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Report on Roller-Compacted Mass Concrete

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

The materials, processes, quality control measures, and inspections described in this document should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI certifications or equivalent.

Keywords: admixtures; aggregates; air entrainment; compacting; compressive strength; conveying; creep properties; curing; lift joints; mixture proportioning; monolith joints; placing; shear properties; vibration; workability.

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CHAPTER 1—INTRODUCTION

1.1—General

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

Fig. 1.1—RCC compaction with dual-drum, vibrating roller (Serra do Facão Dam, Brazil, 2008).

capacity by providing a means by which they can be safely overtopped. RCC has allowed new embankment dams to optimize spillway capacity in over-the-embankment-type emergency spillways (Hansen 1992).

This document summarizes the current state of the art for design and construction of RCC in mass concrete applications. It is intended to guide the reader through developments in RCC technology, including materials, mixture proportioning, properties, design considerations, construction, and quality control and testing. Although this report deals primarily with mass placements, RCC is also used for pavements (refer to ACI 325.10R) and for dam stability improvement and as embankment dam slope protection (United States Society on Dams 2003).

1.2—What is roller-compacted concrete?

ACI Concrete Terminology (2010) defines roller-compacted concrete (RCC) as "concrete compacted by roller compaction; concrete that, in its unhardened state, will support a roller while being compacted." RCC is usually mixed using high-capacity continuous mixing or batching equipment, delivered with trucks or conveyors, and spread with bulldozers in layers prior to compaction with vibratory rollers (Fig. 1.1). Because of RCC's zero-slump consistency, subsequent lifts can be placed immediately after compaction of the previous lift. RCC can use a broader range of materials than conventional concrete, and derives its strength and durability from a mixture philosophy that relies on using just enough paste volume to fill the aggregate voids and no more water content than what is needed for proper workability.

1.3—History

The rapid worldwide acceptance of RCC is a result of economics and of RCC's successful performance. A bibliography of dams constructed is available from the International Commission on Large Dams. Other listings of dams constructed can be obtained from the United States Society on Dams (2003) and from the U.S. Army Corps of Engineers (USACE), EM 1110-2-2006 (USACE 2000). During the 1960s and 1970s, applications of RCC materials led to the development of RCC in engineered concrete structures. In the 1960s, a high-production no-slump mixture that could be

Fig. 1.2—Willow Creek Dam, OR. (USACE 1984).

Fig. 1.3—Shimajigawa Dam (Ministry of Construction 1984).

spread with bulldozers was used at Alpe Gere Dam in Italy (*Engineering News Record* 1964; Gentile 1964) and at Manicougan I in Canada (Wallingford 1970). The mixtures were consolidated with groups of large internal vibrators mounted on backhoes or bulldozers.

Fast construction of gravity dams using earthmoving equipment, including large rollers for compaction, was suggested in 1965 as a viable approach to more economical dam construction (Humphreys et al. 1965). The fast construction method did not receive much attention until it was presented for the "optimum gravity dam" (Raphael 1971). The concept considered a section similar, to but with less volume than, the section of an embankment dam. During the 1970s, a number of projects including laboratory and design studies, test fills, field demonstrations, nonstructural uses, and emergency mass uses were accomplished and evaluated using RCC. These efforts formed a basis for the first RCC dams, which were constructed in the 1980s.

Notable contributions were made in 1972 and 1974 by the Tennessee Valley Authority (Cannon 1972, 1974). The U.S. Army Corps of Engineers conducted studies of RCC construction at the Waterways Experiment Station in 1973 (Tynes 1973) and at Lost Creek Dam in 1974 (Hall and Houghton 1974). The early work by the U.S. Army Corps of Engineers was in anticipation of construction of an optimum gravity dam for Zintel Canyon Dam (Sivley 1976). Zintel Canyon Dam construction was not funded at the time, but many of its concepts were carried over to Willow Creek Dam, which was completed in 1982 and became the first RCC dam in the U.S.

Developed initially for the core of Shihmen Dam in 1960, "rollcrete" was used for massive rehabilitation efforts at Tarbela Dam in Pakistan beginning in 1974 (Hansen and Reinhardt 1991). Workers placed 460,000 yd^3 (350,000 m^3) of RCC at Tarbela Dam in 42 working days to replace rock and embankment materials for outlet tunnel repairs. Additional large volumes of RCC were used later in the 1970s to rehabilitate the auxiliary and service spillways at Tarbela Dam (Johnson and Chao 1979).

Dunstan (1978; 1981a,b) conducted extensive laboratory studies and field trials in the 1970s using high-paste RCC in the UK. Further studies were conducted in the UK and led to more refined developments in laboratory testing of RCC and construction methods, including horizontal slipformed facing for RCC dams (Dunstan 1981a,b).

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

Willow Creek Dam (Schrader and Thayer 1982) (Fig. 1.2) and Shimajigawa Dam (Ministry of Construction 1984) (Fig. 1.3) are the principal structures that initiated the rapid acceptance of RCC dams. They are similar from the standpoint that they both used RCC, but they are dissimilar with regard to design, purpose, construction details, size, and cost (Schrader 1982). Willow Creek Dam was completed in 1982 and became operational in 1983. The 433,000 yd^3 (331,000 m^3) flood control structure was the first major dam designed and constructed entirely of RCC. Willow Creek Dam also incorporated the use of precast concrete panels to form the upstream facing of the dam without transverse contraction joints (Schrader and McKinnon 1984).

Winchester Dam was the second RCC dam in the U.S. and was completed in 1983. The major contribution of the Winchester Dam was its use of a polyvinyl chloride (PVC) membrane at the upstream face as the primary method of providing watertightness for the dam (Hansen and Reinhardt 1991). The membrane was attached to the inside (RCC side) of the precast concrete panels. Once the panels were set, the

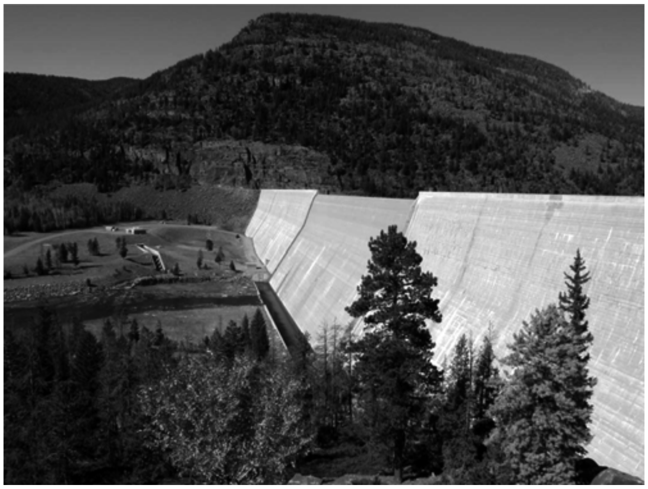

Fig. 1.4—Upper Stillwater Dam, UT. (Photo courtesy of the U.S. Bureau of Reclamation, 1988.)

membrane joints between abutting panels were sealed with a strip of membrane by heat welding. This facing system is referred to as the Winchester method (Sexton et al. 2010) The success of this facing system has contributed to designers specifying a membrane system (with or without precast panels) for 6% of all RCC dams worldwide. An alternative to attaching the membrane to precast panels is to place the membrane on the exposed face of the dam after RCC placement is concluded. As of 2009, the 318 ft (97 m) high Olivenhain Dam near San Diego was the only RCC dam in the U.S. that has the exposed membrane facing system. Wenquanpu Dam in China is the only RCC arch dam that has a membrane (exposed) facing system. Several dams that have a membrane facing system also have a geotextile/geocomposite layer between the RCC and the membrane to collect any leakage. By adding this drainage medium, designers can consider taking a reduction in uplift pressures at lift joints because the drainage medium collects any water that might bypass the membrane.

In the 1980s, the U.S. Bureau of Reclamation used concepts of high-paste RCC for the construction of Upper Stillwater Dam (Fig. 1.4) (Oliverson and Richardson 1984). Laboratory investigations and field trials were performed to demonstrate that an RCC placed with sufficient paste could provide bonding between successive layers without bedding concrete or mortar. Notable innovations at this structure included using a steep compound downstream slope (0.6 horizontal to 1.0 vertical (0.6H:1.0V) for the lower 215 ft (65 m) of the dam and 0.32 horizontal to 1.0 vertical for the upper 75 ft (23 m) and using 3 ft (0.9 m) high, horizontally-slipformed upstream and downstream facing elements as an outer skin of conventional low-slump, air-entrained concrete. The RCC mixture consisted of 70% Class F pozzolan by mass of cement plus pozzolan (Dolen et al. 1988).

In Australia, the Copperfield Dam was constructed in 1984, containing 183,000 yd^3 (140,000 m^3) of RCC that was placed in 16 weeks. (Forbes 1985). It was designed with vertical monolith joints, RCC was placed directly against vertical forms for the upstream face, and a thin conventional concrete facing of 12 in. (300 mm) was placed at the same time as the RCC to create a monolithic spillway facing. The dam experienced high velocity (100 ft/s [30 m/s]) spillway flows and was also constructed in a region with heavy rain seasons.

Other countries quickly started developing their own RCC projects that incorporated lessons learned from early applications. They also started developing new design details and construction methods. The Saco De Nova Olinder Dam was Brazil's first RCC dam, and was completed in 1986. This 184 ft (56 m) high dam used 180,000 yd^3 (138,000 m^3) of RCC and was placed in 110 days. Brazil has constructed 36 RCC dams higher than 50 ft (15 m) (Andriolo 1998), including the 220 ft (67 m) high Salto Caxias Dam that has the largest hydroelectric generating capacity (6500 MW) of any RCC dam constructed to date. The design philosophy in Brazil is centered around using conventional concrete for the upstream facing, using little fly ash (only 2% of Brazil power comes from coal), using stone dust or crushed powder as a filter material (some cases have shown pozzolanic properties), and incorporating 8 to 12% fines in the RCC mixture.

Growth and acceptance of the RCC process increased in the late 1980s (Hansen and Reinhardt 1991). In 1983, there were only two RCC dams in the world. By the end of 2001, there were 264 large (greater than 50 ft [15 m] high) RCC dams in 37 countries. Thirty-three of these dams were greater than 300 ft (90 m) high, and were mainly located in China and Japan. The highest completed RCC gravity dam is the Longtan Dam in southern China, which is 715 ft (218 m) high. Dams are increasingly using larger volumes of RCC. The 1.6 mi (2.6 km) long Tha Dan Dam in Thailand has 6.45 million yd^3 (4.9 million m^3) of RCC whereas the Longtan Dam in China has 6.5 million yd^3 (4.9 million m^3). At the end of 2007, there were 74 completed RCC gravity dams in the U.S., ranging in height from 10 to 318 ft (3 to 97 m); 83 overtopping spillways of existing embankment dams; 12 uses of RCC for added support of existing concrete and masonry dams; and another 72 miscellaneous uses of RCC in water resources applications. Based on these statistics and the potential for using RCC to rehabilitate numerous existing dams that lack sufficient spillway capacity and/or suffer from structural deficiencies, the largest market for RCC in the U.S. may be in the rehabilitation of existing dams. In 2003, the United States Society on Dams published a comprehensive document emphasizing the practical aspects of RCC uses for dam rehabilitation. In addition to RCC mixture design and specifications, the document covers RCC for overtopping protection of embankment dams, dam stability improvement, spillways, dam raising, and seepage control. McDonald and Curtis (1997) summarized a wide variety of RCC applications in rehabilitation and replacement of hydraulic structures. The Taum Sauk replacement dam (Fig. 1.5) has 2.96 million yd^3 (2.25 million m^3) of RCC.

A summary of RCC references is given in the 1994 U.S. Committee on Large Dams Annotated Bibliography (1994). References are also given by CHINCOLD and SPANCOLD, "Proceedings of the International Symposium on Roller

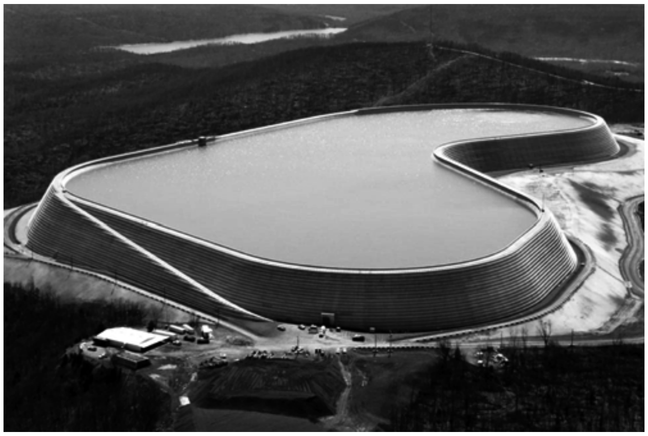

Fig. 1.5—Taum Sauk Dam, MO. (Photo Courtesy of ASI Constructors, Inc., 2007).

Compacted Concrete Dams," Beijing, China, 1991; Santander, Spain, 1995; Chengdu, China, 1999; Madrid, Spain, 2003; and Gulyang, China, 2007.

1.3.1 *Production and delivery*—Many of the early-1980s dams successfully demonstrated the high production rates possible with RCC construction. Nearly 1.5 million yd^3 (1.1 million m^3) of RCC were placed at Upper Stillwater Dam in 11 months of construction between 1985 and 1987 (McTavish 1988). The 150 ft (46 m) high Stagecoach Dam was constructed in only 37 calendar days of essentially continuous placing; it had an average rate of height advance of 4.1 ft/day (1.2 m/day) (Arnold and Johnson 1992). At Elk Creek Dam, RCC placing rates exceeded 12,000 yd^3/day (9200 m^3/day) (Hopman 1992).

For a short time, Olivenhain Dam (Fig. 1.6) held the world record for 1-day placement: 16,000 yd^3 (12,250 m^3) was placed in a 19.5-hour day. It also had a maximum monthly placement of 287,790 yd^3 (220,025 m^3) (Pauletto et al. 2003), and is only one of three RCC dams that had an average of over 130,000 yd^3 (100,000 m^3) per month placement rate.

Placement rates have continued to increase for several reasons. Engineers understand that fast, uninterrupted placement of RCC generally leads to better overall quality, particularly at lift joints, and that minimizing obstructions to RCC placement leads to faster productions rates. Contractors have improved on their means and methods of delivering the RCC to the placement area. At Willow Creek Dam, scrapers were used to bring the RCC from the mixing plant to the dam surface. On smaller lift areas, traffic on the lift surface becomes increasingly confined, and efficiency suffers. Beginning in 1984, conveyors began to deliver RCC from mixing plants to the lift surface. At Middle Fork Dam in Colorado, a series of stacker conveyors was used with a rock ladder to drop the RCC from the conveyor to the lift surface to minimize segregation (Parent et al. 1985). Similar setups using a variety of conveyors and drop chutes were subsequently used at Elk Creek, Upper Stillwater, Grindstone Canyon, Stagecoach, and Quail Creek Dams in the U.S. In all of these cases, haul vehicles were used to deliver RCC from the conveyor discharge above the lift surface to the active placement locations throughout the lift surface.

Fig. 1.6—Olivenhain Dam, CA. (Photo courtesy of San Diego County Water Authority, 2002.)

Fig. 1.7—Continuous all-conveyor placing, Miel Dam, Colombia. (Photo courtesy of INGETEC S.A., 2002).

Beginning in 1989, the benefit of conveyors was extended by using systems that could deliver RCC to essentially every location on the lift surface. At Marmot Dam near Sandy, OR, in 1989, conveyors were used to transport RCC from the mixing plant to a tower embedded in the dam (this dam was removed in 2007 to improve fish migration). A pivoting conveyor on top of the tower could deposit RCC at nearly any location on the dam lift surface. In 1992 at Siegrist Dam near Pine Grove, PA, the first crawler-placer was used to place RCC. This system included a mainline conveyor from the mixing plant to the upstream face of the dam, a conveyor mounted on the upstream face of the dam that was raised with the dam, a tripper conveyor that delivered RCC to the crawler placer, and the crawler placer that traveled across the lift surface. This system was subsequently used on several dams, including Spring Hollow Dam in Virginia in 1993 and at Meil I Dam in Colombia (Fig. 1.7).

Several dams have used a vacuum chute to transport the RCC down very steep abutments without segregation into trucks on the lift surface. At Shapai Dam in China, a high negative-pressure chute was used with a height of 238 ft (72.5 m). A variation of this type of system was used at the Platanovryssi Dam in Greece, and at the 508 ft (155 m) high Ralco Dam in Chile. At Ralco, RCC was conveyed down a

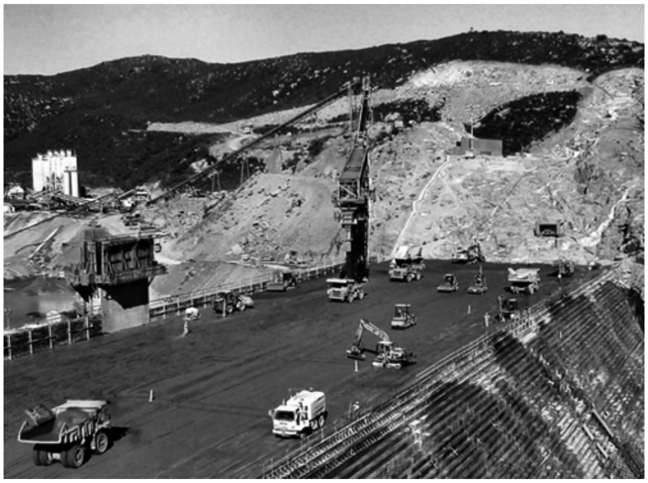

Fig. 1.8—Overview of conveyor transporting RCC to waiting trucks on dam surface, Olivenhain Dam, CA. (Photo courtesy of San Diego County Water Authority, 2002).

45-degree right abutment slope using an additional conveyor belt on top of the RCC to keep it from running down or spilling off the belt (Croquevielle et al. 2003). This system has supported a 10-day moving average production rate of 6860 yd^3 (5244 m^3) per day with a monthly peak of 186,676 yd^3 (142,714 m^3).

Since the early 1990s, a variety of portable conveyor systems have been used throughout the U.S. A popular setup, especially for smaller dams and spillways, uses conveyors on moving crawler-tractors or telescoping conveyors from trucks. These setups are situated off of the structure, minimizing lift surface traffic and facilitating construction of high-quality lift joints. Their portability makes them economical for small-volume projects where access by vehicles is impossible or less practical.

Many of the large production projects used off-road dump trucks as a major component of the delivery system. At Olivenhain Dam (Fig. 1.8) and Yeywa Dam, Myanmar, conveyors were used to transport RCC from the mixing plant to a fixed transfer point on the dam. Trucks were then used to transport RCC to various locations on the lift. This method is a popular method for large dams because of the relatively large work area available for equipment on the dam.

1.3.2 *Facing systems*—There are more than a dozen different facing systems for RCC gravity dams (Hansen 2001). The two most common systems are the conventional concrete facing that is placed concurrently with each RCC lift and RCC placed against conventional formwork using the grout-enriched RCC (GERCC) method. Another name associated with GERCC is grout-enriched vibratable RCC (GEVR) (Forbes 1999). GERCC is used for upstream and downstream facing of RCC dams. The first dam to use GERCC was Jiangya Dam in China. While the grout-enriched zone is generally limited to the facing or abutment contact zones, the location or sequence of grout placement is one of the biggest variations between users. Sometimes the grout is placed on top of the compacted RCC lift just before the next lift is placed. Other times, the grout is placed on top of the uncompacted lift. In both cases, the RCC section with grout is vibrated using large immersion vibrators. The typical process consists of altering the composition of RCC by adding cementitious grout to the RCC mixture. The intent is to distribute the grout through the RCC by internal pneumatic vibrators, producing a mixture similar to conventional concrete. Other facing systems commonly used in RCC construction include stay-in-place precast panels with or without geomembranes, conventional and roller-compacted concrete with geomembranes, and slip-formed concrete.

Shapai Dam in China and Ghatghar Dam in India used GEVR for both upstream and downstream facing. Bolivia's first RCC dam, La Canada Dam at 170 ft (52 m) high, used GEVR. GERCC was used at Ralco Dam for facing and abutment treatment and for the gallery walls. The first significant uses of GERCC in the U.S. were at Olivenhain Dam, where it was used at the upstream face and the abutment contacts, and at Hickory Log Creek Dam, where it was used in the non-overflow steps.

The U.S. Army Corps of Engineers has a research program to study air-entrained RCC and GERCC for potential application in lock and guide walls where the RCC would be critically saturated and in a freezing-and-thawing environment. Early results have demonstrated that an air-entrained RCC face is resistant to freezing-and-thawing cycles, but producing a stable air-entrained grout and ensuring that the grout is uniformly distributed throughout the GERCC in the field is difficult and still undergoing further study (McDonald 2002).

1.3.3 *Lift configurations*—Most RCC dams have horizontal level RCC lift surfaces. Several dams have a cross-fall slope in the upstream direction to increase the resistance to sliding. Miel II Dam used a 1 on 100 cross-fall slope (Marulanda et al. 1992), and Saluda Dam in Columbia, SC, completed in 2004, used a 1 on 30 cross-fall slope. Due to high rainfall at Ralco Dam, Chile, RCC lifts were placed at 1% downstream cross fall to improve drainage (Croquevielle et al. 2003).

For the taller RCC dams being built in particularly high seismic regions, lift joint strength and impermeability are crucial design parameters. To maximize lift joint strength properties, successive RCC lifts should be placed before the initial set of the previous lift has occurred. If no retarder is used in the RCC mixture, most mixtures will have an initial set time of 1 to 3 hours; for large dams, it may take between 15 and 30 hours to cover one lift. The Ta Sang Dam in Myanmar will have 32.3 million yd^2 (2700 hectars) of total lift joint surface area, an average of over 70,000 yd^2 (5.8 hectars) per lift. With the normal horizontal lift construction method, it would take many hours to place one lift. The sloping layer placement method was developed in China as a method to improve lift quality, maximize strength properties, and minimize the use of bedding mortars. It was first used at the 430 ft (131 m) high Jiangya Dam, followed by the Fenghe No. 2 Dam, Mianhuatan Dam, and Dachaoshan Dam, which are all located in China (Forbes 1999). Tannur Dam in Jordan and portions of Lajeado Dam in Brazil have also used the sloping layer method. At Jiangya Dam, the RCC was initially placed on a 1:10 slope in the cross canyon direction