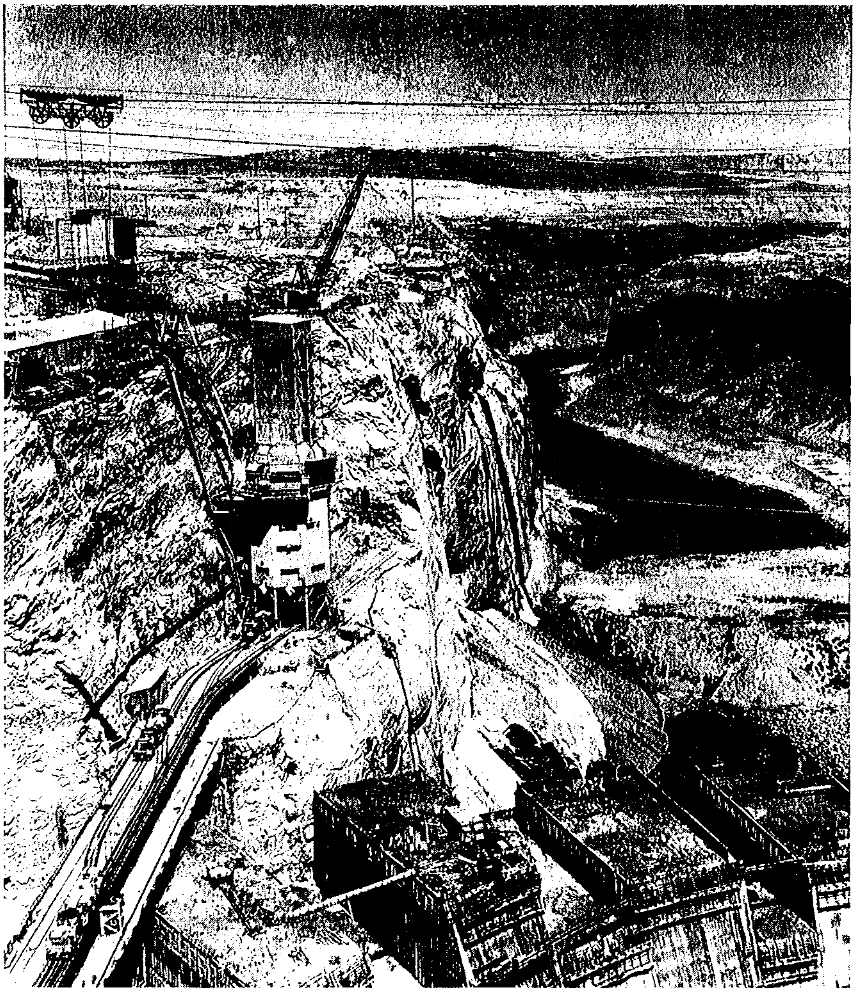

Fig. 3—Glen Canyon Dam — The differential height between adjacent blocks should not exceed 40 ft (12 m) and the highest block should not be more than 60 ft (18 m) above the lowest block

SP 141-7

The Development of Roller Compacted Concrete Mixtures for Bureau of Reclamation Mass Concrete Construction

by T.P. Dolen and K.F. von Fay

Synopsis:

The Bureau of Reclamation has proportioned roller-compacted concrete (RCC) mixtures since 1979, beginning with the Upper Stillwater Dam Project. Reclamation's research and project-related RCC investigations cover a variety of structures and varying site conditions.

Reclamation proportions RCC mixtures to meet both fresh and hardened concrete properties. This assures construction of high quality concrete structures. Ongoing research has continued to identify specific properties of RCC, such as bond strength, freeze-thaw durability, and thermal properties which significantly affect the performance of these structures.
This paper summarizes RCC mixture proportions and properties of fresh and hardened concrete from Reclamation's RCC research and project activities.

Keywords: Air entrainment; bleeding (concrete); bonding; cohesion; compressive strength; construction; cores; creep; density (mass/volume); durability; mass concrete; mix proportioning; permeability; research; roller compacted concrete; shear properties; temperature; tensile strength; thermal properties; workability

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INTRODUCTION

Roller-compacted concrete (RCC) is the most important mass concrete dam construction innovation of the last decade. RCC techniques reduced the cost of traditional concrete dam construction and are now competitive with modern embankment and rockfill dam construction [1].

RCC mixtures are proportioned so that "the quality of RCC is no different from the quality of conventional mass concrete."

Mixture proportions were developed to meet the following criteria:
- adapt to new construction techniques, including rapid construction methods for both the main dam and exterior facing,
- minimize heat generation,
- placing in hot or cold weather environments, and
- assure bond between successive lifts.

This paper presents a brief overview of Bureau of Reclamation (Reclamation) RCC construction projects to date and test results from these studies. RCC fresh and hardened properties, thermal properties, joint bonding studies, and core tests are summarized.

RECLAMATION RCC MIXTURE PROPORTIONING STUDIES - HISTORY

Reclamation began RCC mixture proportioning investigations for Upper Stillwater Dam, Utah in 1979. Upper Stillwater Dam is the largest RCC dam in the United States. These studies evaluated different theories of proportioning, determined the fresh and hardened properties of RCC, and compared various combinations of concrete materials. The pioneering investigations of Cannon [2] and Dunstan [3] influenced Reclamation's philosophy of optimizing the workability of fresh concrete to assure meeting hardened concrete properties.

The basic philosophy resulting from these early investigations was that economical RCC mixtures could be proportioned with conventionally graded concrete sands and gravels. Mixtures are proportioned to a specified consistency which allows vibrating rollers to consolidate RCC. This is different from the soil cement or geotechnical philosophy of proportioning mixtures for maximum density [4].

Our present proportioning methods were developed from both laboratory and field tests conducted since 1979. Highlights of these investigations follow:

RCC Project Studies

Upper Stillwater Dam - Upper Stillwater Dam is located on Rock Creek, about 120 miles southeast of Salt Lake City, Utah. Dam construction began in 1984 and was completed in 1987. The dam is 2,673 ft (8815 m) long, 294 ft (89.6 m) high, and has a RCC volume of 1.47 million yd^3 (1.12 million m^3). At the time of completion it was the largest RCC dam in the world. The design and construction of the dam incorporated new features in RCC construction including:

- transporting of up to 11,000 yd^3/day (8,410 m^3/day) of RCC by conveyors and end-dump trucks,
- slipforming 100 miles (160 km) of upstream and downstream facing elements,
- constructing a "stair-stepped" spillway to aerate spillway flows,
- using 0.6 H to 1.0 V and 0.33 H to 1.0 V slopes on the downstream face to reduce concrete volume, and
- proportioning "high paste" RCC mixture containing up to 70 percent Class F pozzolan [5].

RCC mixtures were proportioned to satisfy two conflicting design requirements:

- provide sufficient paste in the mixture for high bond strength requirements (180 lb/in^2 (1,240 kPa) tensile, and strength and 300 lb/in^2 (2,068 kPa) cohesion across RCC lift joints).
- minimize heat generated by the mass concrete to reduce thermal cracking in the dam [6].

Upper Stillwater Dam was the only RCC dam to incorporate high bond strength in it's design. The major conclusion resulting from studies of bond strength analysis of this structure is that mixtures must have a consistency which assures full consolidation of each lift [7]. We found that a 15 second Vebe consistency [8] was optimum for consolidating 1 ft (0.3 m) thick RCC lifts, producing well bonded lift joints without seepage [9].

The dam suffered leakage through vertical cracks which resulted from foundation and thermal stresses. Though not jeopardizing the stability of the structure, the cracks were injected with polyurethane grout to reduce leakage [10]. By 1992, most of the leakage was stopped.

Santa Cruz Dam - Santa Cruz Dam is a 151 ft (46 m) high concrete arch dam. It is located in the Santa Cruz Mountains, about 26 miles (42 km) northwest of Sante Fe, New Mexico. Significant features of this dam modification were:

- the first arched buttress constructed with RCC in the United States,
- a curved 0.65 H to 1.0 V, stair-stepped downstream spillway and facing,
- use of a pneumatic form with shotcrete to construct the gallery, and
- the first specified use of air-entrained RCC in the United States

Entrained air improved RCC's freeze-thaw durability [11]. The dam modifications were constructed during the winter of 1989/1990. The winter construction enabled spring runoff flows to be captured and released for irrigation the following summer.

Coolidge Dam - Coolidge Dam is a multiple dome, reinforced concrete dam. It is on the Gila River, southeast of Phoenix, Arizona. RCC was studied for foundation erosion protection and to stabilize one abutment. An extensive mixture proportioning study was undertaken to evaluate a host of possible material combinations, including varying the C+P (cement plus pozzolan) content and using two different aggregate sources. The RCC mixtures had a 15 second Vebe time (+/-5 s), a one year design compressive strength of 2,500 lbf/in^2 (17.2 Mpa), and a 180 day cohesion requirement of 250 lbf/in^2 (1720 Kpa) between lift joints. Other properties investigated were elastic properties, drying shrinkage and volume change, freeze-thaw and sulfate resistance, and temperature rise. Ultimately, RCC was not used at Coolidge Dam. After completing the mixture proportioning and testing program, the original areas requiring erosion protection and abutment stabilization were significantly reduced and designers opted to use conventional concrete only.

Camp Dyer Diversion Dam - Camp Dyer Diversion Dam is located downstream of New Waddell Dam, about 40 miles (66 km) north of Phoenix, Arizona. Reclamation modified the 70 ft (21 m) high masonry gravity dam with an RCC downstream buttress for overtopping protection and seismic safety. Innovative features of this dam modification were:

- a stairstepped, RCC spillway facing with no conventional concrete,
- use of air-entrained RCC to improve the workability of the mixture, and
- use of liquid nitrogen to cool the RCC in the hot, desert climate.

The RCC buttress was completed in June 1992. The dam was overtopped twice in January 1993 with flows exceeding 8,000 ft^3/s (226 m^3/s) and functioned as intended.

Milltown Hill Dam - Milltown Hill Dam will be constructed on Elk Creek, which is located midway between Eugene and Roseburg, Oregon. Reclamation designed the dam for Douglas County, Oregon, who also constructed (in 1985) and own Galesville Dam. The 0.75 H to 1.0 V, straight gravity dam will be constructed in a challenging valley location. Claystone seams underlay both abutments.

RCC design strength criteria are 1,800 lbf/in^2 (12.4 MPa) compressive strength and 70 lbf/in^2 (483 Kpa) tensile strength at one year and 100 lbf/in^2 (689 Kpa) cohesion at 180 days. Strength tests compared alternative aggregate sources for the most economical mixture. Construction is scheduled for 1994 or 1995.

Reclamation RCC Research

Bond Strength of RCC - Reclamation began a formalized RCC research investigation "Bond Strength of RCC" in 1984. The research program investigated how to improve bonding between RCC lifts. Test variables included:

- RCC mixture proportions,
- the interval between placing RCC lifts,
- supplemental joint bonding methods such as slurry, mortar, and bedding concrete bonding mixtures, and
- joint cleanup.

Fresh and hardened concrete tests were performed on laboratory and field specimens [12]. These tests led to a better understanding of the requirements for bonding RCC layers and reducing seepage between lift joints.

Investigations in RCC Construction - A second research program, "Investigations in RCC Construction" began in 1989. This research continued studies on improving RCC mixtures for new construction, rehabilitating existing concrete dams, and constructing RCC arch dams.

One of the first accomplishments of the studies was developing air-entrained RCC for improved freeze-thaw resistance. Studies that are currently underway:

- measuring early age (0 to 7 days) strength, elastic, and thermal properties of RCC, and
- comparing the fresh and hardened properties of RCC to coarse-grained, soil-cement.

Completed RCC Dam Concrete Core Investigations

Reclamation tested cores from completed RCC dams to confirm design properties for compressive and bond strength, density, and elastic properties. Six-inch (75 mm) diameter cores were drilled from Upper Stillwater Dam, Galesville Dam, and Stagecoach Dam after construction.

Galesville Dam - Galesville Dam, constructed in 1985, is a 167 ft (51 m) high straight gravity dam. Morrison Knudsen Engineers designed the dam for Douglas County, Oregon. Reclamation funded design and construction through the Small Reclamation Projects Act. Cores from two RCC mixtures were tested for 1-year strength, elastic, and shear properties.

Stagecoach Dam - Stagecoach Dam, a 150 foot (46m) high straight gravity dam, was designed by Woodward-Clyde Consultants for the Upper Yampa Water Conservancy District in Steamboat Springs, Colorado. It was completed in 1988. Design and construction were also funded through the Small Reclamation Projects Act. Compressive and shear tests were done at one year to confirm design strength parameters for the dam.

ROLLER COMPACTED CONCRETE MIXTURE PROPORTIONS

Materials - Reclamation RCC mixtures normally use ASTM C 33 sand and coarse aggregate gradings. The percent passing the 75 µm (No. 200) sieve is less than 7 percent by mass of sand. The low fines content results in a lower water demand than "high fines" mixtures. The unit water content of Upper Stillwater Dam mixtures was only 166 lb/yd^3 (98.5 kg/m^3), although it was considered a "more workable" or even "wet" RCC mixture. High fines mixtures placed at Galesville Dam had a water content of about 190 lb/yd^3 (113 kg/m^3). However, Vebe consistency was very high (more than 60 seconds) due to the high fines content.

Mixture Proportions - Table 1 summarizes RCC mixtures proportioned by Reclamation. RCC mixtures are proportioned to satisfy both design and construction requirements. RCC is typically proportioned to meet compressive strength, elastic properties (modulus of elasticity and Poisson's ratio), bond at lift joints, thermal properties, and durability requirements.

Of particular importance in RCC construction is bond between lifts. RCC dams are constructed in thin horizontal layers from one abutment to the other, versus individual blocks as in conventional mass concrete dam construction. RCC dams do not have post cooling to control thermal cracking in the mass concrete. Bond between lift joints depends on RCC mixture proportions, the time between placing each lift, and supplemental joint bonding treatment methods. Mixtures must be proportioned so that adequate bond between lifts is achieved.

Cement plus Pozzolan Content - Reclamation adjusts the C+P content and C/P ratio to meet ultimate strength requirements and temperature considerations, among others. Structures with higher strength requirements, such as Upper Stillwater Dam, had 425 lb/yd^3 (252 kg/m^3) C+P and 32 percent cement by mass of C+P. Santa Cruz Dam had lower ultimate strength requirements and the RCC had 225 lb/yd^3 (133 kg/m^3) C+P. Since the structure was to be loaded within three months after construction, the cement content was increased to 50 percent by mass of C+P. Coolidge Dam mixtures were proportioned with 250 lb/yd^3 (148 kg/m^3) C+P and 50 percent cement.

Our studies showed that rich mixtures (greater than 250 lb/yd^3 C+P) can be placed on a clean lift joint up to two days old without supplemental joint treatment. The high paste content enables fresh RCC to bond with the older concrete. Lean mixtures (C+P content less than 250 lb/yd^3) may need additional bond treatment between lifts, such as high-slump mortar or bedding concrete, after about 6 to 8 hours. Both rich and lean mixtures must have a consistency which assures the RCC can be fully consolidated. This improves the bond and reduces seepage between lifts.

Consistency - Reclamation uses the Vebe apparatus according to ASTM Method C 1170 [8] to measure the consistency of RCC. Tests by the Japanese Ministry of Construction [13], U.S. Army Corps of Engineers [14], and Bureau of Reclamation conclude the consistency of RCC is primarily dependent on the water content, and if used, the entrained air content of the mixture. The sand/aggregate ratio and percent and type of minus 75 µm (No. 200) fines also influence consistency. At Reclamation, we first test the consistency for a range of water contents to optimize the workability. We then adjust the sand/aggregate ratio and W/C+P (water to cement plus pozzolan) ratio to meet fresh and hardened concrete properties, respectively.

FRESH PROPERTIES OF RCC

Table 2 summarizes the fresh properties of several RCC mixtures studied in the laboratory.

Temperature - The initial temperature of RCC can be an important design consideration for mass concrete dams. Thermal cracking of mass concrete is governed by foundation restraint, the initial placing temperature, adiabatic temperature rise and thermal and elastic properties of the mixture, and the average ambient temperature at the site.

Generally, the placing temperature of RCC will be most influenced by the temperature of aggregates and water. To increase production, aggregates are usually stockpiled before placing begins. The stockpiles usually reach a stable temperature and moisture condition, corresponding to the average ambient temperature and humidity at the site. Thus, without supplemental heating or cooling, the average temperature of RCC will closely follow the average ambient temperature at the time of placing.

Hot water increased the RCC placing temperature at Santa Cruz Dam during the winter construction season. The contractor for Upper Stillwater Dam used ice to decrease the RCC placing temperature. Liquid nitrogen was used to cool the RCC at Camp Dyer Diversion Dam.

The most effective means of changing the placing temperature of concrete is by changing the water temperature. However, the water content of RCC is lower than conventional concrete. Thus, there may be insufficient water to effectively change the placing temperature. Night placing and liquid nitrogen provided supplemental cooling of RCC at Upper Stillwater Dam when other means were insufficient to maintain the necessary placing temperatures. Though liquid nitrogen is expensive, the injection system is easy to set up and operate for short term needs.

Air-Void System - Voids in concrete are categorized as:

- entrapped,
- purposely entrained, and
- voids due to insufficient consolidation.

Internally "entrapped " air voids normally comprise 1 to 2 percent of the volume of RCC. These voids are usually less than 1/8 inch in diameter.

Entrained air voids in RCC are generally similar to their counterparts in conventional concrete, but not commonly used in practice now. The low paste volume, low workability, and large amounts of minus No. 200 fines in some RCC mixtures limit the effectiveness of air-entraining admixtures. However, developing more workable RCC mixtures with clean aggregates makes it possible to effectively proportion mixtures with entrained air.

Entrained air was specified in RCC mixtures at Santa Cruz Dam [11], [15]. The air-entraining admixture increased the total air content an additional 1 to 2 percent. The admixture dosage was about twice that of conventional mass concrete.