# RECLAMATION
*Managing Water in the West*

**Design and Construction Considerations for Hydraulic Structures**

# Roller-Compacted Concrete

**Second Edition**


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


September 2017

# MISSION STATEMENTS

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

Cover photos: (top) Aerial view of Upper Stillwater Dam, Utah, the Bureau of Reclamation's first RCC gravity dam; (right) Upper Stillwater Dam during construction.

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# PREFACE

Since Upper Stillwater Dam was designed and constructed 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 30 years. The information provided herein is intended to emphasize the importance and versatility of RCC as both a material and a construction method. It 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:

- Chapter 1: Definition of RCC and scope of the manual
- Chapter 2: Background information, including history, philosophy, and practical uses of RCC
- Chapter 3: Discussion of RCC materials
- Chapter 4: Design requirements for RCC mixtures, including RCC properties and mixture proportioning procedures
- Chapter 5: Construction methods, from batching through final testing
- Chapter 6: Design considerations for new RCC gravity dams
- Chapter 7: Design considerations for RCC buttresses for concrete dam modifications
- Chapter 8: Design applications for embankment dams, including overtopping protection, upstream slope protection, water barrier, and replacement structures
- Chapter 9: Other design applications for RCC
- Chapter 10: Case histories that illustrate the design, construction, and performance of a variety of RCC projects

In addition, appendices are included that contain guide specifications for RCC construction (appendix A), a summary of RCC costs (appendix B), and samples of adiabatic temperature rise tests of RCC (appendix C).

This manual was developed by Reclamation authors and contributors. Authors of the first edition included (in alphabetical order) Tim Dolen, Tom Hepler, Daniel 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 and Gregg Scott provided the peer review. Lelon A. Lewis performed technical editing of the manual.

Authors of the second edition included (in alphabetical order) Jeff Allen, Veronica Madera, Daniel Mares, and Jerzy Salamon. Walt Heyder and Janet White provided the peer review. Teri Manross performed technical editing of the manual. Nancy Arthur compiled the revised RCC guide specifications, which are in appendix A.

Funding for this manual was provided by Reclamation's Dam Safety Office, Technical Service Center, and Office of Policy. The authors would like to thank these offices for their joint effort in support of the development and publication of this manual.

# Abbreviations and Acronyms

| | |
|---|---|
| % | percent |
| °C | degrees Celsius |
| °F | degrees Fahrenheit |
| ACI | American Concrete Institute |
| AEA | air-entraining admixture |
| AFP | Annualized Failure Probability |
| ALL | Annualized Life Loss |
| ASR | alkali-silica reaction |
| ASTM | American Society for Testing and Materials |
| C:P | cement to pozzolan (ratio) |
| C+P | cement plus pozzolans |
| CRB | Consulting Review Board |
| DOT | Department of Transportation |
| FE | Finite Element |
| FEMA | Federal Emergency Management Agency |
| $ft^3$ | cubic feet |
| $ft^3/s$ | cubic feet per second |
| GERCC | grout-enriched roller compacted concrete |
| GEVR | grout-enriched vibratable roller compacted concrete |
| GMSS | Gravity Method of Stress and Stability |
| lb | pounds |
| $lb/ft^3$ | pounds per cubic foot |
| $lb/in^2$ | pounds per square inch |
| $lb/yd^3$ | pounds per cubic yard |
| LOI | loss on ignition |
| MCE | maximum credible earthquake |
| MWD | Maricopa Water District |
| NEPA | National Environmental Policy Act |
| NMSA | nominal maximum size aggregate |
| PMF | probable maximum flood |
| PVC | polyvinyl chloride |
| RCC | roller-compacted concrete |
| Reclamation | Bureau of Reclamation |
| USACE | United States Army Corps of Engineers |
| USFS | United States Forest Service |
| w/cm | water to cementitious materials |
| WRA | water-reducing admixture |
| $yd^3$ | cubic yards |
| $yd^3/d$ | cubic yards per day |
| $yd^3/hr$ | cubic yards per hour |
| 2D | two-dimensional |
| 3D | three-dimensional |

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# 1. DEFINITION AND SCOPE

The guidelines in this manual 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 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 (Bureau of Reclamation [Reclamation], 1987). RCC differs from soil-cement in that soil-cement generally uses pit-run sand, it 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. Many of these guidelines have been influenced by Reclamation's experience in the design and construction of various RCC structures, 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), Utah and Clear Lake Dam (with contraction joints), California

- New spillways: Cold Springs Dam, Oregon, and Many Farms Dam, Arizona

- Downstream buttresses: Camp Dyer Diversion Dam (straight), and Arizona and Santa Cruz Dams (curved), New Mexico

- Overtopping protection for embankment dams: Vesuvius Dam, Ohio

- Upstream slope protection: Jackson Lake Dam, Wyoming

- Erosion protection:  Ochoco Dam spillway basin, Oregon
- Hydraulic structure foundation and buttress:  Pueblo Dam spillway stilling basin, Colorado
- Deep cutoff wall for auxiliary spillway:  Glendo Dam auxiliary spillway, Wyoming

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

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

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

# 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 cost effectively 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 RCC 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 U.S. Army Corps of Engineers (USACE), and others in the United States, were developing a lean-concrete alternative with high nonplastic fines, which culminated 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, as well as a laser-guided, horizontal slipforming system for facing elements, which became the basis for Reclamation’s design of Upper Stillwater Dam, in Utah, in 1983. Japanese engineers took a similar approach with cast-in-place concrete facing, termed the roller-compacted dam 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, as well as 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 Concrete Mix Design Philosophy

Two distinct philosophies emerged with respect to RCC mix design methods: (1) the concrete approach, and (2) the soils (or geotechnical) approach. RCC mixtures using concrete design methods generally have a more fluid consistency and are more workable than mixtures developed using the soils approach, although both philosophies will produce a no-slump concrete. In the concrete approach, RCC is considered a true concrete composed of sound and clean, well-graded aggregates with a strength, when fully consolidated, that is inversely proportional to its water-cement ratio. In the soils approach, RCC is considered a cement-enriched, processed soil with a mix design 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 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).

When all other factors are constant, RCC mixes based on the concrete approach will typically have a wetter consistency and a higher paste content than RCC mixes based on 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 pounds per square inch [$lb/in^2$]) 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).

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 are related to site-specific conditions and applications; however, mixtures which would have been compacted near optimum moisture in dams are now being specified on the order of ½ to 1 percent wet of optimum to increase workability and reduce segregation. RCC mix designs are strongly influenced both by material availability (particularly aggregate properties) and 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: (1) a richer mix used for external surfaces for improved durability and abrasion resistance, and (2) 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, as well as at locations exposed to high velocity flow to minimize potential cavitation or abrasion damage. Both upstream and downstream facing elements may be conventional cast-in-place concrete for better appearance and aesthetic qualities. RCC dam construction and production rates are strongly influenced by the type and size of the structure, as well as the contractors' selection of equipment for batching, mixing, and transporting RCC. There is a relationship between the selected construction methodology and the required RCC properties, including the hardened properties across lift lines.

Reclamation has used both approaches relating to RCC mix design on various projects, which are discussed in these guidelines. Reclamation has generally used RCC mixes with the concrete approach for RCC dam and spillway construction.

## 2.3 Practical Applications 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 faster and at a lower overall cost when compared to conventional mass concrete gravity dams. Consequently, recent applications have included gravity and gravity-arch RCC dams. 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. If the durability of the RCC overlay for a specific application is expected to be lower than it would be using conventional concrete, a compensating "sacrificial" surface of RCC can be added by overbuilding the structure cross section.

When compared to embankment dams, RCC dams offer advantages that are similar to those of conventional concrete dams because the spillway and outlet works can be integrated into the concrete dam. The smaller cross section of an RCC dam, when compared with an earth dam, can result in a shorter, more economical outlet works conduit. In addition, the vertical upstream face provides the capability of installing a gated intake without the need for a separate intake tower and access bridge. Spillway release capacity for the passage of floodflows can be provided by allowing a portion of the RCC dam to overtop, rather than constructing 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, thus reducing the design requirements for a downstream stilling basin. Rapid construction and the ability of RCC dams to be overtopped safely during construction may also lessen construction risk and public exposure, which together increase project cost effectiveness and the ability to manage project risk.

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 internal erosion and piping concerns (when founded on competent bedrock). It was primarily for these reasons that an RCC type dam was selected for the modification of Clear Lake Dam, in California, rather than several other embankment dam alternatives,

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, rather than an RCC dam alternative, primarily due to the large depth to bedrock at the dam site.

## 2.4 References

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

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

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

Kokubu, M., 1984. "Development in Japan of Concrete Dam Construction by the RCD Method." Technical Lecture at 52nd International Committee on Large Dams Executive Meeting, Tokyo.

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

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

# 3. RCC Materials

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

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 jobsite to maintain the necessary high production rates required for RCC.

## 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 American Society for Testing Materials (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, 2015).

### 3.2.1 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 (ASTM, 2015). The different cement types are based on both physical requirements and chemical properties, and they include the following types:

- 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 and high heat of hydration

- 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 (C+P) as a substitute

- Type V: Moderate strength gain and severe sulfate resistance; used for severe sulfate exposure conditions

Type I/II cements, which meet strength requirements for Type I and moderate sulfate resistance requirements of Type II, have become common in the Western United States. There are also Type II/V cements, which meet strength requirements for Type II and severe sulfate resistance requirements of Type V.

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 IV cement for mass RCC.

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.

For mass RCC applications, modified heat cement should be used to minimize heat generation. In cases where sulfate resistance is required, blended cements with moderate sulfate resistance or high sulfate resistance can also be specified. Depending on the specific requirements of the project, a blended cement meeting the requirements of ASTM C595, *Standard Specification for Blended Hydraulic Cements* (ASTM, 2015), could be used in lieu of batching cement and pozzolan separately onsite.

### 3.2.2 Pozzolan

Pozzolan should meet the requirements of ASTM C 618, *Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan For Use in Concrete* (ASTM, 2015). ASTM C 618 classifies pozzolans into the following three categories:

1. Class N: Raw or calcined natural pozzolans. This class of pozzolan has been correlated with decreases in strength of RCC at Upper Stillwater Dam (Dolen, 2003).

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 fly ash 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 (ASR) and sulfate attack. Some RCC mixtures have used Class C fly ash; 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, because 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 with decreases in strength of RCC at Upper Stillwater Dam (Dolen, 2003).

## 3.3 Admixtures

RCC mixtures have used both chemical water-reducing admixtures (WRA) and air-entraining admixtures (AEA). 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* (ASTM, 2015). 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.

### 3.3.1 Chemical Water-Reducing Admixtures

ASTM classifies WRAs into 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 hours) in setting when combined with low concrete temperatures and Type B or D WRAs.

### 3.3.2 Air-Entraining Admixtures

Reclamation used AEAs to increase the freezing and thawing resistance of RCC. Use of an AEA at Santa Cruz Dam appeared to increase 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 used with a 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 affect 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 durable natural sand, or natural sand supplemented with crushed sand, to make up for any deficiencies in the natural sand gradings. Manufactured 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 be uniformly blended. Crusher fines should generally not be used in the production of RCC aggregates. Where natural sand and gravel may not be available, solely crushed aggregate and sand may be used effectively with increased emphasis on a strong mix design development program.

As RCC application has evolved, there has been a great deal of discussion regarding the use of lower quality aggregates for 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 to including fines is that they will coat the coarse aggregate and reduce the paste-aggregate bond, and clay fines increase the water demand, thus decreasing strength. In addition, the quantity of fines can vary in pit-run materials. Another common cost-savings practice is to use either a combined sand plus coarse aggregate grading, or one sand aggregate and one coarse aggregate. This reduces cost, but at the expense of flexibility, when proportioning the sand or coarse aggregate ratios.

Tests of aggregate physical properties 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 they are used in RCC. As a minimum, fine and coarse aggregate should conform to the quality and grading requirements of ASTM C 33, *Concrete Aggregates* (ASTM, 2015). If additional “fines” are included in the aggregates, the specifier should document the need for such use, as well as the physical properties requirements for the material. If poorer quality aggregates are contemplated, early investigation should be performed to evaluate if project-specific design requirements and long-term mechanical and chemical stability can be achieved, and, if so, under what additional requirements. Whether aggregates are supplied in segregated sizes, combined sizes, or a combination of sizes, the mix design process, specifications, and quality control procedures need to be in place to ensure combined gradation control and so that the constructed mix achieves the required design parameters.

### 3.4.1 Aggregate Grading

Fine aggregate should meet the grading requirements of ASTM C 33, as well as limits for deleterious substances in fine aggregate for concrete. It should be noted that the percent limits for material passing the 75-micrometer (No. 200) sieve are weight percentages of the sand, not of the total aggregate.

Coarse aggregate should meet the grading requirements of ASTM C 33, as well as limits for deleterious substances and physical property requirements. Most mass RCC mixtures will have a nominal maximum size aggregate (NMSA) of 1-½ inches or 2 inches. The recommended ASTM C 33 grading requirements are size No. 4 (1-½ inches to ¾ inch) and No. 67 (¾ inch to No. 4) for a 1½-inch NMSA and size No. 3 (2 inches to 1 inch) and No. 57 (1 inch 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 No. 57 (1 inch to No. 4) or No. 467 (1-½ inch to No. 4) grading. Segregation of coarse aggregate in a single stockpile can be a problem, as was observed at Ochoco Dam, when a single stockpile was used with No. 467 grading.

Figure 3-1 shows the USACE ideal coarse aggregate grading for RCC with 2-inch NMSA compared to the gradation limits for an ASTM C 33, size No. 357. Figure 3-2 shows the USACE ideal fine aggregate gradation for RCC compared with grading requirements in ASTM C 33 for conventional concrete (USACE, 2000). A higher sand content is needed to reduce the segregation potential of RCC mixtures and is generally about 7 percent higher than is typically used for conventional concrete mixtures. The fines are primarily added to fill voids that are normally occupied by paste; however, they do not contribute to strength gain and may increase the density of fully compacted mixtures. Clay fines can lower strength and increase the water demand of RCC mixtures, as well as decrease durability.

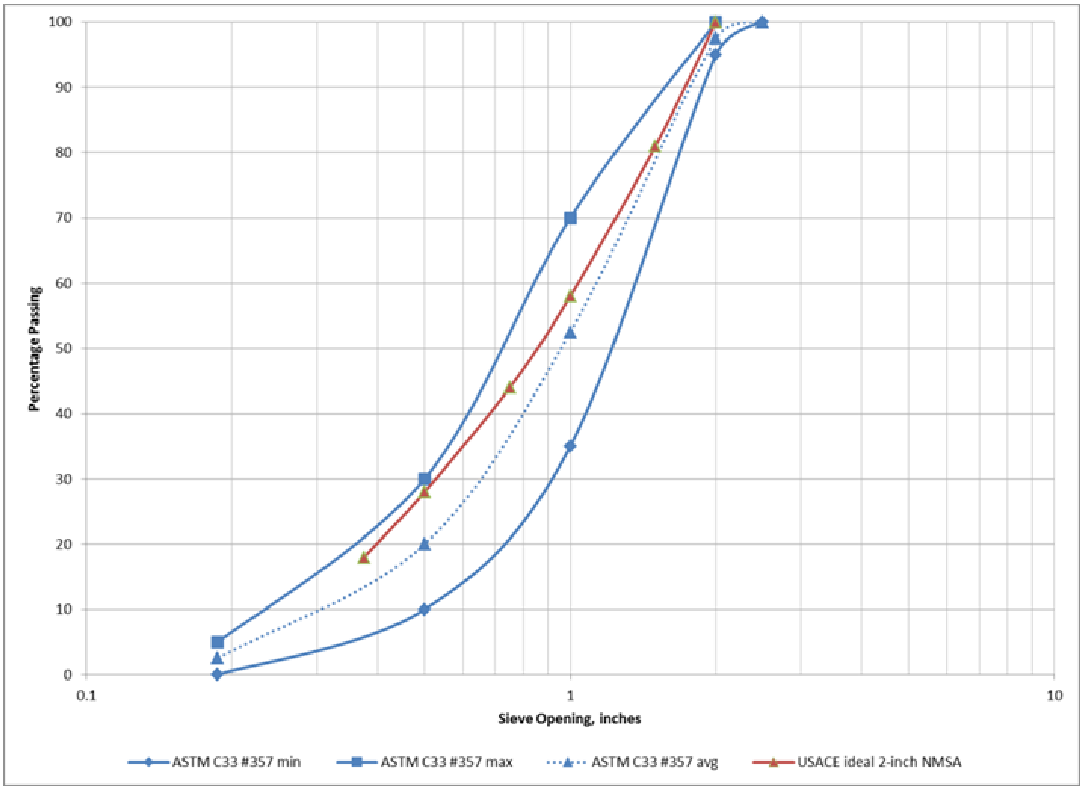



**Figure 3-1. USACE ideal coarse aggregate gradation for RCC with 2-inch NMSA compared with ASTM C 33, size No. 357.**

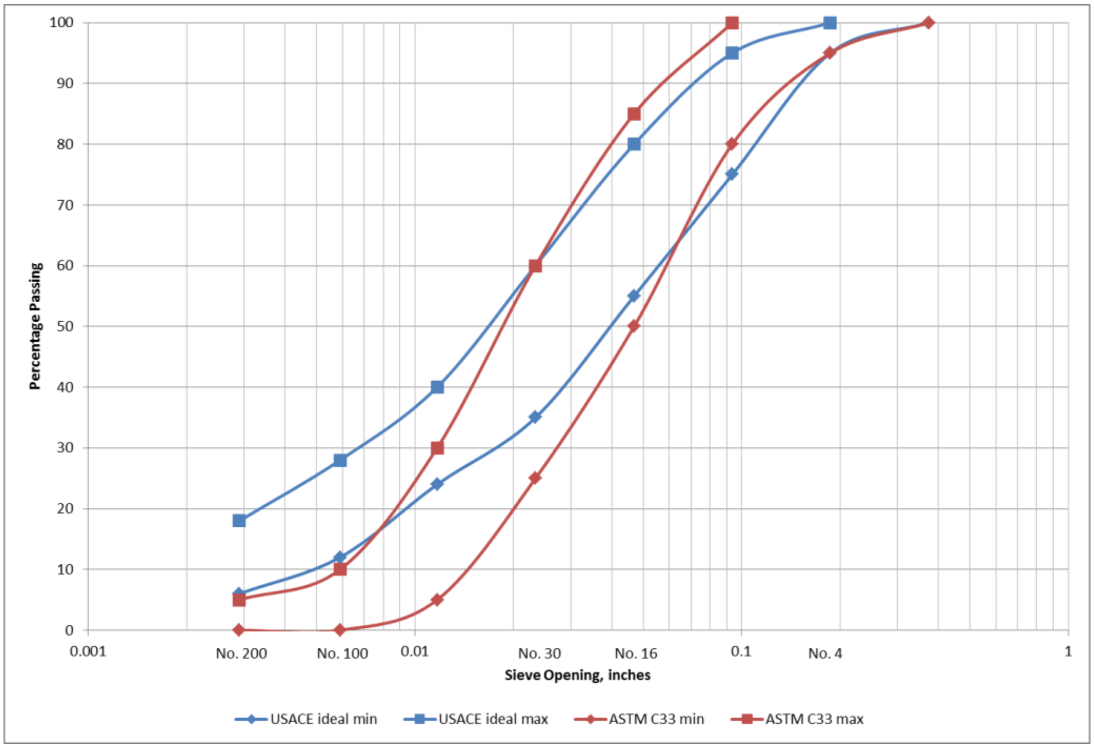



**Figure 3-2. USACE ideal fine aggregate gradation for RCC compared with ASTM C 33 gradation requirements for conventional concrete.**

### 3.4.2 Aggregate Quality

Quality requirements for fine and coarse aggregate are given in ASTM C 33. Of particular concern are the soundness of fine and coarse aggregates 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. Aggregate breakdown will require increased lift surface cleanup and preparation, and it may decrease strength.

### 3.4.3 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, and as often as needed during the shift, to ensure effective mix proportioning and moisture control during batching. 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 aggregate surface, and to obtain consistent moisture contents.

It is important to produce sufficient aggregates at a stable moisture condition to accommodate high RCC production rates. RCC mixtures have a lower water content than conventional mass concrete; therefore, 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-pound-per-cubic-yard (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, 2015. *Annual Book of ASTM Standards.* West Conshohocken, Pennsylvania.

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

USACE, 2000. *Roller Compacted Concrete.* Engineer Manual No. EM 1110-2-2006, U.S. Army Corps of Engineers.

# 4. RCC Mixture Design Requirements

Proportioning RCC mixtures involves optimizing the material contents based on both the performance criteria and the relative cost of the mixture. The materials and proportioning methods that are used depend, in part, on the philosophy of considering RCC as either a concrete material that is modified for the placing methods, or as a cement-stabilized fill material that has concrete-like properties. Although the 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 have not changed. What has changed 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 compared with 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 the RCC; durability requirements; and constructability issues. Strength requirements should address compressive strength, tensile strength, bond (shear and tensile) strength, and associated elastic properties and creep effects. Thermal properties may particularly impact cracking of massive structures. The extent of thermal cracking is 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 (C:P) ratio. Durability requirements include freeze-thaw resistance of the RCC, chemical resistance to ASR 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 typically do not include embedded cooling pipes as used for conventional mass concrete dams; thus, the cementitious materials content and placing temperatures directly impact thermal cracking. RCC can be placed at double or triple the rate 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 it 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 feet per day using slipformed facing systems and 3 to 4 feet per 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 needed for the construction equipment, including the need for the equipment to maneuver and safely pass. This generally limits RCC dams to a minimum crest width of about 20 feet or wider, and it 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.

### 4.1.1 Vebe Consistency

Vebe consistency is an indicator of the workability of RCC and is determined by ASTM C 1170, *Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table* (ASTM, 2015). In this test, a sample of RCC is vibrated under a surcharge until it is fully consolidated, as shown in figure 4-1. 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 time, the easier it is to compact the sample. The typical range of consistency times shown in figure 4-2, for RCC mixtures using the concrete approach for proportioning, 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 four to eight passes of a 10-ton, dual-drum, vibrating roller. Segregation will also be minimized at this consistency range. Most of Reclamation's projects used the 50-pound surcharge, except for the most recent Glendo Dam Modifications.

Figure 4-1. Consolidated Vebe sample.

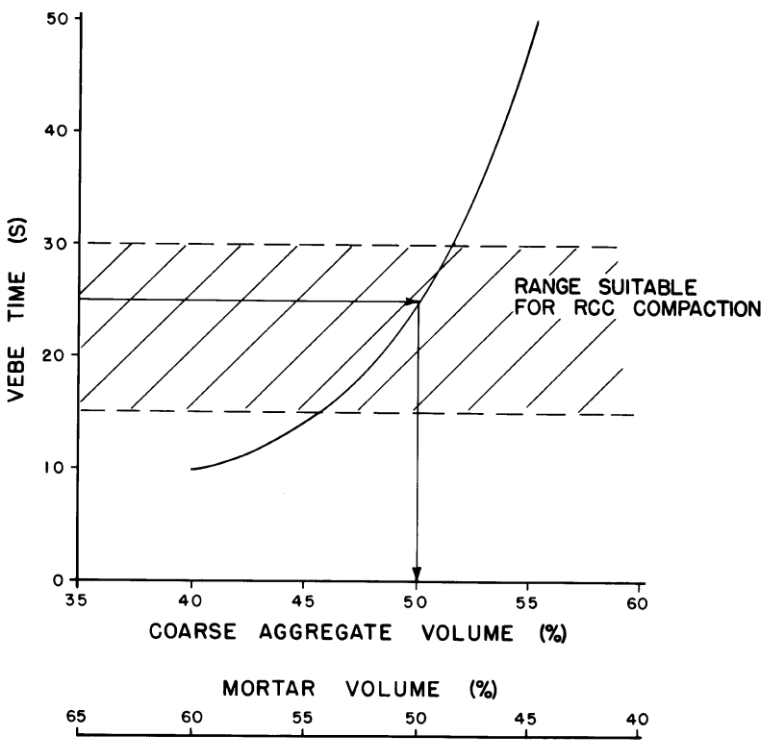



Figure 4-2. Range of Vebe consistency time suitable for compaction in a 1-foot lift with a vibrating roller.

The Vebe consistency test for RCC basically replaces the slump test used for conventional and mass concrete. The Vebe consistometer (shown in figure 4-3), 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 4-4 and 4-5. 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.

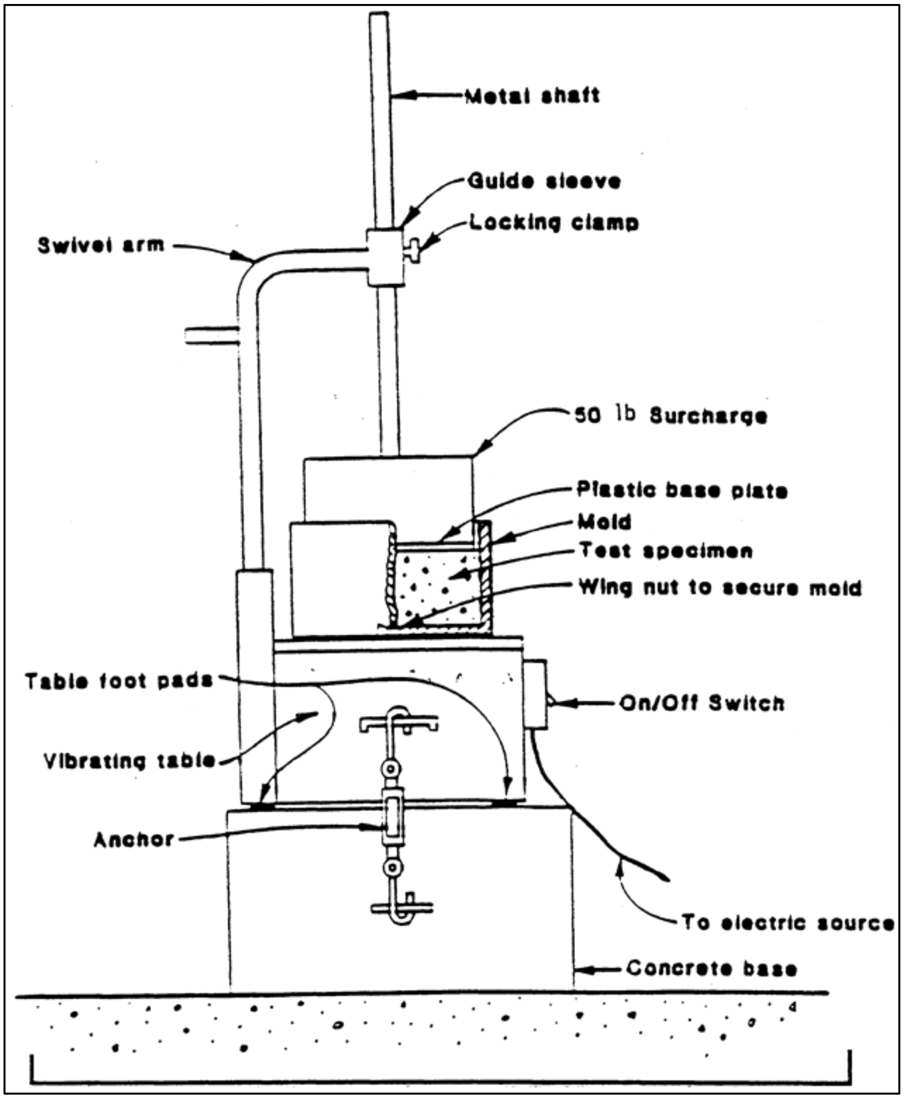



**Figure 4-3. Vebe equipment for a 50-pound surcharge.**

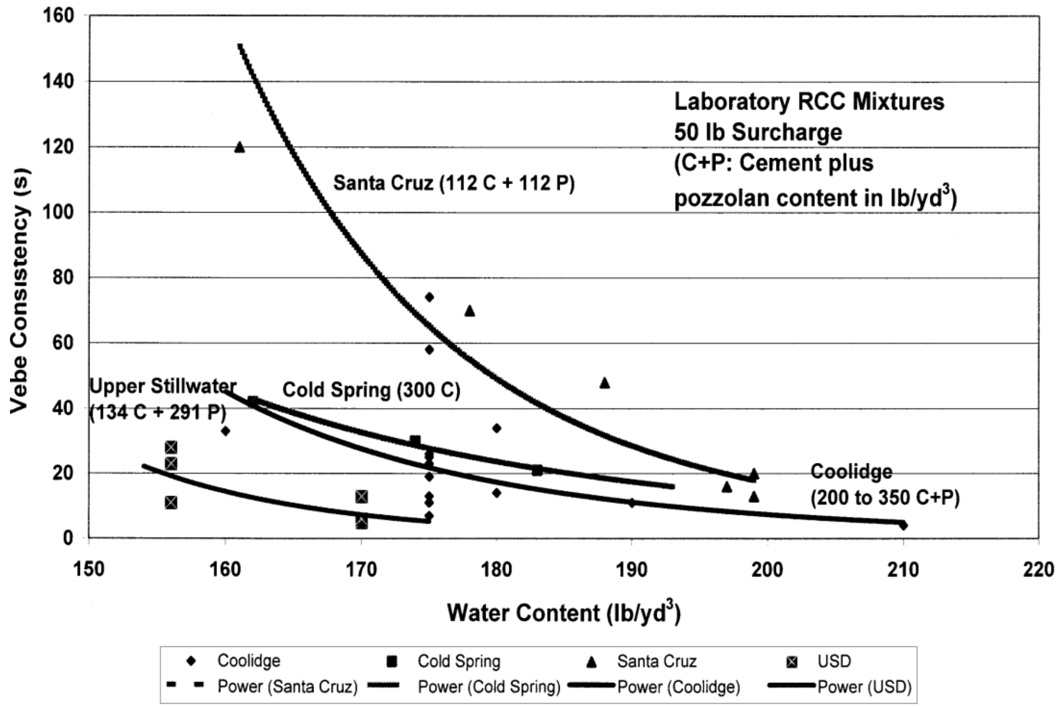



**Figure 4-4. Water content versus Vebe consistency.**

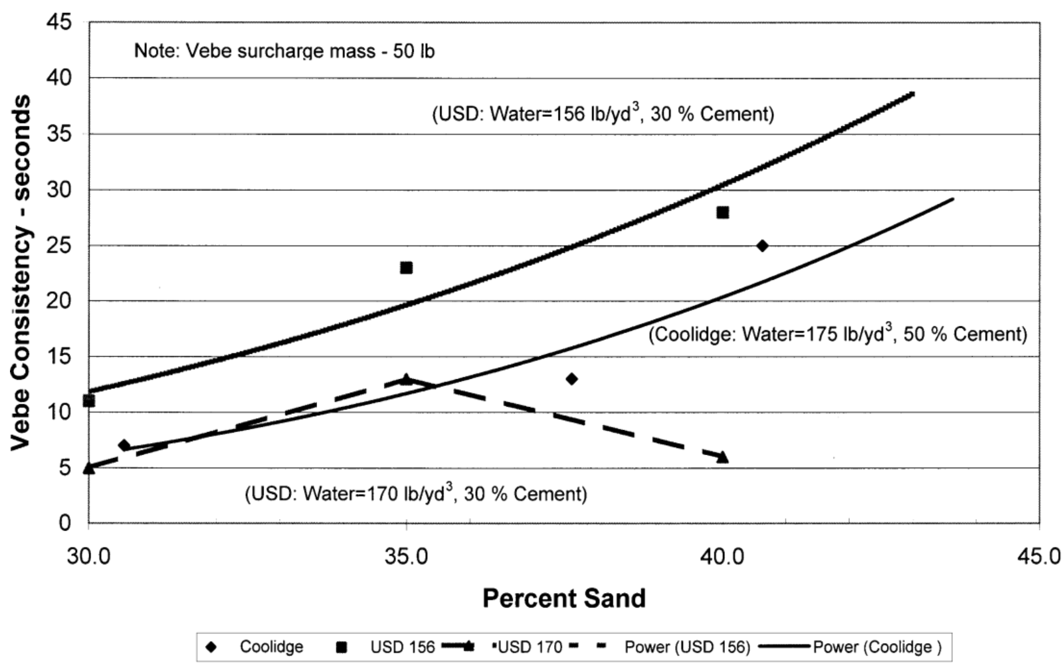



**Figure 4-5. Percent sand versus Vebe consistency.**

### 4.1.2 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, increased volume of voids between aggregates, and may result in excessive seepage between lifts. Segregation is most often caused by a mixture that is too dry combined with poor handling and placing techniques. Mixtures with a Vebe consistency less than 20 seconds generally have less segregation than mixtures with a higher consistency time. Mixtures compacted near optimum moisture are now being specified about ½ to 1 percent wet of optimum to reduce segregation.

### 4.1.3 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 it can also influence the bond potential between lifts. Lower placing temperatures, combined with a set-retarding WRA and high pozzolan contents, can delay the initial set of fresh RCC up to 36 hours.

### 4.1.4 Density

The density and volume of voids in 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 pounds per cubic feet (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 Reclamation has constructed have shown it is possible to entrain air in RCC. This slightly lowers the density to about 145 lb/ft$^3$, but it 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.

## 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 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.

### 4.2.1 Compressive Strength and Elastic Properties

The design compressive strength is normally specified for most RCC structures. Although it may not be the governing design criterion, compressive strength is a good indicator of mixture composition and variability, and it 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/cm) ratio of the mixture and the degree of compaction. Table 4-1 shows compressive strength and elastic properties data, and figure 4-8 shows the relationship between compressive strength and w/cm ratio. Figure 4-8 is a compilation of results of laboratory or field construction control cylindrical test specimens, mostly at 1 year in test age. The test results indicate that RCC mixtures using ASTM graded aggregates may have a higher compressive strength than comparable mixtures using “all-in” aggregate gradings with fines. Figure 4-9 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 removed.

Some RCC mixtures cannot be effectively compacted for the full depth of the lift, leaving porous, unbonded lift lines. This is due to insufficient workability for compaction and, particularly, 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, which results in the inability to fully compact the entire lift.

**Table 4-1. 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 | 1,460 | 2,470 | 3,720 | 1.92 | 2.7 | 3.57 | 5.06 | 0.16 | 0.18 | 0.18 | 0.19 |
| Coolidge | Ctwd-1 | 0.7 | 890 | 1,860 | 3,350 | 4,450 | 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 | 1,300 | - | 0.86 | 1.39 | 2.03 | - | 0.25 | 0.25 | 0.21 |
| Research | 150 | 1.3 | - | 250 | 665 | 1,120 | - | - | - | - | - | - | - | - |
| Research | 300 | 0.55 | - | 1,480 | 2,640 | 4,540 | - | - | - | - | - | - | - | - |
| Upper Stillwater | L1 | 0.47 | 1,360 | 2,130 | 3,510 | 5,220 | - | 1.03 | 1.32 | 1.71 | - | 0.13 | 0.14 | 0.17 |
| Upper Stillwater | L2 | 0.45 | 770 | 1,220 | 2,150 | 4,780 | - | 0.82 | - | 1.59 | - | 0.13 | - | 0.2 |
| Upper Stillwater | L3 | 0.43 | 1,110 | 1,620 | 2,770 | 4,960 | - | 0.92 | - | 1.76 | - | 0.13 | - | 0.18 |
| Average | All mixes | 0.69 | 890 | 1,220 | 2,160 | 3,760 | - | 1.49 | 2.55 | 2.75 | - | 0.16 | 0.19 | 0.19 |

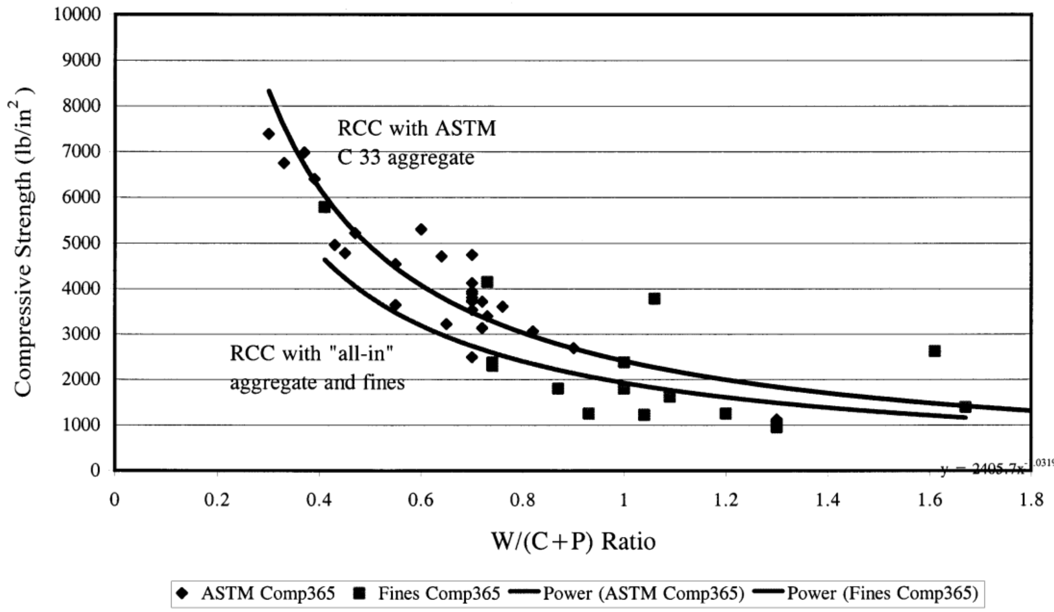



**Figure 4-6. RCC compressive strength versus w/cm ratio, 365 days old—ASTM C 33 aggregate versus "all- in" aggregate with fines.**

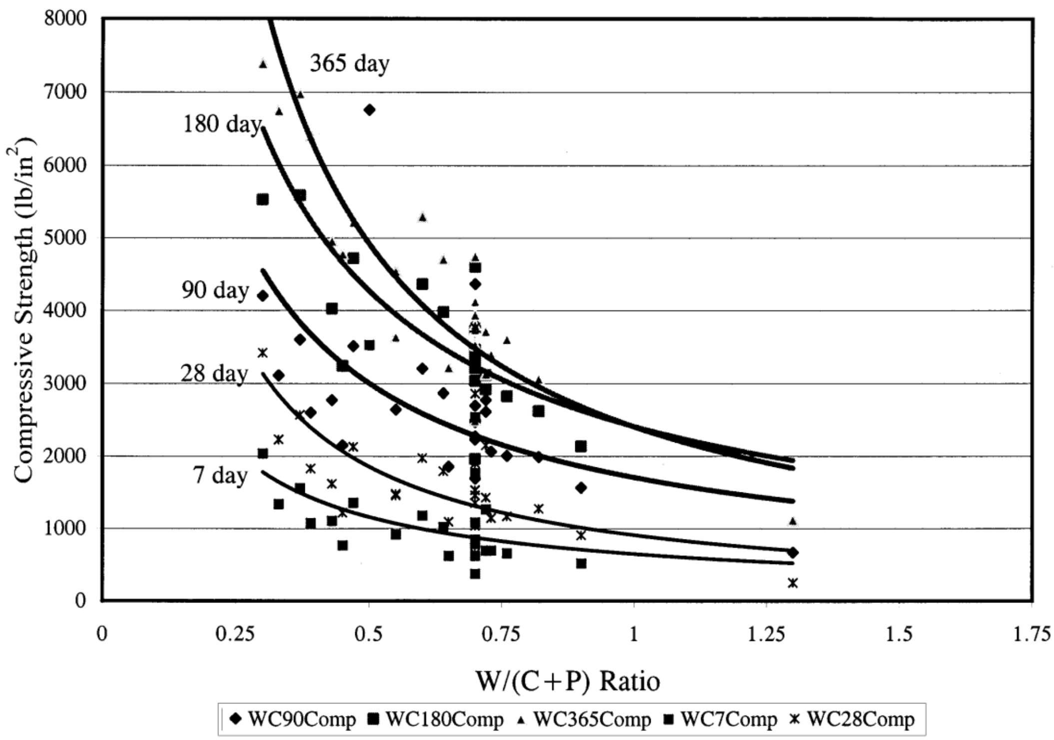



**Figure 4-7. Variation in compressive strength versus w/cm ratio for RCC mixtures with ASTM C 33 aggregates.**

### 4.2.2 Cement Plus Pozzolan Content and Cement to Pozzolan Ratio

The cementitious materials content influences the ultimate strength gain of RCC. Mixtures with higher total cementitious materials content have higher strengths for a given material and water content. The higher cementitious materials content can increase the bond between lifts of RCC. Extremely lean RCC mixtures may meet minimum compressive strength requirements, but little or no bond strength in either shear or tension. The rate of strength gain primarily depends on the C:P ratio. For example, RCC mixtures from Upper Stillwater Dam, with a C:P 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.

The C:P ratio is also adjusted 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 total cementitious materials. Pozzolan has good resistance to both ASR and sulfate attack, and it uses an abundant mineral resource (fly ash) that would otherwise require disposal 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 total cementitious materials. 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 total cementitious materials. The spherical shape of fly ash particles increases the workability of high fly ash RCC mixtures, thus permitting a reduction in water content compared to a mix without fly ash.

### 4.2.3 Thermal Properties

The influence of mixture proportions on thermal properties of RCC is primarily associated with the thermal properties of the aggregates and the total cementitious materials content. Higher total cementitious materials content will increase the heat of hydration generated within the mass, resulting in thermal cracking as the RCC cools. As an example, 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. Due to high temperature gradients, this may increase the cracking potential of dams if the RCC is placed just prior to the winter season. Table 4-2 provides sample temperature rise data for a variety of RCC mixtures.

Table 4-2. Temperature Rise Properties of RCCs

| Feature | Mixture | Cement plus pozzolan content (lb/yd$^3$) | Pozzolan (percent by mass) | Maximum aggregate size (inches) | Initial temperature (°F) | Adiabatic temperature rise (°F), at age, days | | | | | Maximum temperature 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 | |
| Santa Cruz | 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).
Note: °F = degrees Fahrenheit.
See appendix C for examples of the adiabatic temperature rise plots. Examples are provided for Upper Stillwater Dam, Pamo Dam, and Middle Fork Dam

### 4.2.4 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 it is protected from freezing or critical saturation by conventional concrete or use of an AEA. Air-entrained RCC increases the resistance to freezing and thawing, as well as 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 use of 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 (hydrologic), 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 for shear and tension, not the design compressive strength requirement, often govern the total cementitious materials content of RCC mixtures. The w/cm ratio and cementitious materials content of the mixture affect the ultimate shear and tensile strength capacity across lift joints, as well as the percentage of the joint surface area that is bonded. Mixtures with cementitious 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 percentage of the lift surface that is bonded may be significantly less than 50 percent unless supplemental joint treatment is used, such as a layer of bonding mortar. Mixtures with cementitious 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 cementitious 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. If precipitation occurs that is determined to be detrimental to the RCC, RCC placing should immediately be suspended, and the lift surface should be protected. Generally, no RCC placements should take place during rain and snow because precipitation can potentially affect the compressive strength, consolidation of the lift, and reduce the potential for bonding on the lift surface.

Because it is generally necessary to maintain true "cohesion" on concrete dam lift surfaces to meet 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 careful examination of drilled cores 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. In addition, Reclamation 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 RCC mixture proportioning methods, quality control practices, design parameters, and construction specifications. Table 4-3 summarizes the results of laboratory testing.

The shear strength at lift lines can be determined using a biaxial testing apparatus (McLean and Pierce, 1988; Reclamation, 1992). 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 $\phi$, 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, ca, or residual shear stress at the zero normal load intercept and a friction resistance, tan $\phi_a$, representing the slope of the best fit line.

**Table 4-3. Shear bond strength properties of laboratory RCC mixtures**

| Project | Joint age[1] (hour) | W/(C+P) ratio | Cohesion (lb/in²) 28 days[2] | Cohesion (lb/in²) 90 days | Cohesion (lb/in²) 1 year | Internal friction (tan Ø) 28 days | Internal friction (tan Ø) 90 days | Internal friction (tan Ø) 1 year | Residual cohesion (lb/in²) 28 days | Residual cohesion (lb/in²) 90 days | Residual cohesion (lb/in²) 1 year | Sliding friction (tan Ø) 28 days | Sliding friction (tan Ø) 90 days | Sliding friction (tan Ø) 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 | 1.56 | - | 80140 | - | - | 0.93 | - | - | 4580 | - | - | 0.67 | - |
| | 7-B | | - | | - | - | 1.23 | - | - | | - | - | 0.70 | - |
| Milltown Hill | 8-NB | 0.85 | - | 160 | 280 | - | 1.17 | 0.95 | - | 30 | - | - | 0.57 | 0/79 |
| Research 150 | 8 | 1.30 | 70 (56) | 1e+10 | 2e+10 | 0.93 (56) | 1.15 | 1.07 | 35 (56) | 6e+07 | 5e+07 | .81 (56) | 1.00 | 0.97 |
| | 24 | | 40 (56) | | | 0.87 | 1.15 | 0.65 | 20 (56) | | | .65 (56) | 0.70 | 0.90 |
| | 72 | | - | | | (56) | 0.78 | 1.28 | 5 (56) | | | .73 (56) | 0.81 | 0.81 |
| | 24-B | | - | | | - - | 1.10 | 1.13 | - | | | - | 0.82 | 0.92 |
| Research 300 | 8 | 0.55 | 80 | 4e+11 | 600 | 1.04 | 0.75 | 1.28 | 5e+07 | 4e+07 | 50 | 0.87 | 0.97 | 1.07<br>0.97<br>0.84 |
| | 24 | | 265 | | 620 | 0.36 | 0.58 | 0.70 | | | 25 | 0.93 | 0.87 | |
| | 72 | | 220 | | 480 | 0.58 | 1.28 | 2.15 | | | 21 | 0.75 | 0.87 | |
| | 24B | | - | | - | - | 1.26 | - | | | - | - | 0.91 | |
| Upper Stillwater | 24-NB | 0.47 | 220 | 380 | | | | | | | | | | |
| Upper Stillwater | 24-NB | 0.45 | 140 | 240 | | | | | | | | | | |
| Upper Stillwater | 24-NB | 0.43 | 230 | 280 | | | | | | | | | | |
| Average | NB | - | 180 | 270 | | | | | | | | | | |
| Average | B | - | - | 240[4]<br>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-inch-diameter specimens, except Galesville Dam test specimens, which were 9-inch-diameter specimens.
[5] Average cohesion for three mixtures with bonding mixture.

The direct tensile strength of bonded lift lines is determined using a specimen with the lift line at its midpoint (USBR 4915) (Reclamation, 1992). 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.

Based on the tests performed by 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.

5. Placing a bonding layer of mortar or concrete between lifts of RCC.

6. Placing RCC at a high rate, reducing the exposure time between lifts.

7. Maintaining good construction practices for mixing, placing, compacting, and curing RCC.

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 should be maintained in a moist condition and not be allowed to dry. Lift surfaces that are allowed to dry must be cleaned by vacuum or air/water jetting before the next lift is placed. 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 feet per 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.

For item 6 in the list above, depending on the mix design, an RCC placement rate of a least two lifts per day generally 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 cores extracted following the 1985 season, demonstrated the effect of the placing rate on bond. The 1986 construction had about a 2-foot-per-day placement rate and had significantly better percent bonding than the previous year's construction. Tests from Pueblo Dam Modification mixture proportioning investigations showed a mixture with 300 $lb/yd^3$ of C+P had more than a 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 the same careful attention to the construction operations that are 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. Lift line bond properties will depend on construction control during placing and on the rate of placing or time interval between lifts. Table 4-4 summarizes mixture proportions for several RCC mixes used in construction. Table 4-5 shows fresh RCC properties based on field construction records. Table 4-6 presents strength and elastic properties of cores, and table 4-7 shows bond strength properties of 6-inch-diameter RCC cores.

**Table 4-4. Mixture Proportions of RCC Used in Construction**

| Project | NMSA (inches) | 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 | 1,310 | 2,560 | 4,235 |
| Research -Amc1 | 2.5 | - | 180 | 150 | 0 | 1,367 | 2,327 | 4,024 |
| Research-Amc2 | 2.5 | - | 200 | 150 | 0 | 1,359 | 2,315 | 4,024 |
| Research-Bmc1 | 2.5 | - | 180 | 150 | 150 | 1,312 | 2,233 | 4,025 |
| Research-Bmc2 | 2.5 | - | 200 | 150 | 150 | 1,304 | 2,221 | 4,025 |
| Stagecoach | 2.0 | - | 233 | 120 | 130 | 1,156 | 2,459 | 4,098 |
| Upper Stillwater RCC-A85 | 2.0 | 1.5 | 159 | 134 | 291 | 1,228 | 2,177 | 3,989 |
| Upper Stillwater RCC-A86/87 | 2.0 | 1.5 | 166 | 134 | 291 | 1,148 | 2,231 | 3,970 |
| Upper Stillwater RCC-B85 | 2.0 | 1.5 | 150 | 159 | 349 | 1,171 | 2,178 | 4,007 |
| Upper Stillwater RCC-B86/87 | 2.0 | 1.5 | 169 | 155 | 343 | 1,162 | 2,128 | 3,957 |
| Pueblo test section | 1.5 | 4.5 | 166 | 121 | 181 | 1,293 | 2,202 | 3,963 |

**Table 4-5. Properties of Fresh RCC Mixtures Used in Construction**

| Project | Mixture | Temperature (°F) | Density ($lb/ft^3$) | Vebe consistency[1] | Air content (gravimetric) (%) |
|---|---|---|---|---|---|
| Galesville | RCC-1 | 61 | 156.0 | NA | - |
| Research | RCC-150 | - | 151.8 | - | - |
| Research | RCC-300 | - | 151.4 | - | - |
| Stagecoach | | - | 150.8 | (60) [2] | - |
| 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] These consistency times are based on a 50-pound surcharge.
[2] Limited test data; estimated time.

**Table 4-6. 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 (106 $lb/in^2$) | Poisson's ratio |
|---|---|---|---|---|---|---|
| Galesville | RCC 1 | 1.09 | 415 | 2,080 | 3.12 | 0.18 |
| Research | RCC-150 | 1.30 | 72 | 840 | _ | _ |
| Research | RCC-300 | 0.55 | 72 | 1,920 | _ | _ |
| Stagecoach | | 0.93 | 160 | 1,670 | 2.18 | 0.17 |
| Stagecoach | | 0.93 | 180 | 1,960 | 2.58 | 0.12 |
| Stagecoach | | 0.93 | 365 | 1,920 | 2.38 | 0.16 |
| Upper Stillwater | RCC A85 | 0.37 | 108 | 3,870 | 1.96 | 0.23 |
| Upper Stillwater | RCC A85 | 0.37 | 200 | 4,890 | 1.55 | 0.23 |
| Upper Stillwater | RCC A85 | 0.37 | 633 | 6,510 | 2.32 | 0.21 |
| Upper Stillwater | RCC B-85 | 0.3 | 102 | 3,760 | _ | _ |
| Upper Stillwater | RCC A86 | 0.39 | 335 | 5,220 | 2.18 | 0.22 |
| Upper Stillwater | RCC B86 | 0.34 | 320 | 5,130 | 2.28 | 0.15 |
| Upper Stillwater | Average, all RCC | 0.36 | 322 | 5,140 | 2.15 | 0.20 |

**Table 4-7. Bond Strength Properties of 6-Inch-Diameter RCC Cores Used in Construction**

| Project | Joint type[1] | Percent joint bond | Vebe time(s)[2] | W/(C+P) ratio | Age (days) | Compressive strength (lb/in$^2$) | Tensile strength (lb/in$^2$) | Break bond | | Residual cohesion, $C_a$ (lb/in$^2$) | Sliding friction (tan Ø) $_a$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Cohesion (lb/in$^2$) | Internal friction, c (tan Ø) | | |
| 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 B-85 | 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<br>90 | 1,260 | 150<br>180 | (430) [3] | (0.93) | (40) | (0.92) |
| Pueblo test section RCC-8TS | 6-NB | 92 | 8 | 0.55 | 35<br>90 | 1,260 | 170<br>170 | (330) [3] | (0.99) | (30) | (1.05) |
| Pueblo test section RCC-8TS Lab cast specimens | 6-NB<br>6-B<br>6-P | NA | 8 | 0.55 | 35 | 1,260 | 155<br>150<br>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] These consistency times are based on a 50-pound surcharge.
[3] 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: (1) the "concrete approach," where mixtures are proportioned as a mass concrete adjusted to support the construction placing and compaction equipment; and (2) the "soils approach," where mixtures are 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.

### 4.5.1 Mixture Proportioning

Proportioning RCC mixtures with the concrete approach generally follows classical concrete proportioning concepts that incorporate both workability and strength. First and foremost, a mixture that does not have the necessary workability cannot be economically and effectively placed and compacted. Second, 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* (ASTM, 2015). After optimizing the proportions for workability, the w/cm ratio is varied to achieve the required strength and durability properties. The C:P 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 C:P ratio. Higher C:P ratios will gain strength faster, but they will generate more heat. Balancing the strength versus heat relationships is a part of the cementitious materials proportioning process.

### 4.5.2 Steps in Proportioning RCC Mixtures

The process of proportioning RCC mixtures will depend on 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 4-8 and 4-9, which illustrate the RCC trial mix program used for Coolidge Dam in Arizona. The first three mixtures varied the 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 desired 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 C:P ratio to evaluate the effect of the C:P ratio on Vebe consistency and on compressive strength development. The next two mixtures varied the total cementitious content about 50 lb/yd$^3$ above and below the initial trial mixture to show the effect of w/cm ratio on strength. The remaining mixtures were used to cast additional strength and thermal property test specimens as needed from the design mixture.

Based on the tests Reclamation performed, 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 with sand and coarse aggregate meeting the requirements of ASTM C 33 are assumed.

**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).

2. Select an initial cementitious materials content of 250 lb/yd$^3$.

3. Select a C: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 inch 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.

**Table 4-8. RCC Trial Mixture Proportioning Program Input Parameters—2-Inch NMSA**

| Trial mix No. | Air[1] content (%) | Water content ($lb/yd^3$) | C+P[2] content ($lb/yd^3$) | C:P ratio (by mass) | Percent sand[3, 4] | Comments |
|---|---|---|---|---|---|---|
| 1 | 1 | 175 | 250 | 1:1 | 37 | First trial mix—C:P ratio for compressive strength of 2,500 $lb/in^2$ at 180 days' age or 3,000 $lb/in^2$ at 1 year |
| 2 | 1 | 160 | 250 | 1:1 | 37 | Reduce water—effect of water on Vebe consistency; effect of W/C+P ratio on compressive strength |
| 3 | 1 | 190 | 250 | 1:1 | 37 | Increase water—effect of water on Vebe consistency; effect of W/C+P ratio on compressive strength |
| 4 | 1 | 175 | 250 | 1:1 | 30 | Decrease sand—effect of sand content on Vebe consistency and segregation |
| 5 | 1 | 175 | 250 | 1:1 | 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 C:P ratio on Vebe consistency and compressive strength gain |
| 7 | 1 | 175 | 250 | 1:1.5 | 37 | Increase percent pozzolan—effect of C:P ratio on Vebe consistency and compressive strength gain |
| 8 | 1 | 180 | 200 | 1:1 | 37 | Decrease C+P content—effect of W/C+P ratio on compressive strength |
| 9 | 1 | 180 | 300 | 1:1 | 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] The initial sand content for this mixture was selected at 37 percent due to its coarse grading.
[4] CA1:CA2 ratio: (coarse aggregate size 3) to (coarse aggregate size 57) ratio—1:1 by mass. Determined from dry-rodded density study.

**Table 4-9. RCC Mixture Proportioning Program—Batch Quantities for Coolidge Dam Mixture Proportioning Program[1]**

| Trial No. | Water (lb) | Cement (lb) | Pozzolan (lb) | Sand (lb) | No. 4 1 inch (lb) | 1 to 2 inches (lb) | Total (lb) | W/(C+P) ratio | Vebe consis-tency(ies) | Density (lb/ft$^3$) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 175 | 125.0 | 125.0 | 1,427 | 1,183 | 1,184 | 4,219 | 0.70 | 13 | 155.4 | Basic starting mixture |
| 2 | 160 | 125.0 | 125.0 | 1,442 | 1,196 | 1,196 | 4,245 | 0.64 | 33 | 157.4 | Reduce water 15 lb/yd$^3$ |
| 3 | 190 | 125.0 | 125.0 | 1,412 | 1,170 | 1,171 | 4,193 | 0.76 | 11 | 156.9 | Increase water 15 lb/yd$^3$ |
| 5 | 210 | 150.0 | 150.0 | 1,372 | 1,138 | 1,138 | 4,159 | 0.70 | 4 | 156.9 | Increase paste volume |
| 6 | 175 | 125.0 | 125.0 | 1,157 | 1,315 | 1,315 | 4,212 | 0.70 | 7 | 157.0 | Decrease sand to 30 percent |
| 7 | 175 | 125.0 | 125.0 | 1,543 | 1,127 | 1,128 | 4,223 | 0.70 | 25 | 156.6 | Increase sand to 40 percent |
| 8 | 175 | 250.0 | 0.0 | 1,140 | 1,194 | 1,194 | 4,253 | 0.70 | 58 | 156.2 | Change C:P ratio to 1:0 |
| 9 | 175 | 157.5 | 62.5 | 1,414 | 1,198 | 1,198 | 4,235 | 0.70 | 74 | 159.0 | Change C:P ratio to 75:25 |
| 10 | 175 | 62.5 | 157.5 | 1,401 | 1,187 | 1,187 | 4,201 | 0.70 | 11 | 155.1 | Change C:P ratio to 25:75 |
| 11 | 175 | 150.0 | 100.0 | 1,430 | 1,185 | 1,185 | 4,226 | 0.70 | 26 | 157.1 | Change C:P ratio to 60:40 |
| 12 | 175 | 100.0 | 150.0 | 1,424 | 1,181 | 1,181 | 4,212 | 0.70 | 23 | 156.6 | Change C:P ratio to 40:60 |
| 13 | 180 | 150.0 | 150.0 | 1,403 | 1,163 | 1,164 | 4,210 | 0.60 | 14 | 156.4 | Increase C+P 50 lb/yd$^3$ |
| 14 | 180 | 100.0 | 100.0 | 1,441 | 1,195 | 1,195 | 4,210 | 0.90 | 34 | 157.1 | Decrease C+P 50 lb/yd$^3$ |
| 15 | 175 | 125.0 | 125.0 | 1,543 | 1,127 | 1,128 | 4,223 | 0.70 | 19 | 154.6 | Repeat of mix 7 |

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

**Trial mixture adjustments:** Keeping the initial cementitious materials content, C: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 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/cm 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: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 cementitious materials content, while maintaining the water content, total cementitious materials 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/cm 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.

Table 4-10 shows the typical mixtures Reclamation proportioned using these methods. 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.

**Table 4-10. RCC Mixtures Proportioned by Reclamation**

| RCC mixture | Air (%) | Water (lb) | Cement (lb) | Pozzolan (lb) | Sand (lb) | Coarse aggregate (lb) | Total (lb) | Design strength (lb/in²) | Test age (days) |
|---|---|---|---|---|---|---|---|---|---|
| Upper Stillwater-A | 1.0 | 167 | 134 | 292 | 1,149 | 2,218 [1] | 3,960 | 3,000 | 365 |
| Santa Cruz[3] | 2.2 | 170 | 128 | 127 | 1,227 | 2,301 [1] | 3,953 | 3,000 | 365 |
| Milltown Hill | 1.0 | 189 | 111 | 111 | 1,380 | 2,367 [1] | 4,160 | 1,800 | 180 |
| Camp Dyer | 3.8 | 152 | 139 | 137 | 1,261 | 2,257 [2] | 3,946 | 3,000 | 365 |
| Coolidge | 1.5 | 174 | 123 | 123 | 1,534 | 2,238 [1] | 4,194 | 2,500 | 180 |
| Research 150 | 1.0 | 195 | 74 | 74 | 1,340 | 2,324 [2] | 4,010 | 1,000 | 365 |
| Research 300 | 1.0 | 165 | 150 | 150 | 951 | 2,680 [2] | 4,096 | 4,000 | 365 |
| Cold Springs spillway | 1.0 | 157 | 302 | 0 | 1,593 | 2,271 [2] | 4,323 | 4,000 | 28 |
| Ochoco spillway | 1.0 | 218 | 434 | 0 | 1,539 | 1,881 [2] | 4,072 | 4,000 | 28 |
| Pueblo Dam Modification | 5.0 | 165 | 120 | 180 | 1,287 | 2,191 [2] | 3,943 | 3,000 | 365 |

[1] 2-inch NMSA.
[2] 1-½-inch NMSA.
[3] Air-entrained RCC.

## 4.6 References


ASTM International, 2015. *Annual Book of ASTM Standards.* West Conshohocken, Pennsylvania.

McLean, F.G., and J.S. Pierce, 1988. "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.

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

USACE, 2000. *Roller Compacted Concrete.* Engineer Manual No. EM 1110-2-2006, U.S. Army Corps of Engineers, January 15.

# 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. However, such quality assurance activities 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 on the complexity and criticality of the project or feature. A critical feature is one in which a failure could injure personnel or jeopardize the overall success of the project, and it will normally require greater quality assurance measures than a noncritical feature.

## 5.2 Aggregate Production

Although the designer should always identify potential local sources for 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 that meet 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 that do 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 cubic yards ($yd^3$) of RCC required for the work. Quarry sources, however, may be much more attractive for larger projects 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 stockpiled at the job site before batching any RCC.

If warm weather is expected to cause the RCC to exceed the specified maximum temperature during placement, precooling of the aggregates may be required, along with other mix cooling techniques. In areas of relatively low humidity, aggregate cooling is frequently performed by sprinkling water on the coarse aggregate stockpiles to produce evaporative cooling. More aggressive aggregate and sand cooling may involve aggregate wet-belt cooling, flushing stockpiles with chilled water, and air-chilled sand 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, and they often benefit from compulsory rather than drum mixing. Continuous plants may be belt-scale feed plants or volumetric plants. Plants equipped with weigh scales on the material's 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 construction begins. Volumetric plants do not easily detect mixture proportion changes or 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 effectively monitoring plant feed and confirming batched mix proportion quantities, preferably on a per shift or more frequent basis.

Batch size shall be at least 50 percent of, but not in excess of, the rated capacity of the mixing equipment. Often, the bulking of the RCC mix during batching results in ineffective mixing at mixer rated capacities. 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, as well as to provide RCC of uniform workability and consistency continuously or from batch to batch. Truck mixers are ineffective for discharging mixed RCC and 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. It is common that hardened and built-up RCC must be cleaned from mixers every shift during routine operations. 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 rated at the volume of RCC necessary 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. 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 cubic yards per hour ($yd^3$/hr) and a sustained average capacity of 150 $yd^3$/hr for the duration of the work shift.

One of the most important requirements 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 very difficult to maintain good mixture proportioning and is a common source of error for batch plants. Where possible, aggregates should be stockpiled well in advance of construction so that they are well drained and have reached consistent moisture content. This helps ensure that sufficient materials are available and the RCC mixed product is free from moisture fluctuations. Water-cooled aggregates need to be managed as well to yield consistent premix moisture contents. It is important to recognize that wet aggregate stockpiles limit the batch water otherwise available for heating and cooling the mixture.

The batch plant or batching system 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. RCC mix temperature requirements frequently require reducing the natural mix temperature. Common, and sometimes combined, RCC mix cooling techniques include placing at night, limiting placement seasons, precooled aggregate, flake ice, and liquid nitrogen. Adding flake ice or liquid nitrogen to the mixture requires that special provisions be incorporated into the plant.

## 5.4 Transporting and Delivering

The RCC delivery system should be correctly sized for the placing rate. If the desired sustained placement rate (i.e., placement per shift, day or week) is also the batch plant and delivery systems' capacity, the desired placement will rarely be met. System capacities need to be sufficiently higher than the desired sustained rate to allow for fluctuations in the related operations. The delivery system should transport and place the RCC rapidly without excessive or detrimental 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 turnaround areas should be considered when the placement areas become too small.

RCC is usually delivered in single batches by truck or in larger amounts by hauling equipment, by conveyor, or by combinations of truck and conveyor systems. In order to prevent RCC contamination and deterioration, it is desirable to have a delivery system that does not require hauling vehicles to travel on and off the lift surface. Conveying has become a common method of transporting RCC to the site of placement. A conveyor system can be capable of continuous delivery to the point of placement or to truck-loading stations. For conveyor-to-truck systems, the conveyor usually delivers the concrete into dumptrucks on the lift surface, which then deliver the RCC to the placement location. The transfer points on the conveyors can create debris or safety problems when they are not effectively cleaned and maintained, or when they become plugged. Transfer points should be designed and maintained to avoid delivery interruptions 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 smooth transfers or well-designed baffles at transfer points to minimize segregation. Free falls, other than through tremie control, are usually limited to 4 feet or less 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 operation from being interrupted by 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. Vehicles (such as trucks or scrapers) used to haul RCC from the plant to the lift surface should not be allowed to contaminate lift surfaces, and it is commonly prohibited. If transporting and delivering RCC is allowed, washing the tires of the haul vehicles is generally required to prevent contamination of 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-monitored and/or laser-controlled systems for grade control have been used successfully on Upper Stillwater Dam and many 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 (mixes with both cement and pozzolan), or as determined prior to construction based on the mix design, 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 six to eight 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 may be necessary when smaller compacting equipment is used. Compaction equipment and procedures should be proven during a test section or during a controlled area of the placement. However, the number of lift lines in a structure should be minimized as much as possible, while still providing 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 and the RCC is left unworked for more than 15 minutes, or 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. If aggregate is crushed during compaction, it indicates a lack of workability of the RCC mix.

## 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) prevent uplift pressures that may structure stability safety factors, and (4) the need for 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.

Curing is discussed in detail in Section 5.10, "Curing and Protecting." In general, the RCC lift surface must be kept continuously moist and free of standing or running water to ensure curing and maximum bond development. Specifications generally require that the RCC surface be saturated surface dry prior to placement of the next lift 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.

The quality of bonding between RCC layers improves significantly if the placements are made while the previous lift placement is still considered a fresh joint. The lift surface treatment and cleanup requirements are time dependent and affected by the RCC mix, weather, ambient temperature, placing methods, and placing schedule. In the simplest approach, the type of joint treatment required can be defined by a set amount of time before the next placement.

The type of joint treatment can also be defined by maturity factors associated with time and temperature. Cooler temperatures, pozzolan, and retarder admixtures can delay the set time of the RCC. A maturity factor can take into account variable ambient temperature conditions in addition to the time requirements for joint treatment. Reclamation would consider using maturity factors for large projects that require more flexibility.

Reclamation currently uses three types of joint treatments associated with the time between placements:

- **Hot joint** (or fresh joint) occurs when a new RCC lift is placed before the concrete in the previously placed lift has reached its initial set (usually within 6 and up to 12 hours from placement). The main factors influencing the initial set time include the RCC mixture proportions (cement, pozzolan, and admixtures used), ambient and placement temperatures, moisture conditions at the concrete surface, and wind conditions at the project site. For hot joints, the standard cleanup treatment (Type 1) should be specified, which generally consists of removing loose materials and free water, and then cleaning of the lift surface with approved vacuum equipment. The 6- to 12-hour time period is usually reduced to 4 hours if the RCC mix contains no pozzolan or other factors such as warm ambient temperatures exist during the time of placement.

- **Cold joint** occurs after the initial set and before the final set of the concrete (can occur between 6 hours and 24 hours, depending on the RCC mix proportions, ambient and placement temperatures, etc.). For cold joints, the treatment (Type 2) consists of cleaning by air jetting or air-water jetting to completely remove laitance, and loose or defective concrete, followed by air jetting and vacuuming to remove any water or remaining loose materials. Bonding mortar may be specified based on design requirements.

- **Construction joint** occurs after the final set of the concrete (lift surfaces older than 24 and up to 48 hours, depending on the RCC mix proportions, ambient and placement temperatures, etc.). For construction joints, joint treatment (Type 3) is necessary, which consists of high-pressure water jetting or wet sand blasting to expose aggregate, followed by mechanical broom and vacuuming of the entire surface to remove laitance standing water or loose materials. Bonding mortar is generally specified.

The actual hours used to define the type of joint and treatment will be determined based on the RCC mix design and ambient temperature at the site during placement. Laboratory testing programs and the RCC test section following by concrete coring can be used to verify the number of hours for each type of joint and any specific types of treatment necessary to meet the design requirements.

Construction equipment may deposit dirt or debris on the lift surface, which decreases the bond strength of the joint. Another concern is the speed and sharp turns made by construction equipment, which can disturb a previously compacted lift. Specifications often include requirements for the type of tires that can be used, as well as limits to the maneuvers and maximum speed limit permitted for construction equipment such as trucks or front-end loaders.

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 2-½ parts sand with enough water to bring the mortar to a broomable consistency. The maximum w/cm ratio for bonding mortar should generally be 0.45, by weight. Bonding mortar is placed just before the RCC placement and must be covered by RCC before it dries.

## 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 using 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 5-1 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 jackhammer. Other methods include forming of the RCC and installation of a bond breaker material, such as plastic sheeting.


**Figure 5-1. Installation of galvanized steel sheet at Pueblo Dam Modification.**

## 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 construction loads. Smaller RCC dams with insufficient thickness for a gallery, such as the Clear Lake Dam Modification, have used a collector pipe or manifold, instead of a gallery, through which drainage holes have been drilled from the dam crest. The primary problem with this type of system is that once it become plugged, it cannot be cleaned.

## 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; specifically, the cementitious materials content. Curing of RCC is usually accomplished with water. The application of a curing compound is not an acceptable method of curing 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, hand-held hoses with fog spray nozzles, and plastic sheets. During warm weather, or when the lift placements proceed 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/cm 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's (ACI) Manual of Concrete Practice, *Hot Weather Concreting,* ACI 305R-10, figure 4.2 (ACI, 2010) provides excellent guidance on how the temperature of the air and concrete, relative humidity, and wind velocity affect the rate of evaporation of the surface moisture for conventional concrete. This information may be used to help anticipate potential curing requirements related to temperature, humidity, and change in wind conditions.

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 the concrete is properly protected 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 can freeze and also begins to draw heat out of the concrete. Placement should stop if the localized foundation cannot be kept above freezing, if placed RCC cannot be kept from freezing, and if placement temperatures cannot be maintained within the specified range. Measures must be in place, such as heating the aggregates and mix water, using insulating blankets or tenting, heating areas of previously placed RCC, and using conventional concrete at the foundation contacts to obtain earlier concrete strength at locations vulnerable to freezing.

## 5.11 Methods to Control Placement Temperatures

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 replaces cement with a large percentage of pozzolan (up to 70 percent) to reduce the initial heat rise. Because Type IV cement is rarely available, it is important to specify Type II cement with the moderate heat of hydration option. RCC has very little mix water, which will limit the benefit of using ice to reduce its placing temperature.

Other common methods to minimize the heat rise of the concrete mix is to reduce placement temperature of RCC by scheduling the placement of the RCC during cooler times of year and precooling the concrete constituents. In some climates, it may be effective to place RCC exclusively or partially at night. 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.

When necessary, it is common to spray water on the aggregate stockpiles during the day for evaporative cooling, and using chilled mix water is commonly employed when needed. The use of more aggressive measures, or combinations of measures (such as aggregate and sand cooling using chilled water or air, flake ice, or liquid nitrogen), may sometimes be necessary. Some measures require special modifications to the batch plant and include significant additional capital or operating expense. Other methods to control the placement temperature in RCC include the following:

- Stockpiling aggregate in shaded locations
- Precooling aggregate by using ice or liquid nitrogen
- Covering the conveyor belts to reduce solar heating and drying
- Water cooling aggregate on a wet belt
- Insulating silos

Cooling coils systems, commonly used in cooling of conventional mass concrete dams, have been implemented only on a few RCC dams. Technical difficulties of cooling tubing installation in compacted RCC layers, delay of the construction, and the additional cost of cooling tubing are the primary issues making the cooling coil system less attractive for RCC dam construction.

## 5.12 Testing and Quality Control

### 5.12.1 Compressive Strength

Compressive strength is determined by testing concrete cylinders before and during the concrete placement stages, as well as 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. Considering the continuous and sometimes fast rates of placement, compressive strength testing is problematic as an acceptance test for RCC. RCC acceptance is frequently based on wet mix testing, visual observation during placement, and achieving specified in-place moisture and density requirements. Consequently, the burden is great on real-time inspection, observation, testing, and communicating.

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 involves the use of the Vebe apparatus (ASTM C 1170-14) (ASTM, 2015). This method has been successful for almost all types of RCC mixes and has been used to consolidate both 6-inch-diameter and 9-inch-diameter by 18-inch-high specimens with 3-inch maximum size aggregate (NMSA). Specimens should be consolidated to their maximum density, provided that 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 (ASTM, 2015).

Compressive strength tests should be performed on test specimens that are representative of the mix. If a larger NMSA is used (greater than 2 inches), 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 (with a specimen diameter equal to three times the NMSA) 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. If timing permits, coring can be used to correlate cylinder testing to in-place mass concrete strengths.

### 5.12.2 Elastic and Mechanical Properties

Elastic property testing (modulus of elasticity and Poisson's ratio) can be performed on specimens in compression by following the procedure in ASTM C 469 (ASTM, 2015) or with surface-bonded strain gauges. Test specimens can be obtained by casting concrete cylinders and performing testing before and during the concrete placement stages, as well as 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. A portion of the 150-foot-high, Stagecoach Dam construction included 60 lifts placed in a 10-day period. When performing creep testing, it is important to test specimens that represent the actual aggregates that will be used in the RCC mix during construction.

### 5.12.3 Density

There are two reasons to verify density: (1) to confirm the design assumptions for unit weight of the structure used in stability calculations, and (2) to indirectly assess the compaction of the lift and compaction at the joint interface. Failure to properly compact the lower portion of the lift results in a low or no-bond situation for sliding stability, and it 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 be more likely to develop 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 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 because oven drying for moisture determination often provides erratic results. Wet density testing also provides an additional real-time means of identifying potential mix proportioning problems that are not evident in the batch tickets or continuous batch records.

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 gauge 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. Coring and sawing test section placements help to identify the effectiveness of testing and compaction effort for a given mix.

A nuclear density gauge is helpful in evaluating real-time mix and moisture consistency, but it 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.

### 5.12.4 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 usually take place on RCC until the concrete obtains a compressive strength of about 1,000 lb/in$^2$. Because the concrete continues to gain strength, bond on lift joints also continues to improve. A quality assurance program over 1 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.

### 5.12.5 Thermal Properties

In most RCC dams and mass concrete dams, it is generally necessary to investigate thermal properties of the mix. The adiabatic temperature rise test simulates the expected heat rise potential of the RCC mix. The adiabatic temperature rise depends on the cementitious content of the mix. Because pozzolan generally generates approximately half of 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 that the initial temperature is representative of the placing temperature during construction. Appendix C gives examples of temperature rise curves for different mixes Reclamation tested.

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

Thermal properties of concrete are heavily influenced by the thermal properties of the aggregate as they compromise the bulk of the concrete volume. Concrete made with aggregates that have higher coefficients of linear thermal expansion have lower thermal volume stability. If thermal movements are of concern, use of aggregates with lower thermal expansion coefficients (certain granites, limestones, and dolomites) should be considered. However, in areas where freeze-thaw durability is required, differences greater than about $9 \times 10^{-6}$ per 1 degree Fahrenheit (°F) between thermal expansion coefficients of the coarse aggregate and mortar in which they are embedded could result in thermal cracking, which then allows water to penetrate the concrete and begin or accelerate freeze-thaw deterioration (Alexander and Mindess, 2005).

### 5.12.6 Durability

The important factors in obtaining and improving durability in the concrete are concrete strength, consolidation, and air entrainment. RCC is not considered as durable as conventional concrete 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 protecting the concrete include using 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 help indicate 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.

### 5.12.7 Workability

Material workability is measured with a Vebe test. Vebe times of 15 to 20 seconds indicate 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.

### 5.12.8 Consistency

The primary means of evaluating batch-to-batch consistency of RCC is with the Vebe test. This test indicates the batch-to-batch consistency of mixes and the working range at which 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 with six to eight passes of a vibratory roller.

### 5.12.9 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 exercising care during the depositing, transporting, and placing of RCC. Also, the use of maximum size aggregates within the range of 1 to 2 inches can reduce the potential for segregation. Rounded aggregates and aggregates larger than a 2-inch maximum size can increase the potential for segregation.

Use of 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, helps reduce segregation. Small amounts of segregation that occur during a placement should be corrected by having laborers remove and dispose of loose aggregates or shovel the aggregates to the top of the lift placement prior to compaction.

### 5.12.10 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 the test section 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 also allows the contractor an opportunity to verify that he can handle the RCC without segregation, allows for 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. A secondary purpose of test sections is to provide opportunity for owner representatives and contractor staff to become familiar with the RCC operation, timing, and practical application of specification requirements.

The test section should closely simulate actual RCC placement operations, including mixing, transporting, placing, and compacting procedures. Test sections are generally 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 that is expected during construction. The test section should be made accessible for coring, saw-cutting, or other types of testing for at least 28 days after RCC placements. The core samples are visually evaluated to determine if segregation has occurred, if compaction appears to be adequate, and if bond has been achieved between lifts. This visual evaluation can be used to indicate 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 them occur during the first few lift placements in the dam, which are considered to be the most critical to the dam's structural stability.

### 5.12.11 Placement Temperatures

The RCC placement temperature is extremely important for massive structures. If the placement temperature is too high in massive structures, the heat generated during cement hydration could lead to thermal cracking as the structure cools, which may cause more cracking than was anticipated during design. It is recommended that a maximum placement temperature of RCC be specified, which will depend on the anticipated temperature rise of the RCC, average ambient temperatures at the site, and the contraction joint spacing. Sometimes, unanticipated delays in construction can lead to RCC placements during 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 be checked periodically to ensure that it meets the specifications. Temperatures are generally recorded at both the batch plant and the placement locations.

## 5.13 Reference

ACI, 2010. *Manual of Concrete Practice.* American Concrete Institute.

Alexander, M., and S. Mindess, 2005. *Aggregates in Concrete.* Taylor & Francis.

ASTM International, 2015. *Annual Book of ASTM Standards.* West Conshohocken, Pennsylvania.

# 6. DESIGN OF NEW RCC DAMS

## 6.1 General Design Considerations

In this section, a procedure for the design of new gravity RCC dams is described. The design philosophy implemented here is based on the "concrete design approach" (see Section 2.2, "Concrete Mix Design Philosophy") for high-paste RCC mixes (with a cementitious material content above 300 lb/yd$^3$, depending on the mix design and gradation).

In general, the new RCC gravity dam needs to be designed as an impervious structure and constructed to meet the design criteria requirements for safety, strength, stability, and durability.

### 6.1.1 Strength and Stability

A gravity dam is considered stable when the induced stresses are within distinct limits and the weight is sufficient to prevent overturning and resist shearing and sliding on a horizontal plane for all defined load conditions. The required strength of concrete should also be satisfied for early construction loads at the specific age and for the specified operational loading conditions.

The design considerations for a concrete dam composed of RCC are similar to the criteria for a conventional concrete dam. Because 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. More information is included in Section 6.10 "Design Features and Considerations."

### 6.1.2 Durability

Durability of RCC is its ability to resist the effects of freezing and thawing cycles, erosion, ASR, sulfate attack, or other processes of deterioration. Durable RCC structure should retain its original form, quality, and function when exposed to its environment.

### 6.1.3 Watertightness

Watertightness of RCC dams can be enhanced by several lines of defense against seepage that include upstream concrete facing or facing membranes, and internal drainage. High-quality RCC mixes with good compaction, good quality control during construction and well-bonded lift joints can contribute significantly to the watertightness of an RCC dam and in some instances additional impervious barrier features may not be needed other than the leakage control measures incorporated into the contraction joint design. More information is included in Section 6.10 “Design Features and Considerations.”

### 6.1.4 Safety of Dams

Reclamation established a Dam Safety Program to ensure that the dams in Reclamation inventory do not present unreasonable risk to people, property, and the environment. Reclamation has developed risk-informed analysis methods to estimate the likelihood that various potential outcomes may result from the possible loads placed on a dam, and to identify the most effective way to provide public protection over the full range of loading conditions. This includes evaluating the environmental, social, cultural, ethical, political, and legal considerations of all parts of the decision process. A short description of Reclamation’s risk informed design approach is included in Section 6.13, “Risk Informed Design Approach” (Reclamation 2011).

## 6.2 Site Selection

The initial site selection for a new RCC dam focuses on adequacy of the foundation, adequacy of the water supply, and adequacy of the reservoir for water retention. The best site is then selected based on the feasibility of the design and economics. Foundation issues are discussed in more detail in Section 6.3, “Foundation Considerations.” Other factors related to selection of the project site may 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 project operation, and the cost/benefit ratio for the project. Selection of the project site for an RCC dam may also be influenced by construction cost considerations including the type of RCC delivery system, the haul distances for coarse aggregate and sand sources, the cost of the development of access roads needed for construction equipment, the steepness of the abutments, and the location of the batch plant. The cost of supplying the cement and pozzolan may be a factor at some sites. Other site-specific issues should be identified and evaluated during the planning process to ensure that the best dam site is selected.

## 6.3 Foundation Considerations

### 6.3.1 General

Foundation considerations for RCC dams are similar to those for conventional concrete gravity dams. The design engineer needs to consider several factors for the adequacy and preparation of the foundation including the path of the loads from the dam, stress distribution on the foundation, the adequacy of the rock foundation when subjected to the loads from the dam, and the amount of excavation and surface treatment needed to obtain an adequate foundation.

Foundation stability also needs to be evaluated to determine if the joints in the rock mass 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.

### 6.3.2 Foundation Considerations and Investigations

Investigations to determine the top of rock profile; depth of weathering; characteristics of rock, such as jointing, spacing of joints, and rock quality designation; and material property data, such as modulus of elasticity, generally need to be obtained to determine the adequacy of the foundation. Foundation investigations need to be performed early in the design process but no later than in the feasibility stage of the project. The cost of excavation and foundation treatment required at some dam sites, for example, may result in a change of the dam site location or the dam type.

Acceptable rock foundations are subject to the site-specific geologic conditions, the type of concrete dam, and the imposed loads, but they generally consist of slightly to moderately weathered and slightly fractured rock. The best foundations have fairly uniform slopes without sharp geometric changes. Stress concentrations can occur at changes in geometry of the foundation and can induce unwanted cracking in the concrete. Shaping of the rock foundation may be required. Thrust blocks and dental concrete can be used to replace weak foundation rock or improve deficiencies in the foundation, as well as to reduce the potential for stress concentrations. These design features improve the foundation geometry by filling depressions in the foundation, spreading out the dam loads, reducing the potential for stress concentrations, spanning faults and fissures in the foundation, or providing an abutment where one does not exist.

Foundation weathering will affect the strength of the rock and will generally determine the depth of the excavation. Generally, all weathered and more deformable rock is removed to obtain a foundation that provides a uniform deformation pattern. Differential deformations could cause undesirable cracking in 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 consolidation grouting of the top 30 feet of the foundation 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 is usually considered to reduce loss of reservoir water.

Cohesion or bond on the rock/concrete contact surface is generally necessary to maintain sliding resistance on the foundation contact surface. Therefore, a clean foundation surface is required. This is usually accomplished using strict specifications requirements and the use of high-pressure, water jet equipment.

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 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 they are 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.

### 6.3.3 Foundation Shaping

Abrupt irregularities in the profile of the dam foundation can cause local stress concentrations that can potentially initiate cracks in concrete. Localized excavation and shaping or dental concrete placements may be needed 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 RCC difficult. Leveling conventional concrete should be considered on the foundation/RCC contact surface when the irregularity and roughness of the rock surface make it difficult to properly compact RCC. The need for proper bonding of the concrete to the rock foundation may also require leveling concrete. If leveling concrete is not used at the foundation/RCC contact, special attention must be given to ensure that segregation of the aggregates and rock pockets, or poor consolidation, do not result in voids that can allow seepage at a critical foundation contact zone.

### 6.3.4 Foundation Grouting

A complete discussion of foundation grouting is outside the scope of this document. Any grouting plan requires a team consisting of dam design and construction engineers, engineering geologists, and experienced grouting specialists. The current design practice for foundation grouting of concrete dams includes both curtain and consolidation grouting. Reclamation specifies rotary-type drilling with diamond drill bits and water as the circulating media for drilling grout holes.

Consolidation grouting is also called “B-hole” grouting and is low-pressure grouting to fill near-surface (20- to 50-foot-deep) voids, fracture s, and cracks. “B-holes” are drilled from the excavated surface and can be staggered on alternate lines to provide better coverage of the area. Consolidation grouting is generally performed to depths of about 30 feet and over the upstream one-third of the foundation. With less favorable geologic conditions, these holes may be deepened and the full foundation area grouted. The spacing of holes is normally at 20-foot centers for consolidation grouting. The minimum diameter of the grout holes is 1-1/2 inches.

Foundation curtain grouting is performed to improve the impermeability of the rock foundation. Generally, curtain grouting is performed to a depth equal to one-third of the hydraulic height of the dam (H) plus 50 feet. The designers and geologist should determine the depth of the grout curtain and the orientation of the grout holes based on the site-specific foundation conditions. Vertical or high angle joint sets may be missed, depending on the orientation of the grout holes. Curtain grouting in the foundation is also designated as “A-hole” grouting, or “C-hole” grouting. “C-hole” grouting is performed relatively deep along the upstream face of the dam, upstream from the A-hole grout curtain, and provides a supplemental barrier to the “A-hole” grout curtain. The grouting for the “A-hole” grout curtain is performed from a foundation gallery located in the upstream portion of the dam footprint. Holes for curtain grouting are usually spaced 10 feet on centers.

To facilitate drilling, metal pipes are embedded in the floor of the gallery or foundation tunnel, or in the upstream fillet. Pipe embedment of 5 feet into rock is typically used for appraisal and feasibility studies. For final design, the determination of the embedment depth of the pipe into rock should take into consideration the pressure to be used during grouting, the foundation geology, and quality of the rock. When the structure has reached an elevation sufficient to prevent movement of concrete, the grout holes are drilled through these pipes and into the foundation. During high-pressure grouting, grout travel can be a significant distance from the injection point of the grout. Drain holes should not be drilled until the foundation grouting is completed.

## 6.4 Streamflow Diversion

Streamflow diversion concepts for RCC dams are generally similar to the concepts for conventional concrete dams. RCC dams provide an economic and public safety advantage over embankment dams when evaluating construction risks and diversion planning. Freshly placed and compacted RCC has proven to be very resistant to erosion during overtopping. With any type of dam, it is important to evaluate the risks during construction.

A major consideration in RCC construction is the placement operation and the economy of maintaining continuous placements from abutment to abutment. Therefore, the economy of diversion plans that split the construction site into two separate RCC placement areas should be evaluated with other options.

## 6.5 Dam Layout

### 6.5.1 General

The design process of a new RCC gravity dam starts with an initial layout that is followed by the stress and stability analysis. If the analysis results do not fall within the established design criteria requirements, modifications will be required to reshape the dam geometry. The proper design process of the RCC gravity dam is accomplished by preparing successive layouts based on the results of the stress and stability analyses.

### 6.5.2 Nonoverflow Sections

Gravity dams can either be straight or curved in plan across the canyon. The structure needs to be thick enough to be stable for sliding and overturning along the dam-to-foundation contact and along horizontal lift joints in the dam. Special consideration may be necessary to the layout and design of the dam if the dam is designed with a change in direction in plan. Abrupt changes in alignment may induce 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.

The downstream slope of a gravity dam is generally 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 ratios. Gravity dams located in high seismic zones may necessitate or benefit from a radius transition from the downstream slope to the vertical chimney section.

### 6.5.3 Spillway Section

When the spillway is located on the dam, stability requirements for the overflow section are the same as for the nonoverflow section of the dam. Sizing of the spillway and the hydraulic design of the spillway are not discussed here. It should be noted that stepped spillways are commonly used on RCC dams and provide a significant benefit associated with energy dissipation if the flow depth is relatively shallow.

### 6.5.4 Construction Considerations

The ability for equipment to maneuver on the dam crest during construction should always be considered when laying out the dam. The top of the dam should have sufficient width to accommodate construction equipment that will deliver, place, and compact the RCC. A minimum crest width of 20 feet should be considered to accommodate construction equipment. However, a 25-foot or wider crest would better accommodate large construction equipment, which could improve compaction and placement rates. Some sites may need an additional turnaround area on one or both abutments.

## 6.6 Material Properties

In the final design phase, actual properties of the rock foundation from the field exploration and laboratory testing program should be established. The properties of RCC need to be determined based on the trial mix design program specific for the project considering the type of the aggregate to be used in the mix. However, in appraisal and feasibility level designs, if the RCC mix design was not performed and limited information is available for the project site, the average properties of RCC material and the foundation rock can be assumed as listed in Section 6.6 below.

### 6.6.1 Concrete Properties

Thermal and mechanical properties of RCC are concrete age dependent. Properties for young RCC mixes significantly differ from these of a matured RCC mix. Variations in properties of the RCC mix should be considered in the design of the dam for the construction phase.

#### *6.6.1.1 Modulus of Elasticity and Poisson's Ratio*

The modulus of elasticity and the Poisson's ratio are the primary mechanical properties of concrete. Both properties vary with the age of RCC mix. The actual modulus of elasticity in mass concrete can significantly differ from the results determined in laboratory. Table 6-1 provides average values for preliminary level designs.

**Table 6-1. Typical Average Mechanical Properties of RCC for Preliminary Analysis**

| Concrete properties | Typical value | Note |
|---|---|---|
| Density (unit weight), $\gamma_C$ | 145 to 150 lb/ft$^3$ | Depends on aggregate type |
| Compressive strength, $f_c'$<br>[8-day]<br>[28-day]<br>[56-day]<br>[90-day]<br>[1 –year] | <br>1,500 lb/in$^2$<br>2,000 lb/in$^2$<br>2,700 lb/in$^2$<br>3,000 lb/in$^2$<br>4,000 lb/in$^2$ | Design strength at 1 year |
| Tensile strength, $f_t'$<br>[8-day]<br>[28-day]<br>[56-day]<br>[90-day] | <br>75 lb/in$^2$<br>100 lb/in$^2$<br>135 lb/in$^2$<br>150 lb/in$^2$ | |
| Poisson's ratio, $\nu$<br>[8-day]<br>[28-day]<br>[56-day] | <br>0.15<br>0.16<br>0.20 | |
| Modulus of elasticity, Es<br>[8-day]<br>[28-day]<br>[56-day]<br>[90-day] | <br>2,500,000 lb/in$^2$<br>3,400,000 lb/in$^2$<br>4,100,000 lb/in$^2$<br>4,300,000 lb/in$^2$ | |
| Dynamic modulus of elasticity | 1.5 x Es | |
| Apparent cohesion | 50 lb/in$^2$ | Over entire surface area |
| Friction angle | 40 degrees | |
| Hysteretic damping of the dam | 0.10 (= 5% viscous) | |
| Reservoir bottom reflection coefficient | 0.8 | |

#### *6.6.1.2 Dynamic Properties*

Concrete, when subjected to dynamic loadings, may exhibit characteristics unlike those occurring during static loadings. Until sufficient test data are available, static strengths and the instantaneous modulus of elasticity should be used.

#### *6.6.1.3 Other Mechanical Properties*

In addition to the strength, elastic modulus, and thermal properties, several other properties of concrete should be evaluated during the laboratory testing program. These properties, which must be determined for computations of deformations and stresses in the concrete structures, are Poisson's ratio, unit weight, and any autogenous growth or drying shrinkage.

#### *6.6.1.4 Thermal Properties of Typical RCC Concrete Mix*

The primary thermal properties of RCC mixes are the specific heat, thermal diffusivity, thermal conductivity, and the coefficient of thermal expansion. A description of these thermal properties is provided below.

**Specific heat** *(c)* is the amount of heat required to raise the temperature of a unit mass of material by 1 degree. Values of 0.20 to 0.25 British thermal units per pound per degree Fahrenheit are representative for a wide range of aggregate materials and temperature conditions.

**Thermal diffusivity** *(D)* is the rate at which a material experiences temperature change. In this report, it pertains to the rate at which temperature changes take place in the concrete. Values of 0.034 to 0.058 square feet per hour are representative for a wide range of aggregate materials.

**Thermal conductivity** *(k)* is the rate at which heat is transmitted through a material of unit volume subjected to a temperature difference between two faces. Thermal conductivity ($k$) is calculated from specific heat ($c$), diffusivity ($D$), and the concrete density ($\rho$) with the following equation:

$$k = c \cdot \rho \cdot D$$

**Linear coefficient of expansion** describes the relation between the material volume change and temperature. The coefficient ranges between $5 \times 10^{-6}$ and $7 \times 10^{-6}$ inch per inch per degree Fahrenheit for concrete.

#### *6.6.1.5 Concrete Properties for Preliminary Analysis*

Until laboratory test data are available, the necessary values for preliminary studies may be estimated from table 6-1. Until long-term load tests are made to determine the effects of creep, the sustained modulus of elasticity should be taken as 60 to 70 percent of the laboratory value of the instantaneous modulus of elasticity. If no tests or published data are available, the concrete properties are average typical values appropriate for the appraisal and feasibility level design of the RCC dams as listed in tables 6-1 and 6-2 above.

### 6.6.2 Typical Rock Foundation Properties

Table 6-2 shows typical rock foundation properties that are appropriate for the appraisal and feasibility level design when no tests or published data are available.

**Table 6-2. Summary of Typical Average Foundation Rock Properties**

| Foundation rock properties | Typical value | Note |
|---|---|---|
| Static modulus of elasticity | | Determined using typical values for rock type and rock mass rating |
| Dynamic modulus of elasticity | | $E_{F\,Dyn}$ should not be less than $0.8E_{D\,Dyn}$ |
| Poisson's ratio, $\nu$ | 0.33 | |
| Hysteretic damping of the foundation | 0.10 (= 5% viscous) | |

## 6.7 Loads

In the design of gravity RCC dams, the primary loads that need to be considered are the dead load, external water pressure, temperatures, internal water pressure (pore pressure and uplift at the dam/foundation interface), ice load, silt pressure, and seismically induced loads. The schematic in figure 6-1 shows loads acting on RCC gravity dams. A more detailed discussion of loads is provided in *Design of Gravity Dams* (Reclamation, 1976).

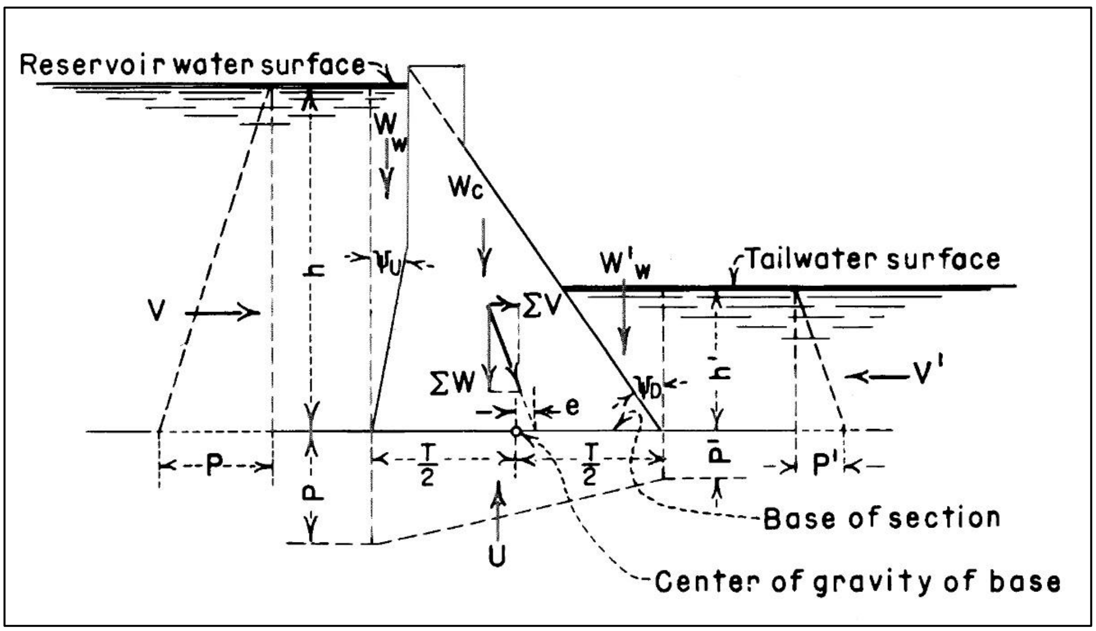



**Figure 6-1. Schematic of loads acting on RCC gravity dams.**

### 6.7.1 Dead Load

The total dead load is the weight of the RCC dam combined with the weight of piers, bridges, gates, and other appurtenant structures installed at the dam. For the preliminary analyses, where actual properties of RCC mix are not available, a conservatively lower RCC mix density of 145 $lb/ft^3$ can be assumed.

### 6.7.2 External Water Pressure

Loads from the reservoir and the tailwater are determined based on the hydrologic investigations and the reservoir operating studies. In the *Design of Gravity Dams* (Reclamation, 1976), a normal design reservoir elevation (defined as the reservoir water elevation allocated for joint uses for flood control and conservation purposes) and the reservoir elevation for flood condition (overtopping) are used with the tailwater at the minimum level. For the defined reservoir surface levels, the hydrostatic load on the dam can be determined for the water-specific weight of 62.4 $lb/ft^3$.

### 6.7.3 Internal Hydrostatic Pressure

Internal hydrostatic pressure from reservoir water and tailwater occurs within the dam and foundation as internal pressures in pores, cracks, and joints. The distribution of pressure through a horizontal section of the dam is assumed to vary linearly from full hydrostatic head at the upstream face to the tailwater pressure at the downstream face when the drains are not provided. The internal pressure distribution would be adjusted when the drains are constructed, based mainly on the drain efficiency.

### 6.7.4 Silt Load

If the information on silt accumulation is not available for the project, horizontal and vertical load can be assumed in the design of a new RCC dam corresponding to an equivalent fluid pressure of 85 $lb/ft^3$ and 120 $lb/ft^3$, respectively. These values include the effects of the water within the silt. Traditionally, a 100-year sedimentation level is used to establish the silt load on the dam. However, consideration will need to be given to the service life of any future dams and whether a higher silt load would be critical to the stability of the structure (see figure 6-2). The reservoir sedimentation level is also used to set the intakes for the outlet works structures and, in some structures, multiple intake levels have been used in anticipation of high reservoir sediment levels.

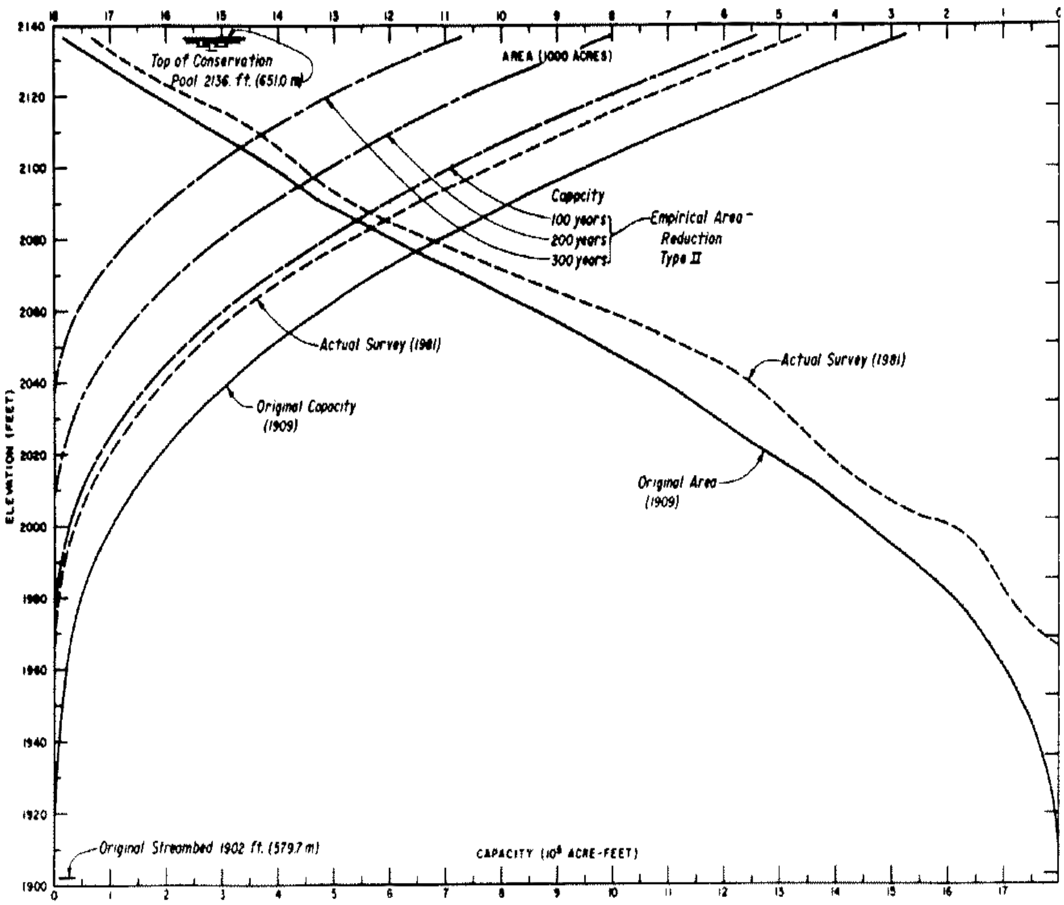



**Figure 6-2. Example of reservoir storage capacity and reservoir area (sedimentation) estimates for 100, 200, and 300 years, and actual reservoir survey results 72 years after construction.**

## 6.7.5 Ice Load

Thermal expansion of the ice can produce significant loads on dams located in cold climates areas. The load depends on the temperature rise of the ice, thickness of the ice sheet, its strength, and the thermal expansion coefficient. Not all dams will be subjected to ice loads. The designer will need to determine whether it is appropriate to design the dam for ice loading conditions. The anticipated ice load may be determined from Reclamation (1948); or, if the project specific data is not available, a uniform pressure of 10,000 pounds per foot, for an assumed thickness of 2 feet, could be applied to the dam at the reservoir level.

## 6.7.6 Temperature Loads

Temperature loads are those loads applied on a concrete dam when the concrete undergoes a temperature change, which results in volumetric change. Volumetric changes of concrete are directly related to temperature variation of the dam structure. The two primary sources of the temperature variations are the cement hydration related heat generated/dissipated in the structure and the cyclic ambient temperature.

When the deformation of any part of the dam is restrained by the foundation and the abutments, a drop in temperature will cause tensile stresses. Thermal stress analyses are performed to determine the contraction joint spacing, size of joint openings, and RCC placement temperatures. Temperature studies also assist in estimating internal concrete temperatures due to the heat of hydration. The heat rise due to the heat of hydration in mass concrete is roughly estimated to be 15 °F for each sack of cement in the RCC 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 size of the RCC dam, ambient temperature conditions, and concrete placement temperature are the most significant factors influencing temperature distribution in the dam.

### 6.7.7 Drying and Autogeneous Shrinkage

Drying shrinkage and autogeneous shrinkage are other factors associated with volume change and potential initiation of cracks in concrete dams. Drying shrinkage is limited to the exposed face of the dam. The level of autogeneous shrinkage in RCC dams is significantly lower when compared with the concrete volume change caused by temperature. It is assumed that the effect of autogeneous shrinkage is insignificant in the design practice.

### 6.7.8 Seismic Loads

The earthquake loads on RCC gravity dams are induced in similar ways as they are for conventional concrete dams. For small gravity dams constructed on a rock foundation, a pseudo-static analysis is an appropriate approach for determining seismic loads acting on the dam. For medium and large dams, an advanced dynamic analysis is required to determine the seismically induced internal forces in the dam structure. The manual, *State-of-Practice for the Nonlinear Analysis of Concrete Dams* (Reclamation, 2014) provides guidelines for the advanced analysis of concrete dams.

#### *6.7.8.1 Pseudo-Static Method*

Stresses in gravity dam structures are generated during earthquakes due to the inertia of their own mass and the hydrodynamic loads of the reservoir water acting on the dam. For small-sized RCC gravity dams, the fundamental period of free vibrations is significantly smaller than the period of vibrations for dominating earthquake horizontal accelerations. When the ratio of the dam fundamental period to the forced period of the earthquake is small, it can be assumed that the dam is "rigid," and the entire dam has the same acceleration as the base (no amplification of ground accelerations is expected). For such an assumption, the hydrodynamic pressure on a vertical face of the dam could be determined from Westergaard's approximate equation (Westergaard, 1931):

$$p = 0.875\,\alpha (h\,y)^{0.5}\,w$$

The total horizontal load, $P_h$, and the moment, $M_h$, per unit length of the dam can be calculated using the following equations:

$$P_h = W\alpha \ + 0.583\,w\,H^2\,\alpha/g \qquad M_h = h_c\,W\alpha \ + 0.233\,w\,H^3\,\alpha/g$$

where:

$W$ = weight of the concrete dam
$w$ = unit weight of water
$H$ = depth of the reservoir
$\alpha$ = horizontal acceleration at the base of the dam
$g$ = acceleration due to gravity
$h_c$ = height to the center of gravity of the dam, measured from the base
y = vertical distance from the reservoir water surface to the elevation in question

For the hydrodynamic pressure on a sloping upstream face of the dam, Zanger approach applies (Reclamation, 1952).

#### *6.7.8.2 Time Domain Analysis*

For large dams, or when more accurate seismic loads are required during the final design of a RCC dam, an advanced analysis should be performed using the Finite Element (FE) method. General guidelines for the FE analysis of concrete dams are provided in the manual, *State-of-Practice for the Nonlinear Analysis of Concrete Dams at the Bureau of Reclamation* (Reclamation, 2014).

## 6.8 Dam Design Methodology

### 6.8.1 General

Three levels of investigations are considered in the design process of a new RCC dam: appraisal design, feasibility design, and final design.

#### *6.8.1.1 Appraisal Level Design*

The appraisal level investigation includes an initial selection of the project site, preliminary evaluation of the foundation, selection of the dam types, preliminary layout, preliminary estimation of the concrete volume, and appraisal level cost estimations. The scope of appraisal investigations is defined in chapter 2 of Reclamation's *Manual for Design Data Collection for Appraisal Investigations* (Reclamation, 2007a).

#### *6.8.1.2 Feasibility Level Design*

In the feasibility design phase, the location of the dam is finalized, and geologic mapping is usually updated with additional data from the drilling program and from laboratory testing of the foundation rock. An initial layout of the dam is usually followed by a structural analysis, using classical analysis approaches. The layout of the dam allows estimation of the construction cost and evaluation of the risk associated with safety of the dam. Guidelines for the feasibility design data collections are provided in chapter 3 of Reclamation's *Manual for Design Data Collection for Feasibility Designs* (Reclamation, 2007b).

#### *6.8.1.3 Final Design (Specification Designs)*

In the final design phase, detailed foundation investigations are required. The design of the dam structure and the RCC mix are finalized, followed by the risk evaluation of dam safety. Stability of the dam and analyses for thermal and seismic loads using advanced techniques are implemented. Guidelines for the final design data collections are provided in chapter 4 of Reclamation's *Manual for Design Data Collection for Specification Designs* (Reclamation, 2007c).

### 6.8.2 Design of RCC Gravity Dams by Classical Analysis Methods

There is no one universal approach used by the entire engineering industry for the design of RCC gravity dams. Rather, many agencies, including Reclamation, follow their own design criteria based on their own design and construction experience. In this section, the background of the analysis methods used in the design process of RCC gravity dams is discussed.

#### *6.8.2.1 General*

The stress and stability analysis method used for RCC gravity dams is similar to the classical analysis methodology developed for the design of conventional concrete gravity dams. Gravity Method of Stress and Stability (GMSS) is a classical approach implemented by Reclamation for the analysis of gravity dams. In the GMSS method, the gravity dam is considered as a series of independent, vertical, cantilevered blocks fixed at the base. The main advantage of the GMSS approach is its simplicity, straightforwardness, and the ease with which the design engineer can interpret the results. The approach was successfully used in the design of several gravity dams over many years. GMSS is a proven conservative design method for normal load conditions. Very few gravity dams have failed due to instability; however, seismic and thermal loads require special attention when the design is based on a GMSS approach.

In general, GMSS computations are based on a Bernoulli-Euler theory for the shallow beams and the elastic theory of materials. The Gravity Method of Stress and Stability Analysis is well documented in the design manuals for concrete gravity dams (Reclamation, 1976; 1987).

#### *6.8.2.2 Load Combinations*

In the GMSS approach, the loading combinations are defined below:

- **Usual loading combination** – This loading combination consists of the reservoir and tailwater at normal design elevations with corresponding uplift pressure, silt load, dead load of the dam structure, usual temperature conditions, and the specified drain efficiency.

- **Unusual loading combination** – This loading combination consists of the following load conditions listed below in combination with applicable normal design loads:

  - The reservoir and tailwater level is defined for flood conditions at the maximum reservoir elevation.

  - Ice load.

- **Extreme loading combination** – This loading combination consists of the following load conditions listed below in combination with applicable normal design loads, which may include uplift pressure, silt load, dead load of the dam structure, usual temperature conditions:

  - Drains inoperative with zero drains efficiency.

  - Seismic load is associated with the earthquake event.

#### *6.8.2.3 Requirements for Stability*

A gravity dam is designed so that the entire structure and each of the dam monoliths maintain stability against all the imposed loads. Safety in the design, using the Gravity Method of Stress and Stability Analysis, is defined by a global safety factor. The acceptance criteria for stability of RCC gravity dams are similar to those defined for conventional concrete dams in Reclamation's Engineering Monograph No. 19, *Design Criteria for Concrete Arch and Gravity Dams* (Reclamation, 1977):

- **Overturning stability:** Overturning is not allowed for any horizontal plane within and at the base of the dam structure.

- **Shear stress and sliding stability:** Sliding is not allowed for any horizontal plane within and at the base of the structure. The allowable unit stress in the structure and at the foundation must not be exceeded.

#### *6.8.2.4 Shear Stress and Sliding Stability Analysis*

For the sliding stability of RCC dams, the shear strength and tensile strength of the in-place RCC along the lift lines and foundation are the primary design considerations. The sliding factor of safety for shear friction is the measure of safety against sliding or shearing. The sliding factor of safety, *Q*, is the ratio of resisting to driving forces as computed by:

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

where:

*C* = unit cohesion
*A* = area of uncracked portion of section considered
$\Sigma N$ = summation of normal forces
$\Sigma U$ = summation of uplift forces
tan$\boldsymbol{\Phi}$ = coefficient of internal friction
$\Sigma V$ = summation of driving or shear forces

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.

Design requirements for compressive, tensile, and shear strengths can be verified by sampling, using core drilling and laboratory testing, a set time period after construction Concrete cores of the RCC 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 sampled lift lines 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. In addition, not all conditions will produce a 95-percent bond, even if bond on lifts is a design requirement.

Uplift is an important factor in the stability of concrete dams. Stability analyses need to be performed at the dam/foundation contact, as well as at horizontal lift lines 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 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. More information on calculating uplift pressures in included in *Design of Gravity Dams* (Reclamation, 1976).

Sliding failure modes for RCC gravity dams are listed below and shown on figure 6-3:

- Mode 1A: sliding at a horizontal crack in the dam at lift lines
- Mode 1B: sliding at a curvilinear crack in the dam

- Mode 2A: sliding at a horizontal crack at the base of the dam
- Mode 2B: sliding at a curvilinear crack in the dam and/or foundation
- Mode 3: sliding on foundation contact or sliding plane

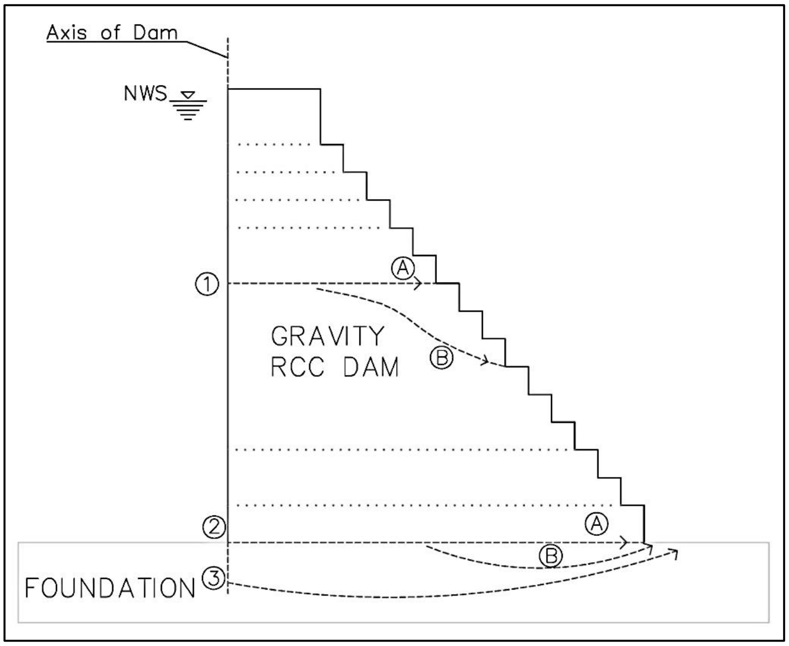



**Figure 6-3. Illustration of failure mechanisms for RCC gravity dams.**

Reclamation has adopted a risk informed methodology in the design of dams (refer to Section 6.13, "Risk Informed Design Approach"). However, the target criteria documented in *Design of Gravity Dams* (Reclamation, 1976) are still used. The recommended safety factors for the maximum allowable average shear stress on any plane in the dam 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 shall be 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 shall be 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 shall 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.

#### *6.8.2.5 Cracking*

The main concerns are the tensile strength of the parent concrete and shear strength properties of the lift lines. Tensile stress may need to be evaluated for each load combination by considering the location, magnitude, and direction of stress and the effects of potential cracking on the behavior of the structure.

Cracking is assumed to occur in a gravity dam if the vertical stress, computed without internal water pressure, at the upstream face of the dam is less than the minimum required stress computed. Cracking is not permitted in a new RCC dam for usual load combinations.

Because bond on lifts is an important aspect of the design of most RCC dams, any deviation from the approved construction materials or procedures can affect bond on lifts and 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. The influence of a single lift joint on sliding stability is greatest near the base of the dam. This emphasizes the need for good quality control from the beginning of construction. A test section is usually necessary to develop the proper batching and placement procedures before RCC is placed in the most critical portion of the dam (Reclamation, 1987a).

#### 6.8.2.6 Tensile Stresses and Compressive Strength

The acceptance criteria for tensile stresses in RCC gravity dams are similar to those defined in Reclamation's Engineering Monograph No. 19, *Design Criteria for Concrete Arch and Gravity Dams*, (Reclamation, 1977) for conventional concrete dams. The primary difference in design would pertain to the assumptions and safety factors used to account for the uncertainty related to the bond on lifts. Guidelines on acceptable stresses for Reclamation's gravity dams are defined as follows:

- Usual loading combinations:
  - No tensile stresses at the upstream face of the dam are permitted.
  - The maximum allowable compressive stress in the concrete should not be greater than the specified compressive strength divided by a safety factor of 3.0, but it should not exceed 1,500 lb/in$^2$.
- Unusual loading combinations:
  - Small tensile stresses are permitted.
  - The maximum allowable compressive stress in the concrete should not be greater than the specified compressive strength divided by a safety factor of 2.0, but it should not exceed 2,250 lb/in$^2$.
- Extreme loading combinations:
  - The maximum allowable compressive stress in the concrete should not be greater than the specified compressive strength with a safety factor of 1.0.

Typical compressive stresses induced in gravity dams are usually significantly smaller than the actual compressive strength of RCC. The primary considerations for RCC are the tensile strength of the parent concrete and shear strength properties of the lift lines. The RCC mix design is usually based on the specific need for bond and shear strength on lift joints, rather than the compressive strength.

#### *6.8.2.7 Foundation Stability*

The maximum allowable compressive stress in the foundation should not be greater than the specified compressive strength of the foundation rock divided by a safety factor of 4.0, 2.7, and 1.3 for the usual, unusual, and extreme loading combinations, respectively. 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).

### 6.8.3 Design of RCC Gravity Dams Using Advanced Analysis Methods

In a narrow canyon with steep abutments, the height of a gravity dam varies from the center of the dam towards the abutments, resulting in a three-dimensional (3D) stress distribution. The 3D stress distribution differs from the assumptions of the classical (gravity analysis) method in which the effect of interaction between cantilever blocks of various height and deformation of the rock foundation is neglected. Reclamation initially considered the 3D effect in gravity dams when the “twist effect” of cantilever blocks was incorporated in the Trial-Load Twist Method of Analysis (Reclamation, 1976). The new analysis model, implemented in the Trial-Load Twist Method, combined bending and twisting of the vertical cantilever dam blocks with grouted and ungrouted joints.

With rapid development of computer technology, numerical methods (in particular, the FE method) became a primary approach in the structural analysis of concrete dams. General formulation and the theory of the FE method is given is several publications, including Bathe (1982). The state-of-practice for the analysis of concrete dams, using the FE procedures, is described in (Reclamation, 2014). The FE method allows investigation of two-dimensional (2D) and 3D effects in the dam structure for elastic and nonlinear properties of the RCC concrete.

## 6.9 Thermal Analysis of RCC Gravity Dams

### 6.9.1 General

The primary focus of a thermal analysis performed for a new RCC dam generally centers on the temperature distributions in the body of the dam for various construction and post-construction conditions. The specific purposes of such an analysis are to determine thermal gradients in the dam structure, define the temperature for concrete placements, simulate the sequence of concrete placements, control temperature drop, determine required spacing between contraction joints, and evaluate possible intermediate cracking of the dam blocks. Reclamation has implemented two primary approaches for thermal analysis of concrete dams: (1) the simplify method, and (2) advanced analysis using FEs.

Cracking in RCC dams results from thermal strains that are induced as the concrete cools from the peak temperature rise. Thermal stresses in concrete dams are directly related to volume changes of concrete that are generated during the process of concrete hydration and by variations in the ambient temperature.

### 6.9.2 Simplified Approach

Engineering Monograph No. 34 (Reclamation, 1981) describes an approach to control the temperature of conventional mass concrete dams. The approach can be implemented in the analysis of RCC dams for feasibility level design. Reclamation's computer program, DAMTEMP, can be used to automate the computations. The program is based on the theories presented in Engineering Monograph No. 34, combining parameters such as concrete thickness, diffusivity, ambient air and reservoir temperatures, and solar radiation to reproduce effective mean internal temperature distribution in the dam.

### 6.9.3 Thermal Analysis Using FE Analysis

Three sets of data are required for FE 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 resulting from the hydration of concrete.

Figure 6-4 presents the thermal analysis results of a 100-foot-tall RCC dam. The results illustrate the construction phase with 2 feet of placement per day (shown on figure 6-5) and mix placement temperature at 70 °F (21.1 degrees Celsius [°C]). Construction was completed in the summer, and the reservoir remained empty each winter. For the presented example, the largest temperature gradient can be observed during the first winter.

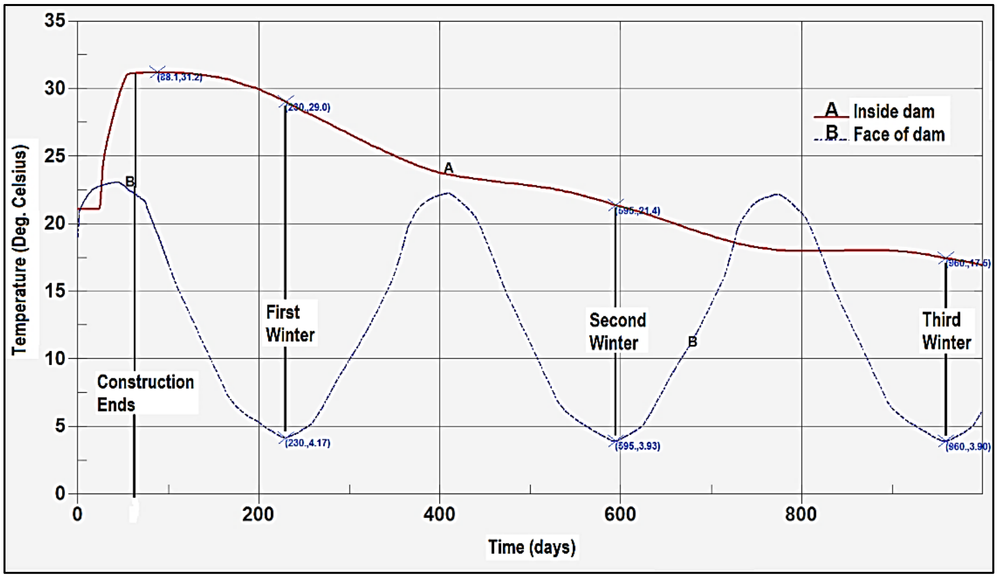



**Figure 6-4. An example of temperature variation inside the dam at mid-height (red line A) and at the downstream face of the first lift placement (blue line B) for the dam presented on figure 6-5.**

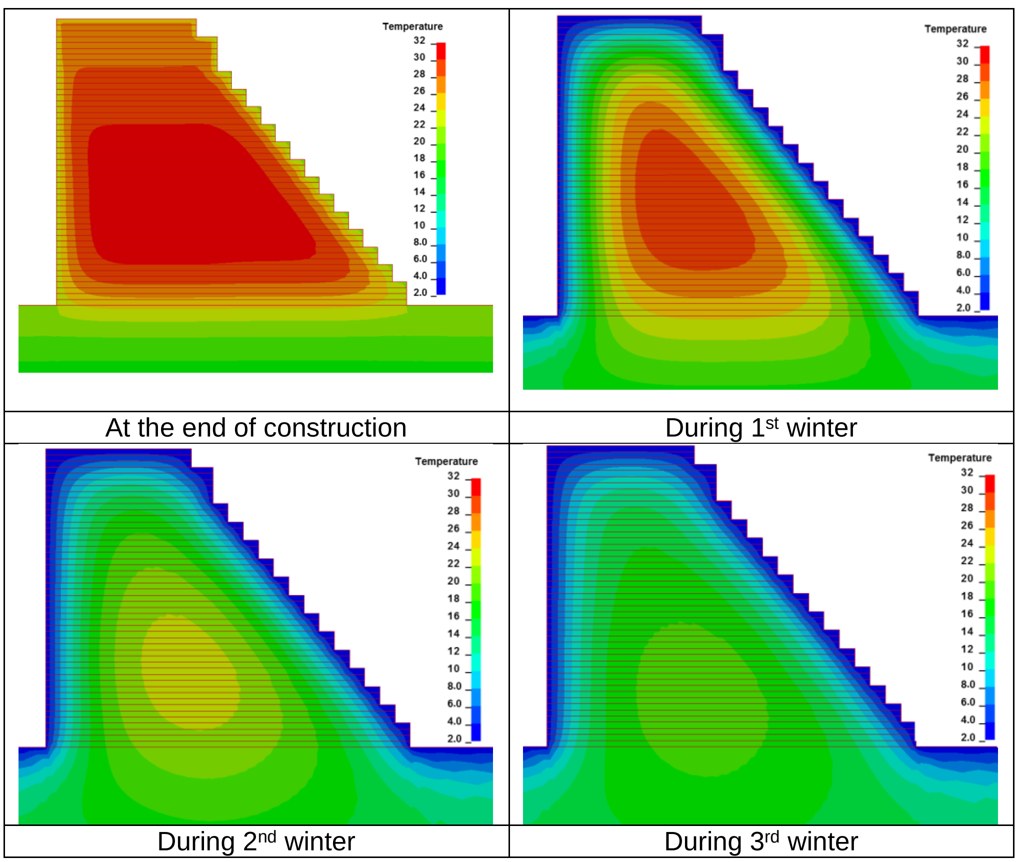



**Figure 6-5. Illustration of temperature (°C) distribution at the center of the 80-foot-wide block.**

### 6.9.4 Temperature Induced Stresses

Cracks in RCC dams develop as a result of tensile strains, which are induced as the concrete cools from the peak temperature. Thermal stresses in concrete dams are directly related to concrete volume changes that occur during concrete hydration and ambient temperature variations.

Lowering the placement temperature reduces the maximum temperature attained within the dam, thereby reducing the possible surface temperature gradients. Placement of concrete in the spring allows additional time for the dam's interior concrete to cool before the first winter occurs, and it reduces the possible surface temperature gradients. However, the peak temperature may be lower if concrete is placed in the fall because complete curing is attained before the onset of summer heat.

Surface cracking is most likely to occur during the first winter of operation because 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.

Temperature studies can identify the maximum and minimum placement temperatures, appropriate construction sequence, and optimum spacing of contraction joints to eliminate potential intermediate cracking in the dam. It is very important to control thermally induced horizontal cracking on the upstream face of a dam. This cracking potentially reduces the stability of the dam by permitting increases in uplift pressures and reducing the tensile capacity in a horizontal lift joint.

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 placed near the foundation surface with a height equal to or less than 20 percent of the block length established by contraction joints may require a lower placement temperature than RCC placed higher in the dam.

### 6.9.5 Creep and Relaxation in RCC

Creep and relaxation are rheological (time-dependent) processes observed in concrete. Creep can be defined as a deformation of the concrete structure under long-term loadings, whereas relaxation is described as a decrease in stress in response to restraints introduced in the structure. Rheological properties for a specific RCC mix should be determined during the final design phase of the dam.

# 6.10 Design Features and Considerations

## 6.10.1 Leakage and Crack Control Features

### *6.10.1.1 Contraction Joints*

The primary function of vertical contraction joints in RCC dams is to control cracking that occurs as a result of volumetric change associated with thermal expansion and contraction of the concrete. Spacing of contraction joints in RCC commonly ranges from approximately 30 to 120 feet and will vary from structure to structure based on the mix design, concrete strength, placement temperature and ambient temperature variations, size of the dam, and other factors. Temperature studies will be helpful in determining the contraction joint spacing. One of the main objectives of the thermal analysis is to determine the optimum spacing of the contraction joints for the maximum allowable placing temperature of the mix to avoid concrete cracking between joints. Frequency of random cracks and their sizes will vary based on the RCC mix design, concrete strength, concrete placement temperature, ambient temperature variations, volume of concrete in the dam, sequence of construction stages, and several other factors.

The current industry practice to control cracking in RCC dams is to include vertical contraction joints in the design. In general, two types of vertical contraction joints can be used in RCC dams:

- **Induced joints** are post-formed by vibrating crack inducer plates. The joints extend over the entire, or a part of, the dam width. The partial joints allow extension of the crack as the stresses in RCC change.

- **Groutable joints** are formed against formwork in a way similar to joints formed for conventional concrete dams and joints formed by crack inducers.

Contraction joints in dams should include seepage control features such as waterstops, membranes, and drainage. This design philosophy limits the opening of the cracks and the amount of the leakage through the cracks.

Methods to control leakage through vertical contraction joints or potentially unbonded lift lines 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, 1987a). Conventional leveling concrete on the foundation contact has been used for bond and watertightness. Conventional concrete or grout-enriched RCC (GERCC) have also been used at the abutment/RCC contact to obtain a well consolidated and water tight foundation contact surface.

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 using a crack inducer plate, which consists 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 (figure 6-6) 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 be 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 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.

**Figure 6-6. Galvanized steel sheet metal installation at Pueblo Dam to create a joint with a crack inducer.**

When the concrete in the dam begins to cool, the upper portion of the dam usually cools more quickly due to the reduced thickness. Cracks will generally initiate at the joint locations at the top of the dam. Another method to supplement the crack-induced contraction joints is to sawcut the RCC at the top of the dam after it has obtained sufficient hardness and strength. Placing conventional reinforced concrete with formed joints could be another option. Foundation deformations and stress concentrations, resulting from abrupt irregularities or discontinuities, can also initiate cracking in a dam.

#### *6.10.1.2 Drainage Systems*

An internal drainage system consisting of vertical drill holes or formed drains 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. Galleries are often considered a seepage control feature because they are generally used to control internal drainage within the dam and control foundation drainage to reduce uplift pressures.

#### *6.10.1.3 Design Considerations for Bond on Lift Joints*

The design and construction of the dam structure, and the concrete mix design are integral to ensure the RCC mix design will meet the design requirements. Table 6-3 includes a summary of RCC mix design data for Reclamation's RCC projects.

Bond on lift joints is a very important aspect of the design and construction of an RCC dam for both structural stability and seepage control. If bond on lifts with a specified tensile or shear strength is required, the paste content would need to be increased accordingly. The w/cm ratio and cementitious materials content of the mixture affect the ultimate shear and tensile strength capacity across lift joints, as well as the percentage of the joint surface area that is bonded. Mixtures with cementitious 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 properly prepared and adequate compaction is achieved.

The quality of bonding between RCC layers improves significantly if the placements are made while the previous placement is still considered a fresh joint. Specifications may require the number of placements per day or maximum time between lift placements to improve the potential for bond on lifts. Lift surface preparation and quality control is also important to improve the potential for bond on lift joints. Lift joint treatment during construction is discussed in detail in Section 5.7, "Lift Surface Preparation."

The RCC has to have sufficient paste to be workable. The paste reduces the potential for segregation and makes the RCC easy to compact. Reducing the potential for segregation during RCC placements will generally reduce the potential for leakage on lift joints.

The results of the drilling program at Upper Stillwater Dam indicated that 95 percent of the lift lines sampled were bonded. 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.

**Table 6-3. Summary of Reclamation Projects and the RCC Mix Design Data**

| Application | Year[1] | NMSA (inches) | Compressive strength ($lb/in^2$) | Density ($lb/ft^3$) | Water content (lb) | Cement plus pozzolan (lb) | Sand (lb) | Coarse aggregate (lb) | Air content (%) | Fines[9] (%) | Water-cement ratio[5] | RCC volume ($yd^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Concrete Approach** | | | | | | | | | | | | |
| Upper Stillwater Dam (new RCC gravity dam) | 1987 | 2 | 3,000 [2] | 147.0 | 166 | 135+292=427 | 1,154 | 2,214 | 1.0 [7] | < 1 | 0.39 | 1,471,000 |
| | | | 3,000 [2] | 146.2 | 167 | 151+337=538 | 1,156 | 2,244 | | | 0.34 | |
| Santa Cruz Dam (RCC buttress for existing arch dam) | 1990 | 2 | 3,000 [2] | 147.4 | 170 | 131+131=262 | 1,227 | 2,301 | 2.4 [8] | < 1 | 0.65 | 38,500 |
| Camp Dyer Diversion Dam (RCC buttress for existing gravity dam) | 1992 | 1-½ | 3,000 [2] | 147.9 | 151 | 139+137=276 | 1,264 | 2,265 | 3.5 [8] | < 1 | 0.55 | 15,400 |
| Cold Springs Dam (RCC spillway replacement) | 1996 | 1-½ | 4,000 [3] | 156.7 | 152 | 292+0=292 | 1,562 | 2,224 | 3.0 [8] | < 1 | 0.52 | 19,100 |
| Ochoco Dam (RCC spillway stilling basin) | 1997 | 1-½ | 4,000 [3] | 150.8 | 218 | 434+0=434 | 1,539 | 1,881 | 0.6 [7] | 2 | 0.50 | 19,000 |
| Pueblo Dam (RCC spillway stilling basin modification) | 2000 | 2 | 3,500 [2] | 145.8 | 143 | 120+180=300 | 1,407 | 2,088 | 5.2 [8] | < 1 | 0.47 | 62,800 |
| Many Farms Dam (RCC spillway replacement) | 2001 | 1 | 4,000 [4] | 149.9 | 141 | 280+100=380 | 1,400 | 2,130 | 3.7 [8] | < 1 | 0.37 | 6,200 |
| Clear Lake Dam (RCC replacement dam for existing embankment dam) | 2002 | 2 | 3,000 [2] | 147.3 | 185 | 150+160=310 | 1,338 | 2,145 | 4.0 [8] | < 1 | 0.60 | 18,000 |
| Glendo Dam (RCC cutoff structure for auxiliary spillway) | 2012 | 1-½ | 3,000 | 153.7 | 140 | 140+210=350 | 1,545 | 750<br>1,185 | 0.0 | | 0.40 | 18,500 |
| **Soils or Geotechnical Approach** | | | | | | | | | | | | |
| Jackson Lake Dam (RCC upstream slope protection for embankment dam) | 1988 | 1-½ | 1,220 [11]<br>1,761 [12] | 149 | 254 | 400+0=400 | 1,340 | 2,150 | 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.
[7] Entrapped air.
[8] Entrained air.
[9] Nonplastic fines with maximum percent passing No. 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.

Pozzolan in the mix design is beneficial because it tends to extend the set time for the previously placed RCC lift surface. Pozzolan will lengthen the time during which 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 it 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 produces a better quality concrete. Pozzolan may also be less expensive than cement depending on the location of the project. This may provide for some economy if a portion of the cement can be substituted with pozzolan.

Admixtures are commonly used in RCC. WRAs have set-retarding characteristics particularly when used with Class F pozzolans and can be used to extend the set time of the RCC.

In summary, bond on lifts can be improved with the following methods:

- Placements are made while the previous placement is still considered a fresh joint. Replacement of some of the cement content with pozzolan can lengthen the set time of the RCC.

- Good surface preparation and the use bonding mortar spread over each (cold or construction joint) lift surface prior to the placement of the next lift,

- The RCC mix can be proportioned to provide a greater volume of mortar than is required to fill the aggregate voids.

### 6.10.2 Facing Systems

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 to enable the upstream facing elements to act as an effective water barrier. Facing systems are used with RCC dams for the following purposes:

> **Forming a durable dam face:** The resistance to freezing and thawing of saturated RCC is relatively poor when compared with the resistance of conventional concrete. Unprotected RCC should not be used in portions of a structure subjected to freezing and thawing cycles in a critically saturated state. Conventional cast-in-place or precast, air-entrained, concrete facing elements of adequate thickness should be used to protect the RCC from damage due to freezing and thawing.

- **Forming an impervious barrier:** Some facing systems may provide a barrier or limit seepage of water into the RCC dam.

- **Maintaining aesthetics:** Appearance of the dam faces may dictate whether a facing system or surface treatment is needed.

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 of an RCC dam and providing a continuous water barrier. 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 because compaction is difficult at this location.

- **Formed conventional facing concrete:** The conventional facing concrete is usually placed in 1-foot lifts against vertical upstream forms, followed by the RCC. Contraction joints can be provided at and consist 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 conventional concrete between the contraction joints to control temperature and shrinkage cracking expected in the higher paste, exposed, conventional concrete mix. A similar procedure is usually 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 facilitate the energy dissipation.

- **Formed grout-enriched RCC:** The process for GERCC, sometimes referred to as grout-enriched-vibratable RCC (GEVR), consists of first placing unconsolidated RCC near the upstream and downstream forms and then adding 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. Ever since the GERCC method was developed in China in 1987, it has been a common method used on RCC dams in that country. 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 had 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 a Marsh funnel viscosity of about 35 seconds. GERCC generally improves the appearance and durability of the upstream face of RCC dams. In addition, GERCC has comparable or improved compressive strength compared to exposed and formed RCC faces. However, the upstream GERCC mix design is not as consistent and 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 provides the primary water barrier. A richer conventional concrete mix is placed adjacent to the forms. Formed RCC without conventional concrete is generally not used because it is extremely difficult to compact RCC on an upstream vertical face. In addition, it is difficult to get vibratory rollers near the vertical face, and smaller compaction equipment is usually required. The forms also have to be designed to handle the transfer of the load due to compaction and construction equipment.

- **Placing RCC against formwork:** In this method, the RCC is placed directly against formwork. Relatively good finish and a durable RCC face may be achieved by placing workable, high-cementitious RCC mix in a mild climate. However, in severe climate conditions, freeze-thaw cycles may significantly damage the RCC face (see figure 6-7). Segregation near the formwork often creates labor-intensive repairs. As a result, this method is not usually used on dams. There may, however, be some applications where appearance is not a concern and a sacrificial RCC thickness can be provided.

**Figure 6-7. Photograph of the downstream face of Clear Lake Dam showing segregation that occurred against formwork.**

- **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 method increases the cost of the construction. It requires separate forming for the vertical upstream face of the RCC, as well as for the conventional concrete overlay. Anchor bars drilled into the RCC may be required to support the reinforced concrete. This reinforcement can assist in controlling both cracking and seepage. The reinforcement ends 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. The thickness of the overlay will depend on the need to accommodate the embedded items, including reinforcement, waterstops, and anchor bars.

- **Slip-formed facing elements:** A richer conventional concrete mix may also be used near the upstream face of the dam with slip-formed facing elements (see figure 6-8). It is very difficult, however, to provide joints in slip-formed facing elements. Because of the time required for the facing element concrete to gain strength, this method usually limits the placement of RCC to two or three lifts per day. Both faces of Upper Stillwater Dam were formed of 3-foot-high, slip-formed facing elements. Slip-formed facing concrete has been used on a very small number of RCC projects.

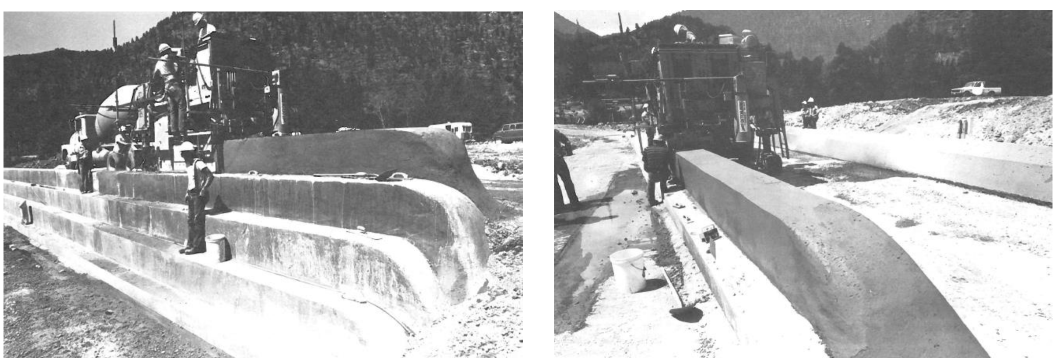


**Figure 6-8. Construction of slip-formed facing elements at the test placement for Upper Stillwater Dam.**

### 6.10.3 Curved Gravity RCC Dams

For a curved-in-plan RCC gravity dam with contraction joints that are not grouted, the analysis and design should follow the approach described above for straight RCC gravity dams. However, if the induced joints are grouted, the arch action could be incorporated following the proper analysis methods for arch dams. The design of curved RCC dams is not discussed in this report.

# 6.11 Appurtenant Structures (Spillways, Outlet Works, and Galleries)

## 6.11.1 General

Appurtenant structures such as spillways, outlet works, and galleries are generally incorporated into the RCC dam design in a way similar to conventional concrete dams. One of the key differences between conventional mass concrete dams and RCC dams is that the location of galleries or openings in the RCC dam are more critical to the placement rates and compaction requirements, and any interference with RCC placements is generally minimized or avoided to the greatest extent possible.

## 6.11.2 Spillways

Spillways are generally incorporated into the RCC dam design in a similar manner to that of conventional concrete dams (Reclamation, 1976). 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 reasonably estimated. Conventional concrete side walls can be used to confine the flows to the center portion of the dam and stilling basin.

Steps can be incorporated into the downstream face of the RCC dam, as part of the spillway chute section, to provide some energy dissipation and potentially reduce the size and cost of the stilling basin.

Coefficients of discharge (C) for the standard weir equation ($Q = CLH^{1.5}$) between 2.9 and 3.5 are fairly common in RCC dams, depending on the crest configuration and overall efficiency of the spillway.

## 6.11.3 Outlet Works

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.

## 6.11.4 Galleries

Foundation galleries are usually provided in RCC dams higher than 100 feet. These galleries have been 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. Galleries have the same purpose in RCC dams as they do in conventional concrete dams:

- For drilling and grouting of the foundation grout curtain and drilling foundation drain holes during the construction phase
- For collection of internal and foundation drainage, access to drainage system for maintenance, and access to instrumentation and other mechanical equipment in the post-construction operation
- For internal inspection of the dam

Galleries are often considered a seepage control feature because they are generally used to control foundation drainage to reduce uplift pressures, as well as to control internal drainage within the dam.

The construction of galleries has presented some challenges on several projects. The key considerations with galleries or openings in the dam are to minimize impacts to the RCC placements, ensure adequate compaction of the RCC in areas adjacent to the gallery or openings, and ensure that the gallery forms can support the opening during the construction and service loads. Galleries are often located near the upstream face of the dam, and sufficient space must be provided between the upstream face and the gallery to obtain good compaction and avoid stress concentration potential.

Galleries should be sized to facilitate both operation and maintenance needs and construction needs, such as drilling for the drainage and foundation grouting curtains. Most dams have a foundation grouting and drainage gallery that is 5 feet wide by 7 or 8 feet high. Larger galleries up to 8 feet wide by 10 feet high could be considered, however, for larger dams and dams with more extensive work or maintenance requirements. The potential for stress concentrations, and the need for reinforcement around galleries and other openings within the dam, need to be evaluated.

## 6.12 Performance Monitoring of Completed RCC Dams (Instrumentation)

### 6.12.1 General

Reclamation establishes performance monitoring requirements for concrete dams based on an evaluation of potential failure modes, such as differential movements in the foundation, foundation rock block instability, earthquake loadings, and increased loadings during a large hydrologic event. Reclamation documents the key monitoring parameters for each failure mode and the expected behavior. Damtenders 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.

In addition to the performance monitoring mentioned above, a periodic schedule of monitoring and a visual checklist are also prepared. Some of the most common monitoring considered for RCC dams includes the following (Reclamation, 1987b):

- Uplift pressure monitoring (usually at five points in the upstream to downstream direction) in the foundation and at three or more lines based on the length of the dam
- Gallery flow monitoring with weirs in various locations to isolate flows in each abutment and internal drainage flows within the dam
- Structural measurement points to monitor potential differential movements in the RCC dam or foundation and monitor potential foundation rock instability including sliding
- Internal movement monitoring to determine relative movement using plumblines, inclinometers, single point and multipoint borehole extensometers, strain meters, joint meters, and collimation surveys
- Temperature monitoring of the mass of the RCC dam during construction and generally continuing until contraction joint grouting is completed or until the dam reaches a stable temperature

### 6.12.2 Performance

Performance of RCC dams is based on an evaluation of potential failure modes.

#### *6.12.2.1 Leakage and Uplift Pressures*

It is important to understand how leakage through an RCC dam and foundation may be changing with time. If, over a period of time, the flow monitoring in the gallery indicates that flows are decreasing, it may indicate that the foundation drains are plugging and need to be cleaned. Drain plugging can lead to increased uplift pressures. On the other hand, if the drain flows increase, it may indicate an opening of joints or cracks in the dam and foundation, possibly resulting in decreasing uplift pressures.

#### *6.12.2.2 Structural Behavior Monitoring, Instrumentation, and Inspection*

Direct evidence of concrete dam foundation instability may be the presence of contraction joint offsets or cracking that is 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 indicate 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 what was estimated during design. Collimation, extensometers, inclinometers, 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 that produces 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.

## 6.13 Risk-Informed Design Approach

In recent years, there has been an increasing interest toward using risk-informed and probabilistic design methods for water resource projects. These risk-informed design methods are currently evolving and changing as the methodology is used and developed. Although, the risk informed design process of new concrete dams is outside the scope of this report, a short description of the risk-informed design approach is provided below.

Both risk-informed (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, 2011).

Reclamation established a Dam Safety Program to ensure that the dams in its inventory do not present unreasonable risk to people, property, and the environment. Reclamation has developed risk-informed analysis methods to estimate the likelihood that various potential outcomes may result from the various loads placed on a dam, and to identify the most effective way to provide public protection over the full range of loading conditions. These methods are used when existing dams and appurtenant structures are evaluated and modified, as well as when new dams and/or structures are designed. Potential failure modes are identified for normal, hydrologic, and seismic loading conditions. The estimated annual probabilities of loading or occurrence are developed, as well as the estimate of the structural response to these various loads, to produce annual probabilities of failure for each potential failure mode.

Risk is considered in terms of the likelihood of an adverse event, and the consequences of that event, expressed in terms of lives lost. It is measured by Annualized Failure Probability (AFP) and Annualized Life Loss (ALL). Protection of human life is of primary importance to public agencies that construct, maintain, and/or regulate civil works. When using a risk-informed approach to evaluate design, it is important to understand the consequences of a potential failure of the dam or a feature of the dam. For dams upstream of large population centers, the guidelines for risk-informed decisionmaking demand a much more robust design than for those in remote areas with minimal or no downstream consequences that would be impacted by a dam failure. Risk is portrayed using the two factors defined as:

*AFP = (Probability of the Loading) x (Probability of Failure given the Loading)*

*ALL = (Probability of the Loading) x (Probability of Failure given the Loading) x (Adverse Consequences given the Failure)*

where: Probability of the loading is the annual probability that the chosen load range responsible for a failure will occur.

Probability of failure given the loading is the likelihood that the dam will fail under the specific loading (ranges from 0.001 to 0.999) and may involve multiple steps or events in an event tree.

Adverse consequences given the failure is typically expressed in terms of the estimated number of lives lost given a dam failure.

Both the total AFP and ALL for construction of a new RCC dam should be compared to the Reclamation Public Protection Guidelines (Reclamation, 2011). Reclamation compares the total AFL and total ALL estimates at a given dam to threshold values, above which there is increasing justification to take action to reduce risk. The threshold values are 0.0001 for AFP and 0.001 for ALL.

Risk estimates are often developed by a team that has a broad range of expertise. The estimation of failure probabilities and risk estimates depends on data and analysis of the design, geology, construction, performance, 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. Monte Carlo computer simulations may be used, and sensitivity studies may be included, to determine a potential range of uncertainty for the risk estimates.

Safety evaluation of modifications to existing dams should include risk reduction estimates compared to the existing (baseline) conditions and estimates of risk during construction

## 6.14 References

ACI 207.2R-07, 2007. *Report on Thermal and Volume Change Effects on Cracking of Mass Concrete*. American Concrete Institute.

ACI 207.5R-11, 2011. *Roller-Compacted Concrete*. American Concrete Institute.

Bathe, K.J., 1982. *Finite Element Procedures in Engineering Analysis*. Prentice-Hall, Englewood Cliffs, New Jersey.

FERC, 2002. *Engineering Guidelines for Evaluation of Hydropower Projects*, Chapter III, "Gravity Dams." Federal Energy Regulatory Commission, October.

Forbes, B.A., 1999. "Grout-Enriched RCC: A History and Future," *Water Power and Dam Construction*, June 10.

International Committee on Large Dams, 2003. *Roller Compacted Concrete Dams: State of the Art and Case Histories*. Bulletin 126.

Reclamation, 2014. *State-of-Practice for the Nonlinear Analysis of Concrete Dams.* Bureau of Reclamation.

Reclamation, 2011. *Interim Dam Safety Public Protection Guidelines.* Bureau of Reclamation, Dam Safety Office, Denver, Colorado, August.

Reclamation, 2007a. *Design Data Collection Guidelines*, Chapter 2, "Appraisal Investigations - Dams." Bureau of Reclamation, September.

Reclamation, 2007b. *Design Data Collection Guidelines*, Chapter 3, "Feasibility Designs – Dams." Bureau of Reclamation, September.

Reclamation, 2007c. *Design Data Collection Guidelines*, Chapter 4, "Specifications Designs – Dams." Bureau of Reclamation, September.

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

Reclamation, 1987b. *Concrete Dam Instrumentation Manual.* Bureau of Reclamation, October.

Reclamation, 1984. *Mix Design Investigation – Roller Compacted Concrete Construction – Upper Stillwater Dam, Utah.* REC-ERC-84-15, Bureau of Reclamation.

Reclamation, 1981. *Control of Cracking in Mass Concrete Structures.* Bureau of Reclamation, Engineering Monograph No. 34.

Reclamation, 1977. *Design Criteria for Concrete Arch and Gravity Dams*. Bureau of Reclamation Engineering Monograph No. 19, February.

Reclamation, 1976. *Design of Gravity Dams.* Bureau of Reclamation.

Zanger, C.N., 1952. *Hydrodynamic Pressure on Dams Due to Horizontal Earthquake Effects.* Bureau of Reclamation, Engineering Monograph No.11.

Monfore G.E., and F.W. Taylor, 1948. *The Problem of an Expanding Ice Sheet.* Technical Memorandum, Bureau of Reclamation, March.

Reed III, G.E., M.F. Rogers, and J.L. Ehasz, 2003. "Building the Olivenhain," *Civil Engineering*, Vol. 73, Issue 4, pp. 46-53. American Society of Civil Engineers, April.

Westergaard H.M., 1931. "Water Pressures on Dams During Earthquakes," *ASCE Transactions*, pp. 418-433. American Society of Civil Engineers, November 1933.

# 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 economic advantages 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 effect 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, for hydrologic overtopping, foundation erosion protection and stability, and to perform 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 Streamflow Diversion and Foundation Unwatering

One of the first tasks in modifying an existing dam is the diversion 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 modification, 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 pumpout test was performed to estimate the quantity of water entering the spillway to help determine pumping requirements.

## 7.3 Design Details

Key considerations in designing modifications that buttress an existing dam, such as the buttress design for Santa Cruz Dam and 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 determine 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 was 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 transfer of compression and shear stresses 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 removed with high-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 require that the aggregates be exposed, or conform to a minimum roughness by specifying the number and amplitude of offsets per lineal foot and a method to measure the offsets. Water jetting or sandblasting a test surface before bidding can also be used to demonstrate the required surface preparation. Higher pressures up to and exceeding 20,000 lb/in$^2$ may be needed to effectively expose aggregates and create aggregate-level amplitude when joining against higher strength concretes or concretes that have high strength surficial coatings, such as carbonation.

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.

# 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 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 8-1 shows Vesuvius Dam, in Ohio, following RCC placement. Depending on 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 where RCC was used for overtopping protection of embankment dams. The USACE 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).

**Figure 8-1. Overtopping protection at Vesuvius Dam during construction.**

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. More case histories, and design and construction considerations, are provide in the Federal Emergency Management Agency's (FEMA) *Technical Manual, Overtopping Protection for Dams* (FEMA, 2014).

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 that has a downstream slope of 2:1 (horizontal to vertical). Lanes wider than 8 feet may be needed to provide additional weight, if it is required in the design for uplift forces.

It is important to consider appropriate filter and drainage capability of the embankment with an RCC overlay on the downstream face. 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. These conditions could result from static conditions caused by plugging of the internal drainage system, or they could occur 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. It is common to have a filter and drainage blanket with a toe drain beneath an RCC overlay. Additional drainage capability can be provided by using formed holes through the RCC, or by drilling holes after RCC construction has been completed, if appropriate filter material is in place beneath the RCC.

Several key issues must be considered during hydraulic design for dam overtopping protection. The design head, head drop, and unit discharge will influence the design of an RCC overlay. For flow depths of 2 feet or less, hydraulic studies show 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 require evaluation, and a cutoff wall to the bedrock foundation may be required if erosion damage could be extensive. If a stilling basin is determined necessary, the type must be selected by considering economics and energy dissipation requirements based on the erosion potential and downstream consequences. Abutments generally slope toward the river channel and then funnel discharges into the river channel downstream. Abutments often need treatment with concrete armoring for overtopping protection to prevent erosion. In addition, hydraulic model studies may be required to gain an understanding of complex 3D flow conditions that may result from overtopping of a concrete-capped embankment dam.

Another key consideration for concrete overlays, 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, as well as 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 placement of RCC overtopping protection, concern about cracking due to additional settlement is reduced. However, some settlement could still occur due to the additional weight of the RCC, loads associated with construction, and the additional weight of water during an overtopping event.

## 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) (figure 8-2). 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 sacrificial. An 8-foot-wide lane with a 9- to 10-inch lift thickness was used.

**Figure 8-2. Upstream slope protection at Jackson Lake Dam, Wyoming.**

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 embankment dam. The crack spacing was 40 feet at the north end of the dam. 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 that formed as a result of the stair-step construction and weakly bonded lift lines (figure 8-3).

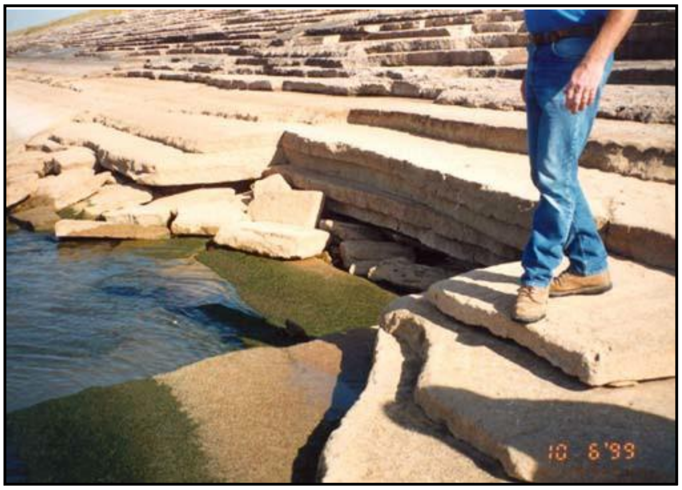



**Figure 8-3. Upstream soil-cement slope protection showing damage from weakly bonded lift lines and freeze-thaw cycles.**

## 8.3 Water Barrier

Concrete core walls have been frequently used in embankment dams, but few case histories exist of core wall construction using RCC. However, an early form of RCC was used in 1960 to provide the central impervious core for an earthfill embankment cofferdam for Shihmen Dam in Taiwan.

Adequate foundation is a key consideration for constructing a concrete core wall within an embankment dam. The foundation requirements must be equal to those required for an RCC gravity dam. If an adequate foundation exists, RCC dams are generally cost effective because the footprint and the volume of material required for a concrete dam are fairly small, compared to those for an embankment dam. The availability of construction materials and cost effectiveness of an embankment dam with an RCC core wall, as compared to an RCC gravity dam, would also be key factors in selecting the preferred alternative.

If an adequate impervious material is not available, an RCC core wall can be used to substitute for a soil core. The main function of an RCC core wall is to provide a water barrier; therefore, it must be designed to be relatively impervious. Bond on lifts would be required, with zoned filter materials downstream, in the event that seepage occurred 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 exist, embankment dams with dam safety deficiencies have been replaced with RCC dams. This can be a key advantage because the abutment waterways can be incorporated into the new structure, and the use of RCC can reduce the overall volume of the dam, thereby also reducing construction time and cost. Typically, the top of the RCC dam can be used as a spillway, which eliminates the cost of constructing a separate one. The outlet works can be incorporated into the concrete dam or taken through one of the abutments.

In 2002, Clear Lake Dam in California was modified by constructing 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.

## 8.5 References

Casias, T.J., and A.K. Howard, 1984. *Performance of Soil-Cement Dam Facings–20-Year Report.* Report No. REC-ERC-84-25, Bureau of Reclamation.

FEMA, 2014, *Technical Manual: Overtopping Protection for Dams*. FEMA P-1015, Federal Emergency Management Agency.

McLean, F.G., and K. Hansen, 1993. "Roller Compacted Concrete for Embankment Dam Overtopping Protection," *Proceedings of the Specialty Conference, Geotechnical Practice in Dam Rehabilitation.* American Society of Civil Engineers, Raleigh, North Carolina, April 25-28.

# 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 an overflow or gated spillway; when economics determine that the ideal location for a main or auxiliary spillway is 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 Section 9.2, "Overflow Weirs," in 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 preparing RCC lift surfaces; and placing bonding mortar and leveling concrete. The equipment needed to batch and handle three separate mixes (RCC, leveling concrete, and bonding mortar) may not be cost effective on smaller projects. Space limitations at the site, or small volumes of leveling concrete or bonding mortar, may make it uneconomical to batch these separate materials onsite, so they are often batched offsite at commercial facilities.

### 9.1.1 Leveling and Conventional Concrete

Spillways constructed from RCC are generally more massive than those constructed from structural concrete. When bond to the foundation is not necessary, and sliding resistance is high enough without bond between the RCC and foundation, leveling concrete may not be necessary. If bond and water tightness is required, conventional concrete can be used at the interface between existing concrete or foundation rock and the RCC (see figure 9-1).

If an acceptable flow surface can be obtained from either formed or compacted RCC surfaces and air-entrained concrete for durability is not needed, 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 common. 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 that the flow surface will not be subject to cavitation damage.

**Figure 9-1. 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.**

A conventional reinforced concrete flow surface may be required in stilling basins, as it was at Pueblo Dam. There is often 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 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.

### 9.1.2 Bonding Mortar

Bonding mortar (figure 9-2) can help improve bond or cohesion between RCC lifts in spillways, as well as reduce seepage through lift lines. Bonding mortar may also be necessary when there are long delays between lift placements. However, stress and stability issues are different for spillways than for RCC dam construction. Designers should evaluate the need for bonding mortar for each design.

**Figure 9-2. Bonding mortar used to improve sliding stability below the spillway crest.**

In some cases, bonding mortar between RCC lifts may be eliminated if the analysis shows 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 subsequent lifts can be placed in 8 to 12 hours or less and placing temperatures are low. However, if pozzolan is not used in the mix design, bond between lifts may not be achieved, even with high placement rates. If necessary, bonding mortar can be transported to the site from a commercial offsite plant.

### 9.1.3 Drainage and Stability

Since RCC is generally placed in 1-foot lifts, there are more lift lines or construction joints than in 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 stresses 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 it is 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. 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 is needed for stability, so the drainage envelope may not require separate trenching beneath the base of the structure.

Under some conditions, the RCC spillway can be constructed without contraction joints or crack-induced joints, and simply allowed to crack; however, in many cases, uncontrolled cracking is undesirable. Due to the potential for piping problems and/or high uplift pressures to develop 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.

### 9.1.4 Hydraulic Considerations

Spillways constructed of unlined RCC will produce a rougher flow surface than spillways constructed with a conventional 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 9-3, 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.

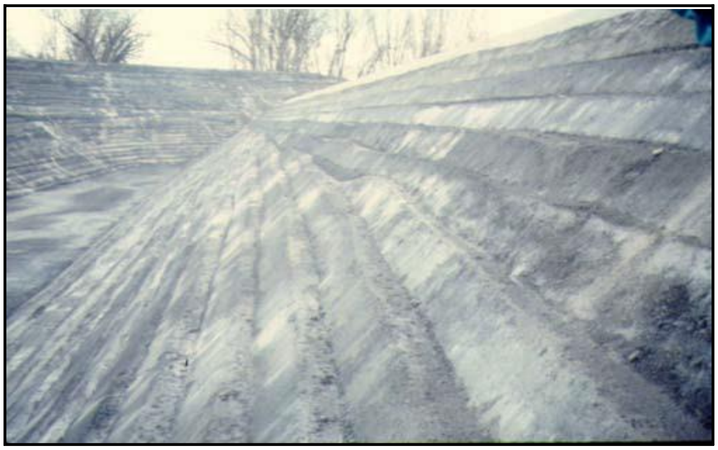


**Figure 9-3. Stair-stepped slope downstream from the spillway crest.**

If velocities are high enough, cavitation damage can become an issue. This is true for longer, steeper chutes. A stair-stepped design can help reduce flow velocity and aerate the flow to reduce the potential for cavitation. RCC construction lends itself well to stair-stepped 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. Generally, simple transitions and large radius horizontal curves are most desirable for RCC placements. Complicated shapes; vertical, parabolic curves; and sharp, horizontal angles may slow down construction, are generally not practical, and in some cased may require formed conventional concrete.

### 9.1.5 Construction

Constructing abutment spillways using RCC can be more difficult than constructing 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 because it reduces the time operators spend maneuvering their equipment, and this 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 a 14-percent grade at Ochoco Dam. Sloping placements may also be made in a stair-stepped manner and may require that a horizontal lift be terminated as placements proceed up the slope.

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 onsite will have limitations in its ability to maneuver and access construction areas. The equipment with the largest minimum turn radius will generally dictate the sharpest horizontal bend. Because 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 (figure 9-4). 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.

**Figure 9-4. Tight radius corners at the upstream end of a spillway chute.**

Spillway chutes can typically be constructed with side slope that are at least one lane wide, depending on the equipment used. Higher slopes may require wider placements for safety. Because it is impossible for construction equipment to pass on a single lane, areas must be provided for the equipment to pull off. 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 a backhoe stationed above or below the placement.

Most abutment spillways are constructed in relatively tight construction areas with relatively steep side slopes, which can create the potential for RCC lift contamination. Debris falling from the side slopes above the placement or 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 efforts.

## 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 are relatively long and massive. It is generally not economical to use RCC to construct small overflow weirs unless RCC is also used for other structures at the site.

RCC is generally placed in 12-inch lifts, which results in more lift lines than in conventional concrete; therefore, a greater potential exists for leakage through RCC weirs. Additionally, due to rapid RCC placement rates and the low paste content, lift lines in RCC may not be bonded as well 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.

When freeze-thaw durability is not a concern, weirs that are only used occasionally and do not have water stored against them, or weirs that are normally submerged, may be constructed using RCC without conventional concrete facing (figure 9-5). 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 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 of controlling seepage may be necessary. Overlay concrete can be used for waterstop installation.

Construction using RCC generally will not produce smooth, controlled, finished surfaces. For example, weirs constructed with RCC 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 (figure 9-6). 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.

Figure 9-5. Small RCC weir in the Cold Springs spillway chute.

Figure 9-6. Conventional concrete ogee spillway crest placed over RCC.

Designers must address the stability of structures 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. It may be necessary to provide drainage, upstream seepage barriers, or reinforcement with 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. Higher weirs, however, 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 edge compaction can be used to consolidate and smooth out unformed RCC stair-stepped surfaces. When the weir is capped with conventional concrete, the stepped RCC surface can be shaped 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 to make this option economically beneficial.

Stepped flow surfaces, often associated with RCC, can be used to dissipate hydraulic energy and prevent erosion, given the right flow range, head differential and purpose of the structure. Steps in formed RCC can be difficult to fully compact because 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. Durability of unformed RCC is also a concern, and air-entrained conventional concrete may be required in climates where freezing temperatures occur.

Exposed RCC surfaces will normally be rougher than conventional concrete surfaces, depending on the RCC mix and specific compaction equipment used. 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 because its 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 they 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 designed 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. Based on the 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) floodflow, 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. The structure would be partially buried and normally not subject to large differential heads; therefore, 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 allow emergency overflow for the canal, while also allowing RCC construction equipment to turn around, thereby facilitating RCC placement. With a total RCC volume of only 15,000 yd$^3$, this design was less economical than a mechanically stabilized earth wall alternative, and it 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 cost effectiveness of a wide range of potential cofferdam alternatives, including the cost of removing 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 used as a cofferdam, provided that it could be constructed in the dry. 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 dam.

## 9.5 Gravity Retaining Walls

Reclamation has not yet used RCC to construct large gravity retaining walls. The primary consideration for using RCC in large gravity retaining wall construction is its cost effectiveness compared to conventional concrete construction. Gravity retaining walls were used on the Stacy Dam spillway, which is located on the Colorado River near San Angelo, Texas. 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 when a suitable structure foundation does not already exist. For RCC to be an economical alternative, the required RCC volume would have to be sufficiently large to warrant its use.

# 10. PERFORMANCE OF COMPLETED PROJECTS

The 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. Table 6-3, in section 6 of this report, summarizes the RCC mix design data for each of these projects.

## 10.1 Upper Stillwater Dam (New RCC Gravity Dam)

### 10.1.1 Background

Upper Stillwater Dam, pictured in figure 10-1, was the first Reclamation concrete gravity dam constructed with RCC. In 1987, at the time of its completion, Upper Stillwater Dam was the largest RCC dam in the world. Upper Stillwater Dam is located on Rock Creek in eastern Utah, about 120 miles east of Salt Lake City. The dam has a total concrete volume of 1,620,000 $yd^3$. 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 is used to provide water storage for irrigation, municipal and industrial use, and recreation as part of the Bonneville Unit of the Central Utah Project. In 1994, the dam's care, operation, and maintenance responsibilities were transferred from Reclamation to the Central Utah Water Conservancy District in Orem, Utah.

The upstream and downstream faces of Upper Stillwater 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 it was only partially successful because 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. Because 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. The washing of silty sand from foundation joints and bedding planes into the foundation drains and gallery resulted in the need to regrout 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 amounts of sand continue to wash into the foundation drains, as well as through the cracks in the RCC, from the backfill placed at the upstream face.

**Figure 10-1. Aerial view of the completed Upper Stillwater Dam, showing the downstream face and seepage from cracks following the first winter and first filling.**

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 walls at each end of the spillway crest are streamlined to provide a smooth approach to the crest. Water flowing over the crest travels down 99 steps that have been built in the spillway chute surface, which dissipates much of the hydraulic energy before the flow reaches the stilling basin. The stilling basin at the dam's toe stills the spillway discharges. The stilling basin floor is constructed of unreinforced RCC.

### 10.1.2 Design Considerations

The final designs for Upper Stillwater Dam were completed in the early 1980s, using currently acceptable analytical methods, and the dam was constructed between 1983 and 1987. The dam has performed well under a full range of reservoir operating conditions since construction, despite the sliding movements during initial filling and 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 dam safety conditions.

Upper Stillwater Dam was constructed without either contraction joints or internal mass concrete cooling. Temperature control for the dam's mass concrete was achieved by placing the RCC at a temperature below 50 ºF 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 a shear strength of 300 lb/in$^2$. In addition, the mix design took into consideration the need to reduce thermal heat generation, ensure concrete durability, and maintain a workable mix to obtain adequate compaction.

During the dam's construction, the spillway design was modified to pass a revised PMF, which required increasing the maximum spillway flow capacity to five times the original capacity. 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.

### 10.1.3 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, primarily to support the two-lift-per-day placement rate. A high fly ash, low water content RCC was used, which consisted of 31-percent cement to 69-percent fly ash/yd$^3$, 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 have a tensile strength of 180 lb/in$^2$, resulting 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 damsite 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 was used for the main body of the dam and contained 425 pounds of cement and flyash. Mix RCC-B contained 508 pounds of cement and pozzolan, and it was used to place a 14-foot-wide lane against the upstream face of the dam. A richer mix was used because the upstream portions of the dam were more critical.

The maximum size aggregate was 2 inches for the RCC and foundation leveling concrete, and it was 1 inch for structural concrete and concrete facing elements. The coarse aggregate for the dam was obtained from an upstream quarry, and the fine aggregate was obtained from a downstream river source. The coarse aggregate has been described as fine-, medium-, and coarse-grained; quartz cemented; quartzose sandstone. The average compressive strength of rock cores from the coarse aggregate quarry was about 21,000 lb/in$^2$ and ranged from 13,000 to 28,000 lb/in$^2$. The temperature studies discussed below were based on the RCC mix designs with a weaker aggregate than was actually used during dam construction, which may have affected the modulus of elasticity results. Based on the compressive strength, it is likely that the actual modulus of elasticity of the RCC used was high and may have been variable.

Figure 10-2 shows the variation in compressive strength versus modulus of elasticity for Upper Stillwater Dam as compared with test data from other Reclamation mass concrete dams. The lower modulus of elasticity at Upper Stillwater Dam from the RCC mix testing program was likely due to the lower modulus of elasticity of the sandstone aggregate.

Thermal expansion studies were performed on the RCC mix. Figure 10-3 shows the results of the thermal studies for L-5 mix. A 2D temperature analysis study was performed during design to simulate the layer-by-layer construction of the RCC dam. The analysis included air temperature, solar radiation and heat of hydration, and a maximum specified placement temperature of 50 ºF. The analysis of the thermal behavior of the dam indicated that the dam could crack at 50-foot spacing.

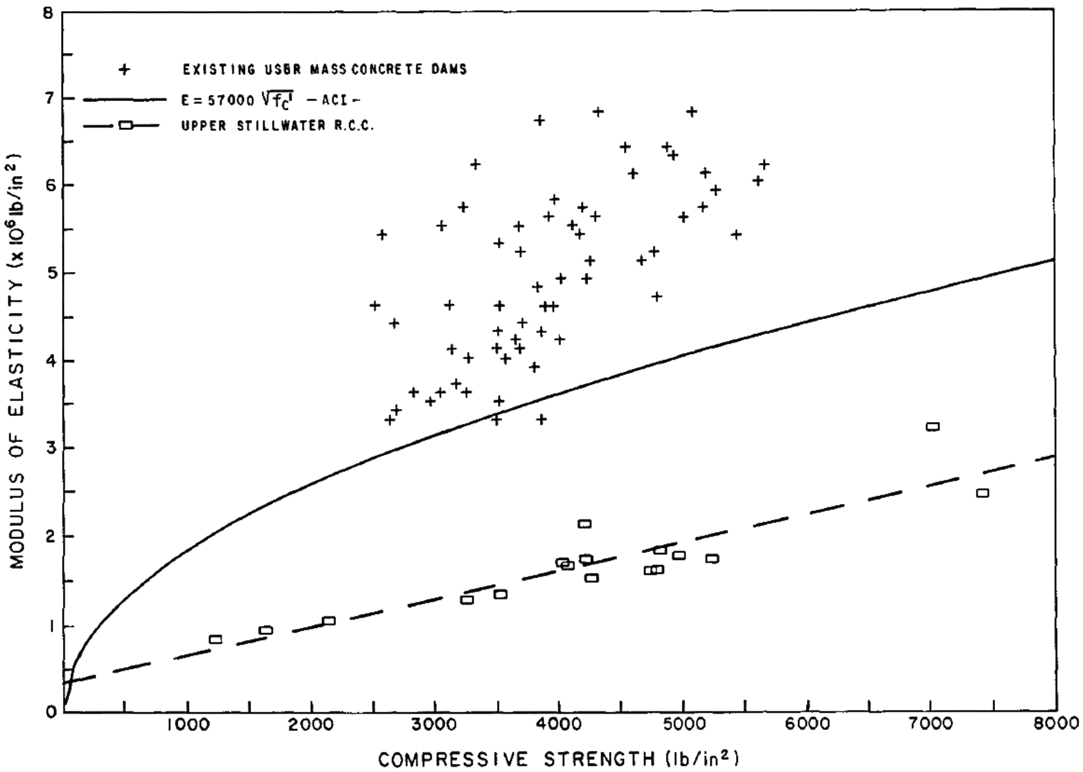



**Figure 10-2. Upper Stillwater Dam laboratory RCC mix program - elastic properties of concrete versus compressive strength.**

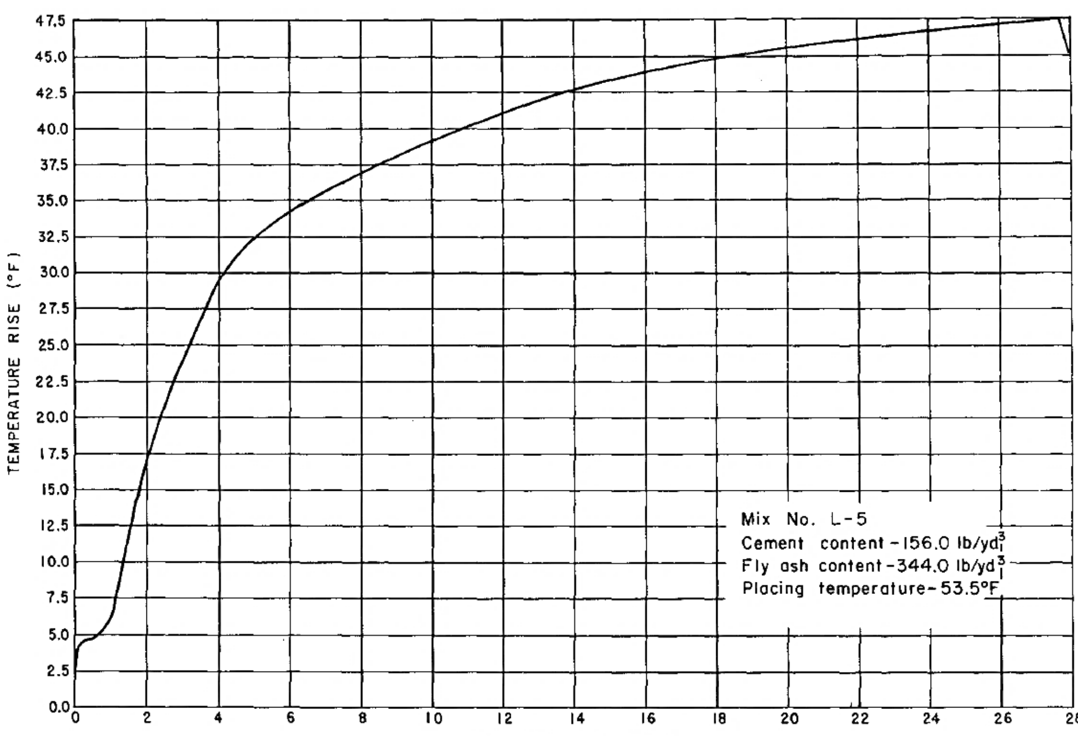



**Figure 10-3. Laboratory RCC mix program for adiabatic temperature rise for mix L-5.**

### 10.1.4 Construction

Tyger Construction Company was awarded the contract for constructing Upper Stillwater Dam in December 1983. The bid price for RCC-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 spaced about 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 on each abutment. Consolidation grouting of the abutments was completed after the dam was topped out.

Upper Stillwater Dam is located in the Uintah Mountains at an elevation of over 8000 feet. The climate conditions at the dam allowed for an RCC construction season of only 5 months between May and September. The specified placement temperature of 50 °F required that the RCC be placed primarily at night.

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. Generally, the facing element concrete placements using the slipform paver were performed in an 8-hour shift during the day, with a required 4-hour delay before the RCC could be placed on the facing concrete. 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. The parapets on the dam crest were constructed using the slipformed, conventional concrete elements and were reinforced. Two-inch-deep chamfers or crack inducer grooves were hand tooled into the parapets at a spacing of 40 feet on center.

The construction sequence required placing both upstream and downstream slipformed elements and raising the outside faces 2 feet. Two lifts of RCC were then placed. Each lift was compacted to a 1-foot-thick layer continuously from abutment to abutment between the elements. A conveyor belt system was used to transport the RCC to the placement (see figures 10-4 and 10-5). The conveyor belt was 36 inches wide and about 1,000 feet long, and it traveled about 750 feet per minute. Two 30-inch-diameter tremie tubes were used at the end of the conveyor system to discharge the RCC into one of the two end-dump trucks waiting beneath the tremie tubes (see figure 10-6). 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 finely spread the RCC. A laser system was used on the dozer to control the elevations of the placement within the specified tolerances.

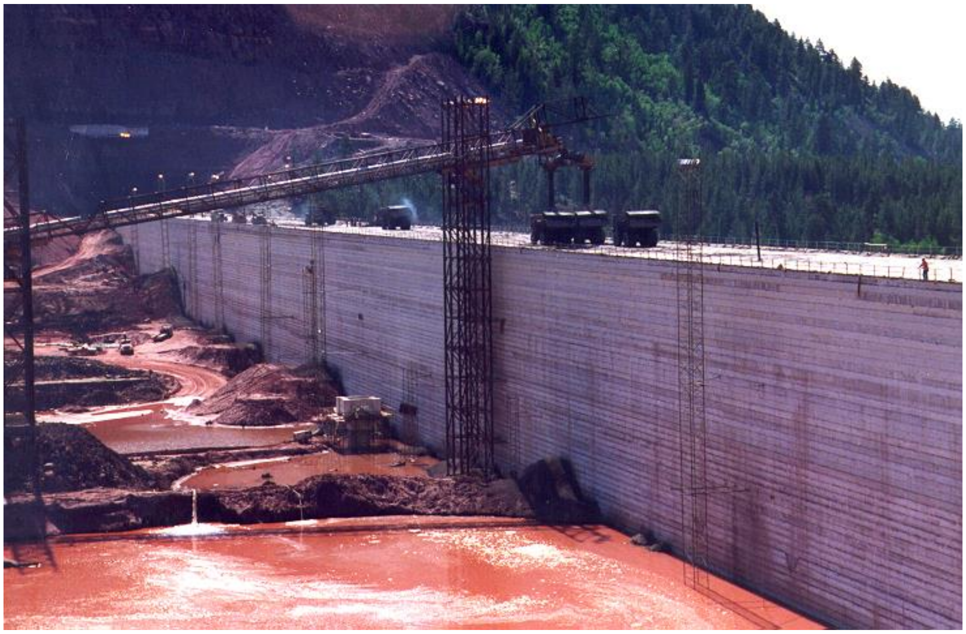


**Figure 10-4. Photograph of the upstream face of Upper Stillwater Dam during construction.**

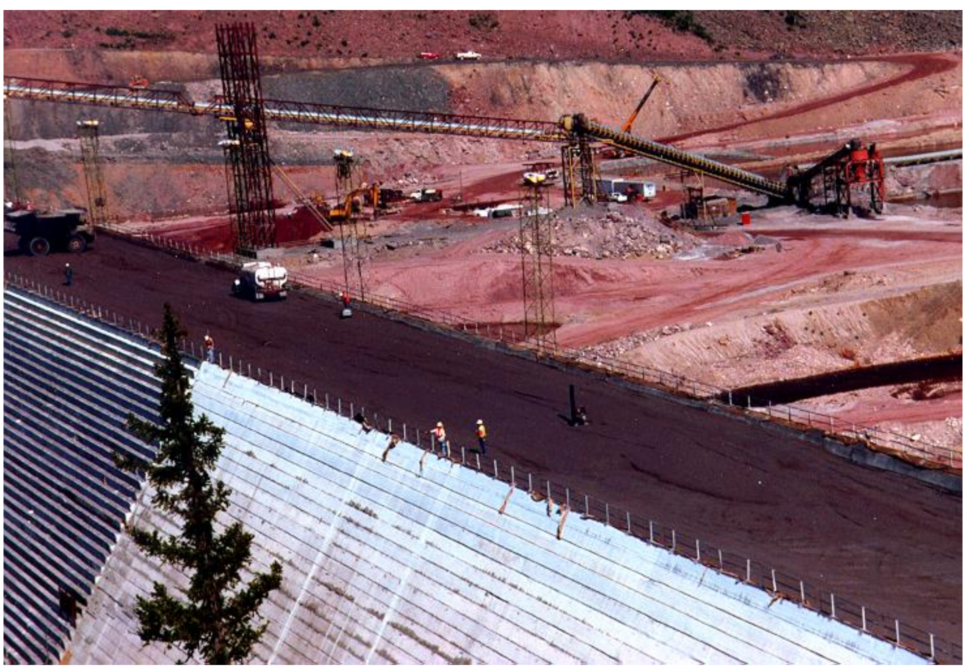


**Figure 10-5. Photograph of the downstream face of Upper Stillwater Dam and the conveyor layout during construction.**


**Figure 10-6. RCC placements showing spreading, compaction, and delivery systems.**

RCC was compacted to 1-foot-thick lifts using a double-drum, 15.6-ton, vibrating roller in the interior mass of the dam. The rollers had an operating frequency of about 2,400 vibrations per minute. About four to six passes were needed to obtain adequate compaction of the RCC.

RCC was generally placed between 8:00 p.m. and 12:00 noon to meet the RCC placement temperature requirements of 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 to maintain the RCC surface in a moist condition. In general, lift surface treatment for this mix design was performed as follows:

- Lift surfaces up to 48 hours old were cleaned using the vacuum truck.
- Lift surfaces considered cold joints more than 48 hours old were cleaned with high-pressure water jetting, and the surface was broomed and vacuumed.

RCC placements commenced in 1985, and the dam was completed in August 1987, with over 1,620,000 $yd^3$ of concrete placed, including over 1,470,000 $yd^3$ of RCC. Peak production rates were about 800 $yd^3$ in a 1-hour period and about 10,000 $yd^3$ in a 16-hour period. Figure 10-7 shows the monthly RCC placement rates. The highest monthly production rate was in June 1987, with 240,000 yd$^3$ of RCC placed. The RCC dam was raised about 40 vertical feet in June 1987 and about 50 vertical feet in July 1987.

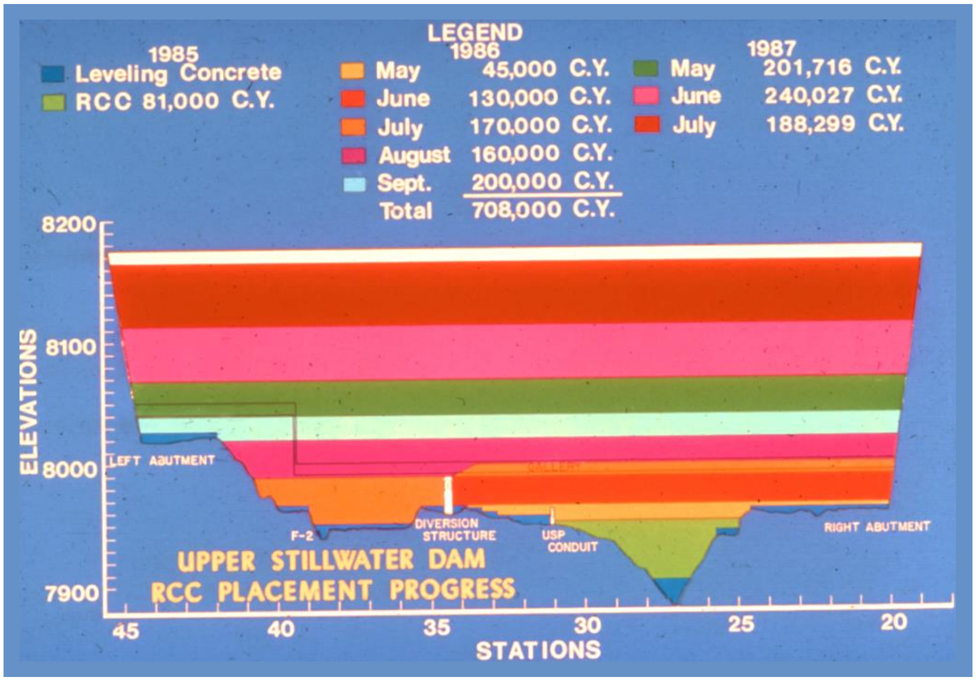



**Figure 10-7. RCC placement record for Upper Stillwater Dam.**

Drainage for the dam was provided by a single 6-foot wide by 10-foot-high gallery, with the gallery centerline located 20 feet from the upstream face of the dam, running lengthwise through the dam from one abutment to the other (see figure 10-8). The purpose of the gallery is to facilitate foundation drainage and grouting, and for observation of the condition of concrete within the dam. The gallery walls were slipformed concrete. The crown of the gallery was formed by a 3-foot radius, half-round corrugated metal pipe, covered with leveling concrete. A mat of reinforcing steel was placed on the lifts 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 foundation drainage curtain was drilled from the gallery and abutment adits. The drain holes were 10-foot on 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.

**Figure 10-8. Gallery at Upper Stillwater Dam showing slipformed concrete walls and corrugated metal pipe crown.**

The uncontrolled ogee spillway was constructed using reinforced conventional concrete (see figure 10-9). A physical hydraulic model study was used to define the ogee shape and the step configuration. The conventional reinforced concrete ogee crest increased hydraulic efficiency over a broad crested weir. Figure 10-10 shows the spillway operating.

Following placement of the dam concrete, the fillets or spaces that remain 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.

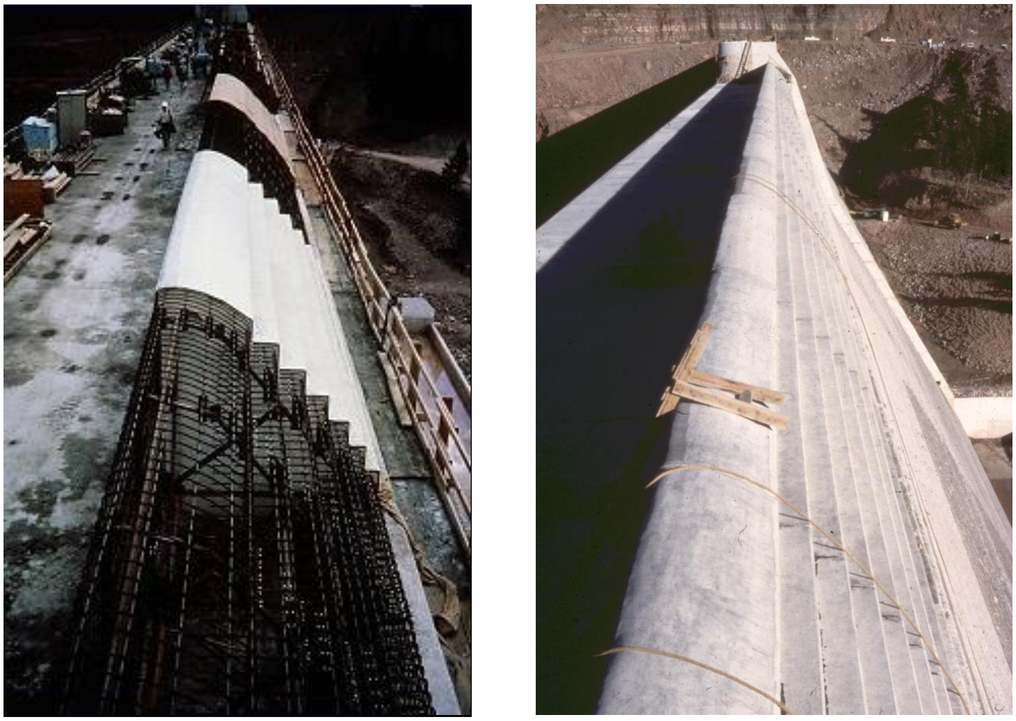


**Figure 10-9. Spillway ogee crest under construction.**

**Figure 10-10. Aerial photograph of Upper Stillwater Dam with the stepped spillway operating.**

### 10.1.5 Mitigation of Seepage through Longitudinal Cracks Formed After Construction

The dam was designed without any contraction joints or crack inducers through the RCC, although contraction joints were placed on the conventional concrete on the crest of the dam. Structural cracking, due to thermal stresses, initiated on the crest contraction joints. Temperature studies were performed during the design phase and analysis indicated that cracks would not extend all the way through the dam and could have an estimated spacing of 50 feet. 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, which initiated cracking at the dam crest. Some of the cracks extended vertically and in the upstream-downstream direction throughout the dam width and into the gallery. In 1989, noticeable flow was reported from 15 different cracks on the downstream face of the dam. This type of vertical cracking is similar to vertical contraction joints and was not considered detrimental to the structural performance of the dam, although it resulted in significant leakage through the dam.

The vertical thermal cracks had an average spacing of 115 feet, which was greater than anticipated during design and resulted in larger crack openings. The largest crack occurred during first filling, initiated at the foundation, and was apparently associated with foundation deformation rather than thermal expansion. Inclinometers installed within the dam measured an offset of about 1 inch. Total seepage from the dam was about 9 cubic feet per second ($ft^3/s$), with the largest crack contributing a large percentage of the total leakage. The cracks tend to widen during the winter months, as a result of colder concrete temperatures, which offsets the reduction in reservoir head due to the lower operating levels. Crack seepage was especially persistent at stations 25+20, 41+10, and 42+85.

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.

Various permanent seepage control methods have been investigated to seal cracks and reduce leakage. Hydrophilic polyurethane resin grouting was first performed for the vertical cracks at stations 25+20 and 41+10 in 1988 and1989, but it did not result in a complete sealing of the cracks, and seepage continued to reach the downstream face. Hydrophilic polyurethane resin injection was performed again in 1992 and 1993 from the upstream face and in the gallery for the cracks at stations 19+80, 22+50, 25+20, 26+00, 28+65, 33+85, 39+70, 39+82, 40+15, 41+10, and 42+85. Pressure grouting with cement was also performed from drill holes in the foundation gallery to depths from 20 to 75 feet below the dam foundation contact along the length of the dam.

The decrease in seepage following the 1992-1993 hydrophilic crack grouting modification was temporary, leading to the decision to pursue further action. A contract was awarded in 2004 to address the cracking and the continued seepage. Cracks grouted in 1992-1993 were regrouted with hydrophilic polyurethane grout above the gallery floor elevation and cement grout below the gallery floor.

The modifications were performed in two phases. In Phase 1, 14 cracks were grouted from the dam foundation to the dam crest. The hydrophobic grout utilized was injected from both the upstream face of the dam and from inside the dam gallery. A series of drains were drilled into each of these 14 cracks. The drain holes for each crack were drilled from inside the gallery and were located on a fan pattern that crossed the crack at various elevations with a seepage collection manifold for each crack. At the three worst cracks (stations 25+20, 41+10, and 42+85), an interior slot waterstop was constructed downstream of the upstream dam face. At these locations, a series of 6-inch-diameter, vertical holes were drilled from the dam crest down into the foundation in an overlapping pattern (aligned with the dam axis) to form a slot. The two ends of this slot were then each drilled with a 12-inch-diameter anchor hole and a 12-inch-diameter side hole. Corrugated stainless steel panels were fabricated and connected together as they were placed vertically from the bottom to the top of the slot, with anchor sections in the larger anchor holes. Once the entire panel assembly was in place in a slot, the slot (between the anchor holes) was filled from bottom to top with heated asphalt grout, the side holes were grouted closed, and the concrete deck was reconstructed over the top of the new waterstops.

Phase 2 modifications consisted of installing an upstream, impermeable membrane over each of the 14 cracks that had been grouted and equipped with a drain during Phase 1. The dam face was cleaned for a distance of 20 feet on either side of each crack, the edges of the crack were ground smooth, and a 40-foot-wide, Permaproof membrane was installed. Although the membrane was capable of accommodating a 300-percent elongation, it was bonded to the dam too closely to the edge of the cracks and experienced cracking at several of the locations shortly after being installed. A second application (of a slightly different membrane material) was placed extending about 1 foot on either side of the crack. This application was anchored some distance back from the crack which allowed movement to be spread over a larger length of membrane. This second application has performed satisfactorily.

### 10.1.6 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 was a 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.

Total leakage from the dam through vertical cracks into the foundation gallery and from the downstream face was about 9 $ft^3/s$ with about 6 $ft^3/s$ originating from the crack that resulted from the foundation movement. 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 leakage was especially persistent at stations 25+20, 41+10, and 42+85. Chemical grouting of the vertical cracks was initially successful. A gradual degradation of the chemical grout has occurred, however, 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 was 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 used at Upper Stillwater Dam 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. At that time, the 70-percent fly ash content was the highest fly ash content mix design for a concrete dam in the United States. The high pozzolan content delayed both the initial setting time, which contributed to improved lift line bond, and delayed the strength (28-day compressive strength was about 35 percent of 1-year strength), yet it still produced long-term compressive strengths exceeding 4,000 $lb/in^2$.

Upper Stillwater Dam was Reclamation’s first RCC dam and was the largest RCC dam in the world at the time of construction. RCC placement rates of 10,000 $yd^3$ in a 16-hour period and 800 $yd^3$ in a 1-hour period remain some of the highest rates accomplished in dam construction. Upper Stillwater Dam proved that RCC is an economical and viable method of concrete placement for large concrete dams. The Upper Stillwater case history affirmed the need to incorporate contraction joints or crack inducers with leakage control measures in RCC dams as a standard practice.

### 10.1.7 References

Dolen, T.P., A.T. Richardson, and W.R. White, 1988. *Quality Control/Inspection, Upper Stillwater Dam*. American Society of Civil Engineers, March.

International Committee on Large Dams, 2003. *Roller-Compacted Concrete Dams*. State of the Art Case Histories, Bulletin 126.

Karl, R.W., Jr., 1985. "Upper Stillwater Dam Construction Program." ASCE Symposium Proceedings, Roller Compacted Concrete, May, Denver, Colorado.

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

Reclamation, 1984a. *Construction Considerations, Upper Stillwater Dam, Central Utah Project, Utah.* Bureau of Reclamation. April.

Reclamation, 1984b. *Mix Design Investigations, Roller-Compacted Concrete Construction, Upper Stillwater Dam, Utah*. Report No. REC- ERC-84-15, Bureau of Reclamation.

Reclamation, 1987. *Hydraulic Model Studies of Upper Stillwater Dam Stepped Spillway and Outlet Works*. Report No. REC-ERC-87-6, Bureau of Reclamation.

Richardson, Alan T., n.d. *Upper Stillwater Dam, Design, Construction and Performance*.

## 10.2 Camp Dyer Diversion Dam Modification (RCC Buttress for Masonry Gravity Dam)

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

### 10.2.2 Design Considerations

When Reclamation constructed New Waddell Dam approximately midway between the original Waddell Dam and Camp Dyer Diversion Dam, it 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 to increase the dead load and sliding resistance to provide a sliding factor of safety greater than 3.0 for normal loads and greater than 1.0 for the maximum credible earthquake (MCE). RCC was selected over conventional concrete for its relative economy and ease of construction. A buttress width of 20 feet with a 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 (figure 10-11).

**Figure 10-11. Heavy equipment safely passing on 20-foot-wide lift at 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, so that neither a concrete apron nor a terminal structure were required. 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. In September 1991, a $3-million contract was awarded to Commercial Contractors, Inc., for construction of the RCC buttresses and associated work.

### 10.2.3 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 less than 2 miles downstream from the damsite. Improved workability and durability of the exposed RCC were achieved by adding an air-entraining agent at a dosage rate two to three times the dosage rate used for conventional concrete having similar mix proportions, for a total air content of about 3.5 percent at the placement. Bonding mortar consisting of cement, sand, water, and admixtures was required on all lift surfaces older than 8 hours 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.

### 10.2.4 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 (figure 10-12). 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 six 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. The concrete was then consolidated by internal vibration to ensure adequate bond and compaction at the contacts. Lift surfaces were cleaned with a power broom to remove all laitance, coatings, and loose materials (figure 10-13), 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 compacted by a power tamper and plate vibrator adjacent to the forms. 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 these measurements were compared with the computed average maximum density of the control section initially established by the prequalification placement. RCC placements for the dike buttress were completed in February and March, and RCC placements for the dam buttress were completed in April and May (figure 10-14). A total RCC volume of 15,400 $yd^3$ was required for the dam and dike at a unit bid price of $45.60/$yd^3$ (excluding cement).

**Figure 10-12. Delivery of RCC from conveyor belt to front-end loader on a lift at Camp Dyer Diversion Dam, with dozer and vibratory roller nearby.**

**Figure 10-13. Power broom for cleaning RCC lift surface at Camp Dyer Diversion Dam.**

**Figure 10-14. Completed Camp Dyer Diversion Dam and Dike, viewed from the right abutment (flow left to right).**

### 10.2.5 Conclusions

Although this was only Reclamation's third RCC project, it was the first to use exposed RCC at a formed face. In addition, it is believed to be the first application of flat drains for internal drainage of a concrete dam (later used for modifications to Theodore Roosevelt Dam). Some innovative forming techniques were also employed for the downstream face and the 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 any detrimental effects to the project.

### 10.2.6 References

Hepler, T.E., 1990. *Design and Construction Considerations for Modification of Camp Dyer Diversion Dam.* Technical Memorandum No. NW-3110-12, Bureau of Reclamation.

Hepler, T.E., 1992. "RCC Buttress Construction for Camp Dyer Diversion Dam." 1992 Annual Conference Proceedings, Association of State Dam Safety Officials, Lexington, Kentucky, September.

# 10.3 Santa Cruz Dam Modification (Curved Gravity RCC Buttress)

## 10.3.1 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 is150 feet high. The curved axis of the dam has a radius of 300 feet and a crest length of 500 feet.

## 10.3.2 Design Considerations

The dam had some Safety of Dams concerns related to the MCE and PMF. The dam was also experiencing severe concrete deterioration due to freeze-thaw. The New Mexico Interstate Stream Commission contracted with 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 (figure 10-15) 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 concerns related to the PMF, the entire dam was to be capable of accommodating overtopping and acting as a spillway. The central 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.

**Figure 10-15. Downstream face of Santa Cruz Dam under construction.**

### 10.3.3 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 $lb/yd^3$. Table 6-3, in section 3 of this report, shows the results of the mix proportioning investigation.

Santa Cruz Dam Modification was the first to use an air-entraining admixture to improve the freeze-thaw performance. 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 C+P ratio.

### 10.3.4 Construction

Twin Mountain Construction Company, a Kiewit subsidiary, was awarded the contract with a total bid of $7.1 million. The bid price for RCC was $45.74/yd$^3$, which did not include the cost of cement. The RCC was placed in two phases. The pugmill was capable of producing 400 tons of RCC per hour. The batch plant was capable of producing both conventional concrete and RCC. In phase I, both the RCC and conventional concrete were produced onsite. For phase II, the RCC was produced onsite, and the conventional concrete was supplied by a local producer. The RCC was delivered to the placement location by a 380-foot conveyor. A Rotec swinger or a front-end loader was used to deposit the RCC in its final location. A dozer was used to spread the RCC, and a vibratory roller was used to compact it. The RCC was compacted to a 1-foot lift height. Leveling concrete was used around the perimeter of the RCC placement, so that adequate bond would be obtained with the existing dam concrete surface and the foundation rock. A minimum of six roller passes was required for compaction. Between phase I and phase II, the outlet works jet flow gates, butterfly valves, and 42-inch outlet pipes were installed. The access house and gallery also needed to be completed before the RCC for phase II could begin. When the placements narrowed to 15 to 25 feet wide, a crane with a 2-$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 conventional concrete using 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 were placed.

The original design for the gallery for the Santa Cruz Dam modification included locating the gallery directly on the downstream face of the existing dam with an 8-foot radius, multiplate, corrugated metal pipe to form and provide support for the RCC for the crown and downstream side of the gallery. This forming system would need internal support. The contractor 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.

### 10.3.5 Conclusions

Santa Cruz Dam Modification was the first to have an air-entraining admixture used to improve the freeze-thaw durability of the RCC. In addition, it was Reclamation's first use 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.

### 10.3.6 References

Metcalf, M., T.P. Dolen, and P.A. Hendricks, 1992. *Santa Cruz Dam Modification.* ASCE Third Conference on Roller Compacted Concrete, February 1992.

Vaskov, S., 1990. "Rehabilitating Santa Cruz Dam," Rocky Mountain Construction, May 21.

## 10.4 Cold Springs Dam Modification (New Abutment Spillway)

### 10.4.1 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.

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 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.

Two potential failure modes were discovered on the original spillway. The first failure mode was 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 Safety of Dams 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 spillway 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.

### 10.4.2 Design Considerations

RCC was used in the modified spillway to provide a more stable structure and help reduce construction cost. The costs for using RCC, compared to reinforced concrete, for the side channel and chute would be similar if the structural concrete was only about 1 foot thick. However, a 1-foot-thick concrete chute was considered 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 feet per second) 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 of the new structure 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 into 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 they 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, high-density polyethylene 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, which made it necessary to design unprotected RCC surfaces with relatively high strength. Anticipated high costs for forming or 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 wraparound RCC (figure 10-16). The original design was a typical rectangular section with sharp, angular corners. The specifications allowed for a radius to be formed in the corners.

**Figure 10-16. Tight turn radius at the upstream end.**

### 10.4.3 Concrete Mix Design

Local materials were not available for the RCC construction, and 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 RCC mix was designed to provide a compressive strength of 3,500 lb/in$^2$ 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. In addition, 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 offered the contractor the option to eliminate pozzolan from the RCC mix, based on the limited space onsite for the batch plant. The contractor decided to use the no-pozzolan mix. Tables 4-10 and 6-1 show the concrete mix design details.

### 10.4.4 Construction

The 18,000 yd$^3$ of RCC was placed in nearly horizontal layers that were approximately 1 foot thick and had 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 the mix included pozzolan. 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 placement of the next lift. The specified cleanup of the day-old lifts could not adequately remove all contaminants from the hardened surface. In addition, the hardened lifts did not bond well to subsequent lifts unless bonding mortar was used. When typical mixes are used, the lifts will bond well after 12 hours if 60 percent or more of the cement is replaced with pozzolan; however, the time period 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 and then placed in front of the dozer blade with the backhoe (figure 10-17). The RCC was spread in uniform layers by the dozer and compacted by the roller.

The 10-foot-wide, 1-½:1 (horizontal to vertical) chute side slopes were unformed. The dozer blade was retrofitted with side extensions located 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 fixing the plate rigidly at a 45-degree angle from horizontal proved more effective. 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 that were fairly well compacted (figure 10-18).

**Figure 10-17. Placing RCC with a backhoe.**

**Figure 10-18. Completed RCC chute (Cold Springs Dam).**

### 10.4.5 Conclusions

The lessons learned from Cold Springs Dam Modification are summarized below:

- On this project, cleanup requirements after 12 hours or more were the same for RCC mix without pozzolan as they are for conventional mass concrete.
- Unless the subsequent lift is placed immediately, bonding mortar is needed if bond is expected on lift lines.

- RCC can be placed over the 6-inch-diameter, high-density polyethylene without protection, as long as care is taken to avoid damage.

- Sharp corners are difficult to construct in RCC but are possible if the corners are allowed to be rounded.

- It is difficult to compact the exposed sloping face unless it takes place after the horizontal lift is compacted. However, if a lower density material is acceptable on the surface, the exposed sloping face can be successfully compacted using a dozer blade with an extension.

### 10.4.6 References

Reclamation, 1988. "Draft Corrective Action Alternatives Report, Cold Springs Dam, Umatilla Project, Oregon." Bureau of Reclamation.

Reclamation, 1993. *Spillway Alternatives, Cold Springs Dam, Umatilla Project, Oregon*. Bureau of Reclamation, Decision Memorandum No. 3110-0193.

Reclamation, 1994. *Value Engineering Final Report, Cold Springs Dam Modification Conceptual Design*. Bureau of Reclamation,

Reclamation, 1996. *Analyses and Design of the Spillway Modifications and Other Hydraulic/Hydrologic Corrective Actions*. Bureau of Reclamation, Technical Memorandum No. COL-8130-FD-TM-96-01.

## 10.5 Ochoco Dam (Spillway Basin)

### 10.5.1 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 the deficiencies was the lack of an energy-dissipating structure (stilling basin). The spillway prior to modifications was a concrete, uncontrolled overflow structure, located just off of the left abutment of the dam. The spillway had a 627-foot-long, trapezoidal-shaped chute with a width that tapered from 64 to 50 feet. The crescent-shaped spillway ogee crest had a length of 275 feet. Spillway flows discharged into an unprotected channel, which directed the flow back into Ochoco Creek. Subsurface field explorations and geotechnical analysis indicated that erosion of the unprotected downstream channel was a concern. As a measure to address and reduce this potential, a stilling basin (figure 10-19) using 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.  This summary focuses on the RCC stilling basin that was added at the end of the existing chute.

**Figure 10-19.  Aerial view of Ochoco spillway.**

### 10.5.2 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.  In this case, however, the foundation for the left side slope and most of the floor was bedrock, while 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 required that the left RCC basin side slope be made as steep as possible.

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

All conventional-type stilling basins were eliminated from consideration due to these site conditions listed above.  In order to address these site conditions, a scaled-down hydraulic model was used to evaluate the size, shape, and configuration of the RCC stilling basin.

A concern arose that a nonuniform foundation could develop excessive or significant cracks in areas having a potential for highly dynamic flow conditions. Therefore, drains were placed under the structure to relieve uplift pressure and to pick up seepage should future cracking of the RCC occur. No significant cracking has been visible at the right side wall of the structure that was placed on the new backfill, even following a significant spillway discharge.

The foundation for the RCC stilling basin can be divided geologically into two categories: (1) the entire left side, most of the floor, and a small part of the right side founded on the bedrock formation identified as John Day; and (2) most of the right side founded on compacted backfill above John Day. Alluvium was encountered at the downstream end of the floor for approximately the last 50 feet. This alluvium 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 to ensure public safety and minimize freeze-thaw damage to the RCC.

### 10.5.3 RCC Materials

The contractor attempted to produce sand and coarse aggregates for the RCC from onsite material, but 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. Ultimately, several different sources were used for both sand and gravel. Because RCC operations are very fast moving and, in this case, took place continuously around the clock, it became a common battle to continually adjust the mix proportions and/or obtain consistent strengths.

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.

### 10.5.4 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 the need to shut down RCC placement to make additional excavation, as well as difficulties in obtaining required slopes and configuration.

- Changing aggregates throughout the RCC placement resulted in inconsistent strengths and made it difficult to recognize when it was necessary to adjust the mix.

- The contractor chose a relatively low-end mixing plant, which did not meet specifications requirements. The plant was eventually approved because the alternative was to delay construction until the following year, which would have significantly increased costs and posed significant risk to the downstream residents.

### 10.5.5 Conclusions

The spillway modifications began in July 1996 and were completed in March 1997. It took 3 weeks on a 24-hour basis to place approximately 19,000 $yds^3$ of RCC in the stilling basin. The work was delayed when significant survey problems were encountered. In an ideal situation, the RCC could have been placed in about 2 weeks.

### 10.5.6 References

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

Stanton, D., 1997. *Ochoco Dam Spillway Modification Designs*. USCOLD Newsletter No. 11, United States Committee on Large Dams, March.

## 10.6 Pueblo Dam Modification (Foundation Stabilization)

### 10.6.1 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. The original construction began in 1970 and was completed in 1975.

### 10.6.2 Design Considerations

Potential Safety of Dams deficiencies were identified during the 1997 risk analysis. In 1998, modifications were completed to address the potential for sliding failure of the spillway foundation. 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 was capped using reinforced concrete. Impact blocks were 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 that 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 (figure 10-20). 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.

**Figure 10-20. RCC construction in the stilling basin at Pueblo Dam.**

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.

### 10.6.3 RCC 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. Table 10-1 shows the average RCC starting mix proportions for the bonding mortar.

**Table 10-1. Average starting mix proportions for bonding mortar for construction**

| Ingredient | Quantity |
|---|---|
| Water | 410 lb/yd$^3$ |
| Cement | 915 lb/yd$^3$ |
| Sand | 2515 lb/yd$^3$ |
| Admixture | Manufacturer’s recommended dosage |

### 10.6.4 Construction

ASI RCC, Inc., was awarded the construction contract. The RCC placements began on January 7, 1999, and were completed on March 30, 1999. About 63,000 yd$^3$ of RCC was placed in 3 months. The concrete overlay and side panels were placed between June and November 1999.

The high-strength rock bolts were double corrosion protected, and they consisted of 1-3/8-inch-diameter, high-strength bars that were grouted into polyethylene sheaths. Some rock bolts did not meet specification requirements and pulled out of the sheaths during testing, due to manufacturing problems. These rock bolts were replaced.

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 rock bolts placed through the apron.

A February 18, 1999, site visit with RCC consultants resulted in concerns related to RCC lift line bond strength. Testing was performed after construction to evaluate lift line integrity. The designers evaluated the test results. 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 on the same day as the previous lift and were considered 12 hours old or less, while other lifts were placed the following day or even 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 uncertain, but one theory suggests 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 site conditions. The rounded aggregates used in the RCC mix may also have contributed to the problem.

In addition, the use of front-end loaders was not excluded in the specifications, and 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. 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 of this damage was discovered 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.

The low cement content of the RCC, compared to the pozzolan (approximately 120 pounds of cement to 180 pounds of pozzolan), prevented the RCC from gaining 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, which also may have contributed to the problems. Also, damage to the partially cured RCC surface can result in loss of strength in partially hydrated cement paste and can loosen the compacted surface. Compaction of the next lift likely did not supply adequate energy to recompact the damaged lift below. RCC 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.

An additional possibility is that lift surfaces were damaged by the use of equipment other than front-end loaders during construction, such as dozers, vacuum trucks, transient mixers, dump trucks, cranes, or other vehicles. This other equipment may have traveled on the surface during the critical first 48-hour period and could have damaged lift surfaces that were more than 1 day old at the time subsequent placements were made. Cleanup efforts were more vigorous for older lift surfaces making it more likely that any damaged RCC on them was removed. The type of tires and turning radius of this equipment also make it less likely to produce damage as extensive as the damage produced by front-end loaders, which were most active the day a subsequent placement was made. 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. Due to the length of time to place a lift, however, the lift surfaces may not have been adequately protected initially while a placement was ongoing due to limited 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 placements, the crews had time to apply additional water to the drying RCC surface, which may partially explain why the concrete cored showed that the older lifts surfaces experienced fewer problems.

The RCC mix at Pueblo Dam used rounded coarse aggregates instead of crushed coarse aggregates. A similar mix and construction conditions were used at Upper Stillwater Dam in Utah, but the problems associated with a porous zone below the lift lines were not observed at that dam. One significant difference may be that crushed aggregate was used at Upper Stillwater. When round aggregates are used, two factors may come into play. First, round aggregate is smooth and may more easily separate from the paste when it is deposited on the lift surface. The lack of surface friction between the aggregates and the paste can also result in more damage from equipment travel. Second, the Vebe times, which indicate the workability of the RCC, were similar for round aggregates at Pueblo and crushed aggregates at Upper Stillwater. However, due to 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. Without adequate paste, any surface damage would be more pronounced.

### 10.6.5 Crack Inducer Joint Grouting

The RCC was designed and constructed using crack inducer plates on every other lift at a spacing of 40 feet on center along the length of the spillway stilling basin. The crack inducer plates were installed to create a controlled crack location in the RCC similar to a contraction joint. Grouting supply, vent, and return lines were embedded in the overlay concrete. Six-inch-diameter vertical holes were drilled into the RCC at 10-foot spacing for the contraction joints running upstream to downstream for temperature loading, and at 5-foot spacing for the cross-canyon contraction joints. The primary reason for grouting the RCC contraction joints was to provide adequate transfer of loads from the foundation. Additional isolation holes were drilled in the contraction joints to create isolation zones to limit the size of the zones for grouting.

The overlay concrete was anchored to the RCC with anchor bars, and waterstops were installed at all contraction and control joints (see figures 10-21 and 10-22). Some grout leakage occurred into adjacent grouting zones because the waterstops in the overlay concrete and the isolation holes were not connected, which created a small gap in the overlay panel contraction joint between the top of the RCC and the waterstop.

**Figure 10-21. Conventional concrete overlay on the RCC stilling basin placements.**

The contraction joint monitoring included 22 vibrating wire joint meters and 51 thermal couples. The contraction joints were grouted after the second winter, when the measured RCC temperatures dropped below 50 °F. Figure 10-23 shows the RCC temperature measurement data, and figure 10-24 shows the joint meter measurement data.

**Figure 10-22. Conventional reinforced concrete overlay on the RCC placements. Note the embedded supply and return lines for RCC crack inducer joint grouting, as well as waterstops and reinforcement embedded in the conventional concrete overlay control joints.**

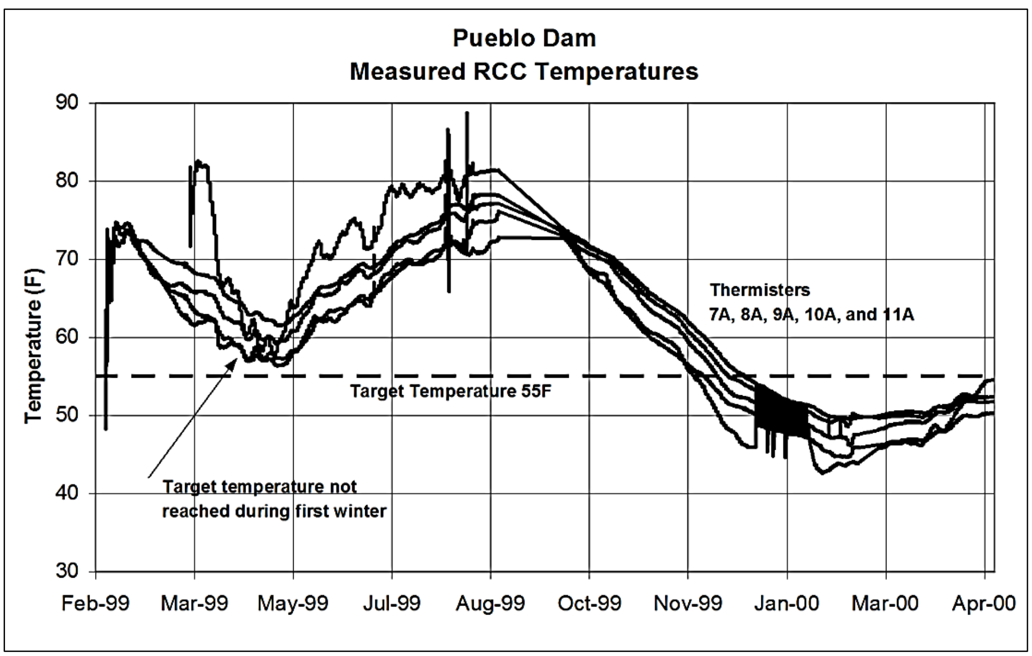



**Figure 10-23. Measured RCC temperatures.**

Grout plant and equipment consisted of a movable, hydraulically powered grout plant; an 18-cubic-foot ($ft^3$) colloidal mixing tub with a high-speed centrifugal pump; a 24-$ft^3$ agitator tub; a helical screw grout pump; a 1½-inch, reinforced rubber hose connected to the circulating grout line with "camlock" couplers;

pressure gauges; and radios. A signal light system was also used to facilitate communication. The green and red light system was controlled by the plant inspector to indicate when a specific batch of grout was being pumped.

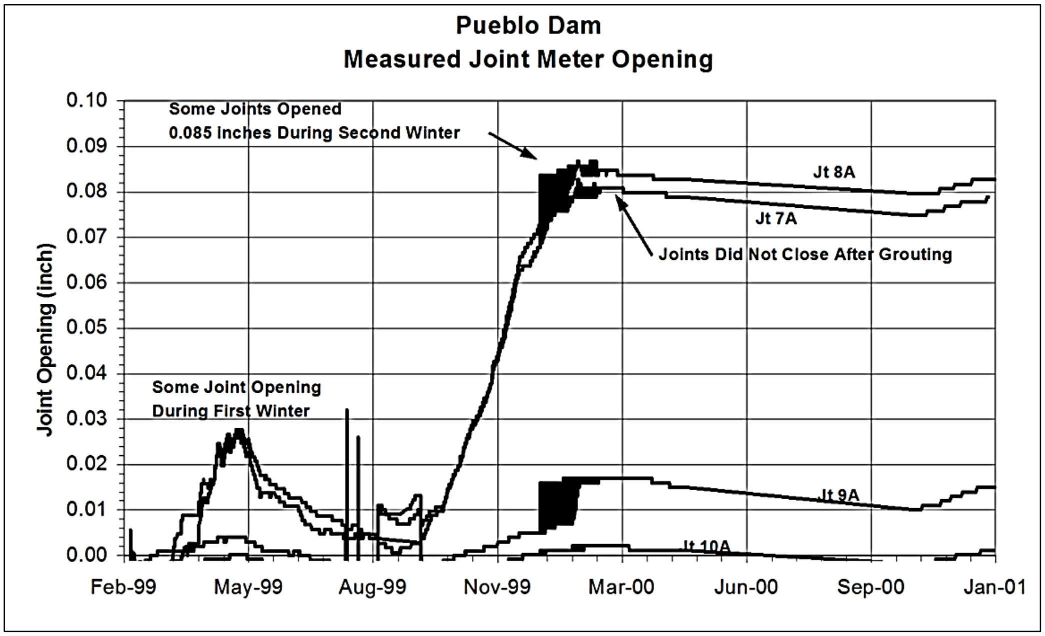
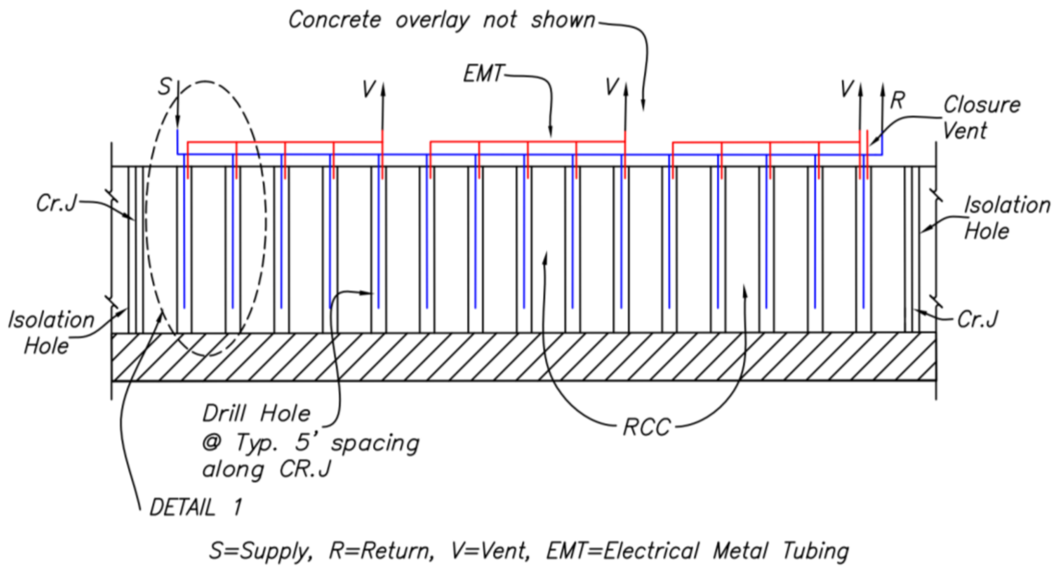



**Figure 10-24. Measured crack inducer joint meter opening in the RCC.**

Grouting of the crack inducer (contraction) joint began February 14, 2000, and was completed March 3, 2000. The water table was lowered before grouting. Water testing took place at least 1 day before a zone was grouted. Water testing was performed to determine leakage and interconnnection of the joint systems. After grouting began on a group of joints, water was injected on all adjacent joints that were not being grouting at the time. Water hookups to these joints was planned well in advance so that grout leakage could be determined and the joints could be washed clean before any grout could set up in them.

The stilling basin crack inducer joints were basically below ground level and, therefore, could not be drained by gravity flow. The piping system (figure 10-25) was designed to inject grout into the bottom of the joint zone to be grouted, and the venting system was at the top of the joint, allowing the water to flow out of the vent pipes. Initial grouting was used to force air and water out of the system using a 2:1 water/cement ratio. The 2:1 mix was used as an interface mix so that the thinner grout mix would flow ahead of the heavier grout. A mix of 1:1 to 0.8:1 was used to complete the grouting. Grout was injected at a slow rate using batches that varied from 1 to 3 $ft^3$ per batch, which required at least 4 hours per zone. Multiple zones were grouted. A pressure of 10 to 20 $lb/in^2$ was held for 1 to 2 hours. A total of 1,361 bags of cement were accepted during the crack inducer joint grouting.



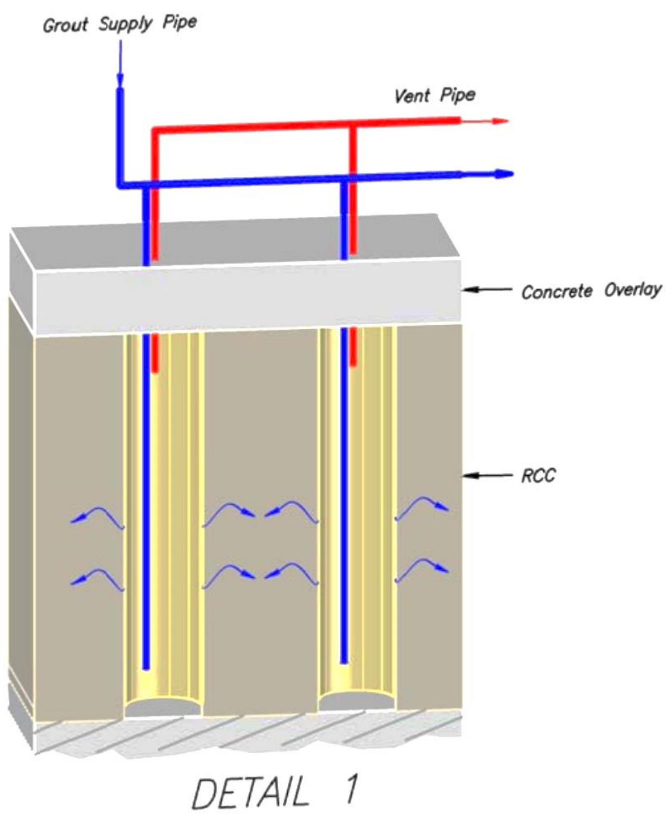




**Figure 10-25. Section view through a RCC stilling basin crack inducer joint at Pueblo Dam, showing the concept for the insolation holes and the supply, return, and vent line layout for crack inducer joint grouting. Detail 1 shows a schematic of the grout supply and vent pipes in a typical grout hole.**

It was anticipated that water could enter the stilling basin though weep holes originally installed in the stilling basin floor. A water removal system, including a sump, was installed to control water entering the stilling basin. The water removal system was grouted March 3, 2000. The system accepted 388 bags of cement.

### 10.6.6 References

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

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

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

## 10.7 Vesuvius Dam (Overtopping Protection for Embankment Dam)

### 10.7.1 Background

Vesuvius Dam (figure 10-26) is an embankment dam owned and operated by the U.S. Department of Agriculture, U.S. Forest Service (USFS). The dam is located in the Wayne National Forest in southern Ohio. The USFS built the dam in 1937 as a Civilian Conservation Corps project.

### 10.7.2 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

**Figure 10-26. A view of Vesuvius Dam, Ohio, showing RCC armoring of the crest and downstream face.**

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.

A park with picnic shelters is located 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 significant flood event, 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 considered necessary. 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, as well as three rows of 6-inch-diameter, perforated PVC drain pipe: two rows on the face of the dam and one row in the stilling basin. The PVC drains exit into the spillway and outlet works channels.

### 10.7.3 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 cost savings. This also allowed the use of one aggregate stockpile instead of two. The USFS agreed to this change, as long as the RCC mix met the strength requirements. The Ohio DOT allowed aggregate to have 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 design became a soils approach, rather than a concrete approach, mix design. The specifications allowed the use of 20-percent 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 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.

### 10.7.4 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 $94.65/yd$^3$, for a total of 9,500 yd$^3$ of RCC.

An Aran 200-ton/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 six 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 lift height of 1 foot after a minimum of six roller passes. The upper one-third of the steps were unformed and were 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 fines content. Moisture tests were performed on the stockpiles.

A test section was constructed from October 17-20, 2001. The test section was part of the stilling basin and was 100 feet long by 8 feet wide. RCC placements were started November 29, 2001 and took 4 weeks to complete. RCC production averaged about 400 cubic yards per day (yd$^3$/d). 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 at 151.5 lb/ft$^3$.

## 10.8 Many Farms Dam (Emergency Spillway)

### 10.8.1 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 Navajo Indian Tribe owns and operates the reservoir for irrigation and recreation. From 1999-2001, major dam safety modifications were made to the dam embankment, outlet works, and spillway. 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 spillway was inadequately sized to pass the PMF and more frequent flood events.

### 10.8.2 Design Considerations

Agreements between the Bureau of Indian Affairs and the Navajo Indian Tribe included the following design requirements for the spillway modifications:

- A new spillway would be located north of the main embankment at Dike BC to enable spillway discharges to enter Chinle Wash downstream of the dam access road bridge and canal flume.

- Spillway discharges would be limited to the safe channel capacity at Rock Point, Arizona.

- The original spillway crest elevation would be maintained.

- The spillway structure would 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. 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 was set approximately at 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, but it could result in the need for repairs following 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 feet per second during the PMF.

The RCC used to form the downstream stilling basin and apron was 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 no zone 2 filter material exists to act as a filter. The stilling basin would induce a hydraulic jump and reduce the velocities exiting the discharge channel for events less than a 1,000-year flood. For conditions where the hydraulic jump sweeps out of the stilling basin, 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.

The design was modified to include the use of conventional concrete between the RCC and any sloping foundation, largely because it worked well for RCC placements at the Pueblo Dam Modification.

The original design called for making 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 made 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.

### 10.8.3 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 unit weight for RCC was 140 lb/ft$^3$. The RCC mix design was based on a cementitious materials content of 350 lb/yd$^3$ (with 20 percent pozzolan), a water content of 165 lb/yd$^3$, and an air content of 3 percent.

### 10.8.4 Construction

The new RCC spillway structure was constructed between September 18 and December 1, 2000. The excavation for the spillway began after the embankment portion of Dike BC was constructed and the downstream toe drain was installed. The contractor used a Caterpillar D6 dozer and a 330 excavator to excavate and shape the spillway channel for placement of the RCC. The excavation was completed September 21, 2000.

The contractor chose to erect a concrete batch plant immediately downstream of the spillway apron and began mobilizing the plant on August 4, 2000, with the hauling and stockpiling of concrete aggregates, cement, and flyash. The plant was tested, calibrated, and then approved for use on September 28, 2000. Several test batches of RCC were produced to determine the quality of the RCC mix, and RCC test section placement began. 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 on each side of the spillway to enable access to the placement and an opportunity to clean 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 then shoveled it into place. Immediately after the leveling concrete was placed, RCC was batched directly into a 10-wheel, end dump truck and transported to the upstream side of the dike, where it was offloaded into a holding bin. A Caterpillar 966, front-end loader then picked up the RCC and transported it to the placement site, where it was spread in approximately 14- to 16-inch lifts using the Caterpillar D3 dozer (figure 10-27). After 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.


**Figure 10-27. View of spillway stilling basin placement operations at Many Farms Dam.**

A laborer remained onsite to spray the RCC surface to maintain a water cure. The following day, laborers cleaned larger debris from RCC surface with brooms and shovels, then power washed the RCC at 3,000 lb/in$^2$ and a jet vacuumed it to provide a clean 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. To prepare for the next RCC lift, laborers used concrete rakes to spread a ¼- to ½-inch-thick layer of bonding mortar on the cleaned surface. Reclamation's Farmington Construction Office core drilled the test section. A 14-day period followed to allow data to be collected and analyzed on the test section, as well as to permit the placement to cure.

On October 16, 2000, the contractor resumed placing RCC, beginning with the bottom lift of the stilling basin downstream of the dike, using the same procedures, lift thickness, and equipment that were 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 used a Caterpillar 302.5 excavator with a shop-fabricated vibrating plate to compact the edge (figure 10-28). The vibrating plate was constructed with a 45-degree angle to allow compaction of the outside 1 foot of the lift's top surface 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.

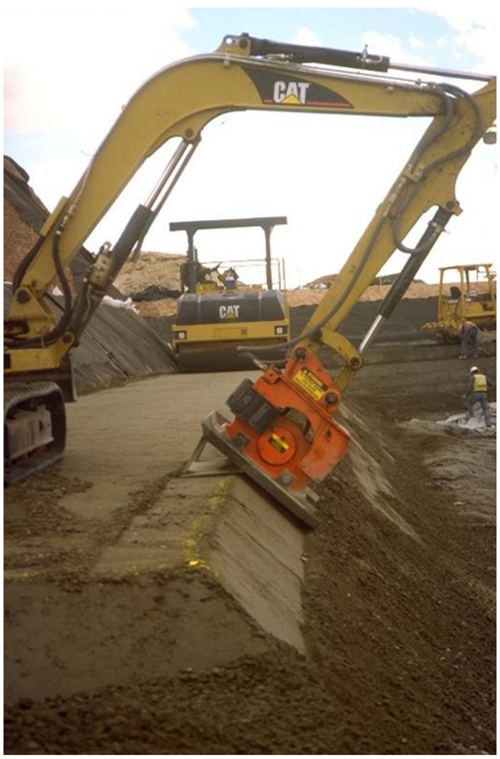



**Figure 10-28. View of Caterpillar 302.5 excavator equipped with vibrating, angled plate used to compact the top and outside edges of a compacted RCC lift along the left spillway wing wall at Many Farms Dam.**

The contractor used several methods to cure the RCC, including water, a wax-based curing compound on the exposed RCC surfaces, 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. Geotextile fabric was then placed in the trench, and a Caterpillar excavator or front-end loader was used to overlay it with Zone 4A rock. The RCC placement operations for the spillway were completed December 1, 2000 (figure 10-29). The total project cost was $12,795,228. The RCC has performed satisfactorily; however, the spillway has not yet operated.

**Figure 10-29. View of the completed spillway located in Dike BC of Many Farms Dam. Note the installed safety fencing and the sand backfill of the stilling basin.**

### 10.8.5 References

Reclamation, 2001a. *Hydraulic and Structural Design for Modification of the Outlet Works—Many Farms Dam Modifications.* Bureau of Reclamation, Technical Memorandum No. NMF-FDES-3110-1.

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

## 10.9 Jackson Lake Dam (Upstream Slope Protection for Embankment Dam)

### 10.9.1 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 (figure 10-30). The dam was completed in 1914. The dam was modified from 1987-1989 to address Safety of Dams concerns related to the MCE.

Reclamation was unable to locate a viable riprap source to protect the upstream slope 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; however, this was the first time Reclamation used a coarse-grained soil-cement.

**Figure 10-30. North-facing aerial view of Jackson Lake Dam under construction.**

Based on current RCC technology at the time of dam modification, 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, and the thicker lift placements were proposed to reduce the construction time.

### 10.9.2 Concrete Mix Design

A Type II cement was proposed at Jackson Lake Dam due to the potential for reactive aggregates. The cement content was increased from the initial mix proportion of 224 lb/yd$^3$ to 400 lb/yd$^3$. No specific design requirements existed 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 and averaged 10.5 percent. Moisture content ranged from 5.5 and 8.6 percent. Table 6-3 shows the average of the field test data mix proportioning investigation results.

### 10.9.3 Construction

The contract solicitation required a request-for-proposal for the Safety of Dams modification. National Projects, Inc., was selected as 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 $14/yd$^3$ for the first 27,000 yd$^3$ and $11/yd$^3$ for soil-cement in excess of 27,000 yd$^3$. The cost of cement was not included in the soil-cement bid price. The prime contractor used two subcontractors to produce and place the soil-cement: Judd Brothers Construction Company and Peltz Construction Company, respectively.

From July 26-30, 1988, a test section strip was placed between stations 50+50 and 55+00. Based on the test section results, a determination was made to place the soil-cement in 9- to 10-inch lifts and use an initial mix design with a 9-percent cement content and 8.5-percent moisture content, by dry weight. Both the cement and moisture content were adjusted during construction.

The soil-cement placements began August 8, 2002. The contractor worked six 10-hour shifts per week. Production averaged about 1,000 $yd^3$ 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 and then spread using an ABG Titan 280 paving machine with a duo-tamp, high-density screed. The soil-cement was compacted by six passes of an Ingersol Rand SD100, steel drum vibratory roller (three passes with the vibrator engaged, and three static passes). To achieve bonding on lifts, a cement slurry bonding agent was applied between them. 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 1988. A total of 44,900 $yd^3$ of coarse-grained soil-cement was placed.

## 10.10 Clear Lake Dam Modification (RCC Gravity Dam with Joints)

### 10.10.1 Background

Clear Lake Dam is located on the Lost River in northern California and is owned and operated by Reclamation. It provides irrigation water to the Langell Valley and Horsefly Irrigation Districts, as well as providing drainage control onto reclaimed lands adjacent to the Lost River within the Tule Lake and Klamath Irrigation Districts. The reservoir is 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 from 1908-1910 and was raised 3 feet in 1938.

### 10.10.2 Design Considerations

Safety of Dams 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 used to maintain reservoir levels during the modification work, and then be breached. An RCC dam was selected, rather than 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 and constructability, less hydrologic risk during construction, and less disturbance of downstream wetlands compared to 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 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 it has a slope of 2/3:1 between elevations 4530.0 and 4506.0. A 4-foot-high, concrete parapet wall is located on the upstream edge of the dam crest to provide flood protection to elevation 4548.0, which is 0.8 foot 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, as well as a beam-type guardrail along the downstream edge. The final RCC lift surface has a 1-percent slope downstream for drainage. The dam has a total RCC volume of 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 to match the original ground surface and provide a downstream buttress. Compacted backfill was to be placed along the upstream face to elevation 4515 to buttress the upstream channel alluvium.

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.

### 10.10.3 Concrete Mix Design

Reclamation materials laboratory personnel prepared final mix designs for RCC. 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 its 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.

### 10.10.4 Construction

Specifications for Clear Lake Dam modification were issued April 26, 2001, and bids were opened June 19, 2001, for the firm-fixed-price contract. The low bidding contractor was ASI Civil Constructors of Carlsbad, California, for a total bid price of $5,991,250. The bid price for RCC was $103.50/yd$^3$, plus cementitious materials, for a total volume of 18,000-yd$^3$. Project costs were most impacted by the remoteness of the site and by the 40-mile haul distance for concrete aggregates. The contractor was awarded the contract July 10 and received a Notice-to-Proceed 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, which delayed the start of RCC placing operations at 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, and conventional leveling concrete was placed just prior to RCC placement at the following locations: (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 2/3:1 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, and smaller power tampers were used near the abutment contacts and downstream forms. To allow development of bond strength, RCC lift surfaces were cleaned by vacuuming, air jetting, air-water jetting, high-pressure water jetting, and sand blasting, depending on 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 construction joints more than 12 hours old.

Figure 10-31. Contraction joint detail in formed upstream face of Clear Lake Dam, showing chamfer strip for sealant, ½-inch joint filler, and PVC waterstop within leveling concrete (from test section).

Contraction joints were provided within the RCC dam at maximum 50-foot intervals, and at abrupt changes in the foundation surface, to control cracking. 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 (figure 10-31).

Construction of the RCC dam occurred in two shifts. Joint surface preparation and form work construction took place during the day shift, and all RCC placements were 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 °F, 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.

To provide internal drainage for the RCC dam, vertical holes were drilled on the completed dam crest at 10-foot centers, extending approximately 20 feet into the dam foundation. 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 seven 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 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 (figure 10-32). 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.

**Figure 10-32. First filling of the completed Clear Lake Dam, an RCC gravity dam. New outlet works intake tower with control house and jib crane shown near left abutment. Original outlet works intake tower shown at left, on alignment of original embankment dam.**

### 10.10.5 Conclusions

Safety of Dams 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 contraction joints with waterstops, an upstream face using conventional leveling concrete and exposed RCC on the dam crest and downstream face.

On formed RCC without GERCC, segregation can result in rock pockets, such as those shown in figure 10-33.

**Figure 10-33. Photograph of the downstream face of Clear Lake Dam showing the formed RCC. Note the segregation that occurred against the forms during the RCC placements.**

### 10.10.6 References

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

Hepler, T.E., 2002. "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.

# 10.11 Glendo Dam (RCC Cutoff Wall for Auxiliary Spillway)

## 10.11.1 Background

Glendo Dam is an embankment dam owned and operated by Reclamation. The dam is located in the Wyoming and was constructed in 1959.

## 10.11.2 Design Considerations

Glendo Dam was evaluated and found to have inadequate spillway capacity. The Safety of Dam modification design included constructing a new auxiliary spillway at the dam to provide additional spillway capacity. The uncontrolled ogee auxiliary spillway consists of a conventional, reinforced concrete overlay on top of an RCC cutoff. The conventional concrete ogee had contraction joints every 20 feet with waterstops, and every other contraction joint matched the RCC crack inducer joint locations, which were installed every 40 feet. The spillway consists of an unlined approach channel sloping 0.01 foot per foot from the upstream side of the ogee crest structure, at elevation 4655, to the reservoir. The RCC cutoff consisted of a trapezoidal-shaped base with ½:1 (horizontal:vertical) slopes that extended 28 feet below the invert of the approach channel to the heel, at elevation 4627. The invert then slopes downstream at 0.01 foot per foot for a distance of 23.3 feet to the toe of the RCC plug. The concrete overlay is anchored to the RCC plug with No. 8 bars that are embedded 5 feet into the RCC. If the auxiliary spillway operates, the RCC plug is intended to perform as a deep cutoff/gravity wall to prevent a breach through the Brule ridge. The auxiliary spillway is considered an emergency spillway.

Leveling concrete with a thickness of about 3 inches was placed on the rock surface to provide a uniform surface for the first RCC placement and to protect the foundation (much like a mud slab) to prevent deterioration of the exposed Brule, which tended to weather immediately after exposure, drying and rewetting. A 4-inch slump was allowed on the leveling concrete.

GERCC was used on the perimeter of the RCC placement, on the interface surface with the Brule formation and RCC. The GERCC was applied on the edges of the previously compacted RCC lift after the next uncompacted RCC lift was spread. Then, the grout was covered by uncompacted RCC and consolidated using immersion vibrators and plate vibrators. The application rate of grout was determined and then controlled by buckets per linear footage. Small piles of uncompacted RCC at 4-foot spacing were used to control the application rate.

## 10.11.3 Concrete Mix Design

The design requirements for the RCC included a compressive strength of 3,000 lb/in$^2$ at 365 days. The initial RCC mix was based on aggregates from the local area. The initial mix proportion of the RCC had an estimated cementitious content of 350 lb/yd$^3$ and included the use of 210 lb/yd$^3$ of pozzolan, 140 lb/yd$^3$ of cement, 140 lb/yd$^3$ of water, 1,545 lb/yd$^3$ of sand, 1,935 lb/yd$^3$ of coarse aggregate, and an air content of 4 percent. The coarse aggregate with a maximum aggregate size of 1-1/2 inches was used. The sand was based on ASTM C 33, fine aggregate, with an allowed range of 0 to 10 percent passing No. 200 sieve. The gravel was based on ASTM C 33, size No. 57 (750 lb/yd$^3$) and No. 3 (1,185 lb/yd$^3$). The starting mix proportion for the grout used in the GERCC was 410 lb/yd$^3$ of water and 915 lb/yd$^3$ of cement.

### 10.11.4 Construction

Reclamation designed the modification. The contract was awarded to Johnson Wilson. The bid price for RCC was \$95/yd$^3$, for a total of 18,500 yd$^3$ of RCC.

The test section was constructed from September 9-15, 2011, and was located just downstream of the auxiliary spillway site (figure 10-34). The test section was 100 feet long by 8 feet wide and consisted of five lift placements. The contractor also constructed a gravel-covered ramp to reduce contamination of the RCC lift surfaces during the RCC test section placements. The purpose of the RCC test section was to evaluate:

- Methods for forming, placing, consolidating, and curing RCC; as well as methods for placing GERCC and leveling concrete
- Prequalification of vibratory rollers, power tampers, and plate vibrators
- Methods and equipment for batching, mixing, transporting, placing, compacting, curing, protecting, and cleanup
- Methods for installing crack-inducer plates

The specifications also required that eight 6-inch-diameter, 5-foot-deep core holes be drilled from the top of the RCC test section for inspection and evaluation. The concrete core drilling was completed September 29, 2011, which was 11 to 14 days following final placement of the RCC test section. The formed RCC surface included in the test section also provided a visual indication of the RCC without GERCC (figure 10-35).

After evaluation of the test section and core holes, a summary report was prepared and given to the contractor, specifying areas where specifications were met and areas that required improvement. The Government examined drilled cores and, based on the number of core breaks that occurred on the top of the first RCC lift, better cleanup was required on Type 2 lift surfaces (cold joints between 24 and 72 hours old) and Type 3 lift surfaces (greater than 72 hours old) lift surfaces. The required cold joint (Type 2) cleanup consisted of power brooming, followed by standard cleanup (air and water jetting, followed by vacuuming, did not adequately prepare cold joint surfaces), and sand blasting was used where necessary. For construction joints (Type 3) greater than 72 hours old, sandblasting or high-pressure water jetting, followed by a standard cleanup, was specified.

**Figure 10-34. Placement of RCC test section using a Telebelt and dozer for placing and spreading.**

**Figure 10-35. Placement of RCC test section demonstrating formed RCC without GERCC.**

RCC placements began March 26, 2012, and were completed May 4, 2012 (see figures 10-36 through 10-38). The average amount of cementitious material used was 350 lb/yd$^3$, including 140 pounds of cement and 210 pounds of pozzolan.

Sand was obtained from a local stockpile and was screened and washed to meet the ASTM C-33 requirements. Aggregates were obtained from a local quarry in Guernsey, Wyoming. A mixture of crushed and rounded river rock, with a maximum size of 1-1/2 inches, was used. A tremie pipe was used from the Telebelt conveyor to the placement area to reduce the potential for segregation resulting from the drop height (see figure 10-36). The drop into the trench and the height of piles were both limited in the specification to 5 feet. Overall, the specification requirements were adequate to reduce segregation potential. Some segregation occurred when the height of the piles exceeded 5 feet. The use of crushed aggregate or smaller maximum size aggregate (1 inch) may have reduced some of the segregation.

**Figure 10-36. RCC placements for the deep cutoff section of the auxiliary spillway.**

A central mixing concrete batch plant with a drum mixer was used to produce the RCC. This type of mixing plant required diligence in cleaning of fins at the end of each shift. Rear dump trucks delivered the RCC into a dump hopper, which dropped the RCC into a conveyor that transported it onto the Telebelt. The Telebelt was used to convey the RCC to the placement location. A Cat D4H dozer with grade control laser was used to spread the RCC. The RCC was compacted by six passes of a Hypac C-766, double drum, vibratory roller (two static passes, and four passes with the vibrator engaged). The nuclear density gauge was used to take in-place wet density measurements and were also used establish the computed average maximum density during the test section, and then again at a control section at the beginning of the RCC placements. Based on the nuclear density gauge, the measured density of the RCC was about 159 lb/ft$^3$ with six roller passes. Each RCC lift was compacted to a height of 1 foot. Test cylinders were obtained each day and were tested for compressive strengths at 7, 14, and 28 days. The RCC met the required concrete strength of 3,000 lb/in$^2$ at 56 days. The 1-year strength of the RCC was 5,000 lb/in$^2$. Vebe tests for the RCC were in the 15- to 20-second range.

**Figure 10-37. RCC placements in the cutoff.**

**Figure 10-38. RCC placements in the upper portion of the RCC auxiliary spillway cutoff.**

The RCC production ranged from about 250 to 650 $yd^3/d$. The Telebelt delivery rate appeared to be the choke point. Crack-inducer plates were installed into the 1-foot thick RCC placements at 40-foot spacing on every other lift. The crack-inducer plates were installed using a vibrator plate attachment on a Bobcat. RCC surfaces were water cured. GERCC was used to consolidate the RCC in the areas adjacent to the rock slopes and adjacent to formed surfaces. GERCC was consolidated using immersion vibrators.

After completion of the RCC placements, a conventional reinforced concrete overlay was placed to form the ogee spillway. Figure 10-39 shows the concrete placement for the ogee spillway, and figure 10-40 shows the completed spillway. No RCC was exposed. The air-entrained conventional concrete provided freeze-thaw durability. The conventional concrete ogee had contraction joints every 20 feet with waterstops. Every other contraction joint in the conventional concrete ogee matched the location of a RCC crack-inducer joint, which was installed every 40 feet.

**Figure 10-39. Conventional concrete placements for the ogee crest spillway.**

### 10.11.5 Conclusions

Due to observed segregation, consideration could be given to reducing the maximum size aggregate to 1 inch and specifying crushed aggregate on future projects.

This project provided an excellent opportunity for GERCC application because good consolidation of the RCC was achieved along the rock perimeter, and all the RCC was capped with conventional air-entrained concrete. The contractor elected to use GERCC on all formed RCC surfaces to prevent cleanup associated with potential rock pockets. Using GERRC saved a considerable amount of cleanup time.

**Figure 10-40. Completed auxiliary spillway.**

### 10.11.6 References


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

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

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

Dolen, T.P., and S.D. Tayabji, 1988. "Bond Strength of Roller-Compacted Concrete." Proceedings of the ASCE Conference.

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

Portland Cement Association and Association of State Dam Safety Officials, 1998. "Roller Compacted Concrete '98." Technical Short Course and Construction Tour, May 18-19.

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

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

Zhu, B., 1995. "Thermal Stresses in Roller Compacted Concrete Gravity Dams," *Dam Engineering*, Vol. VI, Issue 3.

## Appendix A

# Guide Specifications (CSI Format)

**SECTION 03 37 70**

**ROLLER-COMPACTED CONCRETE**

GUIDE SPECIFICATION

DEPARTMENT OF THE INTERIOR – BUREAU OF RECLAMATION

**NOTES**

(1) Consult the design engineer and material specialist for selection of mix design, performance criteria, RCC mixing and placing equipment.

(3) Use this Section for small and medium RCC projects. Significant modifications will be required for large complex projects.

(2) This Section includes leveling concrete, bonding mortar, and crack inducers. Waterstops, drains, sealants, bond breakers, and joint materials are specified elsewhere. For example Section 03 15 12 - PVC Waterstops. Provide other specifications as needed.

(3) Reclamation practice for RCC has been to design the mix and do extensive Quality Assurance testing during construction. This guide assumes Government (owner) will design the mix and perform extensive quality assurance testing. If this Section is revised to have the Contractor responsible for mix design and required to hire an independent third party agency to perform testing, significant revisions are required. If Contractor will be responsible for third party quality testing, include Section 01 46 20 - Testing Agency Services; change the titles of articles entitled "Batch Plant Quality Assurance" to "Contractor Batch Plant Quality Testing" and "Field Quality Assurance" to "Contractor Field Quality Testing"; and consult with materials specialist for input to these articles.

Please provide corrections or comments to address shown on home page of USBR Guide Specifications intranet site: intra.usbr.gov/guidespecs

# SECTION 03 37 70

# 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. Includes Grout-enriched Roller Compacted Concrete (GERCC).
    b. 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 as shown on the drawings.]
    b. Does not include weight of cement in RCC test section.
    c. Does not include weight of cement in leveling concrete.
    d. Does not include weight of cement in RCC that is wasted or removed.
    e. 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. [2][Includes weight of pozzolan in bonding mortar as shown on the drawings.]
    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.
    a. Includes cementitious materials.

---

[1] Include payment for cementitious materials when the Government designs the mix. This provides for unit price compensation to the Contractor for quantities that are out of the Contractors control. Pay for cement and pozzolan separately to account for potential mix variations during construction. Recommended deleting these pay items if the Spec is changed to place mix design responsibility on the Contractor.

[2] Delete if bonding mortar is not required.

F. Facing Concrete:

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

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

a. Includes cementitious material and waterstops.

G. [3][Bonding Mortar:

1. Measurement: Surface area as shown on drawings.

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.

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 [4]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 lift surface to improve bonding of RCC to underlying material.

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

D. Facing Concrete: [5][Conventional concrete] placed with RCC on exposed faces of RCC structures. Facing concrete may be required where permeability and durability is a concern (spillway flows, freeze-thaw climates).

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

F. Roller-Compacted Concrete (RCC): No-slump concrete placed by earth-moving equipment and compacted with vibrating rollers in horizontal lifts.

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

1. During construction, total moisture content measured using a nuclear gauge.

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[3] Include when required for job. Consult with design engineer and materials specialist for requirement for bonding mortar.

[4] Verify definitions are appropriate for the project and that definitions match terminology on the drawings.

[5] Other materials may be used, such as GERCC. Modify as appropriate for project.

H. Grout-enriched RCC (GERCC): RCC enriched with grout to enable consolidation with an internal vibrator.

## 1.03 REFERENCE STANDARDS

A. American Concrete Institute (ACI)

| | | |
|---|---|---|
| 1. | ACI 305R-10 | Guide to Hot Weather Concrete |
| 2. | ACI 306R-10 | Guide to Cold Weather Concrete |

B. ASTM International (ASTM)

| | | |
|---|---|---|
| 1. | [6][ASTM A653/A653M-11 | Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process] |
| 2. | ASTM C31/C31M-12 | Making and Curing Concrete Test Specimens in the Field |
| 3. | ASTM C33/C33M-13 | Concrete Aggregates |
| 4. | ASTM C39/C39M-14a | Compressive Strength of Cylindrical Concrete Specimens |
| 5. | ASTM C42/C42M-13 | Obtaining and Testing Drilled Cores and Sawed Beams of Concrete |
| 6. | ASTM C94/C94M-14a | Ready-Mixed Concrete |
| 7. | ASTM C114-13 | Chemical Analysis of Hydraulic Cement |
| 8. | ASTM C127-12 | Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate |
| 9. | ASTM C128-12 | Density, Relative Density (Specific Gravity), and Absorption of and Absorption of Fine Aggregate |
| 10. | ASTM C138/C138M-14 | Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete |
| 11. | ASTM C150/C150M-12 | Portland Cement |
| 12. | ASTM C171-07 | Sheet Materials for Curing Concrete |
| 13. | ASTM C172/C172M-14 | Sampling Freshly Mixed Concrete |
| 14. | ASTM C183-13 | Sampling and the Amount of Testing of Hydraulic Cement |
| 15. | ASTM C231/C231M-14 | Air Content of Freshly Mixed Concrete by the Pressure Method |

[6] Delete if crack inducers are not specified.

| | | |
|---|---|---|
| 16. | ASTM C260/C260M-10a | Air-Entraining Admixtures for Concrete |
| 17. | ASTM C295/C295M-12 | Petrographic Examination of Aggregates for Concrete |
| 18. | ASTM C309-11 | Liquid Membrane-Forming Compounds for Curing Concrete |
| 19. | ASTM C311-13 | Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete |
| 20. | ASTM C494/C494M-13 | Chemical Admixtures for Concrete |
| 21. | ASTM C511-09 | Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes |
| 22. | ASTM C566-13 | Total Evaporable Moisture Content of Aggregate by Drying |
| 23. | ASTM C617/C617M-12 | Capping Cylindrical Concrete Specimens |
| 24. | ASTM C618-12a | Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete |
| 25. | ASTM C685/C685M-11 | Concrete Made by Volumetric Batching and Continuous Mixing |
| 26. | ASTM C702/C702M-11 | Reducing Samples of Aggregate to Testing Size |
| 27. | ASTM C1040/C1040M-08(2013) | In-Place Density of Unhardened and Hardened Concrete, Including Roller Compacted Concrete, By Nuclear Methods |
| 28. | ASTM C1064/C1064M-12 | Temperature of Freshly Mixed Hydraulic-Cement Concrete |
| 29. | ASTM C1170/C1170M-14 | Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table |
| 30. | ASTM C1176/C1176C-13 | Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table |
| 31. | ASTM C1231/C1231M-14 | Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders |
| 32. | ASTM C1435/C1435M-08 | Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer |

| | | |
|---|---|---|
| 33. | ASTM C1602/C1602M-12 | Mixing Water Used in the Production of Hydraulic Cement Concrete |
| 34. | ASTM D75/D75M-09 | Sampling Aggregates |
| 35. | ASTM D4791-10 | Flat and Elongated Particles in Coarse Aggregate |

C. National Institute of Standards and Technology (NIST)

| | | |
|---|---|---|
| 1. | NIST 44-2012 | Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices, adopted by the National Conference on Weights and Measures; available at www.nist.gov/pml/wmd/h44-12.cfm |

## 1.04 SUBMITTALS

A. Submit the following in accordance with Section 01 33 00 - Submittals.

B. RSN 03 37 70-1, 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, including provisions for hot and cold weather
7. Resumes for RCC plant operators.

C. RSN 03 37 70-2, 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 or against forms.]
9. Location and alignment of temporary access roads.
10. Proposed variations from design lines and grades.
11. Methods of controlling RCC temperature within specified limits, including provisions for hot and cold weather.
12. Methods for curing and protecting RCC.
13. Test section placement procedures.
14. Resumes for RCC placement supervisors.

D. RSN 03 37 70-3, 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 03 37 70-4, Fine and Coarse Aggregates:

1. Name and location of sources.
2. Sample.[8]
3. Manufacturer's certification that materials meets specified requirements, within last 6 months.

F. RSN 03 37 70-5, Proposed Water Source:

1. Name and location of source.
2. Lab test results showing conformance with specified requirements.

## 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, GERCC, facing concrete 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.

---

[7] For sloping/stair-stepped spillways, for overtopping protection, or other applications where smaller compaction equipment is needed and forming is not required.

[8] Due date or delivery date - "60 days prior to use" in the submittal table in Section 01 33 00 - Submittals.

4. Procedures for installing of [9][waterstops, crack control notches, crack inducer plates, pipe, and expansion joint filler].

B. [10][Acceptance of the test section will be based on successful demonstration of:

1. Calibration of RCC batching and mixing plant, routine and automatic batching within tolerance, RCC production for both winter or summer concrete placements.

2. Placement of RCC in accordance with these specifications.

3. Transporting, placing, and compacting RCC at the anticipated production rate.

4. Lift surface cleaning and preparation methods and application of bonding mortar.

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

6. Upstream and downstream forming methods at the specified rate.

7. Communication between the plant and placement operations is continuous and effective.

8. Segregation is minimized.]

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 core drilling as described below.

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 [11][3 weeks] before beginning RCC construction.

2. [12][Configuration of test section:

a. Length, minimum: XX feet.

b. Width, minimum: XX feet.

c. Lifts, minimum: X

---

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

[10] Revise acceptance criteria as appropriate for job.

[11] Revise time as appropriate for job.

[12] 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.”

d. [13]One side slope: Constructed against a formed vertical face at a slope of 0.7:1 using 2-ft steps.]

3. Include at least one lift surface exposed longer than [24][14] hours followed by Type 3 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. GERCC Demonstration at RCC Test Section:

1. GERCC placing method in RCC test section. Place GERCC in zones shown on drawings using [15]{Method 1 and Method 2 as shown in Figure 1 and Figure 2 respectively.}

2. COR will select method of placing GERCC based on performance within the RCC test section.

H. Quality Assurance:

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 no sooner than 7 days after final placement.

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

## 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.

---

[13] Confirm with designer and materials specialist that this is appropriate for project. Modify for project if needed.

[14] Confirm time with designer and materials specialist.

[15] Coordinate methods shown on drawings with the designer and materials specialist.

## PART 2 PRODUCTS

### 2.01 CEMENTITIOUS MATERIALS

A. Cementitious materials: Portland cement plus pozzolan.

B. Portland cement:

1. ASTM C150, Type [____] [16], in addition:
    a. Meet equivalent alkalies requirements of ASTM C150.
        1) Low-alkali limitation for portland cement may be waived when tests of concrete aggregate source show that low-alkali cement is not required for ASR mitigation. See Aggregate Article below.
    b. Meet false-set and heat of hydration requirements of ASTM C150.
    c. Free from lumps and other deleterious matter and otherwise undamaged.
2. Pozzolan:
    a. ASTM C618, 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 C114.
        4) F: Ferric oxide content of pozzolan in percent determined in accordance with ASTM C114.

C. Before an RCC placement is started, ensure that sufficient cementitious materials are in storage at RCC plant to complete [3][17] day(s) of placement.

### 2.02 AGGREGATE

A. General

1. Assure aggregates are not deleteriously alkali silica reactive (ASR):
    a. Test sand and coarse aggregates in accordance with ASTM C1260 for potential deleterious ASR.

---

[16] Insert type of cement. Consult with design engineer and materials specialist. For a large project, it may be possible to obtain Type IV cement as a special order to slow the rate of the heat of hydration.

[17] Confirm with designer and materials specialist. Need larger stockpile on site for small jobs.

1) [18] [For ASTM C1260, and other tests when required, continue readings for 28 days after the zero readings.

2) Acceptance criteria specified below are based on [19][{14} {28} day readings after the zero readings.]

3) Expansion is no greater than 0.10 percent:

    a) Aggregates are acceptable.

4) Expansion is greater than 0.10 percent:

    a) Test aggregates according to ASTM C1567 using proposed components (e.g. coarse aggregate, fine aggregate, cementitious materials, and Alkali Silica Reaction (ASR) inhibiting admixtures) in proportions proposed for mixture design.

    b) For mixes using lithium admixtures use test procedure COE CRD-C 662.

    c) Expansion of proposed mixture design test specimens, tested in accordance with ASTM C1567 does not exceed 0.10 percent:

        i. Aggregates are acceptable.

    d) Expansion of proposed mixture design test specimens is greater than 0.10 percent:

        i. Aggregates are not acceptable unless adjustments to mixture design can reduce expansion to less than 0.10 percent, or testing by ASTM C1293 indicates aggregates will not experience deleterious expansion.

b. ASTM C1293 test results may be substituted for ASTM C1260 test results:

1) Average ASTM C1293 concrete prism expansion less than 0.04 percent at one year: Aggregates acceptable.

2) Average ASTM C1293 concrete prism expansion greater than 0.04 percent at one year: Aggregates not acceptable.

---

[18] Include when slow or late reacting aggregates are a possibility. Extended testing ages are necessary for regions with slow reacting aggregates; based on preliminary aggregate survey or local experience. Known areas include but are not limited to parts of ID, NM, and AZ. The normal period for taking readings is 14 days after the zero reading.

[19] Select appropriate days for readings. 14 days is appropriate unless slow or late reacting aggregates are possible. See previous footnote.

c. Verify aggregate is appropriate for proposed use in accordance with ASTM C 295.

2. Stockpiles:

a. Prior to placing RCC, stockpile on site enough sand and coarse aggregate to complete [20][seven days] of RCC construction.

b. Protect stockpiles containing free water from freezing.

c. Do not use sand and/or coarse aggregate below 32 degrees F. Concrete batched with aggregates sand and/or coarse aggregates below 32 degrees F will be rejected.

B. Sand

1. Source:

a. From approved source, with approval of source based on one of the following:

1) Previous testing and approval of source by Government.

2) Preconstruction testing and approval.

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

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

d. Testing and approval:

1) Sources listed in [21][Section 53 10 00 - Geotechnical Investigations], have been tested by the Government.

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

a) Assist the Government in collecting representative samples.

b) Sample size: Approximately 600 pounds.

c) Submit, for testing, to: [22][ ].

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

3) Testing at aggregate processing plant and batch plant:

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

[20] Confirm amount of stockpiled sand with Design Team.

[21] Verify section.

[22] 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

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

2. ASTM C33, except:

a. Gradation:

1) [23][Percent passing No. 100 sieve: 0 to 12 percent.

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

b. [24]Crushed sand: If used, predominantly cubical in shape and free from flat or elongated particles, in accordance with ______.

3. Moisture content for sand, as batched:

a. Uniform and stable moisture.

b. Free moisture, maximum: 6 percent.

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

C. Coarse Aggregate

1. Source:

a. From approved source based on one of the following:

1) Previous testing and approval of source by Government.

2) Preconstruction testing and approval.

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

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

d. Testing and approval:

1) Sources listed in [25][Section 52 10 __ - Geotechnical Data], have been tested by the Government.

2) Preconstruction testing and approval for coarse aggregate obtained from a deposit not tested and approved by the Government:

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

---

[23] Verify percent passing ranges with design engineer and materials specialist. A smaller percent passing may be required when higher compressive and tensile strengths are required. For example concrete dams subjected to seismic loads.

[24] Verify use of crushed sand with materials specialist and designer, and test method to determine shape.

[25] Insert Section number and verify Section name.

b) Sample size:

i. Maximum size aggregate up to 1-inch: 400 pounds.

ii. Maximum size aggregate greater than 1-inch: 200 pounds.

c) Submit, for testing, to: [26][ ].

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

3) Testing at aggregate processing plant and batch plant:

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

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

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

a. Quality: ASTM C33.

b. Nominal Size Aggregate (NMSA) Grading: ASTM C33 [27][{1-inch: No. 57 (1 inch to No.4).} {1-1/2 inch: Size No. 4 (1-1/2 to 3/4 inch) and No. 57 (3/4 inch to No.4)}{2-inch: No. 3 (2 to 1 inch) and No. 57 (1 inch to No.4)}].

3. Material:

a. Crushed rock or a mixture of natural gravel and crushed rock.

b. [28]At least 50 percent crushed rock.

c. No more than 30 percent particles with a maximum to minimum dimension ratio of 3 to 1 in accordance with ASTM D4791.

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

4. Finish screening: Just prior to batching.

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

b. Wash coarse aggregate by pressure spraying. Do not allow wash water to enter batching bins or weighing hoppers.

---

[26] 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.

[27] Select size. Consult with designer and materials specialist. Smaller maximum size aggregate reduces segregation and reduces the potential for rock pockets on lift lines.

[28] Consult with design engineer and materials specialist. Depends on availability.

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

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

e. Do not overload screens.

f. Finish screen:

1) Finished product shall meet specified gradation.

2) Avoid segregation and breakage.

3) 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.

4) 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.

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

## 2.03 WATER

A. Water:

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

2. Chemical limits: ASTM C1602, including optional requirements.

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.

## 2.04 ADMIXTURES

A. RCC:

1. ASTM C494, type D, water reducing and retarding admixture (WRA).

a. Required when ambient daily temperature at placement site exceeds [29][__ degrees F].

2. [30][Air entraining admixtures (AEA):

[29] Insert temperature requirement. Typically 70 degrees F.

a. ASTM C260.

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

3. [31][Alkali Silica Reaction (ASR) Inhibiting Admixture:

a. Lithium Nitrate Admixture for ASR mitigation of reactive aggregates:

1) Meet NSF/ANSI 61.

2) Nominal 30 percent aqueous solution of Lithium Nitrate

a) Density: 10 pounds/gallon (1.2 kg/L).

b) Approximate chemical constituents (percent by mass):

i. LiNo3 (Lithium Nitrate): 30 plus or minus 0.5

ii. SO4-2 (Sulfate Ion), maximum: 0.1

iii. Cl- (Chloride Ion), maximum: 0.2

iv. NA+ (Sodium Ion), maximum: 0.1

v. K+ (Potassium Ion), maximum: 0.1

b. Coordinate with manufacturer regarding Lithium Nitrate dosage.

c. Do not use Lithium Nitrate Admixture for concrete in continuous or nearly continuous contact with water.]

B. Bonding mortar: ASTM C494, type D water-reducing, retarding admixture.

## 2.05 CURING MATERIALS

A. Water: ASTM C1602, including optional requirements.

B. Curing Compound: ASTM C309.

C. Polyethylene Film: ASTM C171, white opaque.

## 2.06 [32][CRACK INDUCERS

A. Galvanized sheet steel, 16 gage thick (0.06 inch) meeting the requirements of ASTM A653.

B. Effective Height/Width: 10-inch minimum.

---

30 Consider specifying AEA for exposed RCC where freeze thaw durability is required. Since RCC does not use much water, AEA may not be as effective as in conventional concrete.

31 Include for VERY SEVERE ASR ONLY. Contact materials specialist before specifying.

32 Delete if crack inducers are not required. Any leg in the sheet metal to facilitate installation is not included in the minimum effective height requirement.

C. Length:

1. Appropriate for installation.
2. Minimum length: 3 feet.]

## 2.07 [33][DENTAL/LEVELING CONCRETE MIX

A. Concrete mix: Section 03 30 00 - Cast-in-Place Concrete, except:

1. Slump:
   a. Dental Concrete: 2-inches plus or minus 1-inch.
   b. Leveling: 3-inches plus or minus 1-inch.
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.]

## 2.08 GERCC GROUT

A. Portland Cement:

1. ASTM C 150, Type II.

B. Water:

1. ASTM C 1602, including optional requirements.

C. Allowable Chemical Admixtures:

1. High Range Water-Reducing Agent (HRWRA): ASTM C 494, Type F.
2. Water Reducing and Set Controlling Admixture: ASTM C 494, Type B or D.
3. Do not use chemical admixtures which contain more than 0.1 percent chloride, by weight.

D. Mix:

1. Water-cement ratio, maximum by volume, not greater than 1 to 1.
2. Use results from tests performed with the HRWRA sample to determine grout mix.
   a. Use according to manufacturer’s instructions.
   b. For HRWRA, dose at 0.5 percent to 1 percent by weight of cement.

---

[33] Recommended maximum size aggregate same as RCC (1-inch or 2-inch). Exception: Typical compressive strength for structural concrete is 4,500 lb/in$^2$. Guide specification 03 30 00 – Cast-In-Place Concrete requires 90 percent of cylinders to exceed specified compressive strength.

c. If needed, add no more than one-half of HRWRA to mix water before adding cement. Add rest of HRWRA after mixing cement and water.

d. If the use of HRWRA produces abnormal grout setting or if the HRWRA does not meet specified requirements, use other HRWRA until results are acceptable.

3. Use of an accelerant is not allowed.

4. Preform weighing, mixing and placing of the grout in the presence of the COR.

5. The COR will determine the usable time allowed before grout placement. Depending on water-reducing agent, usable time allowed will vary.

6. Discard batch if too much time has elapsed between mixing of the grout and placement, as determined by the COR.

7. Use Type B or D water-reducing and set controlling admixture to extend the setting time of grout. Add Type B or D admixture in accordance with manufacturer’s recommendations.

E. Equipment for Grout:

1. Mixing and Placing Equipment:

a. COR will approve type and size of equipment, including circulating line and fittings.

b. Capable of mixing, stirring and transporting to GERCC placement area

2. Water:

a. Adequate amount to meet required pumping rate.

b. Measured to one-tenth of a cubic foot, with no more than a 1 percent error.

3. Mixing tank: Cylindrical, mounted vertically, and high-speed colloidal type.

4. Holdover mechanical agitator tank similar in volume to the mixer.

5. Pump grout from the mixer to the holdover mechanical agitator tank. Deliver grout to site via pump or agitating drum mixer.

6. COR may require changes in the equipment without additional cost to the Government.

F. Temperature of grout for GERCC and allowable holding time.

1. Not to exceed 70 degrees F.

2. Time between mixing, placing, and consolidation of grout in GERCC not to exceed 1 hour or as directed by the COR

3. Remove any grout that exceeds the allowable mixing and placing time.

4. Placing time may be extended by use of a Type B or D set-retarding admixture.

## 2.09 RCC MIX

A. Performance criteria:

1. Design Strength: [34][___ lb/in$^2$ at 365days].

a. [35][At least {80} percent of all test cylinders shall exceed design strength requirements.

b. [36][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 C1170, Procedure B.

1) Vebe Time: [37][20] seconds plus or minus 5 seconds.

3. [38][Entrained air content: [39][4] percent, plus or minus 1 percent.

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

B. 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:

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 [40][and exposed edges of the lift] with minimal segregation or voids.

---

34 Design strength varies between 3,000 and 4,000 lb/in$^2$.

35 Insert the design strength and select appropriate time.

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

37 Consult with materials specialist for appropriate time.

38 Include when application requires air entrained RCC. Consider specifying AEA for exposed RCC in areas where freeze thaw durability is required. Since RCC does not use much water, AEA may not be as effective as in conventional concrete.

39 4 Percent entrained air is typical. Consult with materials specialist for entrained air required for job.

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. Initial mix proportions:

a. Estimated RCC mixture for beginning construction is shown in Table 03 37 70A - Mix Proportions for RCC with Saturated Surface Dry Aggregates.

[41][

Table 03 37 70A – Mix Proportions for RCC with Saturated Surface Dry Aggregates

| INGREDIENT | QUANTITY |
|---|---|
| Cementitious materials | [___] pounds per cubic yard RCC |
| Pozzolan | 50 to 70 percent by weight of cementitious materials |
| Water | [___] pounds per cubic yard RCC |
| Sand | [___] pounds per cubic yard RCC |
| Coarse aggregate | [____] pounds per cubic yard RCC |
| [42]Air Entrainment Admixture (AEA) | As recommended by manufacturer to obtain 4 percent plus or minus 1 percent |
| Other Admixtures | Manufacturer’s recommended dosage |

## 2.10 BONDING MORTAR MIX

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

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

41 Include this table when Government completes the mix design. Delete table if contractor to provide mix design. Select appropriate options and insert component weights based on mix design, consult with materials specialist.

42 Delete row if entrained air not required in RCC. Consider specifying AEA for exposed RCC in areas where freeze-thaw durability is required. Since RCC does not use much water, AEA may not be as effective as in conventional concrete.

1. The Government will adjust water content to bring mortar to a broomable consistency.
2. Maximum water to cementitious materials ratio: [43][0.50], by weight.

B. Starting mix proportions: Conform to Table 03 37 70B - Mix Proportions for Bonding Mortar.

Table 03 37 70B - 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: [44] [______] 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.

---

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

[44] 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.

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.

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

2) Schedule and perform monthly static tests:

a) Frequency:

i. Prior to RCC production.

ii. Monthly after production begins.

iii. As directed by COR.

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

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

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

e) Perform additional tests when requested by the Government.

f) 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. Continuous batching-mixing plants: Not allowed.

## 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) Determine mixing adequacy in accordance with concrete uniformity requirements of ASTM C94, annex A1; except:

a) Vebe consistency test in accordance with ASTM C1170, Procedure 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. Complete batch tickets in accordance with C94 for each load and submit to COR.

F. Continuous batching-mixing plants: Not allowed.

## 2.13 TEMPERATURE OF RCC

A. [45][Temperature of RCC at placement: Not less than 40 degrees F and not more than 70 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. Temperature Control:

1. Restrict temperature placement within specified range.
2. Heat RCC ingredients just enough to keep temperature of the mixed RCC, as placed, from falling below specified minimum temperature. Heat RCC ingredients by approved methods.
3. Employ one or more of the following methods:
   a. Pre-cool aggregates.
   b. Refrigerate mixing water.
   c. Inject liquid nitrogen.
   d. Add flake ice as a portion of mixing water if flake ice has melted prior to completion of mixing RCC.
   e. Cool cement and pozzolan.
   f. Protect RCC from heat gain during handling and transport.
   g. Limit placement as needed to meet specified requirements. Consider:
      1) Cold or hot times of the year.
      2) Night or day time.

C. 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.

[45] Consult design engineer and materials specialist.

## 2.15 BATCH PLANT QUALITY ASSURANCE

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:
    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. 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.
3. Government will obtain samples and conduct tests in accordance with procedures listed in Table 03 37 70C – Standards Used for Batch Plant Testing.
4. Testing Frequency:
    a. At a minimum, Government will test at frequencies specified in Table 03 37 70C - Standards Used for Batch Plant Testing.
    b. Greater frequency of testing is normally performed at beginning of new work, new work crew, or new equipment.
    c. After a successful work operation pattern is established, testing frequency may be performed at the minimum guidelines.

Table 03 37 70C – Standards Used for Batch Plant Testing

| Procedure | Standard No. | [46]Testing Frequency |
|---|---|---|
| Sampling hydraulic cement | ASTM C183 | Prior to RCC production or as directed by COR |
| Sampling pozzolan | ASTM C311 | Prior to RCC production or as directed by COR |
| Sampling aggregate | ASTM D75 | Once daily or as directed by COR |
| Reducing field samples of aggregate to testing size | ASTM C702 | Once daily or as directed by COR |
| Absorption of fine aggregate | ASTM C128 | Prior to RCC production or as directed by COR |
| Absorption of coarse aggregate | ASTM C127 | Prior to RCC production or as directed by COR |
| Total moisture content of aggregate | ASTM C566 | Once daily or as directed by COR |
| Sampling fresh concrete | ASTM C172 | Every 150 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR |
| RCC uniformity | ASTM C94, Annex A1, except vebe consistency test in accordance with ASTM C1170 will be substituted for the slump test. | Prior to RCC production or as directed by COR |

[46] Review frequency of testing. Consult with materials specialist.

Table 03 37 70C – Standards Used for Batch Plant Testing

| Procedure | Standard No. | [46]Testing Frequency |
| --- | --- | --- |
| [47][Air content | ASTM C231 | Every 150 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR] |
| Vebe consistency and density | ASTM C1170 | Every 150 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR |
| [48][Density (unit weight) and yield | ASTM C138, except that a 0.25-cubic-foot container may be used for nominal aggregate sizes up to 1-1/2-inches | Every 50 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR] |
| Making test specimens in field | ASTM C1176 or ASTM C1435 | [49][6] cylinders for every 150 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR |
| Capping cylindrical concrete specimens | ASTM C617 or ASTM C1231 | For each compressive strength test as required |
| Compressive strength of cylindrical concrete specimens | ASTM C39 | [50][28 days age] |

[47] Applies for air entrained RCC or facing/leveling concrete batched on site. Change 150 yards to 50 yards for facing/leveling concrete.

[48] For facing/leveling concrete. Delete for other concrete. ASTM C1170 covers density for RCC.

[49] At least 2 per test per age.

[50] Match design strength and early age requirement in Article 2.09 - Performance Criteria.

## 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, excessive speed and repeated routes 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

A. Foundation surface is defined as any rock surface [51] [or material against which] RCC or leveling concrete will be placed.

B. Prepare surfaces free from frost, ice, water, mud, and debris.

C. Compact earth foundations to form firm foundation for RCC.

D. Prepare foundations for RCC placement so the rock surface is saturated surface dry.]

E. Refer to Section 31 23 15 - Excavation, for foundation approval procedures.

[51] Soil and embankment foundations only for embankment dam overtopping protection.

## 3.05 LIFT SURFACE

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): Before initial set.
   a. Perform standard lift surface cleanup on lift surfaces less than [52][__] 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. Maintain cleaned surface in a moist condition with no ponding water.
   d. RCC that is damaged by air jetting or air-water jetting shall be cleaned with approved vacuum equipment.
2. Cold joints (Type 2): Between initial and final set.
   a. Lift surfaces more than [53][__] 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

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[52] Consult with design engineer and materials specialist. The amount of time can vary depending on the pozzolan content and temperature of placement. Degree hours may be more appropriate way of defining lift surface.

[53] Consult with materials specialist. The amount of time can vary depending on the pozzolan content and temperature of placement. Sometime degree hours may be more appropriate way of defining lift surface.

other foreign material. Vacuum cleaned surface with approved equipment.

c. Maintain cleaned surface in a moist condition with no ponding water.

d. Clean RCC damaged by air jetting or air-water jetting with approved vacuum equipment.

3. Construction joints (Type 3): After final set.

a. Lift surfaces more than [54][ ] hours 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.

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 lift surfaces and cure leveling concrete.

**3.06 GERCC**

A. Measure grout for GERCC into calibrated buckets or hoppers for placement in RCC.

B. Apply grout to GERCC at a minimum rate of 0.6 gallons per sloping square foot of RCC adjacent to the RCC foundation or formed RCC.

[54] Consult with design engineer and materials specialist. The amount of time can vary depending on the pozzolan content and temperature of placement. Sometime degree hours may be more appropriate way of defining lift surface.

C. Method of application of GERCC.

1. Perform two methods of application of GERCC in the RCC test section as shown in Figure 1 and Figure 2 and as described below.

a. Method 1. Placing grout before each lift of RCC.

1) Spread RCC to within 6 inches of the foundation contact.

2) Spread grout between the RCC and foundation surface.

3) Do not place grout more than 15 minutes before covering with RCC.

4) Spread RCC over grout.

5) Consolidate the nominal 1.5-foot wide GERCC zone as shown on drawings by internal vibration before roller compaction near the interface.

6) Compact RCC within 6 inches of GERCC zone with large vibrating rollers in accordance with Compacting RCC article.

7) Compact GERCC zone as shown on drawings with small vibratory rollers or plate vibrators to produce a level surface.

b. Method 2. Placing grout over loosely spread RCC lift.

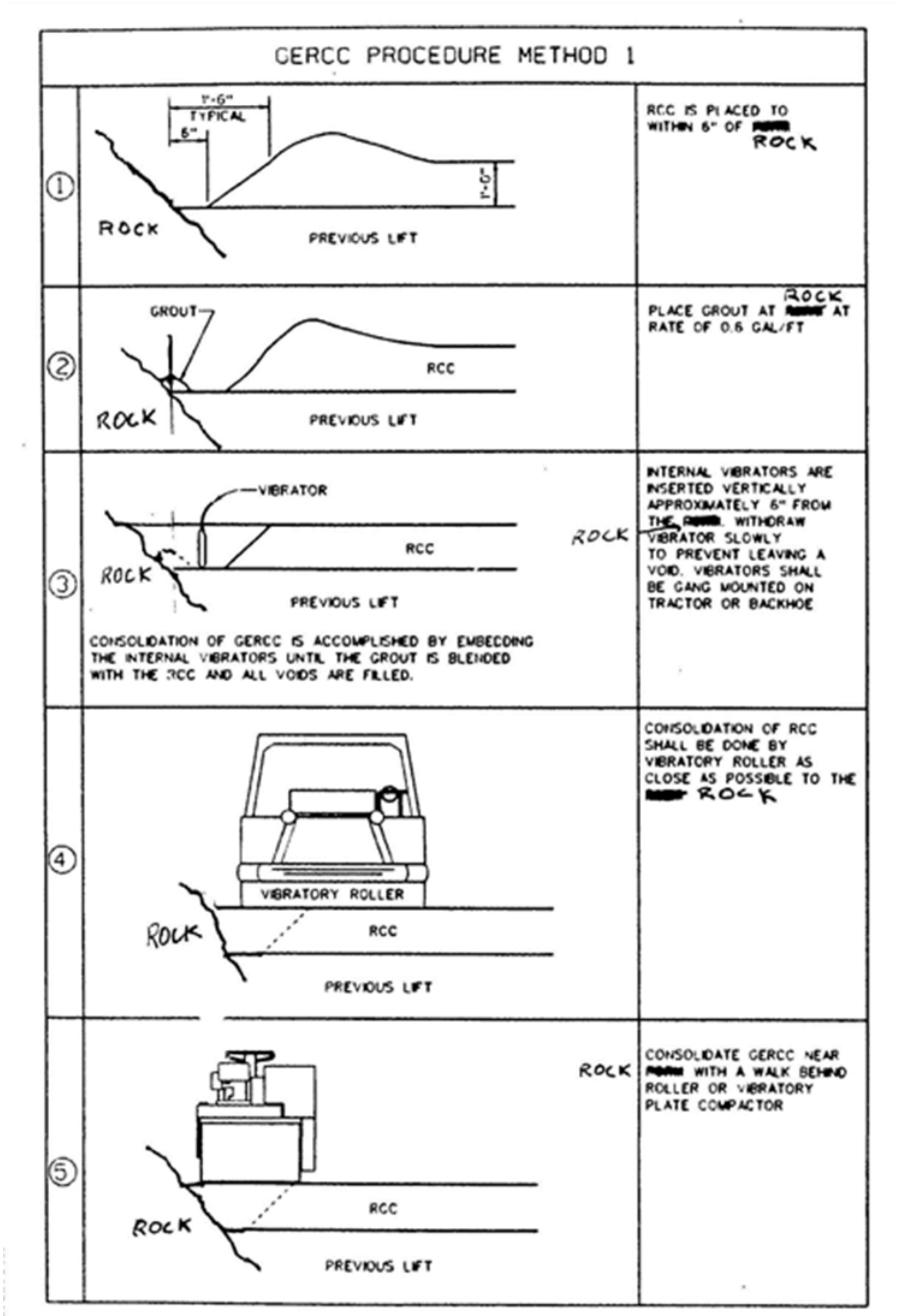
1) Spread RCC onto foundation contact.

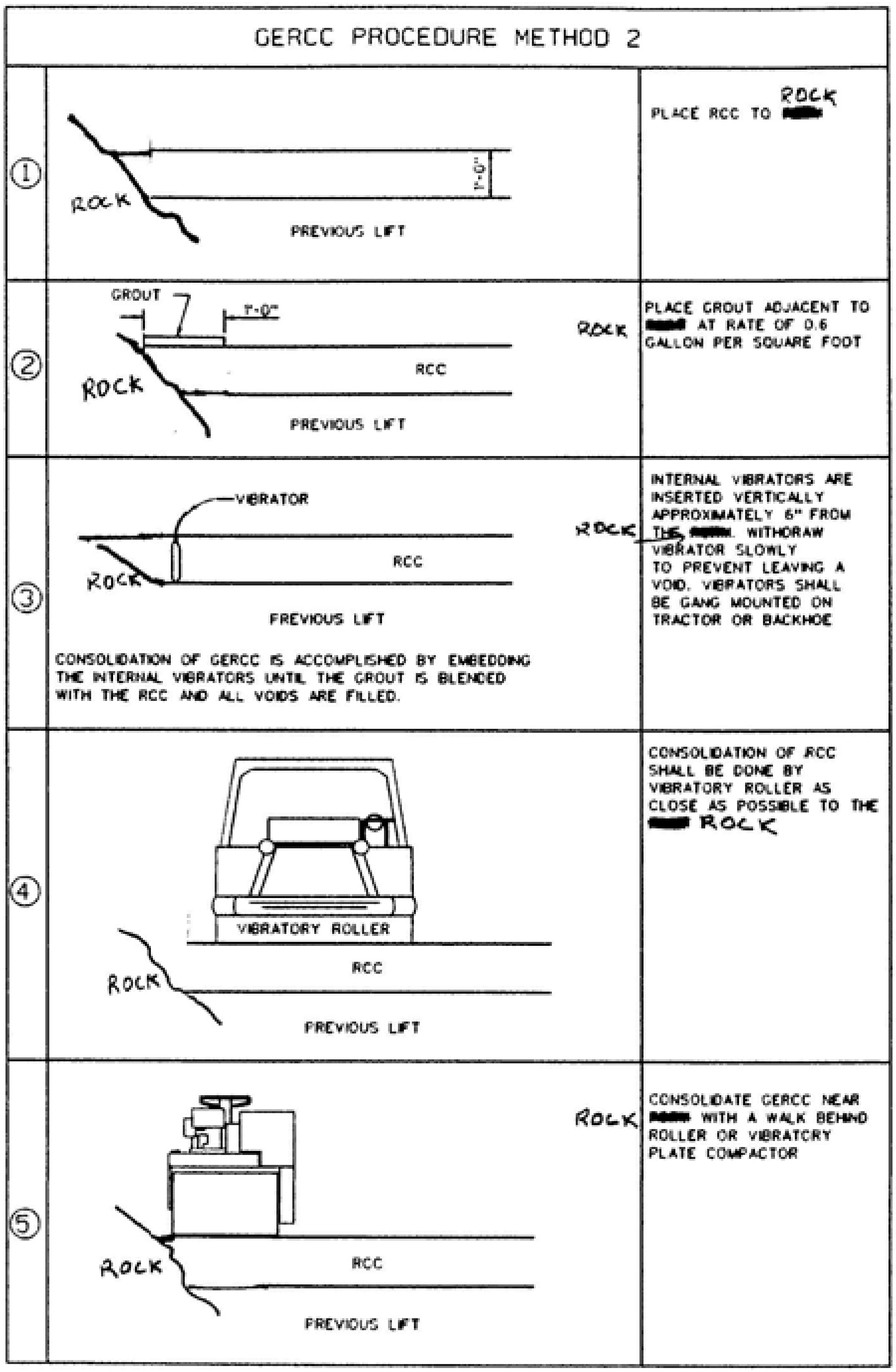
2) Pour grout evenly over a 1.5-foot wide zone over uncompacted RCC/foundation interface at required application rate.

3) Consolidate the nominal 1.5-foot wide GERCC zone by internal vibration before roller compaction near the interface.

4) Compact RCC within 6 inches of the GERCC zone with large vibrating rollers in accordance with Compacting RCC article.

5) Compact GERCC zone as shown on drawings with small vibratory rollers or with plate vibrators to produce a level surface.


GERCC PROCEDURE METHOD 1
1'-6"
TYPICAL
6"
1'-0"
ROCK
PREVIOUS LIFT
RCC IS PLACED TO WITHIN 6" OF [redacted] ROCK
GROUT
RCC
ROCK
PREVIOUS LIFT
PLACE GROUT AT [redacted] ROCK AT RATE OF 0.6 GAL/FT
VIBRATOR
RCC
ROCK
PREVIOUS LIFT
CONSOLIDATION OF GERCC IS ACCOMPLISHED BY EMBEDDING THE INTERNAL VIBRATORS UNTIL THE GROUT IS BLENDED WITH THE RCC AND ALL VOIDS ARE FILLED.
INTERNAL VIBRATORS ARE INSERTED VERTICALLY APPROXIMATELY 6" FROM THE [redacted] ROCK. WITHDRAW VIBRATOR SLOWLY TO PREVENT LEAVING A VOID. VIBRATORS SHALL BE GANG MOUNTED ON TRACTOR OR BACKHOE
VIBRATORY ROLLER
RCC
ROCK
PREVIOUS LIFT
CONSOLIDATION OF RCC SHALL BE DONE BY VIBRATORY ROLLER AS CLOSE AS POSSIBLE TO THE [redacted] ROCK
RCC
ROCK
PREVIOUS LIFT
CONSOLIDATE GERCC NEAR ROCK [redacted] WITH A WALK BEHIND ROLLER OR VIBRATORY PLATE COMPACTOR


GERCC PROCEDURE METHOD 2
1
ROCK
1'-0"
PREVIOUS LIFT
ROCK
PLACE RCC TO [redacted]
2
GROUT
1'-0"
ROCK
RCC
PREVIOUS LIFT
ROCK
PLACE GROUT ADJACENT TO [redacted] AT RATE OF 0.6 GALLON PER SQUARE FOOT
3
VIBRATOR
ROCK
RCC
PREVIOUS LIFT
CONSOLIDATION OF GERCC IS ACCOMPLISHED BY EMBEDDING THE INTERNAL VIBRATORS UNTIL THE GROUT IS BLENDED WITH THE RCC AND ALL VOIDS ARE FILLED.
ROCK
INTERNAL VIBRATORS ARE INSERTED VERTICALLY APPROXIMATELY 6" FROM THE [redacted]. WITHDRAW VIBRATOR SLOWLY TO PREVENT LEAVING A VOID. VIBRATORS SHALL BE GANG MOUNTED ON TRACTOR OR BACKHOE
4
VIBRATORY ROLLER
ROCK
RCC
PREVIOUS LIFT
CONSOLIDATION OF RCC SHALL BE DONE BY VIBRATORY ROLLER AS CLOSE AS POSSIBLE TO THE [redacted] ROCK
5
ROCK
RCC
PREVIOUS LIFT
ROCK
CONSOLIDATE GERCC NEAR [redacted] WITH A WALK BEHIND ROLLER OR VIBRATORY PLATE COMPACTOR

D. Use internal vibrators with sufficient capacity to consolidate GERCC.

1. Overlap radii of action of vibrators to effectively consolidate GERCC.
2. Diameter of internal vibrator, minimum: 2.25 inches.

## 3.07 LEVELING CONCRETE

A. Place leveling concrete at locations indicated on drawings or as directed by COR.

B. Use internal vibrators with sufficient capacity to consolidate leveling concrete and interface zone with RCC.

1. Overlap radii of action of vibrators to effectively consolidate concrete.
2. Diameter of internal vibrator, minimum: 2.25 inches.

## 3.08 FACING CONCRETE

A. Place facing concrete at locations indicated on drawings.

B. Place RCC against facing concrete within 30 minutes of placing facing concrete.

C. Use internal vibrators with sufficient capacity to consolidate facing concrete and interface zone with RCC.

1. Overlap radii of action of vibrators to effectively consolidate concrete.
2. Diameter of internal vibrator, minimum: 2.25 inches.

## 3.09 PLACING RCC

A. 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 [55][45] minutes after adding cement.

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.

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[55] Consult with design engineer and materials specialists.

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.

I. Do not drive on uncompacted RCC, except as required for spreading and compacting RCC.

J. 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.

## 3.10 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 [56][{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 [57][for stepped downstream face].

[56] For small jobs not in remote location, equipment may be specified to be locally available

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) Use vibratory roller within 15 minutes after spreading.

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 and last pass:In static mode.

7) Total number of passes required for complete compaction:

a) Determined by the COR.

b) Initial number based on results of test section [58][but the total number of passes shall not be less than 6 passes].

c) 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.

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[57] Include when appropriate for job.

[58] Confirm with designer if total passes should be included. Delete if not needed.

d) Number of passes may be increased in confined areas to achieve equivalent compaction of the vibratory roller in open areas.

8) Finish rolling:

a) Finish roll 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, to achieve required density.

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. [59][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.

[59] Delete or revise as required.

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.]

## 3.11 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 [60][____ $yd^3$].

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.

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.

[60] Typical requirement is for control section every 10,000 $yd^3$

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 90E 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. 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.

## 3.12 [61][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, as directed by the COR.

D. Place in [62][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.]

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61 Consult design engineer to determine need for crack inducers.

62 Select appropriate choice.

## 3.13 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 Contractors 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.

   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 and isnulatoin blankets.

## 3.14 PROTECTION

A. Protect uncompacted and freshly compacted RCC from damaging precipitation.

   1. When precipitation occurs or is imminent:

      a. When precipitation appears imminent, immediately prepare protective materials at placement site.

      b. Suspend placing operations and cover freshly compacted RCC with polyethylene film.

c. Before operations are suspended due to precipitation, compact RCC that has been deposited and spread.

d. 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.

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.

## 3.15 FIELD QUALITY ASSURANCE

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.

2. Removal of test facilities:

a. Remove from worksite after tests are completed.

b. Contractor-furnished test facilities will remain the property of Contractor.

C. Government will obtain samples and conduct tests in accordance with procedures listed in Table 03 37 70D – Standards Used for Field Quality Assurance Testing.

1. Testing Frequency:

a. At a minimum, Government will test at frequencies specified in Table 03 37 70D – Standards Used for Field Quality Assurance Testing.

b. Greater frequency of testing is normally performed at beginning of new work, new work crew, or new equipment.

c. After a successful work operation pattern is established, testing frequency may be performed at the minimum guidelines.

Table 03 37 70D – Standards Used for Field Quality Assurance Testing

| Procedure | Standard No. | [63]Frequency |
|---|---|---|
| Density (unit weight) and yield | ASTM C138, except that a 0.25-cubic-foot container may be used for nominal aggregate sizes up to 1-1/2-inches | Every 50 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR |
| Density of in-place RCC | ASTM C1040 | Every lift to ensure proper compaction prior to placing next lift |
| Air content | ASTM C231 | Every 150 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR |
| Vebe consistency and density | ASTM C1170 | Every 150 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR |
| Sampling fresh concrete | ASTM C172 | Every 150 cubic yards until uniformity is established, then once per shift throughout production, or as directed by COR |
| Temperature | ASTM C1064 | Every lift at placement or as directed by COR |

[63] Insert testing frequencies.

Table 03 37 70D – Standards Used for Field Quality Assurance Testing

| Procedure | Standard No. | [63]Frequency |
|---|---|---|
| Making test specimens in field | ASTM C31, ASTM C511, ASTM C1176 or ASTM C1435 | [64][14] cylinders for every 150 cubic yards until uniformity is established, then once per shift throughout production, and as directed by COR |
| Capping cylindrical concrete specimens | ASTM C617 | For each compressive strength test as required |
| Compressive strength of cylindrical concrete specimens | ASTM C39 for cast cylinders and ASTM C42 for cores | [65][{7} {28} {56} {90} {180} {365} days age] |

## 3.16 FINAL CLEANUP

A. Clean surfaces by air or air-water jetting to remove loose materials.

B. Dispose of removed materials in accordance with Section 01 74 00 - Cleaning and Waste Management.

**END OF SECTION**

[64] Need at least 2 per test age, plus a couple of extra. Adjust if age of design strength is less than one year.

[65] Match age requirements in Dental/Leveling and RCC Mix articles “At least {80} percent of all test cylinders shall exceed {_____} pounds per square inch at {-------} days age.]

| 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 |
| 03 37 70-1 | Roller-Compacted Concrete | Plan for RCC plant(s) | At least 28 days before bringing equipment on site. | A | ZZZ | 0 | 2 | 2 |
| 03 37 70-2 | Roller-Compacted Concrete | Equipment and placement plan | At least 28 days before bringing equipment on site. | A | ZZZ | 0 | 2 | 2 |
| 03 37 70-3 | Roller-Compacted Concrete | Cementitious materials | At least 28 days before placing RCC | I | ZZZ | 0 | 2 | 1 |
| 03 37 70-4 | Roller-Compacted Concrete | Fine and coarse aggregates | At least 28 days before placing RCC | I | ZZZ | 0 | 2 | 1 |
| 03 37 70-5 | Roller-Compacted Concrete | Proposed water source | At lease 28 days before placing RCC | I | ZZZ | 0 | 2 | 1 |

## Appendix B

# Summary of RCC Costs

# Appendix B

# Summary of RCC Costs

Table C-1 summarizes the roller-compacted concrete (RCC) costs for 10 Reclamation projects completed between 1987 and 2002. Common factors that influenced the bid prices for RCC are briefly summarized in the discussions below.

## Production and Placement Rates

The primary benefit of RCC versus 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 the use of a minimum 20-foot lane width will permit equipment to pass, which 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, lengthen the construction time and result in higher construction 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 suitable material is available. Processing aggregates in large quantities from an onsite 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 onsite 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, if 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 using thermal blankets for protection against freezing. The construction schedule will usually incorporate climate and potential weather conditions. If possible, construction should be scheduled during time periods when potentially adverse conditions such as hot or cold ambient temperatures can be avoided.

## Required Equipment

The type of equipment necessary to place the specified RCC mix can impact costs. Construction costs can increase if the placement equipment is restricted because of the specifications requirements, site conditions, and/or configurations and geometry.

At times, it is necessary to specify the production rate requirements to obtain design requirements for bond on lift lines. For example, allowing a contractor the freedom to choose the batch plant type and size can reduce costs but if the production rate is not sufficient, it may impact the bond strength requirements of the lift lines. Another example is that the need for additional backup pieces of equipment must be weighed against the consequences that may result from interrupting placements, as well as the potential adverse impacts that may occur to the concrete quality and the lift line bond strength.

## Quality Control and Inspection

Quality control should not be compromised if 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 usually approached more conservatively.

Table B-1 shows bid prices for Reclamation projects where RCC was used. Prices have not been adjusted to present-day costs. Costs for cement and pozzolan are not included in the bid prices for RCC.

**Table B-1. Summary of Reclamation Projects and the RCC Mix Design Data**

| Application | | Year [1] | Compressive strength ($lb/in^2$) | Cement plus pozzolan (lb) | Original bid price [5] | RCC volume ($yd^3$) |
|---|---|---|---|---|---|---|
| Upper Stillwater Dam (new gravity dam) | Mix A | 1987 | 3,000 [2] | 134+292=426 | $23.81 | 1,200,000 |
| | Mix B | | 3,000 [2] | 158+348=506 | $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 | 3,000 [2] | 125+130=255 | $45.74 | 38,500 |
| Camp Dyer Diversion Dam (buttress) | | 1992 | 3,000 [2] | 139+137=276 | $45.60 | 15,400 |
| Cold Springs Dam (spillway replacement) | | 1996 | 4,000 [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 |
| Glendo Dam (RCC cutoff structure for auxiliary spillway) | | 2012 | 3000 [6] | 140+210=350 | $95.00 | 18,500 |

[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.
[6] Specified compressive strength at 56 days.

## Appendix C

# Samples of Adiabatic Temperature Rise Tests of Roller-Compacted Concrete

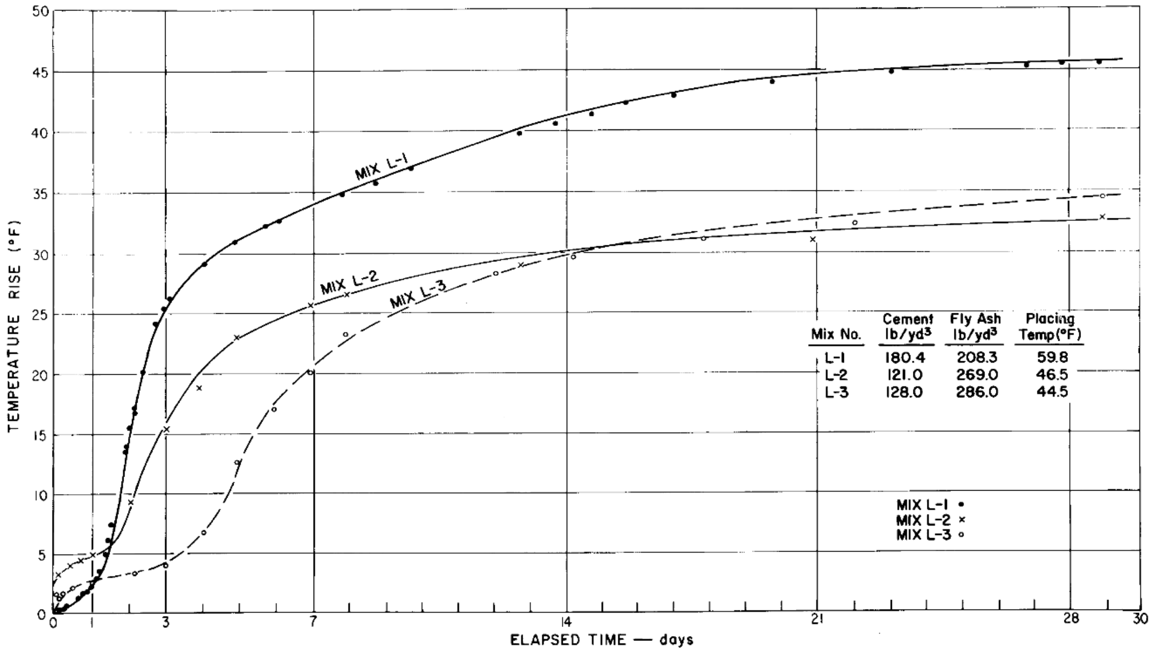


**Figure C-1. Adiabatic temperature rise, Upper Stillwater Dam, Utah.**

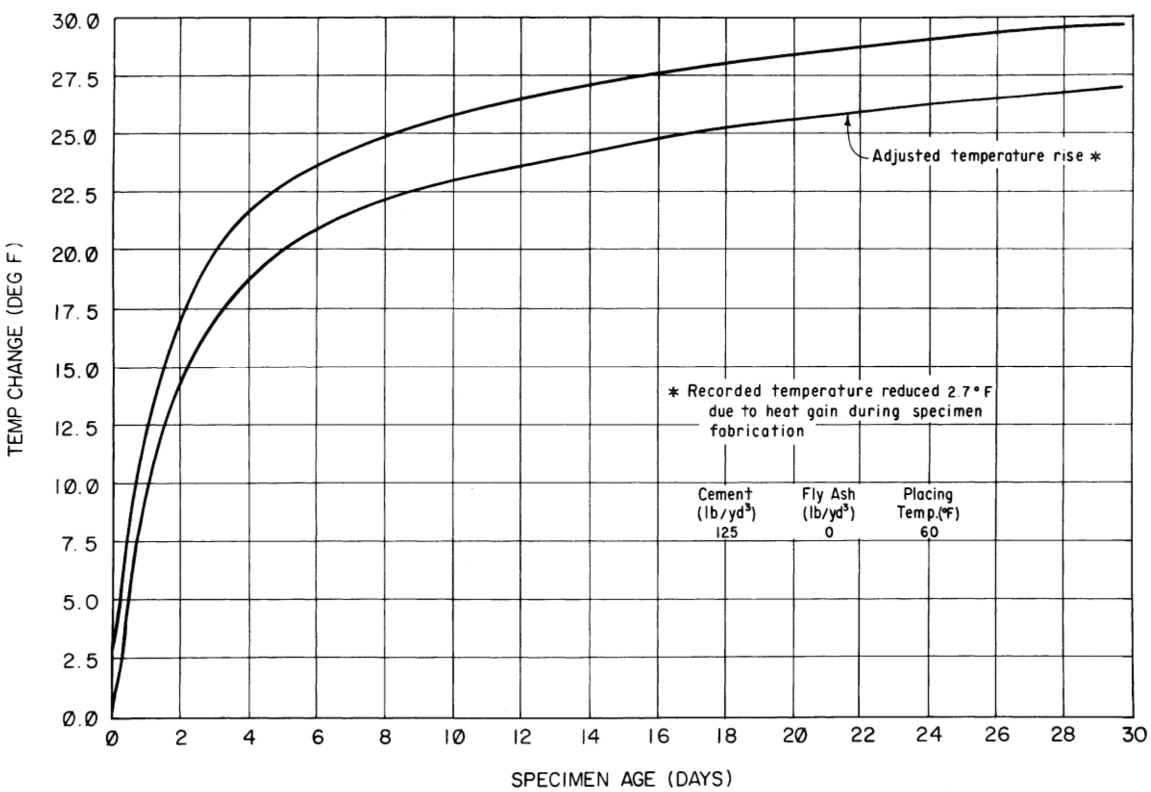


**Figure C-2. Adiabatic temperature rise, Middle Fork Dam, Colorado.**

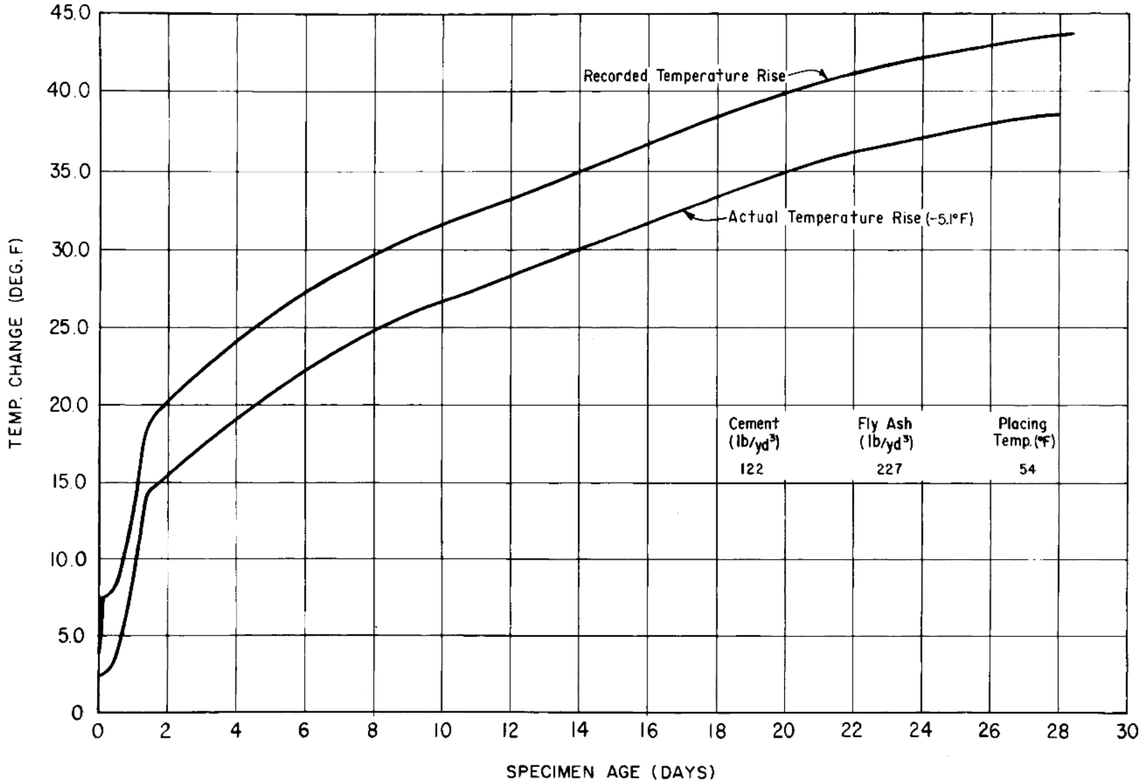


**Figure C-3. Adiabatic temperature rise, Pamo Dam, California.**