]

[1] Pay for cementitious materials to account for variations in mix design during construction. Pay for cement and pozzolan separately.

b. Does not include weight of cement in RCC test section.

c. Does not include weight of cement in RCC that is wasted or removed.

d. Does not include weight of extra cement added for lift surface bonding of cold joints.

2. Payment: Ton price offered in the schedule.

D. Pozzolan for Roller-Compacted Concrete:

1. Measurement: Weight of pozzolan used in RCC.

a. [3][Includes weight of pozzolan in bonding mortar for foundation treatment.]

b. Does not include weight of pozzolan in RCC in test section.

c. Does not include weight of pozzolan in RCC that is wasted or removed.

d. Does not include weight of extra pozzolan added for lift surface bonding of cold joints.

2. Payment: Ton price offered in the schedule.

E. Leveling Concrete:

1. Measurement: Volume measured in place as directed by the COR.

2. Payment: Cubic yard price offered in the schedule.

F. [4][Bonding Mortar for Foundation Treatment:

1. Measurement: Surface area covered by mortar measured in place.

2. Payment: Square foot price offered in the schedule.]

G. [5][Bonding Mortar for Joints:

1. Measurement: Surface area covered by mortar measured in place.

a. Does not include bonding mortar placed on cold joints or construction joints due to expiration of time limits beyond standard lift cleanup.

2. Payment: Square foot price offered in the schedule]

H. Crack Inducers:

1. Measurement: Length of crack inducers installed.

2. Payment: Linear foot price offered in the schedule.

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[2] Delete if bonding mortar for foundation treatment is not required.

[3] Delete if bonding mortar for foundation treatment is not required.

[4] Include when required for job. Consult with materials specialist for requirement for bonding mortar.

[5] Delete when not required for job. Bonding mortar for joints required only when design or construction schedule requires that the RCC not be placed continuously.

I. Cost: Bonding mortar, including cement and pozzolan, required for cold joints or construction joints due to expiration of time limits beyond standard lift cleanup shall be the responsibility of the Contractor.

1.02 DEFINITIONS

A. Average maximum density (AMD): Average in-place wet density of compacted RCC determined from control section.

B. Bonding mortar: Mortar applied to foundation or RCC joint to improve bonding of RCC to underlying material.

C. Leveling concrete: Structural concrete placed to fill in low areas before placing RCC.

D. Nuclear gauge: Single probe nuclear surface moisture-density gauge.

E. Roller-Compacted Concrete (RCC): Similar to conventional concrete, except RCC is constructed and compacted in lifts by earthmoving equipment. RCC is mixed in a moist condition, spread in horizontal lifts, and compacted.

F. RCC total moisture content: Free water plus absorbed moisture of aggregates.

1. During construction, total moisture content of RCC will be measured by the Government using a nuclear gauge.

1.03 REFERENCES

A. ASTM International (ASTM)

1.	[6][ASTM A 653/A 653M-05	Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process]
2.	ASTM C 31-03a	Making and Curing Concrete Test Specimens in the Field
3.	ASTM C 33-03	Concrete Aggregates
4.	ASTM C 39/C 39M-04a	Compressive Strength of Cylindrical Concrete Specimens
5.	ASTM C 42/C 42M-04	Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
6.	ASTM C 94/C 94M-04a	Ready-Mixed Concrete
7.	ASTM C 114-05	Chemical Analysis of Hydraulic Cement
8.	ASTM C 127-04	Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate

[6] Delete if crack inducers are not specified.

9.	ASTM C 128-04	Density, Relative Density (Specific Gravity), and Absorption of and Absorption of Fine Aggregate
10.	ASTM C 138/C 138M-01a	Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
11.	ASTM C 150-05	Portland Cement
12.	ASTM C 171-03	Sheet Materials for Curing Concrete
13.	ASTM C 172-04	Sampling Freshly Mixed Concrete
14.	ASTM C 183-02	Sampling and the Amount of Testing of Hydraulic Cement
15.	ASTM C 231-04	Air Content of Freshly Mixed Concrete by the Pressure Method
16.	ASTM C 260-01	Air-Entraining Admixtures for Concrete
17.	ASTM C 309-03	Liquid Membrane-Forming Compounds for Curing Concrete
18.	ASTM C 311-04	Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete
19.	ASTM C 494/C 494M-05	Chemical Admixtures for Concrete
20.	ASTM C 511-05	Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
21.	ASTM C 566-97(2004)	Total Evaporable Moisture Content of Aggregate by Drying
22.	ASTM C 617-98(2003)	Capping Cylindrical Concrete Specimens
23.	ASTM C 618-05	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete
24.	ASTM C 685/C 685M-01	Concrete Made by Volumetric Batching and Continuous Mixing
25.	ASTM C 702-98(2003)	Reducing Samples of Aggregate to Testing Size
26.	ASTM C 1040-05	In-Place Density of Unhardened and Hardened Concrete, Including Roller Compacted Concrete, By Nuclear Methods
27.	ASTM C 1064/C 1064M-05	Temperature of Freshly Mixed Hydraulic-Cement Concrete
28.	ASTM C 1170-91 (1998)	Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
29.	ASTM C 1176-92(1998)	Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table

30. ASTM C 1435/C 1435M-05 Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer

31. ASTM C 1602/C 1602M-05 Mixing Water Used in the Production of Hydraulic Cement Concrete

32. ASTM D 75-03 Sampling Aggregates

B. National Bureau of Standards (NBS)/National Institute of Standards and Technology (NIST)

1. NBS 44 Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices, adopted by the National Conference on Weights and Measures, 1979

1.04 SUBMITTALS

A. Submit the following in accordance with Section 01330 - Submittals.

B. RSN 03702-1, Plan for RCC plant(s).

1. Location, plan, and schematic drawing of RCC plant.
2. Description of RCC plant.
3. Peak capacity and anticipated daily production rate for completion of construction.
4. Description of methods for handling aggregates and cementitious materials.
5. Description of facilities for sampling constituent materials and batched RCC at plant.
6. Methods of controlling RCC temperature within specified limits.
7. Resumes for RCC plant operators.

C. RSN 03702-2, Equipment and placement plan.

1. Type and number of pieces of equipment for transporting, placing, spreading, and compacting RCC.
2. Equipment for lift surface preparation including capacity in square feet per hour.
3. Plan for handling RCC at intermediate and exit points along conveyor system.
4. Location of fixed equipment.
5. Direction and configuration of placement.
6. Placing schedule, including number of lifts of RCC to be placed each day.
7. Specifications for compaction equipment.
8. [7][Proposed methods for placing and compacting outside edges.]

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[7] For sloping/stair-stepped spillways or for overtopping protection.

9. Location and alignment of temporary access roads.
10. Proposed variations from design lines and grades.
11. Methods for curing and protecting RCC.
12. Test section placement procedures.
13. Resumes for RCC placement supervisors.

D. RSN 03702-3, Cementitious materials:

1. Manufacturer's certifications and test reports for materials.
    a. For each lot of cement or pozzolan from which shipments are drawn.
    b. Manufacturer's certification stating that material was tested during production or transfer, in accordance with the reference specification.

E. RSN 03702-4, Fine and coarse aggregates:

1. Name and location of sources.
2. Manufacturer=s certification that materials meet requirements of ASTM C 33.

F. RSN 03705-5, Proposed water source:

1. Name and location of source.

1.05 TEST SECTION

A. RCC test section will serve as the basis for evaluating the following:

1. Methods for forming, placing, consolidating, and curing RCC and leveling concrete
2. Prequalification of vibratory rollers, power tampers, and plate vibrators.
3. Methods and equipment for batching, mixing, transporting, placing, compacting, curing, protecting, and cleanup.
4. Procedures for installing of [8][waterstops, crack control notches, crack inducer plates, pipe, and expansion joint filler].

B. Evaluation of the test section will be based on:

1. [9][Successful placement of RCC in accordance with these specifications.
2. Successful calibration of RCC batching and mixing plant.
3. Demonstration of acceptable methods for transporting, placing, and compacting RCC at the anticipated production rate.
4. Demonstration of acceptable lift surface cleaning and preparation methods and application of bonding mortar.

---

[8] Revise list of items as appropriate for job.

[9] Revise acceptance criteria as appropriate for job.

5. Verification of acceptable RCC lift compaction by evaluation of density tests and of cores.

6. Demonstration of acceptable upstream and downstream forming methods at the specified rate.]

C. The COR will direct construction of a control section within the test section and will determine the initial AMD.

D. The COR will issue notification of preliminary evaluation of test section within 7 days after successful completion of the test section.

E. Final evaluation of the test section will be within 21 days after successful completion of the test section.

F. Construction:

1. Construct RCC test section at least [10][3 weeks] before beginning RCC construction.

2. [11][Configuration of test section:

a. Length, minimum: XX feet.

b. Width, minimum: XX feet.

c. Lifts, minimum: X

d. One side slope: Constructed against a slope of 0.5:1 provided by a shaping concrete placement.]

3. Include at least one lift surface exposed longer than 6 hours followed by cleanup, placing bonding mortar, and placing the next lift of RCC.

4. Place RCC at anticipated production rate to allow evaluation of lift joints and upstream and downstream facing.

5. Locate RCC test section where shown on drawings.

G. Quality testing::

1. The Government will test batched and placed RCC in accordance with the articles "Batch Plant Quality Testing" and "Field Quality Testing."

2. The Government will extract diamond-drilled, 6-inch diameter cores from RCC test section.

a. Cores will be drilled 7 days after final placement.

b. The Government will examine drilled cores to evaluate methods and quality of RCC construction.

---

[10] Revise time as appropriate for job.

[11] Insert dimensions of test section as appropriate for job. Include side slope requirement when required by designs. If desired, test section configuration can be shown on drawings. If test section shown on drawings, delete dimensions and state "as shown on drawings."

1.06 SEQUENCING

A. Do not proceed with RCC construction until test section has been evaluated and accepted by Government.

B. Make necessary changes to RCC methods and equipment before beginning construction of RCC.

PART 2 PRODUCTS

2.01 CEMENTITIOUS MATERIALS

A. Cementitious materials: Portland cement plus pozzolan.

B. Portland cement:

1. ASTM C 150, Type [12][___], in addition:
    a. Meet equivalent alkalies requirements of ASTM C 150, Table 2.
    b. Meet false-set requirements of ASTM C 150, Table 4.
    c. [13][Sum of tricalcium silicate and tricalcium aluminate: 58 percent, maximum.]
    d. Free from lumps and other deleterious matter and otherwise undamaged.
2. Pozzolan:
    a. ASTM C 618, class F, except:
        1) Sulfur trioxide, maximum,: 4.0 percent.
        2) Loss on ignition, maximum: 2.5 percent.
    b. Does not decrease sulfate resistance of concrete by use of pozzolan.
        1) Demonstrate pozzolan will have an "R" factor less than 2.5.
        2) R = (C-5)/F
        3) C: Calcium oxide content of pozzolan in percent determined in accordance with ASTM C 114.
        4) F: Ferric oxide content of pozzolan in percent determined in accordance with ASTM C 114.

C. Before an RCC placement is started, ensure that sufficient cementitious materials are in storage at RCC plant to complete 1 day of placement.

---

[12] Insert type of cement. Consult with materials specialist.

[13] Include when heat would be a problem, ex. mass RCC.

2.02 SAND

A. Source:

1. From approved source, with approval of source based on:

   a. Previous testing and approval of source by Government. or

   b. Preconstruction testing and approval.

2. Approval of deposits does not constitute acceptance of specific materials taken from the deposits. The Contractor shall provide specified materials.

3. Final acceptance of sand used in RCC will be based on samples taken at the RCC plant.

4. Testing and approval:

   a. Sources listed in [14][Section 0032_ - Geotechnical Data], have been tested by the Government.

   b. Preconstruction testing and approval for sand obtained from a deposit not previously tested and approved by the Government:

      1) Assist the Government in collecting representative samples.

      2) Sample size: Approximately 200 pounds.

      3) Submit, for testing, to: [15][ ].

      4) Submit at least 60 days before the sand is required for use.

   c. Testing at aggregate processing plant and batch plant:

      1) Government may test samples obtained during the aggregate processing and at batch plant.

      2) Provide facilities for procuring representative samples at the aggregate processing plant and at the RCC plant.

B. Quality and grading for sand when batched; or for continuous flow plants for sand just prior to combining with other materials:

1. ASTM C 33, except:

   a. Gradation:

      1) Percent passing No. 100 sieve: 0 to 12 percent.

      2) Percent passing No. 200 sieve: 0 to 10 percent

   b. Predominantly natural sand, which may be supplemented with crushed sand to make up deficiencies in the natural sand gradings.

---

[14] Insert section number and verify name.

[15] Insert address for testing lab. For Bureau of Reclamation jobs with TSC involvement: Bureau of Reclamation, Attn D-8180, Building 56, Entrance S-6, Denver Federal Center, Denver CO 80225-0007

1) Produce crushed sand by suitable ball or rod mill, or disk or cone crusher, so that the particles are predominantly cubical in shape and free from flat or elongated particles.

2) Crusher fines produced by a jaw crusher used other than as a primary crusher shall not be used in production of sand.

3) Blend crushed sand uniformly with the natural sand by routing through sand classifier.

C. Moisture content for sand, as batched:

1. Uniform and stable moisture.

2. Free moisture, maximum: 6 percent.

3. Variations of moisture in sand as batched, maximum: 0.5 percent in 30 minutes.

D. Stockpiles:

1. Prior to placing RCC, stockpile on site [16][{at least one-half} {all}] sand needed to complete the RCC construction.

2. Protect sand stockpiles containing free water from freezing.

a. Screen out frozen materials prior to use to remove frozen particles.

b. Sand containing particles frozen together will be rejected.

2.03 COARSE AGGREGATE

A. Source:

1. From approved source, with approval of source based on:

a. Previous testing and approval of source by Government, or

b. Preconstruction testing and approval.

2. Approval of deposits does not constitute acceptance of specific materials taken from deposits. The Contractor shall provide specified materials.

3. Final acceptance of aggregate used in RCC will be based on samples taken at the RCC plant.

4. Testing and approval:

a. Sources listed in [17][Section 0032_ - Geotechnical Data], have been tested by the Government.

b. Preconstruction testing and approval for coarse aggregate obtained from a deposit not previously tested and approved by the Government:

---

16 Select appropriate amount of sand to have on site. Preferred amount would be "all", however site limitations may make this impractical.

17 Insert section number and verify section name.

1) Assist the Government in collecting representative samples for preconstruction testing and approval.

2) Sample size:

a) Maximum size aggregate up to 1-inch: 200 pounds.

b) Maximum size aggregate greater than 1-inch: 100 pounds.

3) Submit, for testing, to: [18][ ].

4) Submit at least 60 days before the coarse aggregate is required for use.

c. Testing at aggregate processing plant and batch plant:

1) Government may test samples obtained during the aggregate processing and at batch plant.

2) Provide facilities for procuring representative samples at the aggregate processing plant and at the RCC plant.

B. Quality and grading for coarse aggregate when batched, or for continuous flow plants for coarse aggregate just prior to combining with other materials.

1. Quality: ASTM C 33.

2. Grading: ASTM C 33 [19][{1-inch nominal size aggregate: Size No. 57 (1 inch to No.4).} {2-inch nominal size aggregate: Size No. 3 (2 to 1 inch) and Size No. 57 (1 inch to No.4)} {1-1/2 inch nominal size aggregate: Size No. 4 (1-1/2 to 3/4 inch) and Size No. 57 (3/4 inch to No.4)}].

C. Material:

1. Crushed rock or a mixture of natural gravel and crushed rock. Do not use jaw crushers except as a primary crusher.

2. At least 50 percent crushed rock.

3. No more than 30 percent particles with a maximum to minimum dimension ratio of 3 to 1.

4. Separate coarse aggregate into nominal sizes during aggregate production.

D. Finish screening:

1. Locate finish screens so that screen vibration is not transmitted to batching bins or scales and does not affect accuracy of weighing equipment.

2. Just prior to batching, wash coarse aggregate by pressure spraying.

a. Do not allow wash water to enter batching bins or weighing hoppers.

---

[18] Insert address for testing lab. For Bureau of Reclamation jobs with TSC involvement: Bureau of Reclamation, Attn D-8180, Building 56, Entrance S-6, Denver Federal Center, Denver CO 80225-0007.

[19] Select size. Consult with materials specialist.

3. Finish screen coarse aggregate on multideck vibrating screens capable of simultaneously removing undersized and oversized aggregate from each nominal aggregate size.

4. If aggregate moisture content varies during intermittent batching, use a dewatering screen after finish screens to remove excess free moisture.

5. Do not overload screens.

6. Finish screen:

    a. Finished product shall meet specified gradation.

    b. Avoid segregation and breakage.

    c. Feed coarse aggregate to finish screens in a combination or alternation of nominal sizes to avoid noticeable accumulation of poorly graded coarse aggregate in any batching bin.

    d. Minus 3/16-inch material passing through the finish screens shall be wasted or routed back through a sand classifier for uniform blending with the sand being processed.

7. If a continuous flow plant is used, pass aggregate over a vibrating finishing screen after combining on a single feed belt prior to weighing.

E. Moisture content for coarse aggregate, as batched: Uniform and stable moisture content.

F. Stockpiles:

1. Prior to placing RCC, stockpile on site [20][{a minimum of one-half} {all}] coarse aggregate needed to complete RCC construction.

2. Protect aggregate stockpiles containing free water from freezing.

    a. Screen out frozen materials prior to use to remove frozen particles.

    b. Aggregate containing particles frozen together will be rejected.

2.04 WATER

A. Water:

1. Free from objectionable quantities of silt, organic matter, salts, and other impurities.

2. Chemical limits: ASTM C 1602, including optional requirements of Table 2.

3. Wash water shall not be used for mixing RCC.

B. The Government may test water from proposed source by comparing compressive strengths, water requirements, times of set, and other properties of RCC made with distilled or very clean water to RCC made with proposed mix water.

---

[20] Select appropriate amount of coarse aggregate to have on site. Preferred amount to have on site is "all", however site limitations may make this impractical.

2.05 ADMIXTURES

A. For RCC:

1. ASTM C 494, type A, water reducing admixture (WRA).

2. ASTM C 494, type D, water reducing and retarding admixture (WRA).

   a. Required when ambient daily temperature at placement site exceeds [21][__ degrees F].

3. Air entraining admixtures (AEA):

   a. ASTM C 260.

   b. Use air entraining admixtures specifically manufactured for use in low-slump concrete.

B. For bonding mortar: ASTM C 494, type D water-reducing, retarding admixture.

2.06 CURING MATERIALS

A. Water: ASTM C 1602, including optional requirements of Table 2.

B. Curing Compound: ASTM C 309.

C. Polyethylene Film: ASTM C 171, white opaque.

2.07 [22][CRACK INDUCERS

A. Galvanized sheet steel, 16 gage thick (0.06 inch) meeting the requirements of ASTM A 653.

B. Width: Wide enough to fully penetrate a compacted RCC lifts or to depths shown on drawings.

C. Length:

1. Appropriate for installation.

2. Minimum length: 3 feet.]

2.08 [23][LEVELING CONCRETE MIX

A. Leveling concrete mix: Section 03300 - Cast-in-Place Concrete, except:

1. Slump: 2 inches plus or minus 1 inch.

---

21 Insert temperature requirement. Typically 70 degrees F.

22 Delete if crack inducers are not required.

23 Recommended maximum size aggregate same as RCC (1-inch or 2-inch). Exception: Typical compressive strength for structural concrete is 4,000 lb/in^2. Guide specification 03300 – Cast-In-Place Concrete requires 90 percent of cylinders to exceed specified compressive strength.

2. Compressive strength: 3,000 lb/in^2 at 28 days.

a. Acceptance criteria: 80 percent of test cylinders exceed specified strength at 28 days.]

2.09 RCC MIX

A. [24][Composition: Cementitious materials, sand, coarse aggregate, water, and {water-reducing and set controlling} and {air-entraining} admixtures, all well mixed and brought to specified consistency.]

B. Performance criteria:

1. Design Strength: [25][___ lb/in^2 at ___ days].

a. [26][At least {80} percent of all test cylinders shall exceed {_____} pounds per square inch at {7} {28} {90} {180} {365} days.

b. [27][At least {80} percent of all test cylinders shall exceed {_____} pounds per square inch at {28} days age.]

2. Consistency: Uniform from batch to batch.

a. Government will measure consistency with Vebe apparatus in accordance with ASTM C 1170, Method [28][{A} {B}].

1) Vebe Time: [29][15] seconds plus or minus 10 seconds.

3. [30][Entrained air content: [31][4] percent, plus or minus 1 percent.

a. Add air entraining admixture (AEA) at dosage to produce specified air content.]

C. Mix proportions:

1. Designed by the Government and adjusted by the Government during work progress whenever need for such adjustment is indicated by results of testing of aggregates and RCC.

2. Adjustments:

---

24 For sloping/stair-stepped spillways or for overtopping protection.

25 Design strength varies between 3,000 and 4,000 lb/in^2. Time varies between 28 and 365 days.

26 Insert the design strength and select appropriate time.

27 Insert early age strength if required for testing purposes. Early age strength may be about 1/3 of design strength.

28 Select appropriate test method.

29 Consult with materials specialist for appropriate time.

30 Include when application requires air entrained RCC.

31 4 Percent entrained air is typical. Adjust entrained air as required for job.

a. Mix proportions will be adjusted to produce RCC with suitable workability, consistency, impermeability, density, strength, and durability without using excessive cementitious materials.

b. Water:

1) Water will be adjusted so that consistency of RCC allows compaction throughout specified lift thickness [32][and exposed edges of the lift] with minimal segregation or voids.

2) Water will be adjusted to account for variations in consistency due to fluctuations in aggregate moisture content, aggregate grading, ambient temperature, or mixture temperature

3. Starting mix proportions:

a. Estimated RCC mixture for beginning construction is shown in Table 03702A - Initial Mix Proportions for RCC with Saturated Surface Dry Aggregates.

[33][

Table 03702A – Initial Mix Proportions for RCC with Saturated Surface Dry Aggregates

INGREDIENT	QUANTITY
Cementitious materials	300 pounds per cubic yard RCC
Pozzolan	{Facing/overtopping spillways: 20 percent} {Mass placements: 50 percent} by weight of cementitious materials
Water	165 pounds per cubic yard RCC
Sand	1250 pounds per cubic yard RCC
Coarse aggregate	2300 pounds per cubic yard RCC
[34]Air Entrainment Admixture (AEA)	As recommended by manufacturer to obtain 4 percent plus or minus 1 percent
Admixtures: WRA	Manufacturer=s recommended dosage

2.10 BONDING MORTAR MIX

A. Composition: Cement, water, sand, and admixtures.

1. The Government will adjust water content to bring mortar to a broomable consistency.

[32] For sloping/stair-stepped spillways or for overtopping protection.

[33] Select appropriate options.

[34] Delete row if entrained air not required in RCC.

2. Maximum water to cementitious materials ratio: [35][0.50], by weight.

B. Starting mix proportions: Conform to Table 03702B - Initial Mix Proportions for Bonding Mortar.

Table 03702B - Initial Mix Proportions for Bonding Mortar

Ingredient	Quantity
Water	450 pounds per cubic yard
Cementitious materials	915 pounds per cubic yard
Sand	2515 pounds per cubic yard
Admixture	Manufacturer=s recommended dosage

2.11 BATCHING AND MIXING EQUIPMENT

A. Equipment performance requirements:

1. Batching and mixing rated capacity: [36] [______] cubic yards per hour.
2. Provide, maintain, and operate batching equipment to accurately measure and control the prescribed amounts of the various materials entering the mixers.
3. Maintain in a clean and freely operating condition.

B. Batch plants with separate batching and mixing operations:

1. Construct, maintain and operate equipment for conveying batched materials from weighing hoppers into the mixer to prevent spillage of batched materials and overlap of batches.
2. Interlocking controls:
   a. Equip batch plant with automatic interlocking sequential batching controls.
   b. Prevent starting new batch until weighing hoppers have been completely emptied of last batch and scales register zero weight.
   c. Prevent RCC batches from entering mixers if mixers are not empty
3. Weighing and measuring equipment:
   a. Equip with controls to provide a printout of individual batch weights.
   b. Accuracy: 0.40 percent over the working range.

[35] Insert appropriate w/c ratio. Typically, maximum w/c ratio is 0.50.

[36] The minimum plant capacity (in cubic yards per hour) should be sized to produce enough material to place the specified number of lifts in a single shift, assuming 80 percent efficiency.

1) Construction and accuracy of equipment: Conform to applicable requirements of NBS 44.

2) Schedule and perform monthly static tests:

a) Ensure that operating performance of each scale and measuring device is accurate.

b) Supply standard test weights and other equipment to conduct tests.

c) Perform tests in the presence of a Government inspector, for approval.

d) Perform additional tests when requested by the Government.

e) Adjust, repair, or replace devices to meet specified accuracy.

c. Weighing units:

1) Springless.

2) Visibly register and display actual weights during weighing operation.

3) Batch weight indicators and volumetric dispensers: In full view of operator.

d. Equipment tolerances for combined feeding and measuring during normal operation, by weight:

1) Water: Plus or minus 1 percent.

2) Cementitious materials: Plus or minus 1-1/2 percent.

3) Sand and coarse aggregate: Plus or minus 2 percent.

4) Admixtures: Plus or minus 3 percent.

e. Weighing hoppers: Constructed to allow removal of excess materials.

4. Aggregate handling equipment:

a. Equipped with automatic controls to adjust for moisture content of aggregates.

b. Aggregate batch bins: Constructed to be self-cleaning during drawdown.

c. Deposit coarse aggregate in batch bins directly over discharge gates.

1) Deposit aggregate larger than 3/4-inch nominal size in batch bins through effective rock ladders.

2) Prevent breakdown and degradation of course aggregate.

5. Cementitious materials handling equipment:

a. Constructed and operated to prevent noticeable dust during the measuring and discharging of each batch of material.

6. Water batching device:

   a. Construct to discharge water quickly and freely into mixer without objectionable dribble from end of discharge pipe.

   b. Prevent leakage when valves are closed.

   c. Provide means for accurately introducing small increments of water into each mixer after batching for occasional final tempering RCC.

   d. Incremental adjustment capability: 3 pounds per cubic yard, or smaller.

7. Admixture batching equipment:

   a. Dispenser capacity: Sufficient to measure at one time the full quantity of properly diluted solution required for each batch.

   b. If admixtures are measured by a method other than direct weighing, equipment shall be designed for confirmation of accuracy of each batch quantity by use of visual-mechanical gauges readily visible from batch plant operator's station.

   c. Constructed so that required batch quantity can only be added once to each batch.

   d. Discharge each admixture separately into batched mixing water as mixing water is being discharged into mixer.

8. Inform the Government prior to and after changes and adjustments in batching equipment and control instrumentation.

9. Mixing equipment:

   a. Configure plant so that mixing action of each mixer can be observed from a safe location which can be easily reached from the control station.

   b. Operators shall be able to observe RCC in receiving hopper or buckets as it is being dumped from mixers.

   c. The Government will regularly examine mixers for changes in condition due to accumulation of hardened RCC or to wear of blades.

      1) Repair or replace mixers that produce unsatisfactory results.

C. [37][Continuous batching-mixing plants: {Not allowed.}

1. {Required recording devices:

   a. Input recording devices for weight of cement, pozzolan, and aggregates.

   b. Output devices for total weight of mixed product.

   c. Input recording devices for volumetric feed of water and admixtures.

   d. If ice is used for RCC, input recording shall be by weight.

---

[37] Select if continuous batch-mixing will be allowed or not. Include subparagraph when continuous batching and mixing is allowed.

2. Batching-mixing unit: Separate compartments for each RCC ingredient.
   a. Equip each unit with individually calibrated proportioning devices to vary mix proportions of each RCC ingredient.}]

2.12 BATCHING AND MIXING

A. Preparations for batching:
   1. Notify the COR at least 24 hours before batching.
   2. Perform batching only in the presence of Government inspector unless inspection is waived in each case.

B. Dry batching: Not allowed.

C. Truck mixers: Not allowed for mixing or transporting RCC.

D. Batch plants with separate batching and mixing operations:
   1. Batching:
      a. Batch size:
         1) Minimum: 75 percent of rated capacity of mixer.
         2) Maximum: Rated capacity of mixer.
      b. Cement, pozzolan, sand, and each size of coarse aggregate:
         1) Determine quantities for each batch by weighing.
         2) Weigh sand and coarse aggregate with separate scales and hoppers or cumulatively with one scale and hopper.
            a) Adjust for moisture content of aggregates.
         3) Cement and pozzolan may be weighed cumulatively with one scale and hopper so long as weighing is automatically controlled within specified tolerances and cement is weighed first.
      c. Water: Measure by weight or by volume.
      d. Admixtures:
         1) Batch separately in liquid form.
         2) Measure by weight or volume with visual gauges observable by plant operator.
         3) Discharge each admixture separately into mixing water as water is being discharged into mixer.
   2. Mixing:
      a. Mix RCC ingredients thoroughly in mixers designed to ensure uniform distribution of component materials throughout RCC mixture.

1) Adjust feed of materials into mixer, mixing time, and discharge of RCC from the mixers to provide RCC of uniform workability and consistency.

2) RCC as discharged from the mixer: Uniform in composition and consistency from batch to batch.

b. Mixing operations:

1) Add water prior to and during charging of mixer with other ingredients.

2) Mixing time:

a) After all materials are in the mixer, mix each batch for at least 90 seconds.

b) The Government may increase minimum mixing time, based on RCC uniformity test results.

c) Excessive mixing requiring additions of water to maintain the required RCC consistency: Not permitted.

c. Control each mixer with a timing device:

1) Device shall indicate mixing period.

2) Device shall ensure completion of required mixing period.

d. The Government will determine adequacy of mixing.

1) Determination of mixing adequacy will be in accordance with concrete uniformity requirements of ASTM C 94, annex A1; except:

a) Vebe consistency test in accordance with ASTM C 1170, Method [38][{A} {B}] will be substituted for slump test to determine uniformity.

b) Mixer uniformity: Vebe consistency shall not differ by more than 8 seconds for two samples.

2) Samples will be taken from any size batch which is commonly mixed during RCC production.

3) For testing purposes, mix size of batch directed by Government inspector.

4) Assist in collection of required samples.

E. [39][Continuous batching-mixing plants: {Not allowed.}

---

38 Select appropriate method.

39 Select if continuous batch-mixing will be allowed or not. Include subparagraphs only when continuous batching-mixing is allowed.

1. {Continuous batching-mixing plants: Allowed for RCC if plants meet specified tolerances for weigh batching.
   a. If specified tolerances cannot be consistently met and verified, batch by direct weighing.
2. Operate plants in accordance with the manufacturer's recommendations.
3. Check yield quantities at least once per shift of RCC production.
   a. Compute total quantities of materials batched.
   b. Compare total quantities batched to actual volume of RCC placed.
      1) Compute volume placed by survey or from drawings.
   c. Compute cumulative cementitious materials content batched to quantities delivered.
      1) If quantity varies more by more than 1-1/2 percent, resolve differences with COR or re-calibrate cementitious materials feed.
4. Calibration:
   a. Check calibration by weight samples prior to placing RCC.
   b. Calibrate each RCC ingredient at the high, low, and average production rates used during RCC production.
   c. Obtain aggregate calibration check samples from at least 4 minutes operation at planned operating rates.
   d. Obtain water, cement, pozzolan, and admixture calibration check samples from at least 2 minutes operation at the planned operating rate.
   e. Re-calibrate each batcher-mixer following breakdown or replacement of individual proportioning devices or when batcher-mixer fails to meet specified tolerances.
   f. Recalibrate batch plant every [40][___] cubic yards, but not less than once per week.}
5. Adequacy of mixing:
   a. Determined [by Government] in accordance with RCC uniformity requirements of ASTM C685, section 14.2.3, and annex A1, except:
      1) Vebe consistency test in accordance with ASTM C 1170, Method [41][{A} {B}] will be substituted for slump test to determine uniformity.
      2) Mixer uniformity: Vebe consistency shall not differ by more than 8 seconds for two samples.}]

---

[40] For smaller jobs recalibrate about 1/2 of quantity (calibrate at start and at mid point of the job). For larger jobs insert quantity that would result in weekly calibration s.

[41] Select appropriate method.

2.13 TEMPERATURE OF RCC

A. [42][Temperature of RCC at placement: Not less than ___ degrees F and not more than __ degrees F.]

1. Temperature at batch plant: Adjust temperature of RCC at the batch plant to ensure that specified RCC temperature is attained at placement.

2. After placing but prior to compaction, temperature will be determined by the Government by placing a thermometer in RCC at placement site.

B. Cold weather placement:

1. Heat RCC ingredients just enough to keep temperature of the mixed RCC, as placed, from falling below specified minimum temperature.

2. Heat RCC ingredients by approved methods.

C. Hot weather placement:

1. Maintain temperature of RCC below specified maximum temperature.

2. Employ one or more of the following methods:

a. Place RCC at night.

b. Pre-cool aggregates.

c. Refrigerate mixing water.

d. Inject liquid nitrogen.

e. Add flake ice as a portion of mixing water if flake ice has melted prior to completion of mixing RCC.

f. Cool cement and pozzolan.

D. The Contractor shall be entitled to no additional compensation for RCC temperature control.

2.14 CONTRACTOR QUALITY CONTROL

A. Provide quality control measures to ensure compliance of constituent materials, and fresh RCC and bonding mortar meet specified requirements.

2.15 BATCH PLANT QUALITY TESTING

A. The Government will conduct an independent sampling and testing program at the batch plant to verify that constituent materials, and fresh RCC and bonding mortar meet specifications.

B. Sampling and testing facility:

1. Supply the following for use by Government:

[42] Consult materials specialist.

a. Building for testing:

1) Enclosed building of not less than 200 square feet.

2) Locate adjacent to batch plant.

3) Free from plant vibration and excessive plant noises.

4) Furnished with necessary utilities including lighting, compressed air, water, room temperature control, and electrical power.

b. Mechanical sampling devices and means of transporting samples to testing area.

1) Supply equipment capable of obtaining representative samples.

c. For cementitious materials, admixtures, sand, and each size of coarse aggregate: Obtain samples from discharge stream between batch bins and weighing hoppers or between batch hopper and mixer.

d. For RCC samples: From a point in the discharge stream as RCC is discharged from mixers.

2. Removal of test facilities:

a. Test facilities remain the property of the Contractor.

b. Remove from worksite after tests are completed.

C. Government will obtain samples and conduct tests in accordance with procedures listed in Table 03702C – Standards Used for Batch Plant Testing.

Table 03702C – Standards Used for Batch Plant Testing

Procedure	Standard No.
Sampling hydraulic cement	ASTM C 183
Sampling pozzolan	ASTM C 311
Sampling aggregate	ASTM D 75
Reducing field samples of aggregate to testing size	ASTM C 702
Absorption of fine aggregate	ASTM C 128
Absorption of coarse aggregate	ASTM C 127
Total moisture content of aggregate	ASTM C 566
Sampling fresh concrete	ASTM C 172

Table 03702C – Standards Used for Batch Plant Testing

Procedure	Standard No.
RCC uniformity For separate batching/mixing operation For continuous batching operation	 ASTM C 94, Annex A1, except vebe consistency test in accordance with ASTM C 1170 will be substituted for the slump test. ASTM C 685, Annex A1, except vebe consistency test in accordance with ASTM C 1170 will be substituted for the slump test.
Air content	ASTM C 231
Vebe consistency and density	ASTM C 1170
Density (unit weight) and yield	ASTM C 138, except that a 0.25-cubic-foot container may be used for nominal aggregate sizes up to 1-1/2-inches
Making test specimens in field	ASTM C 1176 or ASTM C 1435
Capping cylindrical concrete specimens	ASTM C 617
Compressive strength of cylindrical concrete specimens	ASTM C 39

PART 3 EXECUTION

3.01 TRANSPORTATION OF RCC

A. Capacity of equipment for transporting RCC shall match or exceed capacity of batching and mixing equipment.

B. Transport RCC from mixing plant and deposit in final position.

C. Select transportation equipment to minimize segregation of coarse aggregate from mortar.

D. Transport by any of the following methods:

1. Hauling vehicles traveling from batch plant to placement site.
2. Conveyors transporting RCC from batch plant to hauling vehicles or intermediate holding hoppers on placement site.
3. Conveyors transporting RCC from batch plant directly to final placement.

E. Vehicle travel on surface of previously placed RCC.

1. Do not allow vehicles to travel onto compacted RCC surfaces unless vehicles are in good operating condition and free of deleterious substances.
    a. Clean undercarriage and tires or tracks of vehicles to remove contaminants immediately prior to driving onto RCC surface.
    b. Equip vehicles with catchpans to prevent oil contamination.
    c. Hauling vehicles subject to approval of COR.
2. Rubber-tired equipment tires: Smooth low-pressure tires without lugs to prevent excessive rutting of compacted surfaces.
3. Avoid sharp turns that may damage compacted RCC surface.

F. Conveyors:

1. Design conveyor system to minimize segregation of coarse aggregate.
    a. Equip with baffles at transfer points.
    b. Provide tremies, rock ladders, or other suitable devices on conveyor at point of discharge to minimize segregation or breakage of aggregates.
2. Equip with scrapers to prevent buildup of mortar on belts.
3. Conveyer system shall include method for removing improperly batched or mixed RCC so that this material is not transported to the placement site.
4. Limit free fall at discharge to a maximum of 5 feet.
5. Intermediate holding hoppers, or gob hoppers shall be self cleaning and discharge freely without buildup of mortar or segregation of coarse aggregate.

3.02 SPREADING AND COMPACTING EQUIPMENT

A. Equipment: Capable of placing RCC at specified lift thickness.

B. Skid loaders: Not permitted.

C. Select equipment which will properly handle and place RCC of the specified consistency.

D. Compacting Equipment:

1. Self-Propelled Vibratory Rollers
2. Power Tampers, Small Vibratory Rollers, and Plate Vibrators

3.03 PREPARATIONS FOR PLACING

A. Notify COR at least 24 hours before batching begins for placement of RCC.

B. Unless inspection is waived for a specific placement, batch and place in presence of the COR.

C. Do not begin placement until the COR has approved completion of all preparations for placement.

D. Prior to batching, specified amounts of approved cementitious materials, sand, and coarse aggregate shall be stockpiled at the batch plant.

E. Prior to beginning RCC placement, have on site a sufficient number of properly operating vibratory rollers, power tampers, or other approved compaction equipment; and equipment operators.

3.04 FOUNDATION SURFACE PREPARATION

A. Foundation surface is defined as any surface or material against which RCC will be placed. [43][Foundation surfaces include soil and dam embankment materials.]

B. Prepare surfaces free from frost, ice, water, mud, and debris.

C. [44][Compact earth foundations to form firm foundation for RCC.

D. Prepare damp earth foundations for RCC placement so that earth is thoroughly moist but not muddy to a depth of 6 inches or to impermeable material, whichever is less.]

E. Refer to Section 02315 - Excavation, for foundation approval procedures.

3.05 LIFT SURFACE PREPARATION

A. Do not place RCC until previously placed RCC has been thoroughly compacted and surfaces to receive fresh RCC have been approved.

B. Before RCC is placed, clean substrate surfaces to remove deleterious substances.

1. Deleterious substances include un-compacted, loose, deteriorated, or improperly cured RCC material, grout, or any material other than RCC including, but not limited to, dirt, foundation materials, petroleum products, curing compound, free surface water from any source, ice, remaining concrete materials from removed RCC lifts or concrete, and excavation material from foundation cleanup.
2. Clean lift surfaces just prior to placing RCC or bonding mortar on lift surface.
3. If deleterious materials are spilled on joint surfaces, remove contaminated RCC and replace with fresh RCC or concrete.
    a. Thoroughly consolidate replacement RCC prior to next RCC placement.
    b. The Contractor shall be entitled to no additional compensation for replacement concrete.

C. Clean lift surfaces as follows:

1. Standard cleanup (Type 1) :

[43] Edit for job conditions.

[44] Soil and embankment foundations only.

a. Perform standard lift surface cleanup on lift surfaces less than [45][__] hours old.

b. Remove contaminants, such as liquids, solids, dust, or combinations of liquids and solids with approved vacuum equipment, or by air jetting or air-water jetting.

c. RCC that is damaged by air jetting or air-water jetting shall be cleaned with approved vacuum equipment.

2. Cold joints (Type 2):

a. Lift surfaces more than [46][__] hours old and all joint edges greater than 2 hours old shall be considered a cold joint.

b. Clean by air jetting or air-water jetting to remove laitance, loose or defective concrete or mortar, curing compound and other coatings, and other foreign material. Vacuum cleaned surface with approved equipment.

c. Maintain cleaned surface in a saturated, surface-dried condition until covered by a bonding mortar.

3. Construction joints (Type 3):

a. Lift surfaces more than [47][ ] days old shall be considered a construction joint.

b. Clean by sand blasting, high-pressure water jetting, or water-jetting and brooming to remove all laitance, loose or defective concrete or mortar, curing compound and other coatings, and other foreign material. Vacuum cleaned surface with approved equipment.

c. Maintain the cleaned surface in a saturated, surface-dried condition until covered by a bonding mortar.

D. Bonding mortar

1. Place bonding mortar at lift surfaces shown on drawings.

2. Spread bonding mortar or broom onto RCC surface to a thickness of 1/2 inch plus or minus 1/4 inch.

3. Spread bonding mortar immediately ahead of RCC.

a. Do not place bonding mortar more than 50 feet in front of advancing lift of RCC.

b. While bonding mortar is still broomable, cover bonding mortar with RCC.

c. Do not cover bonding mortar after it has lost its plasticity or has set.

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[45] Insert age, typically 3 to 12 hours depending on location.

[46] Insert age, typically 3 to 12 hours depending on location.

[47] Insert 1 day for cement only RCC or 2 days for cement/pozzolan RCC.

E. After placing leveling concrete and RCC, thoroughly consolidate the interface to remove any air or rock pockets by internal vibration combined with RCC compaction equipment.

F. Clean joint surfaces and cure leveling concrete.

3.06 PLACING LEVELING CONCRETE

A. Place leveling concrete at locations indicated on drawings.

B. Place RCC against leveling concrete within 30 minutes of placing leveling concrete.

3.07 PLACING RCC

A. [48]Rate of placement, minimum:

1. Two lifts per day for single shift construction
2. Three lifts per day for two shifts or continuous construction.

B. Transport, deposit, and spread and compact RCC within 45 minutes after mixing.

C. Place to lines and grades shown on drawings.

D. Depositing:

1. Minimize segregation. End dumping of fresh RCC in piles that results in segregation will not be permitted.
2. Deposit in piles not to exceed 36-inches in height.
3. In confined areas, place RCC in thinner layers to facilitate compaction by power tampers or small rollers.

E. Spreading:

1. Spread in layers that compact to 12 inches thick, plus or minus 1-inch.
2. Prevent segregation, contamination, or drying of RCC and previously placed RCC.

F. Deposit, spread, and compact each lift of RCC prior to proceeding to next lift.

G. Deposit and spread each lift in adjacent lanes parallel to plan centerline of placement.

H. If RCC is not deposited adjacent to exposed edge of preceding lane within 30 minutes after spreading, or if the lift is discontinued:

1. Immediately compact exposed edge of preceding lane on a slope of 3 horizontal to 1 vertical.
2. This exposed compacted edge will be considered a cold joint.

[48] Revise if Contractor is responsible for quality control testing.

I. Cold joints exposed longer than 2 hours: Coat with bonding mortar prior to placing adjacent RCC.

J. Do not drive on uncompacted RCC, except as required for spreading and compacting RCC.

K. Do not allow RCC to dry after spreading and prior to compaction by vibratory rollers.

1. If drying occurs, a fog spray or fine water spray may be used to keep the surface moist.
2. Do not allow spray to wash paste or mortar from aggregates.

3.08 COMPACTING RCC

A. Prevent equipment and vehicle damage to RCC by eliminating tight turns, sudden stops, spinning wheels, and other damaging operating procedures.

B. Compaction equipment:

1. Use largest equipment practicable, which is suitable for use in area to be compacted.
2. Open areas: Use large width, self-propelled, dual-drum or single-drum vibratory rollers.
3. Areas inaccessible by large rollers: Use small vibratory rollers.
4. Other confined areas: Use hand-guided power tampers or plate vibrators.
5. Self-propelled vibratory rollers:
   a. Prequalification:
      1) Vibratory rollers shall be approved by the COR prior to use.
      2) Vibratory rollers will initially be pre-qualified for use in compacting RCC during evaluation of the test section.
      3) If additional vibratory rollers are used during construction, they shall be pre-qualified on a new control section.
   b. Maintain vibratory rollers to ensure maximum compactive effort of each roller is being achieved.
   c. Provide single or dual-drum drive.
      1) Transmission of dynamic impact to surface through smooth, steel drum by means of revolving weights, eccentric shafts, or other equivalent methods.
      2) Dual amplitude:
         a) Minimum amplitude on high setting: 0.030 inch.
         b) Minimum amplitude on low setting: 0.015 inch.

3) Dynamic force: Between 400 and 550 pounds per linear inch of drum width at the operating frequency used during construction.

4) Vibrating frequency: At least 2,200 cycles per minute.

5) Roller drum:

a) Smooth.

b) Diameter: 4 feet to 5-1/2 feet.

c) Width: 5-1/2 feet to 8 feet.

6) Supply and maintain in the placement area at least one self-propelled vibratory roller in good operating condition.

7) Standby roller: Have one roller [49][{on site} {locally available}] on standby to replace a defective roller or due to breakdown of equipment.

6. Power tampers, small vibratory rollers, and plate vibrators:

a. Small vibratory rollers:

1) Similar to the Bomag model BW-35.

2) Capable of operating adjacent to a vertical face.

3) Plate vibrators:

a) Similar to Mikasa model MVC-90 with applied static pressure of approximately 75 pounds per square foot.

b) Suitable for compacting surface defects and compacting RCC adjacent to forms [50][for stepped downstream face].

4) Power tampers:

a) Similar to the Wacker model BS 700 with a static applied pressure of approximately 150 pounds per square foot.

C. Compaction:

1. Complete compaction within 15 minutes after spreading and within 45 minutes after mixing.

2. Water for compaction: Do not apply water by direct spray from water hose.

3. Compactive effort:

a. Vibratory rollers:

1) Compact each lift with a minimum of 6 passes of dual-drum vibratory roller within 15 minutes after spreading.

[49] For small jobs not in remote location, equipment may be specified to be locally available

[50] Include when appropriate for job.

a) One pass of the dual-drum vibratory roller is defined as one trip across the RCC surface from the starting point to the finishing point.

b) One pass with the single-drum vibratory roller is defined as a round trip from a starting point to a finishing point and return to the starting point.

c) Equip single-drum vibratory rollers with "lugged" tires.

2) Operate roller at speeds not exceeding 1.5 miles per hour.

3) Do not allow roller to remain stationary on RCC with vibratory mechanism operating.

4) Overlap at least 1 foot on each pass.

5) Within range of operational capability of equipment, the COR may direct or allow variations to the amplitude, frequency, and speed of operation which result in maximum density at fastest production rate.

6) First pass of the vibratory roller shall be in static mode.

7) The total number of passes of a vibratory roller required for complete compaction:

a) Determined by the COR.

b) Number of passes required for compaction may be increased or decreased by the COR due to changes in workability of RCC at no additional cost to Government.

c) Number of passes by the vibratory roller may be increased in confined areas to achieve equivalent compaction of the vibratory roller in open areas.

8) Finish rolling:

a) Finish roll with vibratory roller to compact surface defects prior to placing the next lift.

b) Perform finish rolling approximately one hour after compaction.

b. Power tampers, small vibratory rollers, or plate vibrators:

1) Compact to density equivalent to the density attained by large dual-drum vibratory rollers.

2) Lift thickness may be less than 12 inches.

4. Compact uniformly throughout entire lift:

a. Surface of compacted RCC shall be dense and sealed with exposed aggregate held firmly in place by mortar.

b. Compacted surface shall be free of undulations, tracks, or roller marks greater than 2 inches deep.

c. Remove and repair damage caused by tracked vehicles, at the expense of the Contractor

5. If compaction operations are interrupted prior to completion of compaction so that RCC is left unworked for more than 15 minutes for any reason, or when RCC is wetted by rain or dried so that the moisture content exceeds the specified tolerance:

a. Remove and replace entire layer, at the expense of the Contractor.

b. No payment will be made for the cement and pozzolan in removed material.

6. [51][Compacting exposed RCC side slopes and outside face of spillways or slope protection.

a. Compact in accordance with approved plan.

b. Equip spreading equipment with a spreader box to prevent loose RCC from spilling over edges and vibrating plate compactor to compact exposed RCC edges.

1) The vibrating plate shall be capable of adjusting to the required slope and any high or low deviations in line and grade.

2) Pneumatic or hydraulic vibrating plate may be used to apply side pressure to the vibrating plate compactor.

c. Or, compact outside exposed edges with vibrating plate on outside edge or compact with external vibrating equipment to apply both top (downward) pressure and side pressure normal to the slope of the outside compacted edge.

d. Compact to specified density.]

3.09 DENSITY AND MOISTURE CONTROL

A. Control sections:

1. First control section: Part of RCC test section as directed by COR.

2. Subsequent control sections:

a. Part of the structure at locations directed by the COR.

b. Control sections required every [52][____ yd^3].

3. Minimum size: 10 feet wide, 100 feet long, and one full lift of RCC in depth.

4. Control section construction procedures:

a. Place and compact RCC.

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[51] Delete or revise as required.

[52] Typical requirement is for control section every 10,000 yd^3

b. The COR will direct the Contractor to discontinue compacting efforts while the Government takes density measurements. Depending on the density measurements, the COR will direct additional vibratory roller passes or will direct that the control section is complete.

1) Density measurements in the control section will generally be taken after the initial four passes and every two roller passes thereafter.

2) The total number of passes of the vibratory roller will be directed by the COR.

c. When the maximum degree of compaction has been achieved throughout the lift, the control section will be considered at maximum density.

B. Determination of AMD and moisture content:

1. The Government will take in-place wet density measurements in the control section with a single probe nuclear surface moisture density gauge (nuclear gauge).

a. Density measurements for computation of AMD will be taken with the nuclear gauge in the direct transmission mode, with the direct transmission probe at a depth of 11-inches plus or minus 1-inch.

b. Intermediate measurements at varying depths of the lift may be taken to ensure full compaction throughout the lift.

2. AMD and moisture content of the control section will be determined by averaging the in-place wet density and moisture content measurements at five sites selected by the COR.

a. Two measurements will be taken at each site. The second measurement to be taken by rotating the nuclear gauge 90° around the vertical axis of the probe from the original position.

b. The AMD will be the average of these 10 density measurements. The moisture content will be the average of these 10 moisture measurements.

c.

C. Density and moisture content control:

1. Density and moisture content control is based on the last completed control section.

2. Average in-place, wet density of the last 10 consecutive tests of RCC: Not less than 99 percent of the AMD of the control section.

a. Prior to completing 10 tests, the average in-place wet density of RCC for all tests: Not less than 99 percent of the AMD, with no more than one test less than 98 percent of the AMD and no single test less than 95 percent of the AMD.

3. Compacted RCC having an in-place wet density less than 95 percent of the AMD of the control section will be rejected.
    a. Re-roll rejected material if the required compaction can be achieved within 15 minutes after the nuclear density measurement has been performed.
    b. Otherwise, remove rejected RCC and replace at the Contractor's expense.
4. On side slopes and exposed edges of lifts, compacted RCC shall have an in-place wet density at least 98 percent of the AMD.
5. The COR will inform the Contractor when placement of RCC is near or below the specified limits.
6. Immediately make adjustments in procedures as necessary to maintain the placement density within the specified limits.

D. Density testing during RCC placement:

1. The Government will perform in-place wet density tests as soon as practicable after compaction.
    a. Measurements will be made using a nuclear gauge similar to Troxler model 3440.
    b. Acceptance of RCC will be governed by density measurements taken in the direct transmission mode with a probe depth of 11-inches plus or minus 1-inch, using the single probe nuclear gauge.
    c. The Government may use a double probe nuclear gauge, similar to Campbell Pacific Strata-Gauge, to evaluate compaction throughout the RCC lift.

E. Moisture control:

1. During compaction, maintain in-place RCC moisture content with a fog or fine spray.
    a. Do not supply additional water to the RCC after completion of mixing with the exception of the fog or fine spray.
2. In-place moisture content during compaction will be monitored by the Government using a nuclear gauge.
3. If moisture content of compacted RCC deviates more than plus or minus 0.3 percent of the moisture content determined during the latest control section, the COR will direct construction of another control section and will compute a new AMD and moisture content.
4. Maintain in-place total moisture content of RCC after compaction is completed at the placed total moisture content of RCC plus or minus 0.3 percent.
5. The COR will inform the Contractor when the moisture content exceeds the specified limits.
6. Adjust procedures to retain the batched moisture content.

3.10 [53][CRACK INDUCERS

A. Place specified crack inducer material at locations shown on the drawings.

B. Carefully align to following tolerances:

1. Line: Plus or minus 2 inches from location shown on drawings

2. Depth: Plus or minus 2 inches from specified depth.

C. Vibrate crack inducers into place after spreading or immediately following compaction of RCC lifts.

D. Place in [54][all lifts} {alternating lifts}].

E. Do not install at locations where embedded materials cross induced joints and such materials will be damaged by installation of crack inducers.]

3.11 CURING

A. Continuously cure RCC.

B. Begin curing immediately after final compaction.

C. After completion of each shift of RCC placement, remove loose or spilled, uncompacted RCC from lift surfaces and side slopes.

D. Cure RCC surfaces to prevent loss of moisture until the required curing period has elapsed or until immediately prior to placement of other concrete or RCC against those surfaces. Only interrupt curing to allow sufficient time to prepare construction joint surfaces or lift surfaces and to bring them to a clean saturated surface dry condition prior to placement of adjacent RCC or concrete.

E. Remove improperly cured RCC at Contractor=s expense.

F. The COR reserves the right to delay RCC placements due to improper curing procedures until proper curing procedures are implemented.

G. Curing methods:

1. Cure with water, or water followed by covering with polyethylene film.

a. Keep surfaces continuously moist, but not saturated, for 14 days or until placement of the next lift.

b. Apply water by sprinkler truck; a system of perforated pipes, hoses, stationary or portable sprinklers; fogging; or other approved methods to keep exposed surfaces continuously moist.

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[53] Consult designer to determine need for crack inducers.

[54] Select appropriate choice.

2. Exposed compacted RCC at sideslopes: Curing compound allowed.
3. Any method which results in the RCC becoming dry will be considered an improper curing method.
4. If freezing weather is imminent:
    a. Discontinue water curing.
    b. Cover surfaces of RCC with polyethylene film.

3.12 PROTECTION

A. Protect uncompacted and freshly compacted RCC from damaging precipitation.

1. When precipitation occurs or is imminent:
    a. Suspend placing operations and cover freshly compacted RCC with polyethylene film.
    b. Before operations are suspended due to precipitation, compact RCC that has been deposited and spread.
    c. If paste is worked up to the surface of the previous lift due to Contractor's failure to suspend operations during rain or due to application of excess curing water, remove the previous lift of RCC at the expense of the Contractor.
    d. When precipitation appears imminent, immediately prepare protective materials at placement site.
    e. The COR may delay placement of RCC until adequate provisions for protection are made.

B. Protect RCC against damage until final acceptance.

C. Protect RCC from freezing:

1. Maintain temperature of RCC above 40 degrees F during curing.
2. Protect from freezing for at least 7 days after discontinuing curing.
3. Use insulated blankets or other approved methods.

3.13 FIELD QUALITY TESTING

A. The Government will conduct tests to extent and frequency necessary to ascertain that fresh RCC and bonding mortar, and hardened RCC and bonding mortar meet the requirements of these specifications.

B. Furnish the following sampling equipment and facilities for use by Government.

1. Ample and protected working space near the placement site and a means for safely procuring and handling representative samples.

C. Removal of test facilities:

1. Remove from worksite after tests are completed.
2. Contractor-furnished test facilities will remain the property of Contractor.

D. Government will obtain samples and conduct tests in accordance with procedures listed in Table 03702D – Standards Used for Testing at Placement.

Table 03702D – Standards Used for Testing at Placement

Procedure	Standard No.
Density (unit weight) and yield	ASTM C 138, except that a 0.25-cubic-foot container may be used for nominal aggregate sizes up to 1-1/2-inches
Density of in-place RCC	ASTM C 1040
Air content	ASTM C 231
Vebe consistency and density	ASTM C 1170
Sampling fresh concrete	ASTM C 172
Temperature	ASTM C 1064
Making test specimens in field	ASTM C 31, ASTM C 511, ASTM C 1176 or ASTM C 1435
Capping cylindrical concrete specimens	ASTM C 617
Compressive strength of cylindrical concrete specimens	ASTM C 39 for cast cylinders and ASTM C 42 for cores

3.14 FINAL CLEANUP

A. Clean surfaces by air or air-water jetting to remove loose materials.

B. Dispose of removed materials in accordance with Section 01740 - Cleaning.

END OF SECTION

RSN	Clause or Section Title	Submittals required	Due date or delivery time	Type *	Respon-sible code	No. of sets to be sent to: **		
						CO	ZZZ	TSC
03702-1	Roller-Compacted Concrete	Plan for RCC plant(s)	At least 28 days before placing RCC	A	ZZZ	0	2	1
03702-2	Roller-Compacted Concrete	Equipment and placement plan	At least 28 days before placing RCC	A	ZZZ	0	2	1
03702-3	Roller-Compacted Concrete	Cementitious materials	At least 28 days before placing RCC	I	ZZZ	0	2	1
03702-4	Roller-Compacted Concrete	Fine and coarse aggregates	At least 28 days before placing RCC	I	ZZZ	0	2	1
03705-5	Roller-Compacted Concrete	Proposed water source	At lease 28 days before placing RCC	I	ZZZ	0	2	1

Appendix B

Test Procedures

The Bureau of Reclamation developed test procedure USBR-4905-92 for determining the consistency and density of RCC, and test procedure USBR-4906-92 for casting RCC in cylinder molds using a vibrating table. These procedures are for information only. Reclamation specifies the most current ASTM procedures for testing RCC and making RCC in cylinder molds.

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

USBR 4905-92

PROCEDURE FOR

CONSISTENCY AND DENSITY OF NO-SLUMP CONCRETE WITH VIBRATORY TABLE

INTRODUCTION

This test procedure is under the jurisdiction of the Concrete and Structural Branch, code D-3730, Research and Laboratory Services Division, Denver Office, Denver, Colorado. The procedure is issued under the fixed designation USBR 4905; the number immediately following the designation indicates year of original adoption or year of last revision. This test procedure is a modified version of ASTM C 1170-91.

1. Scope

1.1 This designation covers the procedures for determining the consistency and density of no-slump concrete when standard slump test procedures, as outlined in USBR 4143, and density procedures, as outlined in USBR 4138, are not applicable. These procedures are applicable in both the laboratory and field.

NOTE 1.–These procedures are considered applicable to plastic concrete having coarse aggregate up to 2 inches (50 mm) in size. If coarse aggregate is larger than 2 inches, procedures are applicable when made on the fraction of concrete passing the 2-inch sieve, with larger aggregate being removed in accordance with USBR 4172 with the exception that a 2-inch sieve is used instead of a 1-1/2-inch (37.5-mm) sieve. The USBR 4172 procedure is not considered applicable for nonplastic and noncohesive concrete.

1.2 These procedures, intended for use in testing roller-compacted concrete, may be applicable to testing other types of concrete such as cement-treated aggregate and mixtures similar to soil-cement.

1.3 Two alternate test methods are provided to determine the consistency and density of concrete using a Vebe vibrating table:

1.3.1 *Test Method A* [using a 50-lbm (22.7-kg) surcharge mass placed on top of the test specimen].–Test Method A shall be used for testing concrete of very stiff to extremely dry consistency in accordance with ACI 211.3-75 (R 1989).

1.3.2 *Test Method B* (no surcharge).–Test Method B shall be used for concrete of stiff to very stiff consistency or when the Vebe time by Test Method A is less than 5 seconds.

1.4 The recommended vibration table for this test procedure is the Vebe vibrating table. To date, all Bureau testing has been performed using this testing apparatus. An alternate vibrating table may be substituted for the Vebe apparatus provided it meets the specifications for the sinusoidal vibration as shown in section 9.3 and the alternate testing requirements of sections 11 and 12.

2. Applicable Documents

2.1 *USBR Procedures*:
4029 Density and Voids in Aggregate
4031 Making and Curing Concrete Test Specimens in Field
4138 Density, Yield, Clean, Separation, and Air Content (Gravimetric) of Concrete
4143 Slump of Concrete
4172 Sampling Freshly Mixed Concrete
4192 Making and Curing Concrete Test Specimens in Laboratory

2.2 *ASTM Standards*:
C 1170 Standard Test Methods for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table[1]
E 1 Specification for ASTM Thermometers[2]
E 11 Specification for Wire-Cloth Sieves for Testing Purposes[1,3]

2.3 *ACI Standards*:
207.5R-89 Roller-Compacted Concrete[4]
211.3-75R-89 Standard Practice for Selecting Proportions for No-Slump Concrete[4]

3. Summary of Procedure

3.1 This procedure is used to measure the consistency of stiff to extremely dry concrete mixtures (note 2). Consistency is meaasured as the time required for a given mass of concrete to be consolidated by vibrating in a cylindrically shaped mold. Denisty of the compacted specimen is measured by determining the mass of the consolidated specimen and dividing by its volume, which is determined using water-displacement methods.

NOTE 2.–Further description of concrete of this consistency is given in ACI 207.5R-89 and ACI 211.3-75 (R 1989).

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1 *Annual Book of ASTM Standards*, vol. 04.02.
2 *Annual Book of ASTM Standards*, vols. 05.03, 14.03.
3 *Annual Book of ASTM Standards*, vols. 04.01, 04.06, 04.07, 05.05, 14.02.
4 *ACI Manual of Concrete Practice*, part 1, 1990. Available from American Concrete Institute, PO Box 19150, Redford Station, Detroit, MI 48219.

4. Significance and Use

4.1 Test methods A and B are intended to be used for determining the consistency and density of stiff to extremely dry concrete mixtures common when using roller-compacted concrete construction.

4.1.1 Because of the stiff to extremely dry consistency of some roller-compacted concrete mixtures, the standard Vebe test method of rodding the specimen in a slump cone is substituted by Test Methods A and B. For Test Method A, the surcharge mass is increased from 6 lbm (2.72 kg) to 50 lbm (22.7 kg); and for Test Method B, the surcharge mass is eliminated.

4.2 Test Method A uses a 50-lbm surcharge and is used for concrete consolidated by roller-compaction methods. The consistency and density of concrete suitable for consolidation by vibrating rollers can be determined using Test Method A.

4.3 Test Method B does not use a surcharge and can be used to determine the consistency and density of some concrete mixtures consolidated by conventional vibration techniques and some concrete mixtures consolidated by vibrating rollers.

5. Terminology

5.1 *Roller-Compacted Concrete.*-Concrete of zero-slump consistency which is placed by depositing loosely in horizontal lifts and consolidated with smooth-drum vibrating rollers.

6. Apparatus

6.1 *Cylindrical Mold.*-The cylindrical mold shall be made of steel or other hard metal resistant to cement paste corrosion and have an inside diameter of 9-1/2±1/16 inches (241±2 mm) and a height of 7-3/4±1/16 inches (197±2 mm). Volume of mold shall be determined in accordance with USBR 4029. The mold shall be equipped with permanently affixed metal slots which can be rigidly clamped to Vebe vibrating table. Top rim of mold shall be smooth, planar, and parallel to bottom of mold; and shall be capable of providing a tight seal. There should be no leakage of air bubbles when mold is filled with water and a smooth glass or plastic plate is placed over top rim.

6.2 *Swivel Arm and Guide Sleeve.*-A metal guide sleeve with clamp assembly or other suitable holding device mounted on a swivel arm. The swivel arm and guide sleeve must be capable of holding a metal shaft attached to a 50-lbm (22.7-kg) surcharge in a position perpendicular to vibrating table, which allows the rod to slide freely when clamp is released. The guide sleeve inside diameter shall be 1/8±1/16 inch (3.2±1.6 mm) larger than the diameter of the metal shaft of the surcharge. The sleeve must be capable of maintaining a locked position with center of sleeve directly over center of vibrating table, and shall also be capable of rotating away from center of table. The Vebe vibrating table comes equipped with this guide sleeve.

6.3 *Surcharge.*-A cylindrical surcharge with a metal shaft at least 18 inches (457 mm) long and 5/8±1/16 inch (16±2mm) diameter attached perpendicularly to the plate and embedded through center of surcharge. The shaft shall slide through the guide sleeve without binding or excessive play. The base of the surcharge shall have a 9±1/8-inch (229±3-mm) diameter. Surcharge shall have a mass of 50±1 lbm (22.7±0.5 kg) including mass of the metal shaft. If the surcharge is hand held, the length of the metal shaft may be reduced to 12 inches (305 mm) and fabricated with a "T" or "D" handle for gripping the surcharge shaft to avoid the hand slipping.

6.4 *Balance or Scale.*-The balance or scale shall be of sufficient capacity to determine total mass of sample and mold, and have sufficient accuracy so that mass of concrete sample may be determined to nearest .01 lbm (4.5 g).

6.5 *Flat Plate.*-A square, flat plate or acrylic plate at least 1/2 inch thick with a length and width at least 1 inch (25 mm) greater than outside diameter of cylincrical mold is required. The plate shall be smooth and planar.

6.6 *Vebe Vibrating Table.*-A vibrating table with a 3/4-inch (19 mm) thick steel deck with dimensions of about 15 inches in length, 10-1/4 inches in width, and 12 inches in height (381- 260- 305-mm). The vibrating table shall be constructed in such a manner as to prevent flexing of the table during operation. The table deck shall be activated by an electromechanical vibrator. The total mass of the vibrator and table shall be approximately 210 lbm (95 kg). The table shall be level and clamped to a concrete floor or base slab having sufficient mass to prevent displacement of the apparatus during performance of the test.

NOTE 3.-The recommended vibrating table for these test procedures is the Vebe vibrating table. To date, testing has been performed using this apparatus. An alternative vibrating table may be substituted for the Vebe apparatus (fig. 1) provided it meets the specifications for the sinusoidal vibration given in subsection 9.3 and is in accordance with the alternative testing requirements of sections 11 and 12. The Vebe apparatus, including cylindrical mold and guide sleeves, is manufactured by Dynapac Maskin (formerly Vibro-Verken), PO Box 1103, 5-171-22, Solna, Sweden; Dynapac Manufacturing, Inc., Stanhope NJ 07874; and Soiltest, Inc., 86 Albrecht Drive, PO Box 8004, Lake Bluff IL 60044-9902.

6.7 *Thermometer.*-ASTM No. 1F or 1C thermometer conforming to the requirements of ASTM specification E 1.

6.8 *Sieve.*-A 2-inch (50-mm) sieve conforming to ASTM specification E 11.

6.9 *Miscellaneous Equipment.*-Also required are a shovel, scoop, slump rod, stopwatch, and flashlight.

7. Precautions

7.1 This test procedure may involve hazardous materials, operations, and equipment, and does not claim to address all safety problems associated with its use. The user is responsible to consult and establish appropriate safety and health practices and to determine applicability of regulatory limitations prior to use.

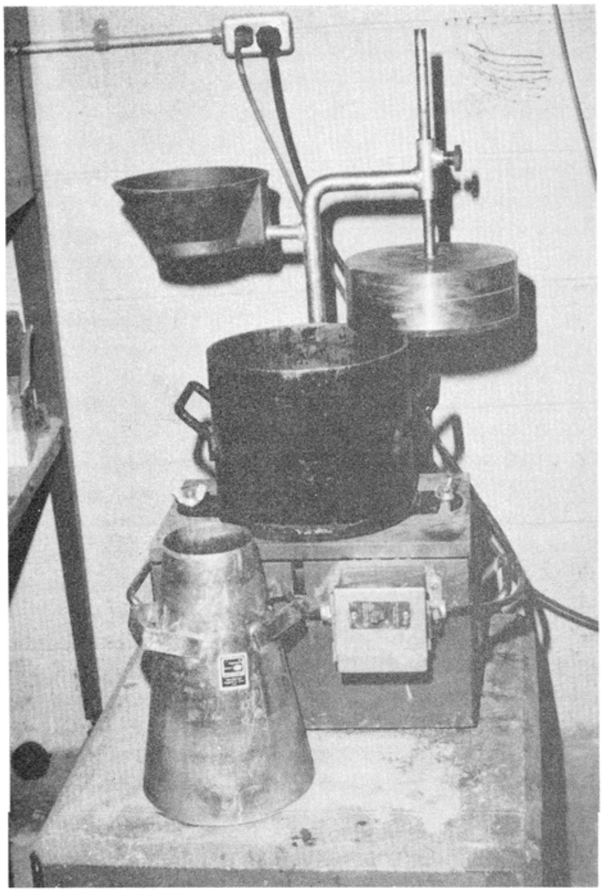

Figure 1. – Vibrating table—consistency test.

8. Sampling, Test Specimens, and Test Units

8.1 Samples of fresh concrete should be obtained in accordance with USBR 4172.

8.2 Concrete samples should have a nominal maximum size aggregate of 2 inches (50 mm) or less. If concrete has aggregate larger than 2 inches, samples shall be obtained by wet sieving over a 2-inch sieve in accordance with USBR 4172.

8.3 Concrete sample testing shall be completed within 45 minutes after the completion of mixing unless otherwise stipulated.

9. Calibration and Standardization

9.1 The calibration and standardization of miscellaneous equipment or apparatus used in performing the tests listed under the Applicable Documents of section 2 are covered under that particular procedure or standard directly or by reference.

9.2 *Cylindrical Mold.*–The volume of the cylindrical mold shall be calibrated to the nearest 0.02 ft^3 (0.000 57 m^3) in accordance with USBR 4029. Calibration shall be performed annually when use is infrequent and monthly during times of heavy use. Mass of cylindrical mold, if used in density computations (i.e., balance with tare unavailable), shall be determined to nearest 0.01 lbm (4.5 g).

9.3 *Vebe Vibrating Table.*–The frequency and amplitude of the vibrating table shall be determined under simulated test conditions prior to initial use, and annually thereafter (note 4). Frequency and amplitude shall be determined in accordance with USBR 4031 or 4192.

NOTE 4.–This determination can be performed by personnel of the Materials Engineering Branch (code D-3735) at the Bureau's Denver Office, and should be coordinated with the calibration of other vibration testing equipment.

9.3.1 The Vebe vibration table or the alternate table shall produce a sinusoidal vibratory motion with a frequency of 3600±100 vibrations per minute (60±1.67 Hz) and an amplitude of vibration of 0.0085±0.0015 inch (0.22±0.04 mm) when a 60±2.5-lbm (27.2±1.1 kg) surcharge is bolted to center of table, as shown on figure 2.

9.4 In addition to the calibration frequency recommended in subsection 9.3, the vibrating table also should be calibrated after any event (including repairs) which might affect its operation and whenever test results are questionable.

9.5 At least, after every 3 months of continuous use, the underside of the vibrating table top should be inspected and cleaned of any hardened concrete or cement paste which may interfere with free movement of the tabletop.

10. Conditioning

10.1 Special conditioning is covered under sections 11 and 12.

TEST METHOD — VEBE TIME

11. Procedure

11.1 *Vebe Consistency Time* (with a surcharge):

11.1.1 Using square-ended shovels and scoops, obtain a representative sample, in accordance with section 8,

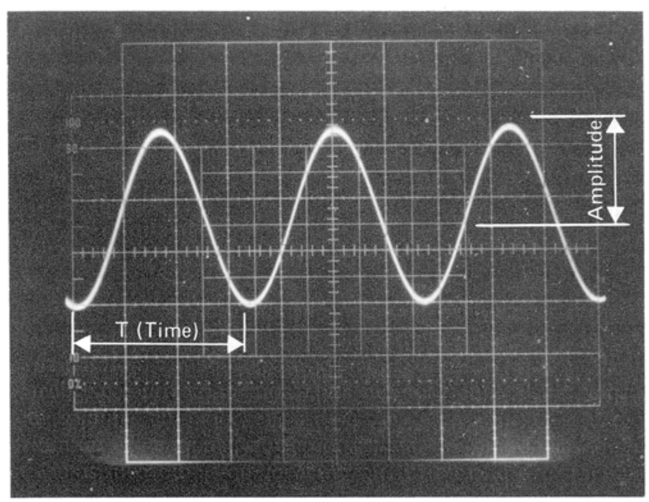

Figure 2. – Sinusoidal vibratory wave motion for vibrating tables. Frequency = 60 Hz, Single amplituide = 0.0085 inch (0.216 mm), and Surchage = 60 lbm (27 kg).

with a minimum mass of 50 lbm (22.7 kg). Handle concrete in such a manner that coarse aggregate does not separate from the mortar.

NOTE 5.–Concrete in the range of no-slump consistency is highly susceptible to segregation during handling. To minimize this, it is essential that care be used in obtaining samples and, during transporting, remixing and testing of the concrete. Square-ended shovels and scoops should be used to obtain a representative sample. Concrete should be handled in such a way that large-sized coarse aggregate does not separate from the mortar.

11.1.2 Dampen the interior of the mold and fill with 29.5±1.5 lbm (13.4±0.7 kg) of concrete. Using a square-edged scoop and tamping rod, place and distribute the concrete evenly to minimize segregation and rock pockets. Level the surface of the loose concrete.

11.1.3 Secure the mold on the Vebe table by hand tightening the wing nuts. Slide the shaft of the surcharge mass through the guide sleeve, and rotate the surcharge to its locked position centered over the mold, ensuring that it will fit inside the mold when released. The surcharge may be lowered into the mold during this procedure to adjust the position of the mold but it shall not be placed on the specimen. Secure the wing nuts of the Vebe table with a wrench to prevent loosening during the test. Gently lower the surcharge onto the surface of the specimen.

11.1.4 If the surcharge cannot be centered in the mold without binding on the inside wall of the mold, place the surcharge directly onto the specimen in the mold without the use of the guide sleeve, and manually hold the surcharge shaft perpendicular to the top of the table. The surcharge shaft must be held manually throughout the remainder of the Vebe test. Do not apply additional hand pressure to the surcharge when manually holding the surcharge.

11.1.5 Start the vibrator and timer. Using a flashlight, observe the concrete in the annular space between the edge of the surcharge and the inside wall of the mold. As the test progresses, mortar will fill in the annular space between the outer edge of the surcharge and the inside mold wall. Observe the mortar until it forms a ring around the total perimeter of the surcharge. When the mortar ring forms completely around the surcharge, stop the vibrator and timer; determine the elapsed time to the nearest minute and second. Record this time as the Vebe consistency time, Test Method A. If the wing nuts loosen during the test, repeat the test with a fresh sample of concrete. If the ring of mortar does not form after 2 minutes of vibration, stop the vibrator and timer; record this condition on the report.

11.1.6 If the following conditions exist after 2 minutes have elapsed, document them in the report, record the elapsed time, and retest if necessary:

11.1.6.1 A rock pocket in the loose specimen prevents the mortar ring from forming at one small location even though the mortar ring forms in all other locations, or:

11.1.6.2 The elapsed time in which the majority of the mortar ring formed is similar to previous readings with the same mixture proportions.

11.1.7 Determine the density of the specimen in accordance with section 11.2.

11.2 *Vebe Density of Freshly Consolidated Concrete*:

11.2.1 Following determination of the Vebe time, remove the surcharge. Vibrate the specimen without the surcharge for an additional 10 seconds to level the top surface of the sample.

11.2.2 Remove the mold with the consolidated specimen from the Vebe table, and wipe any mortar from the inside wall of the cylinder mold above the level of the consolidated concrete. Place the flat plate on the cylinder mold and determine to the nearest 0.01 lbm (4.5 g) the mass of the cylindrical mold, consolidated concrete specimen, and flat plate. Determine the mass of the specimen by subtracting the mass of the cylindrical mold and flat plate from the mass of the cylindrical mold, consolidated specimen, and flat plate. Remove the flat plate.

11.2.3 Place the mold on a level surface and carefully fill the mold with water at room temperature to a meniscus level just above the top rim while minimizing washout of paste from the specimen surface.

11.2.4 Determine the temperature of the water to the nearest 1 °F (1 °C).

11.2.5 Carefully cover the mold with the flat plate in such a way as to eliminate air bubbles and excess water.

11.2.6 Wipe all excess water, and determine the total mass of the cylinder mold, consolidated specimen, water, and flat plate. Determine the mass of the water by subtracting the mass of the mold, specimen, and flat plate as determined in 11.2.2 from the total mass.

11.2.7 Determine the volume of water by dividing the mass of water by the density of water at the recorded temperature in accordance with the values given in tables 1 or 2—interpolating if necessary. Determine the volume of water to the nearest 0.001 ft^3 (0.028 L).

11.2.8 Determine the volume of the specimen by subtracting the volume of the water obtained in 11.2.7 from the volume of the cylinder mold obtained in 9.2.

11.2.9 Determine the density of the specimen in accordance with section 13, Calculations. This is referred to as the Vebe density of the specimen, Test Method A.

11.3 *Vibrating Consistency Time and Density Using an Alternative Vibrating Table, Test Method A*:

11.3.1 Determine the consistency time of concrete in accordance with 11.1. Record the use of an alternative vibrating table, and record the time as vibrating consistency time, Test Method A.

11.3.2 Determine the density of the specimen in accordance with 11.2. Refer to this as the vibrating density of the specimen, Test Method A.

11.3.2.1 When determining the consistency and density of concrete using an alternative vibrating table, it may not be possible to vibrate the specimen without a surcharge. This is due to disturbance of the compacted specimen when large-amplitude, low-frequency vibration waves occur after the vibrator is turned off. If this occurs, leave the surcharge on the specimen after determining the vibrating time, and vibrate the specimen for an additional 10 seconds. Record the use of the surcharge for the density determination.

Table 1. – Absolute density of water in grams per cubic centimeter — °F.[1]

°F	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
32	0.999 841	845	848	852	856	860	863	867	871	874
33	.999 878	881	883	886	889	892	894	897	900	902
34	.999 905	908	910	913	915	918	920	923	925	928
35	.999 930	932	933	935	937	939	940	942	944	945
36	.999 947	949	950	952	953	955	956	958	959	961
37	.999 962	963	963	964	965	966	966	967	968	968
38	.999 969	969	970	970	971	971	971	972	972	973
39	.999 973	973	973	973	973	973	972	972	972	972
40	.999 972	971	971	970	969	969	968	967	966	966
41	.999 965	964	962	961	960	959	957	956	955	953
42	.999 952	951	950	949	948	947	945	944	943	942
43	.999 941	939	936	934	931	929	926	924	921	919
44	.999 916	914	911	909	907	905	902	900	898	895
45	.999 893	890	887	883	880	877	874	871	867	864
46	.999 861	858	855	852	849	846	842	839	836	833
47	.999 830	826	822	818	814	810	805	801	797	793
48	.999 789	785	781	778	774	770	766	762	759	755
49	.999 751	746	741	736	731	726	720	715	710	705
50	.999 700	695	689	684	678	673	667	662	656	651
51	.999 645	641	637	633	629	625	621	617	613	609
52	.999 605	598	590	583	575	568	561	553	546	538
53	.999 531	525	520	514	509	503	497	492	486	481
54	.999 475	468	460	453	446	439	431	424	417	409
55	.999 402	396	389	383	377	371	364	358	352	345
56	.999 339	331	323	315	307	299	290	282	274	266
57	.999 258	251	244	237	230	223	216	209	202	195
58	.999 188	179	170	161	152	144	135	126	117	108
59	.999 099	090	081	071	062	053	044	035	025	016
60	.999 007	001	*994	*988	*981	*975	*969	*962	*956	*949
61	.998 943	931	920	908	896	885	873	861	849	838
62	.998 826	817	809	800	791	783	774	765	756	748
63	.998 739	728	718	707	696	686	675	664	653	643
64	.998 632	623	613	604	595	586	576	567	558	548
65	.998 539	528	516	505	493	482	470	459	447	436
66	.998 424	414	404	394	384	375	365	355	345	335
67	.998 325	313	301	288	276	264	252	240	227	215
68	.998 203	191	178	166	153	141	128	116	103	090
69	.998 078	067	056	046	035	024	013	002	*992	*981
70	.997 970	957	943	930	917	904	890	877	864	850
71	.997 837	826	814	803	792	781	769	758	747	735
72	.997 724	710	696	682	668	655	641	627	613	599
73	.997 585	573	561	549	537	526	514	502	490	478
74	.997 466	451	437	422	408	393	378	364	349	335
75	.997 320	308	295	283	270	258	246	233	221	208
76	.997 196	181	166	150	135	120	105	090	074	059
77	.997 044	028	013	*997	*982	*966	*950	*935	*919	*904
78	.996 888	875	862	848	835	822	809	796	782	769
79	.996 756	740	724	707	691	675	659	643	626	610
80	.996 594	583	572	561	550	540	529	518	507	496
81	.996 485	465	446	426	407	387	367	348	328	309
82	.996 289	275	261	246	232	218	204	190	175	161
83	.996 147	130	112	095	077	060	043	025	008	*990
84	.995 973	958	944	929	914	900	885	870	855	841
85	.995 826	808	790	772	754	736	718	700	682	664

[1] To obtain absolute density of water in pound mass per cubic foot, multiply value shown in table by 62.4278578.
* First three significant digits shown in line below.

11.3.2.2 Determine the density of the consolidated specimen in accordance with 11.2.2 through 11.2.9.

TEST METHOD B — VEBE TIME

12. Procedure

12.1 *Vebe Consistency Time* (without a surcharge):

12.1.1 Obtain a representative sample of concrete having a minimum mass of 50 lbm (22.7 kg) in accordance with section 8, and place the concrete in the cylindrical mold in accordance with 11.1.1 and 11.1.2.

12.1.2 Place the mold on the Vebe table, and tighten the wing nuts to prevent loosening during the test.

12.1.3 Start the vibrator and the timer. Observe the contact between the concrete and inside wall of the mold.

Table 2. – Absolute density of water in kilograms per cubic meter — °C.

°C	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	999.841	.847	.854	.860	.866	.872	.878	.884	.889	.895
1	.900	.905	.909	.914	.918	.923	.927	.930	.934	.938
2	.941	.944	.947	.950	.953	.955	.958	.960	.962	.964
3	.965	.967	.968	.969	.970	.971	.972	.972	.973	.973
4	.973	.973	.973	.972	.972	.972	.970	.969	.968	.966
5	.965	.963	.961	.959	.957	.955	.952	.950	.947	.944
6	.941	.938	.935	.931	.927	.924	.920	.916	.911	.907
7	.902	.898	.893	.888	.883	.877	.872	.866	.861	.855
8	.849	.843	.837	.830	.824	.817	.810	.803	.796	.789
9	.781	.774	.766	.758	.751	.742	.734	.726	.717	.709
10	.700	.691	.682	.673	.664	.654	.645	.635	.625	.615
11	.605	.595	.585	.574	.564	.553	.542	.531	.520	.509
12	.498	.486	.475	.463	.451	.439	.427	.415	.402	.390
13	.377	.364	.352	.339	.326	.312	.299	.285	.272	.258
14	.244	.230	.216	.202	.188	.173	.159	.144	.129	.114
15	.099	.084	.069	.054	.038	.023	.007	*.991	*.975	*.959
16	998.943	.926	.910	.893	.877	.860	.843	.826	.809	.792
17	.774	.757	.739	.722	.704	.686	.668	.650	.632	.613
18	.595	.576	.558	.539	.520	.501	.482	.463	.444	.424
19	.405	.385	.365	.345	.325	.305	.285	.265	.244	.224
20	.203	.183	.162	.141	.120	.099	.078	.056	.035	.013
21	997.992	.970	.948	.926	.904	.882	.860	.837	.815	.792
22	.770	.747	.724	.701	.678	.655	.632	.608	.585	.561
23	.538	.514	.490	.466	.442	.418	.394	.369	.345	.320
24	.296	.271	.246	.221	.196	.171	.146	.120	.095	.069
25	.044	.018	*.992	*.967	*.941	*.914	*.888	*.862	*.836	*.809
26	996.783	.756	.729	.703	.676	.649	.621	.594	.567	.540
27	.512	.485	.457	.429	.401	.373	.345	.317	.289	.261
28	.232	.204	.175	.147	.118	.089	.060	.031	.002	*.973
29	995.944	.914	.885	.855	.826	.796	.766	.736	.706	.676
30	.646	.616	.586	.555	.525	.494	.464	.433	.402	.371

* First three significant digits shown in line below.

As the specimen consolidates, a ring of mortar will form around the perimeter of the specimen against the inside wall of the mold and will fill in between coarse aggregates. Observe the formation of the mortar ring around the perimeter of the mold. When the mortar ring is completely formed, stop the vibrator and timer; determine the elapsed time to the nearest minute and second. Record this time as the Vebe consistency time, Test Method B. If the mortar ring does not form after 2 minutes, stop the vibrator. Record this condition on the report, and repeat the test with a fresh sample of concrete using Test Method A if necessary. If the wing nuts loosen during the test, repeat the test with a fresh sample of concrete.

12.1.4 Record the conditions of 11.1.6, if appropriate.

12.2 *Density of Fresh Concrete, Test Method B*:

12.2.1 Determine the density of the specimen in accordance with 11.2. Refer to the density as Vebe density of the specimen, Test Method B.

12.3 *Vibration Consistency Time and Density Using Alternate Vibrating Table, Test Method B*:

12.3.1 *Vibrating Consistency Time, Test Method B*:

12.3.1.1 Determine the vibrating consistency time, Test Method B, in accordance with 12.1.1 through 12.1.4. Record the use of an alternate vibrating table.

12.3.1.2 If the conditions of 11.3.2.1 are observed, discontinue the test and do not use Test Method B for vibrating consistency time or density.

12.3.2 *Density of Fresh Concrete, Test Method B*:

12.3.2.1 Determine the density of fresh concrete in accordance with 11.2. Refer to the density as vibrating density of the specimen, Test Method B.

13. Calculations

13.1 Following determination of the Vebe consistency time, determine density of sample as follows:

$$D = \frac{M_s}{V_s}$$

where:

D = density in pound mass per cubic foot [kilograms per cubic meter or kilograms per cubic decameter (note 6)]
M_s = mass of sample in pound mass (kilograms), and
V_s = volume of sample in cubic feet (cubic meters or cubic decameters)

13.2 Figure 3 shows a suggested calculation form.

NOTE 6.–To convert from cubic decameters to cubic meters, multiply by 1000.

Spec. or Solic. No. DC-7558	Structure DAM	Tested by T. DOLEN	Date 4-19-85
Project CENTRAL UTAH	Item MIX DESIGN Location DENVER LAB	Computed by K. MITCHELL	Date 4-19-85
Feature UPPER STILLWATER DAM	Station ~ Offset ~ Depth ~ to ~	Checked by T. DOLEN	Date 4-19-85

CONSISTENCY AND DENSITY OF NO-SLUMP CONCRETE WITH VIBRATORY TABLE

Mix No.:	Shift:	Batch or Test No.:
Date:	Time:	Inspector:

Volumetric Calibration

Mold No.: 1

(1)	Mass of mold, plate, and water	54.001	lbm
(2)	Mass of mold and plate	33.560	lbm
(3)	Mass of water, (1) - (2)	20.441	lbm
(4)	Temperature of water	70.0	°F
(5)	Absolute density of water: From table 1: (62.4278578) (0.997970)	62.301	lbm/ft³
(6)	Volume of mold, (3)/(5)	0.328	ft³

Vebe (or Alternate) Determination

Vibrating Time: 0 min 21 sec

Surcharge: ☑ Yes ☐ No, mass 51.440 lbm

Method: ☑ A ☐ B

Comments:

NONE AVAILABLE FOR THIS TEST

Density Determination

(7)	Mass of mold, sample, and plate	63.100	lbm
(8)	Mass of mold and plate	33.560	lbm
(9)	Mass of sample, (7) - (8)	29.540	lbm
(10)	Mass of mold, sample, plate, and water	71.140	lbm
(11)	Mass of water, (10) - (7)	8.040	lbm
(12)	Temperature of water	70.0	°F
(13)	Absolue density of water: From table 1: (62.4278578) (0.997970)	62.301	lbm/ft³
(14)	Volume of water, (11)/(13)	0.129	ft³
(15)	Volume of sample, (6) - (14)	0.199	ft³
(16)	Density of sample, (9)/(15)	148.44	lbm/ft³

Figure 3a. - Sample data and calculation form (inch-pound units).

Spec. or Solic. No. DC-7558	Structure DAM	Tested by T. DOLEN Date 4-19-85
Project CENTRAL UTAH	Item MIX DESIGN Location DENVER LAB	Computed by K. MITCHELL Date 4-19-85
Feature UPPER STILLWATER DAM	Station ~ Offset ~ Depth ~ to ~	Checked by T. DOLEN Date 4-19-85

CONSISTENCY AND DENSITY OF NO-SLUMP CONCRETE WITH VIBRATORY TABLE

Mix No.: Date:	Shift: Time:	Batch or Test No.: Inspector:

Volumetric Calibration

Mold No.: 1

(1) Mass of mold, plate, and water	24.495	kg
(2) Mass of mold and plate	15.223	kg
(3) Mass of water, (1) - (2)	9.272	kg
(4) Temperature of water	21.1	°C
(5) Absolute density of water: From table 2:	997.970	kg/m³
(6) Volume of mold, (3)/(5)	0.009291	m³

Vebe (or Alternate) Determination

Vibrating Time: 0 min 21 sec

Surcharge: ☑ Yes ☐ No, mass 23.379 kg

Method: ☑ A ☐ B

Comments:

NONE AVAILABLE FOR THIS TEST

Density Determination

(7) Mass of mold, sample, and plate	28.622	kg
(8) Mass of mold and plate	15.223	kg
(9) Mass of sample, (7) - (8)	13.399	kg
(10) Mass of mold, sample, plate, and water	32.269	kg
(11) Mass of water, (10) - (7)	3.647	kg
(12) Temperature of water	21.1	°C
(13) Absolue density of water: From table 2:	997.970	kg/m³
(14) Volume of water, (11)/(13)	0.003654	m³
(15) Volume of sample, (6) - (14)	0.005637	m³
(16) Density of sample, (9)/(15)	2377	kg/m³

Figure 3b. - Sample data and calculation form (SI-metric).

L-29 – Vebe Surcharge Test Summary

Central Utah Project
Upper Stillwater Dam
Specifications No: DC-7558

For tests taken from 09/01/86 to 09/30/86

Mix Name: RCC1

Test Identification							Test Results	
TEST DATE	SHIFT 1,2,3	TEST NUM.	TEST BATCH	LOCATION STATION	OFFSET	ELEVATION	COMPACTION TIME (SEC)	DENSITY (lbm/ft^3)
09/01/86	1	01	Y	31+40	32	8018.0	13	147.00
09/01/86	2	01	Y	31+50	75	8019.0	16	147.60
09/01/86	3	01	Y	33+20	20	8019.0	41	148.30
09/02/86	1	01	Y	39+6	35	8019.0	5	145.30
09/02/86	2	01	Y	36+75	75	8020.0	8	146.50
09/02/86	3	01	Y	23+20	25	8020.0	60	147.10
09/03/86	1	01	Y	27+70	70	8021.0	7	144.40
09/03/86	3	01	Y	29+35	35	8021.0	26	146.10
09/04/86	1	01	Y	20+25	87	8022.0	14	147.60
09/04/86	2	01	Y	35+00	50	8022.0	25	146.10
09/04/86	3	01	Y	24+75	45	8022.0	15	146.90
09/05/86	1	01	Y	31+75	28	8023.0	8	145.60
09/06/86	1	01	Y	25+80	7	8023.0	3	145.40
09/06/86	2	01	Y	39+90	40	8024.0	10	146.50
09/06/86	3	01	Y	20+25	80	8025.0	10	145.60
09/07/86	1	01	Y	35+70	63	8025.0	5	145.10
09/07/86	3	01	Y	30+00	50	8026.0	33	145.90
09/08/86	1	01	Y	26+35	95	8026.0	6	147.50
09/08/86	2	01	Y	33+60	70	8026.0	12	147.10
09/08/86	3	01	Y	22+50	40	8027.0	6	147.30
09/09/86	1	01	Y	34+60	92	8027.0	9	146.40
09/09/86	2	01	Y	39+00	65	8027.0	44	146.60
09/09/86	3	01	Y	20+35	43	8028.0	33	147.80
09/10/86	1	01	Y	26+60	70	8028.0	3	145.90
09/10/86	2	01	Y	20+75	90	8029.0	27	148.10
09/11/86	1	01	Y	40+60	86	8029.0	18	146.40
09/11/86	2	01	Y	19+99	95	8030.0	10	146.20
09/12/86	1	01	Y	32+75	88	8030.0	7	147.80
09/12/86	3	01	Y	25+77	18	8030.0	27	146.80
09/13/86	2	01	Y	36+70	94	8031.0	16	147.50
09/13/86	3	01	Y	28+50	50	8031.0	90	146.70
09/14/86	1	01	Y	34+25	25	8031.0	7	148.10
09/14/86	2	01	Y	27+37	68	8032.0	55	150.00
09/14/86	3	01	Y	42+40	88	8032.0	6	148.30
09/15/86	1	01	Y	37+90	20	8032.0	7	148.20
09/15/86	2	01	Y	25+20	85	8032.0	23	147.10
09/15/86	3	01	Y	38+71	91	8033.0	16	145.50

Figure 4. – Typical reporting form.

14. Report

14.1 Figure 4 shows a typical reporting form that was produced by computer.

15. Precision and Bias

15.1 *Precision.*–The precision for this procedure is currently unknown.

15.2 *Bias.*–The procedure in these test methods for determining consistency and density of roller-compacted concrete has no bias because consistency and density can only be defined in terms of these test methods.

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

USBR 4906-92

PROCEDURE FOR

CASTING NO-SLUMP CONCRETE IN CYLINDER MOLDS USING VIBRATORY TABLE

INTRODUCTION

This test procedure is under the jurisdiction of the Concrete and Structural Branch, code D-3730, Research and Laboratory Services Division, Denver Office, Denver, Colorado. The procedure is issued under the fixed designation USBR 4906; the number immediately following the designation indicates year of original adoption or year of last revision. This test procedure is a modified version of ASTM C 1176-91.

1. Scope

1.1 This designation covers the test procedure for making cylindrical test specimens from no-slump concrete when standard procedures by rodding and internal vibration, as described in USBR 4031 and 4192, are not practicable.

NOTE 1.–This procedure is considered applicable for plastic concrete with a coarse aggregate content less than 2 inches (50 mm) in maximum size. If coarse aggregate is larger than 2 inches, the procedure is applicable when made on the fraction of concrete passing the 2-inch sieve, with larger aggregate being removed in accordance with USBR 4172 with the exception that the 2-inch sieve is used instead of the 1-1/2-inch (37.5-mm) seive.

1.2 These procedures, intended for use in testing roller-compacted concrete, may be applicable to testing other types of concrete such as cement-treated aggregate and mixtures similar to soil-cement.

1.3 Method A describes procedures for making test specimens in a steel mold attached to Vebe vibrating table. Method B describes procedures for making test specimens in disposable plastic molds inserted into a rigid sleeve attached to Vebe vibrating table.

1.4 The recommended vibration table for this test procedure is the Vebe vibrating table. To date, all Bureau testing has been performed using this testing apparatus. An alternate vibration table may be substituted for the Vebe apparatus provided it meets the specifications for the sinusoidal vibration as shown in section 9.2.1.

2. Applicable Documents

2.1 *USBR Procedures*:
4031 Making and Curing Concrete Test Specimens in Field
4039 Compressive Strength of Cylindrical Concrete Specimens
4172 Sampling Freshly Mixed Concrete
4192 Making and Curing Concrete Test Specimens in Laboratory
4496 Splitting Tensile Strength of Cylindrical Concrete Specimens

2.2 *ASTM Standard*:
C 470 Standard Specification for Molds for Forming Concrete Test Cylinders Vertically[1]
C 1170 Standard Test Methods for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table[1]
C 1176 Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table[1]
E 11 Standard Specification for Wire-Cloth Sieves for Testing Purposes[1,2]

2.3 *ACI Standards*:
207.5R-89 Roller Compacted Concrete[3]
211.3-75R-89 Standard Practice for Selecting Proportions for No-Slump Concrete[3]

3. Summary of Procedure

3.1 This test procedure is for making cylindrical concrete test specimens using the Vebe vibrating table. Test specimens are cast vertically in cylindrical molds ridigly attached to the vibrating table under a 20-lbm (9.07-kg) surcharge to facilitate consolidation.

4. Significance and Use

4.1 This procedure is intended to be used for stiff to extremely dry concrete mixtures commonly used in roller-compacted concrete construction. This procedure is used instead of rodding or internal vibration, which cannot properly consolidate concrete of this consistency.

NOTE 2.–Further description of this concrete consistency is given in ACI 207.5R-89 and 211.3-75 (R 1989).[3] The consistency of concrete may be determined in accordance with ASTM C 1170.[1]

[1] *Annual Book of ASTM Standards*, vol. 04.02.
[2] *Annual Book of ASTM Standards*, vols. 04.01, 04.06, 04.07, 05.05, 14.02.
[3] *ACI Manual of Concrete Practice*, part 1, 1990, available from American Concrete Institute, PO Box 19150, Redford Station, Detroit, MI 48219.

5. Terminology

5.1 *Roller Compacted Concrete*.–Concrete of zero-slump consistency which is placed by depositing loosely in horizontal lifts and consolidated with smooth-drum vibrating rollers.

6. Apparatus

6.1 *Molds*:

6.1.1 *Type A Mold*.–A cylindrical mold conforming to the requirements of ASTM C 470 for 6-inch (152-mm) diameter by 12-inch (305-mm) high reusable molds. Molds shall be made of steel or other hard metal not readily attacked by the cement paste. Aluminum molds shall not be used. Molds shall be equipped with permanently affixed metal slotted brackets on the baseplate so the molds can be rigidly clamped to a vibrating table. The top rim of the mold shall be smooth, plane, and parallel to the bottom of the mold. The bottom of the mold shall provide a watertight seal.

6.1.2 *Type B Mold*.–A single-use plastic, cylindrical mold 6 inches in diameter and a height of 12 inches (152 by 305 mm). The mold specifications shall conform to ASTM C 470 for single-use plastic molds.

6.1.2.1 *Mold Sleeve*.–A Type B cylindrical mold shall be inserted into a rigid cylindrical sleeve with a bottom baseplate that is clamped to the vibrating table. The mold sleeve shall be made of steel or other hard metal that does not react with concrete containing portland or other hydraulic cement. The sleeve shall be capable of firmly and vertically holding the plastic mold in place without deformation and shall be slotted vertically with adjustable clamps for tightening around the mold. The sleeve shall be hinged so that it can be opened to remove the mold (fig. 1) and shall also have permanently affixed slotted metal brackets so the sleeve may be rigidly clamped to the vibrating table. The mold sleeve shall have a minimum wall thickness of 1/8 inch (3.2 mm), and a minimum baseplate thickness of 1/4 inch (6.4 mm). The inside diameter of the mold sleeve shall be 1/8 ± 1/16 inch (3.2±1.6 mm) larger than the outside diameter of the Type B mold and have a height 1/2 to 1/4 inch (12.8 to 6.4 mm) less than the height of the Type B mold.

6.2 *Vebe Vibrating Table*.–A vibrating table with a 3/4-inch (19-mm) thick steel deck with dimensions of 15 inches in length, 10-1/4 inches in width, and 12 inches in height (381- 260- 305-mm). The vibrating table shall be constructed in such a manner as to prevent flexing of the table during operation. The table deck shall be activated by an electromechanical vibrator. The total mass of the vibrator and table shall be approximately 210 lbm (95 kg). The table shall be level and clamped to a concrete floor or base slab having sufficient mass to prevent displacement of the apparatus during specimen preparation.

NOTE 3.–The recommended vibrating table for these test procedures is the Vebe vibrating table.[4] To date, testing has been performed using this apparatus. An alternative vibrating table may be substituted for the Vebe apparatus provided it meets the specifications for the sinusoidal vibration given in 9.2 and is in accordance with the alternative testing requirements of section 11. The Vebe apparatus, including cylindrical mold and guide sleeves, is manufactured by Dynapac Maskin (formerly Vibro-Verken), PO Box 1103, 5-171-22, Solna, Sweden; Dynapac Manufacturing, Inc., Stanhope NJ 07874; and Soiltest, 86 Albrecht Drive, PO Box 8004, Lake Bluff IL 60044-9902.

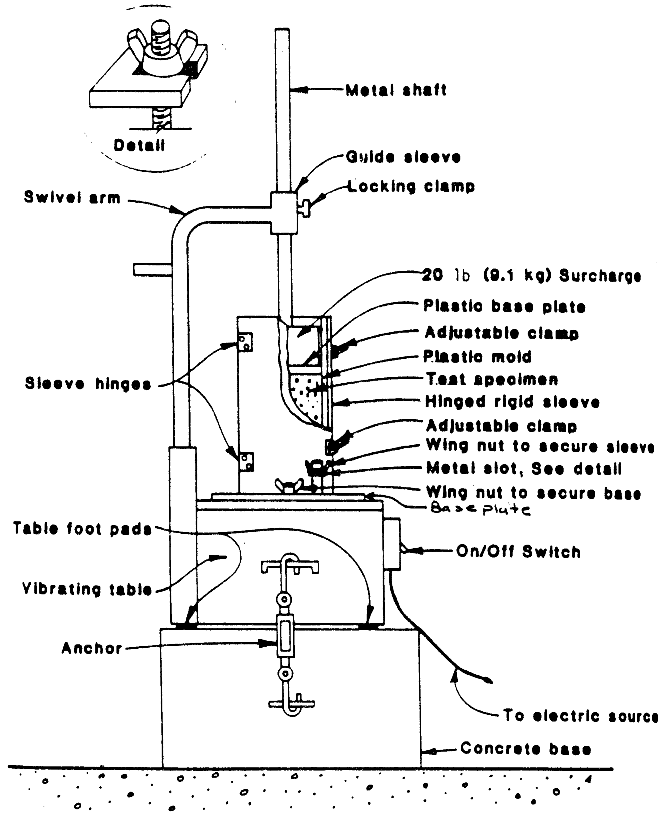

Figure 1. – Vibrating table—cylinder preparation (Type B mold).

6.3 *Swivel Arm and Guide Sleeve*.–A metal guide sleeve with a clamp assembly or other suitable holding device mounted on a swivel arm. The swivel arm and guide sleeve must be capable of holding a metal shaft attached to a 20-lbm (9.1-kg) cylindrical mass in a position perpendicular to the vibrating surface which allows the shaft to slide freely when the clamp is released. The swivel arm must be capable of maintaining the guide sleeve in a locked position directly over the center of the specimens to be vibrated. The swivel arm shall also be capable of being rotated away from the center of the table.

NOTE 4.–The Vebe vibrating table comes equipped with the swivel arm and guide sleeve.

6.4 *Surcharge*.–A cylindrical surcharge with a metal shaft at least 18 inches (457 mm) long and 5/8 ± 1/16 inch (16±2 mm) diameter attached perpendicularly to the plate and embedded through the center of surcharge. The shaft shall slide through the guide sleeve without binding or excessive play. The base of the surcharge shall have a

[4] The Vebe vibrating table, including cylindrical mold and guide sleeves, is manufactured by Soiltest, 86 Albrecht Drive, PO Box 8004, Lake Bluff IL 60044-9902.

5-3/4 ± 1/8-inch (146±3 mm) diameter. Surcharge shall have a mass of 20±0.5 lbm (9.1±0.25 kg) including the mass of the metal shaft (fig. 1). If the surcharge is hand held, the length of the shaft may be reduced to 12 inches (305 mm) and fabricated with a "T" or "D" handle to grip the surcharge shaft to avoid the hand slipping.

6.5 *Sieve.*–A 2-inch (50-mm) sieve conforming to ASTM E 11.

6.6 *Small Tools.*–Trowels, square-ended shovel and hand scoops, steel trowel, wooden float, wrench, tamping rod, and flashlight as required.

7. Precautions

7.1 This test procedure may involve hazardous materials, operations, and equipment, and does not claim to address all safety problems associated with its use. The user is responsible to consult and establish appropriate safety and health practices and to determine applicability of regulatory limitations prior to use.

8. Sampling, Test Specimens, and Test Units

8.1 Samples of fresh concrete should be obtained in accordance with USBR 4172.

8.2 Concrete samples should have 2-inch (50-mm) maximum size aggregate. If concrete has aggregate larger than 2 inches, sample shall be obtained by wet sieving over a 2-inch sieve in accordance with USBR 4172.

8.3 Concrete test specimens shall be made within 45 minutes after the completion of mixing concrete unless otherwise stipulated.

9. Calibration and Standardization

9.1 The calibration and standardization of miscellaneous equipment or apparatus used in performing the tests listed under the Applicable Documents of section 2 are covered under that particular procedure or standard directly or by reference.

9.2 *Vebe Vibrating Table.*–The frequency and amplitude of the vibrating table shall be determined under simulated test conditions prior to initial use, and annually thereafter (note 5). Frequency and amplitude shall be determined in accordance with USBR 4031 or 4192.

NOTE 5.–This determination can be performed by personnel of the Materials Engineering Branch [code D-3735] at the Bureau's Denver Office, and should be coordinated with the calibration of other vibration testing equipment.

9.2.1 The vibrating table shall produce a sinusoidal vibratory motion with a frequency of at least 3600±100 vibrations per minute (60±1.67 Hz) and an amplitude of vibration of 0.0085±0.0015 inch (0.22±0.04 mm) when a 60.0±2.5-lbm (27.2±1.1-kg) surcharge is rigidly bolted to the center of the table.

9.3 *Cylindrical Molds.*–The cylindrical molds shall conform to the dimensional requirements of ASTM C 470.

9.4 At least, after every 3 months of continuous use, the underside of the vibrating table top should be inspected and cleaned of any hardened concrete or cement paste which may interface with free movement of the table top.

10. Conditioning

10.1 No special conditioning process is required for this procedure.

11. Procedure

11.1 *Method A—Type A Molds*:

11.1.1 Coat Type A molds with a suitable lubricant or bond breaker prior to casting the test specimens to facilitate removal from the mold.

11.1.2 Place the mold on Vebe table, and center the surcharge so that the edges of the plastic plate do not touch the walls of the mold. Lower the surcharge into the mold to check for proper clearance. Attach the mold to the Vebe table, and firmly tighten the wing nuts. Move the surcharge away from the mold.

11.1.3 Place enough concrete in the mold so that the mold will be filled to one-third of its volume after consolidation [about 9.5 lbm (4.3 kg)]. A tamping rod may be used to distribute the loose concrete as it is added. During filling, use square-ended shovels and scoops to obtain representative samples, and handle the concrete in such a manner that larger sized coarse aggregate particles do not separate from the mortar.

11.1.4 Move the surcharge over the center of the mold, release the guide sleeve clamp, and place the surcharge gently on the loose concrete. The surcharge shall be able to vertically slide free without binding on the guide sleeve.

11.1.5 If the surcharge cannot be centered in the mold without binding on the inside wall of the mold, place the surcharge directly onto the specimen in the mold without use of the guide sleeve, and hold the surcharge shaft perpendicular to the top of the table. Hold the surcharge shaft manually while vibrating the specimen.

11.1.6 Start the vibrator, and allow the concrete to consolidate under the surcharge. Using a flashlight, observe the concrete in the annular space between the edge of the surcharge and the inside wall of the mold. As the concrete consolidates, mortar will fill in the annular space between the outer edge of the surcharge and the inside mold wall. Observe the mortar until it forms a ring around the total perimeter of the surcharge. When the mortar ring forms completely around the surcharge, stop the vibrator. If the wing nuts loosen while casting the specimen, retighten the wing nuts, then continue vibrating to ensure complete consolidation of the specimen.

11.1.7 If a rock pocket prevents the mortar ring from forming at one small location, even though it has formed in all other locations, the vibrator can be stopped and another layer of concrete added. If a significant portion of the mortar ring does not form, this indicates the concrete may have insufficient mortar due to either improper sampling, segregation, or improper mixture proportioning. In these instances, the concrete specimen should be visually inspected after stripping from the mold, and a decision then made whether to accept or reject the specimen.

11.1.8 Repeat the procedure in 11.1.3 through 11.1.7 for the second lift of concrete, filling the mold to about two-thirds its volume. For the third lift, overfill the mold by mounding the concrete above the top of the mold. Again, place the surcharge on the loose concrete and consolidate. If the surcharge consolidates concrete below the top level of the mold, turn off the vibrating table. Place additional concrete in the mold so that, when consolidated, the concrete will be about 1/8 inch (3 mm) above the top of the mold. Continue vibrating, and slide the surcharge back and forth across the top of the mold until the compacted concrete is level with the top of the mold. This replaces strikeoff with a float since stiff concrete cannot be easily floated. Do not allow the srucharge to remain in one position when the concrete is being finished because this can cause aggregates to be forced down and mortar to be forced out of the mold resulting in a nonrepresentative test specimen. After the surface has been screeded with the surcharge, vibrate the specimen for 4±1 seconds without the surcharge to fill in minor surface tears unless damage to the specimen by large-amplitude oscillations of the vibrator is anticipated.

11.1.8.1 When making test specimens using an alternative vibrating table, it may not be possible to vibrate the specimen without a surcharge. This is due to the disturbance of the compacted specimen when large-amplitude, low-frequency oscillations occur after the vibrator has been turned off. If this occurs, keep the surcharge in place until the vibrating table has completely stopped.

11.1.9 Remove the mold with the consolidated specimen from the vibrating table, and finish the top surface of the specimen with a steel trowel or wooden float. Avoid dislodging aggregate particles from the surface when using a wooden float.

11.2 *Method B—Type B Molds*:

11.2.1 Make concrete test specimens in Type B molds in accordance with 11.1. Prior to making test specimens, insert a Type B mold into the metal sleeve ensuring a close fit but not deforming the plastic mold. A sleeve assembly made from an existing steel cylindrical mold is shown on figure 1. Rigidly clamp the entire assembly to the Vebe table, and make the test specimen in accordance with procedures in 11.1.2 through 11.1.9.

12. Curing

12.1 Unless otherwise specified, all specimens shall be cured in accordance with the sections on curing in USBR 4031 or 4192, whichever is applicable. Specimens tested for compressive strength and splitting tensile strength shall be in accordance with USBR 4039 and 4496, respectively.

13. Calculations

13.1 There are no calculations involved in this test procedure.

14. Report

14.1 A reporting form is not required for this procedure.

15. Precision and Bias

15.1 Currently, the precision and bias for this procedure is unknown.

Appendix C

Summary of RCC Costs

RCC costs for ten Reclamation projects completed between 1987 and 2002 are summarized in table C-1. Common factors that influence the bid price for RCC are briefly summarized below:

- *Production and placement rates*.—The primary benefit of RCC over conventional mass concrete is that the placement and compaction of RCC can be made using earth-moving equipment, which greatly increases the placement rate of the concrete. The placement rate is generally balanced with the cost of the batch plant to obtain the optimum size of the plant.

  Long, straight placement runs and simple layout of the structure being placed generally produce lower RCC costs. Provisions for turnarounds and using a minimum 20-foot lane width to permit equipment to pass could reduce the cost of the RCC placements in the top part of the dam and in other locations where space is restricted. Conversely, complicated geometry, narrow placements, steep slopes, difficult access, and long haul routes, including one-way roads, lead to more time required and higher costs. Features that interfere with placements, including galleries, outlet conduits, embedded instruments, and drain pipes, also affect RCC placement operations and increase costs.

- *Haul distances from aggregate source*.—Depending on the size of the project, materials processed at the site can provide significant cost benefits if the suitable material is available. Processing aggregates in large quantities from an on-site borrow source can save money over commercial sources, although additional risk is involved in producing aggregates that meet specifications. Aggregates that require significant washing, sorting, and/or waste can lead to higher prices. The development of an on-site quarry operation for blasting and crushing of rock materials may be economical for large projects, but a natural source of sand-size materials may still be required.

  Commercial aggregate sources capable of producing materials that meet the specifications requirements, when available, may minimize the cost spread of aggregate by providing a known material at a fixed price. The haul distance from the commercial source to the construction site impacts the price due to hauling time and transportation costs.

- *Cementitious materials*.—The quantities of cementitious materials required by the RCC mix, normally both cement and pozzolan, directly affect costs. A higher percentage of pozzolan can typically reduce the overall cost, assuming that it is locally available and meets the design requirements.

  The mix design or proportioning of the various materials affects the price and is usually a function of design requirements. A higher strength requirement usually means more cement, which will increase costs.

- *Local climate and conditions*.—Time of year and weather can have a direct bearing on costs. Extremely hot and dry conditions, or extremely cold or very wet conditions can increase the price of RCC. Warm weather conditions may require special cooling of the RCC materials and mixture, including sprinkling the aggregate stockpiles, using flake ice in place of mix water, and making the RCC placements at night. Cold weather conditions may require special heating of the RCC materials and mixture, and the use of thermal blankets for protection against freezing. The construction schedule should consider temperature and potential weather conditions and, if possible, schedule construction in time periods that can minimize impacts and avoid potentially adverse conditions.

- *Required equipment*.—The type of equipment necessary to place the RCC mix as specified can impact costs. If the placement equipment is limited due to specifications requirements, site conditions, and/or configurations and geometry, costs can increase. Allowing freedom for a contractor to choose equipment can minimize costs, although sometimes specific equipment is necessary for various reasons. Requirements for additional backup pieces of equipment should be balanced with the consequences of interruptions in placements and the potential adverse impacts to the quality of the structure and the placements.

- *Quality control and inspection*.—Quality control should not be compromised if the there are important design requirements related to the overall performance of the RCC dam or structure. If less quality control and inspection are specified, the designs are approached more conservatively.

The following table shows bid prices for Reclamation projects that utilized RCC. Prices have not been adjusted to present-day costs. Costs for cement and pozzolan are not included in the bid prices for RCC.

Table C-1.—Summary of Reclamation projects and the RCC mix design data

Application		Year [1]	Compr. strength (lb/in^2)	Cement + pozzolan (lb/yd^3)	Original bid price [5]	RCC volume (yd^3)
Upper Stillwater Dam (new gravity dam)	Mix A	1987	4000 [2]	134+291=425	$10.40	1,471,000
	Mix B		4000 [2]	159+349=508	$13.65	157,000
Jackson Lake Dam (upstream slope protection for embankment dam)		1988	N/A	400+0=400 (10.5% average)	$12.95	44,900
Santa Cruz Dam (buttress)		1990	3000 [2]	125+130=255	$45.74	38,500
Camp Dyer Diversion Dam (buttress)		1992	3000 [2]	139+137=276	$45.60	15,400
Cold Springs Dam (spillway replacement)		1996	4000 [3]	300+0=300	$44.00	17,800
Ochoco Dam (spillway basin modification)		1997	4000 [3]	434+0=434	$36.00	19,000
Pueblo Dam (foundation stabilization)		2000	3500 [2]	120+180=300	$30.00	62,800
Many Farms Dam (spillway replacement)		2001	4000 [4]	280+100=380	$170.00	6,200
Clear Lake Dam [5] (replacement gravity dam for embankment dam)		2002	3000 [2]	150+150=300	$103.50	18,000
Vesuvius Dam (overtopping protection for embankment dam)		2002	4000 [3]	425+0=425	$94.65	10,500

[1] Year project was completed
[2] Specified compressive strength at 1 year
[3] Specified compressive strength at 28 days
[4] Specified compressive strength at 90 days
[5] Bid price for RCC per yd^3, not including cost of cement and pozzolan

Appendix D

Samples of Adiabatic Temperature Rise Tests of Roller-Compacted Concrete

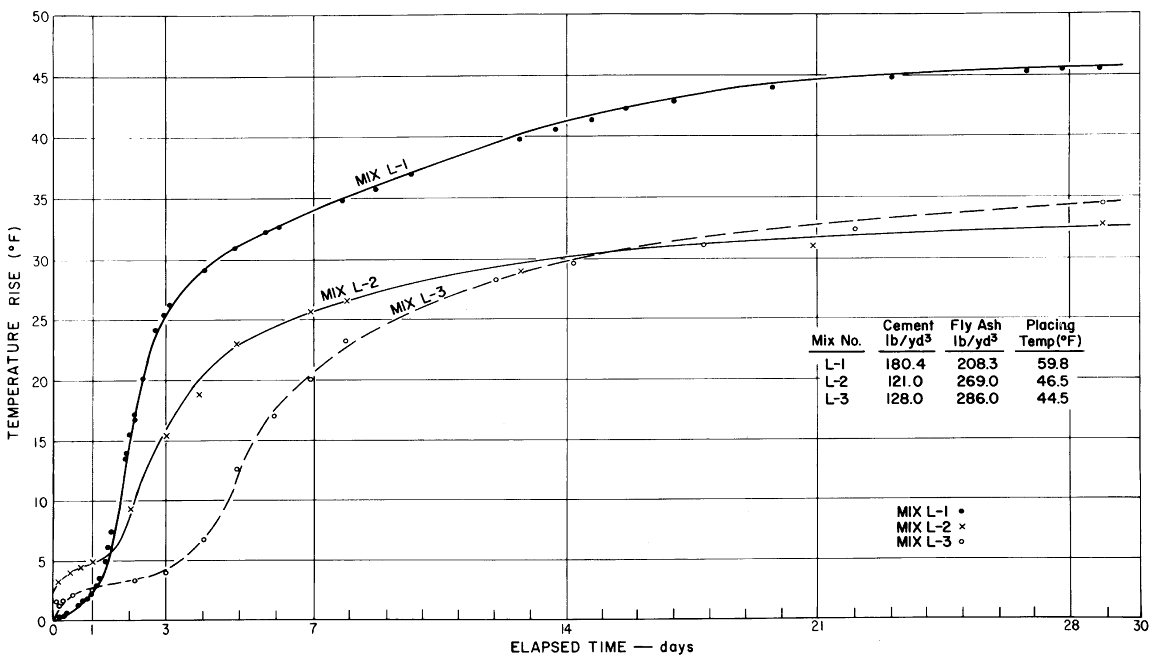

Figure D-1.—Adiabatic temperature rise, Upper Stillwater Dam, Utah.

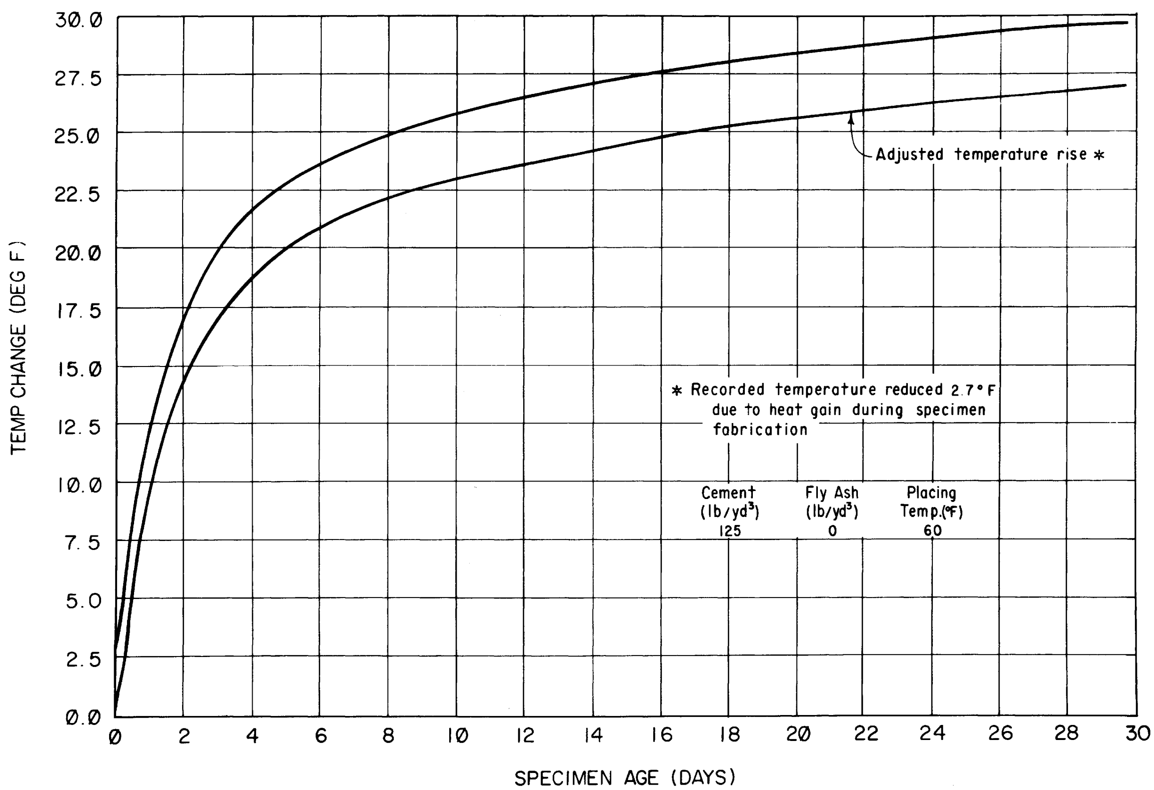

Figure D-2.—Adiabatic temperature rise, Middle Fork Dam, Colorado.

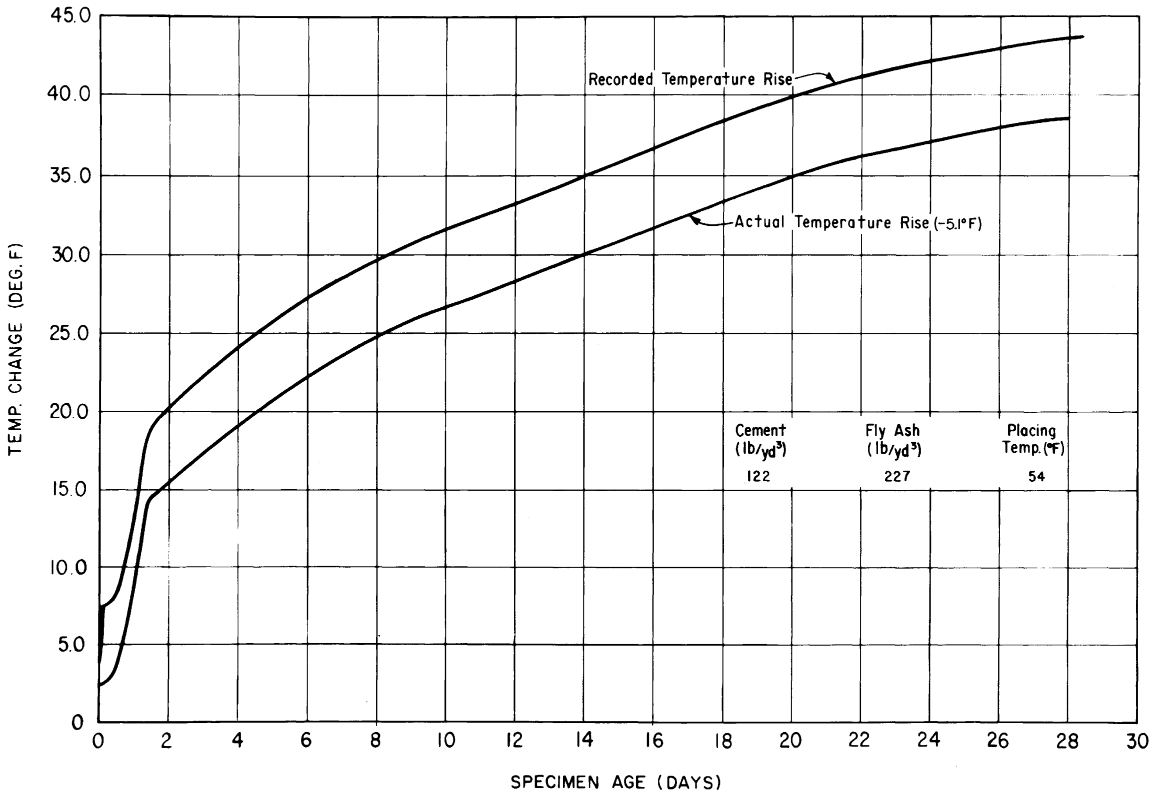

Figure D-3.—Adiabatic temperature rise, Pamo Dam, California.