

Report on Roller-Compacted Mass Concrete

Reported by ACI Committee 207



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Report on Roller-Compacted Mass Concrete

Reported by ACI Committee 207

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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

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 yd³ (350,000 m³) 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 yd³ [165,000 m³]) 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



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



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

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 yd³ (331,000 m³) 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 downstream face of the precast concrete panels. Once the panels were set, the

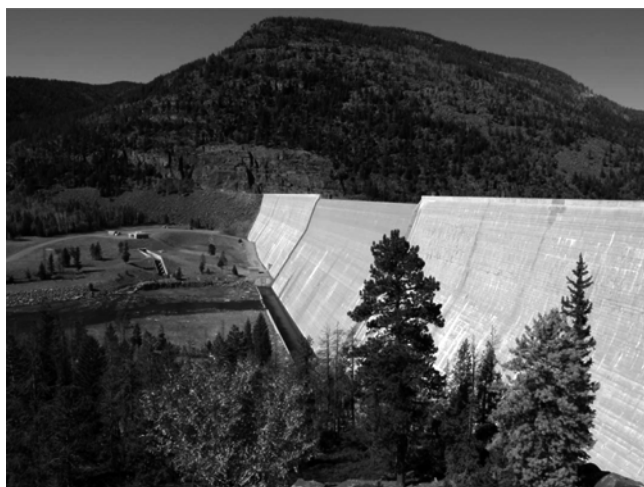


Fig. 1.4—Upper Stillwater Dam, UT. (Photo courtesy of the U.S. Bureau of Reclamation, 1988.)

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 yd³ (140,000 m³) 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 Olinda Dam was Brazil's first RCC dam, and was completed in 1986. This 184 ft (56 m) high dam used 180,000 yd³ (138,000 m³) 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 yd³ (4.9 million m³) of RCC whereas the Longtan Dam in China has 6.5 million yd³ (4.9 million m³). 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 yd³ (2.25 million m³) 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 USACE. "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 yd³ (1.1 million m³) 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 yd³/day (9200 m³/day) (Hopman 1992).

For a short time, Olivenhain Dam (Fig. 1.6) held the world record for 1-day placement: 16,000 yd³ (12,250 m³) was placed in a 19.5-hour day. It also had a maximum monthly placement of 287,790 yd³ (220,025 m³) (Pauletto et al. 2003), and is only one of three RCC dams that had an average of over 130,000 yd³ (100,000 m³) 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 production 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 550-ft (168-m) high Ralco Dam in Chile. At Ralco Dam, RCC was conveyed down a

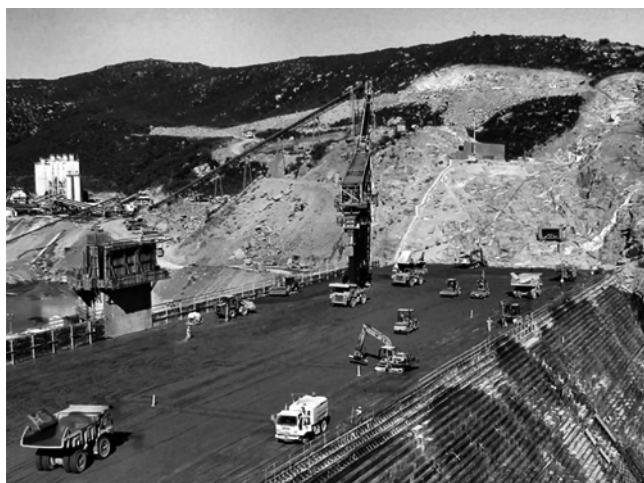


Fig. 1.8—Overview of conveyor transporting RCC to waiting trucks on dam surface, Olivenhain Dam, CA. (Photo courtesy of San Diego County Water Authority, 2002).

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 yd³ (5244 m³) per day with a monthly peak of 186,676 yd³ (142,714 m³).

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 yd² (2700 hectares) of total lift joint surface area, an average of over 70,000 yd² (5.8 hectares) 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.

to an eventual height of 10 ft (3 m). This process proceeded across the entire length of the dam until the dam was brought up by 10 ft (3 m). The process was again repeated for another 10 ft (3 m). The contractor eventually changed to a 1:20 slope.

The first application for the sloping layer method in the U.S. was at Table Rock Dam in Missouri, where RCC was placed to support a large gated conventional concrete spillway.

1.3.4 Design sections—The vast majority of RCC gravity dams have vertical upstream faces and sloping downstream faces. The downstream slopes have ranged from 1H:1V to 0.8H:1V, with a few exceptions. Upper Stillwater Dam has a compound downstream slope. The lower two-thirds of the face was at a 0.6H:1V, and the upper section was at 0.32H:1V. At Olivenhain Dam, the slope was placed at a 0.8H:1V, but transitioned on a 232 ft (70 m) radius to near vertical on the upper quarter of the slope. The radius concept was used to reduce any stress concentrations at an abrupt change in section slope.

Spain has more than 24 RCC dams, and all are straight gravity dams with the exception of one arch-gravity dam. Several of these dams have a sloping or battered upstream face to provide the necessary stability. Santa Eugenia Dam has a 0.05H to 1V upstream face, and Val Dam has a 0.2H to 1V upstream slope transitioning to a vertical upstream approximately halfway up the dam. The first RCC arch gravity dams were constructed in South Africa by the Department of Water Affairs and Forestry for the Knellport and Wolwedans Dams (Fig. 1.9) (Hollingworth et al. 1988). China has built several thin RCC arch dams, starting with Wenquanpu Dam at 208 ft (63.5 m) high, and followed by the 358 ft (109 m) high Shi Menzi Dam. The Shapai Dam is the highest arch dam to date at 423 ft (129 m) high with a crest length of 820 ft (250 m). It is a three-centered single curvature arch dam containing 477,000 yd³ (365,000 m³) of RCC.

1.3.5 Extreme climates—RCC dams are commonly located in regions where extreme weather conditions are prevalent. At La Presa Ralco Dam (Fig. 1.10), the annual rainfall averages 120 in. (3000 mm), with temperatures ranging between 50 to 100°F (12 to 39°C) (Moreno 2003). During normal RCC placement, the mixture had a consistency time of 15 to 18 seconds, but during wet periods, it was increased to 20 to 25 seconds, and the bedding mortar, which was used on every lift, had some water removed. The bedding mixture placement was limited to no more than 20 ft (6 m) in advance of the RCC placement. With these mixture modifications, rainfall rates of up to approximately 0.1 in. (3 mm) per hour could be accommodated. During the cold periods, the mixing water was heated to 140°F (60°C), and extra thick insulation blankets were used. The Bio Bio River Dam had a minimum flow rate of 3000 ft³/s (90 m³/s) and a recorded maximum flow rate of 120,000 ft³/s (3390 m³/s). The original cofferdam failed, and the RCC-modified replacement overtopped on several occasions. The main dam overtopped when the cofferdam was overtopped or its spillway operated.

The first RCC dam in Iran was Jahgin Dam, which was 256 ft (78 m) high. During the summer, the ambient air temperature would reach 122°F (50°C). Because of this,

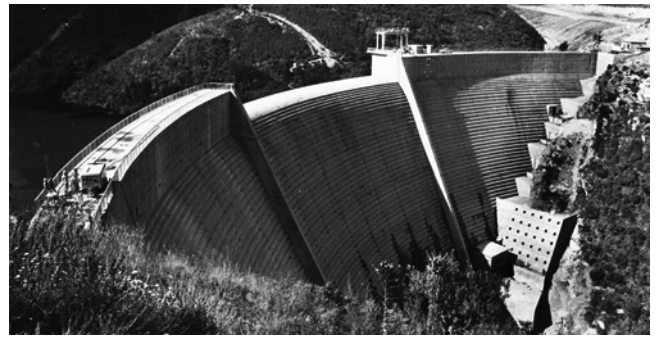


Fig. 1.9—Wolwedans Dam, South Africa (Hollingworth et al. 1988).

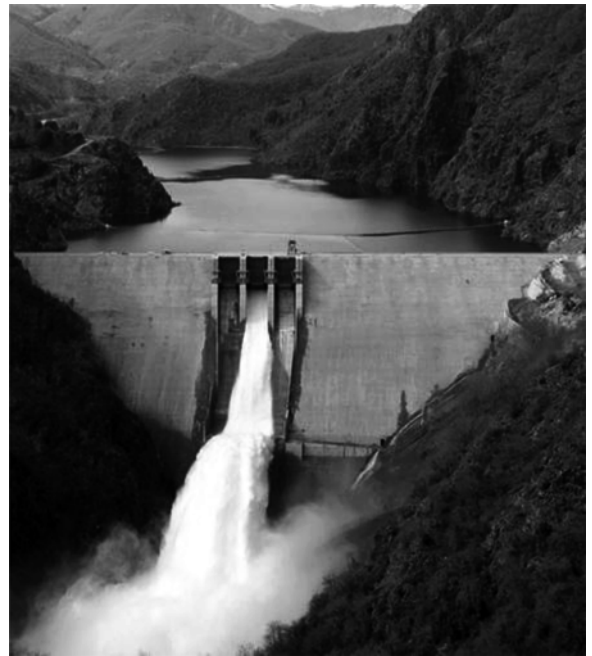


Fig. 1.10—Le Presa Ralco Dam, Chile. (Photo courtesy of B. Forbes and E. Warren, 2003).

RCC production was limited to the time of the year between November to May. Maximum allowable ambient placing temperature was restricted to 73°F (23°C) (Azari et al. 2003). The first RCC dam in India, Ghatghar Dam, had air temperatures as hot as 104°F (40°C) and a monsoon period that lasted 4 to 5 months (Shelke et al. 2006).

1.3.6 Mixture proportions—The mixture proportions used throughout the world have varied widely (Portland Cement Association 2002). Many of the first-generation dams used lean dry mixtures, such as Middle Fork Dam in the U.S., which used a cement content of 112 lb/yd³ (66 kg/m³) and no ash, and Galesville Dam (also in the U.S.), which used 89 lb/yd³ (53 kg/m³) of cement and 86 lb/yd³ (51 kg/m³) of fly ash. The Upper Stillwater Dam is an exception, with 134 lb/yd³ (79 kg/m³) of cement and 292 lb/yd³ (172 kg/m³) of fly ash. Most dams constructed in the U.S. today average more than 200 lb/yd³ (118 kg/m³) of cementitious materials.

Urugua Dam in Argentina has a cement content of only 102 lb/yd³ (60 kg/m³) with no pozzolana. Locally sourced basalt quarry were used to provide adequate paste in the dry



Fig. 1.11—Le Presa Ralco Dam, Chile, overtopping during construction. (Photo courtesy of B. Forbes and E. Warren, 2003).

consistency mixture. The trend in Spain is the use of high paste mixtures of 250 lb/yd³ (150 kg/m³) cementitious materials, with fly ash making up to 70% of the cementitious materials. In Brazil, fly ash is not readily available, so stone dust or crushed powder is used as a filler. Some of these fillers have shown pozzolanic properties. In Jordan, three RCC dams were designed during the same period, with Tannur Dam having a high paste, Wala Dam having a medium paste, and Mujib Dam having a lean consistency.

1.4—Advantages and disadvantages

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

The main advantages are reduced cost, time of construction, and lower spillway costs. Another advantage of RCC dams is that the technology can be implemented rapidly. For emergency projects such as the Kerrville Ponding Dam, RCC was used to rapidly build a new dam downstream of an embankment dam that was in imminent danger of failure due to overtopping (*Engineering News Record* 1986). RCC was also used to quickly construct Concepcion Dam in Honduras after declaration of a national water supply emergency (Giovagnoli et al. 1991). Following the devastating fires at Los Alamos, NM, Pajarito Dam was built as a design/build project. This 130 ft (40 m) high dam was designed and constructed in less than 6 months. When compared with embankment-type dams, RCC usually gains an advantage when spillway and river diversion requirements are large, where suitable foundation rock is close to the surface, and when suitable aggregates are available near the site. Another advantage is reduced cofferdam requirements because, once started, an RCC dam can be overtopped with minimal impact, and the height of the RCC dam can quickly exceed the height of the cofferdam. The 4th Street RCC dam in Fort

Worth, TX, replaced an earth dam that overtopped twice and failed each time during construction before a concrete shell could be completed. Following the second failure, an RCC gravity dam was constructed. During the 16 days of RCC placement, the project was overtopped during a flash flood, but sustained no damage or construction delay. Other projects that overtopped during construction include Big Haynes Dam and Tie Hack Dam in the U.S. and Le Presa Ralco Dam in Chile (Fig. 1.11).

Although it is almost routine for efficiently designed RCC dams to be the least costly alternative when compared with other types of dams, there are conditions that may make RCC more costly. RCC may not be appropriate when aggregate material is not reasonably available, the foundation rock is of poor quality or not close to the surface, or where foundation conditions can lead to excessive differential settlement. Sometimes it is difficult for an RCC dam to compete with an earthfill dam unless the dam is on a large drainage basin. For large inflows, many earthfill dams require a separate large reinforced conventional concrete spillway that can cost more than the dam itself. In these situations, RCC dams can be competitive because flows can then be passed over the dam in a spillway section.

1.5—Performance of RCC dams

Because RCC technology is relatively new and documentation of structural performance is not readily available, the performance record for RCC dams is somewhat limited. The rapid acceptance of this approach to dam construction, however, has resulted in many completed projects with a vast range of details, sizes, and locations. This allows both generalized and detailed comments to be made about performance to date.

Performance involves design and construction in addition to strength and operation of the completed structure. Completed RCC dams are performing their intended purpose quite well. Each type of RCC material and design tends to have advantages and disadvantages, and performs better in some areas than in others. This includes seepage, in-place strength, and properties including lift joints, cracking, and durability.

In 1988, there were eight RCC dams in the U.S., one in Brazil, and one in Australia; other RCC dams were being completed or put into operation. At that time, any RCC dam had been in operation a maximum of only 5 years, with most of the dams having been just recently completed. The major performance aspects of each project, including cost, schedule, strength, thermal stress and cracking, and seepage were reported (ASCE 1988).

Only 15 years later, there were more than 250 completed RCC dams in approximately 39 countries. There are many types of RCC, many approaches to design, and many ways to detail various aspects of the work. No single approach is best for all situations. Each project should be evaluated to determine the best options and overall approach. Data are needed to evaluate the overall performance of RCC dams in different environments. Important data need to include lift line bonding properties, seepage, and the performance of various facing methods, long-term strength, performance,

dynamic properties and performance under seismic loadings, durability in freezing-and-thawing environments, and the overall structural performance of high RCC dams.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A	=	area of cross section
c	=	unit cohesion
N	=	component of confining force normal to the sliding surface
T	=	driving force parallel to the sliding surface
U	=	uplift force acting on cross section
ϕ	=	angle of sliding friction

2.2—Definitions

concrete, roller-compacted—concrete compacted by roller compaction; concrete that, in its unhardened state, will support a roller while being compacted.

dam, arch—a structure resisting the pressure of impounded water by an arch principle, especially a dam having in plan the form of a single arch abutted by natural rock formations.

dam, gravity—a structure resisting the pressure of impounded water through its own weight.

gallery—a tunnel constructed through a dam used for construction access, drainage systems, and inspection activities.

grout-enriched roller-compacted concrete (GERCC)—RCC that is enriched by adding a fluid grout of cement and water to the uncompacted RCC and consolidated with immersion vibrators (also referred to as grout-enriched vibrated roller-compacted concrete).

joint, lift—interface between two successive lifts.

CHAPTER 3—MATERIALS AND MIXTURE PROPORTIONING FOR ROLLER-COMPACTED CONCRETE

3.1—General

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

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

The cementitious material content for RCC dams has varied over a broad range, from 100 lb/yd³ (59 kg/m³) to

more than 500 lb/yd³ (297 kg/m³). At one end of the spectrum, the 3 in. (75 mm) nominal maximum size aggregate (NMSA) interior mixture at Willow Creek Dam contained 112 lb/yd³ (60.5 kg/m³) of cementitious material. The mixture, which contained 80 lb/yd³ (47.5 kg/m³) of cement plus 32 lb/yd³ (19.0 kg/m³) of fly ash, averaged 2620 psi (18.2 MPa) compressive strength at 1 year (USACE 1984). In comparison, the 2 in. (50 mm) NMSA interior mixture at Upper Stillwater Dam contained 424 lb/yd³ (251.6 kg/m³) of cementitious material, consisting of 134 lb/yd³ (79.5 kg/m³) of cement plus 290 lb/yd³ (172.0 kg/m³) of fly ash, and averaged 6170 psi (42.6 MPa) at 1 year (Crow et al. 1984). Many RCC projects have used a cementitious materials content between 175 and 300 lb/yd³ (105 and 180 kg/m³) and produced an average compressive strength between 2000 to 3000 psi (14 and 21 MPa) at an age of 90 days to 1 year. Mixture proportions for some dams are presented in Table 3.1.

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

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

3.2—Materials

A wide range of materials have been used in the production of RCC. Much of the guidance on materials provided in ACI 207.1R may be applied to RCC. The material constraints of gravity RCC structures are often less demanding; thus, other materials quality options and subsequent performance characteristics are possible. The designer, as always, should evaluate the actual materials for the specific project and the proportions under consideration, design the structure accordingly, and provide appropriate construction specifications.

3.2.1 Cementitious materials

3.2.1.1 Portland cement—RCC can be made with any of the basic types of portland cement such as found in ASTM C150/C150M, C595/C595M, C1157/C1157M, and applicable AASHTO standards, or other international standards. ASTM C150/C150M cements are specified by both chemical and physical requirements. For mass applications, cements with a lower heat generation are desirable to control or reduce thermal cracking. Lower heat generation is achieved primarily by decreasing the percentage of tricalcium silicate (C₃A) and the ratio of tricalcium silicate to dicalcium silicate

Table 3.1—Mixture proportions of some roller-compacted concrete (RCC) dams

Dam/ project	Mixture type/ID	Year	NMSA, in. (mm)	Air, %	Water	Cement	Pozzolan	Fine aggregate	Coarse aggregate	Density, lb/ yd ³ (kg/ m ³)	Air-entrained admixture, oz/yd ³ (cc/m ³)	Water-reducing admixture, oz/yd ³ (cc/m ³)
					Quantities, lb/yd ³ (kg/m ³)							
Al Wehdah	70C60F	2006	2.0 (50)	2.0	211 (25)	118 (70)	101 (60)	1530 (910)	2300 (1365)	4260 (2530)	22 (13)	—
Al Wehdah	60C60F	2006	2.0 (50)	2.0	211 (25)	101 (60)	101 (60)	1530 (910)	2310 (1370)	4255 (2525)	22 (13)	—
Camp Dyer	RCC1	1994	1.5 (37.5)	3.6	151 (90)	139 (82)	137 (81)	1264 (750)	2265 (1344)	3956 (2347)	7 (4)	4 (2)
Concepcion	152C	1990	3 (75)	0.5	157 (93)	152 (90)	0	1371 (813)	2057 (1220)	3737 (2217)	—	—
Cuchillo Negro	130C100P	1991	3 (75)	—	228 (135)	130 (77)	100 (59)	1591 (944)	2045 (1213)	4094 (2429)	—	—
Galesville	RCC1	1985	3 (75)	—	190 (113)	89 (53)	86 (51)	1310 (777)	2560 (1519)	4235 (2513)	—	—
	RCC2	1985	3 (75)	—	190 (113)	110 (65)	115 (68)	1290 (765)	2520 (1495)	4225 (2513)	—	—
Middle Fork	112C	1984	3 (75)	—	160 (95)	112 (66)	0	1152 (683)	2138 (1268)	3562 (2113)	—	—
Santa Cruz	RCCAEA	1989	2 (50)	2.3	170 (101)	128 (76)	127 (75)	1227 (728)	2301 (1365)	3953 (2345)	7 (4)	3 (2)
Siegrist	80C80P	1992	1.5 (37.5)	1	162 (96)	80 (47)	80 (47)	1922 (1140)	2050 (1216)	4294 (2548)	—	—
	90C70P	1992	1.5 (37.5)	1	162 (96)	90 (53)	70 (42)	1923 (1141)	2052 (1217)	4297 (2549)	—	—
	100C70P	1992	1.5 (37.5)	1	162 (96)	100 (59)	70 (42)	1920 (1139)	2048 (1215)	4300 (2551)	—	—
Stacey Spillway	210C105P	1989	1.5 (37.5)	—	259 (154)	210 (125)	105 (62)	3500 (2076)	—	—	—	—
Stagecoach	120C130P	1988	2 (50)	—	233 (138)	120 (71)	130 (77)	156 (686)	2459 (1459)	4098 (2431)	—	—
Upper Stillwater	RCCA85	1985	2 (50)	1.5	159 (94)	134 (79)	291 (173)	1228 (729)	2177 (1292)	3989 (2367)	—	12 (7)
	RCCB85	1985	2 (50)	1.5	150 (89)	159 (94)	349 (207)	1171 (695)	2178 (1292)	4007 (2377)	—	20 (12)
	RCCA	1986	2 (50)	1.5	167 (99)	134 (79)	292 (173)	1149 (682)	2218 (1316)	3960 (2349)	—	16 (9)
	RCCB	1986	2 (50)	1.5	168 (100)	157 (93)	347 (206)	1148 (682)	2131 (1264)	3952 (2345)	—	21 (12)
Urugua-I	101C	1988	3 (75)	—	169 (100)	101 (60)	0	2102 (1247)	2187 (1297)	4559 (2705)	—	—
Victoria	113C112P	1991	2 (50)	—	180 (107)	113 (67)	112 (66)	1365 (810)	2537 (1505)	4307 (2555)	—	—
Willow Creek	175C	1982	3 (75)	1.2	185 (110)	175 (104)	0	1108 (657)	2794 (1958)	4262 (2529)	—	—
	175C80P	1982	3 (75)	1.2	185 (110)	175 (104)	80 (47)	1097 (645)	2739 (1625)	4266 (2531)	—	—
	80C32P	1982	3 (75)	1.2	180 (107)	80 (47)	32 (19)	1123 (666)	2833 (1681)	4248 (2520)	—	—
	315C135P	1982	1.5 (37.5)	1.2	184 (109)	315 (187)	135 (80)	1390 (825)	2086 (1238)	4110 (2438)	—	—
Zintel Canyon	125CA	1992	2.5 (63)	4.5	170 (101)	125 (74)	0	1519 (901)	2288 (1357)	4102 (2434)	18 (11)	18 (11)
	125CNA	1992	2.5 (63)	1.4	188 (112)	125 (74)	0	1586 (941)	2371 (1407)	4270 (2533)	—	18 (11)
	300CA	1992	2.5 (63)	—	171 (101)	300 (178)	0	1348 (800)	2388 (1417)	4207 (2496)	36 (21)	42 (25)

(C₃S to C₂S). Higher heat generation may require decreased joint spacing for crack control. ASTM C150/C150M cement with optional heat-of-hydration limits, Type V (sulfate-resistant), and ASTM C595/C595M Type IP (portland-pozzolan cement) and Type IS (portland blast-furnace slag cement) can decrease heat generation. Strength development for these cements is usually slower than for the standard Type I (general use) cement at early ages, but higher strengths than RCC produced with Type I cement are ultimately produced.

Heat generation due to hydration of the cement is typically controlled by use of lower heat-of-hydration cements, use of less cement, and replacement of a portion of the cement with pozzolan or a combination of these. Reduction of peak concrete temperature may be achieved by other methods, such as reduced placement temperatures. The selection of cement type should consider economics of cement procurement. For small- and medium-sized projects, it may not be cost effective to specify a low-heat cement that is not locally available. The availability of cement types varies regionally and over time. Manufacturers in the U.S. are producing fewer cement types (less specialty types such as Type IV and Type V) than in the past. Consequently, the selection of cement type for mass concrete placements needs to be thoroughly researched and confirmed before selecting cement for a laboratory mixture proportioning program and specifying for a project. Due to the high production capability

of RCC, special attention may be required to ensure a continuous supply of cement to the project.

3.2.1.2 Pozzolans—The selection of a pozzolan suitable for RCC should be based on its conformance with ASTM C618. Pozzolans meeting the specifications of ASTM C618 for Class C, Class F, and Class N have been successfully used in RCC mixtures. Class F and Class N pozzolans are preferred because they normally contribute less heat of hydration than Class C and have greater sulfate resistance. For Class C pozzolans, more attention may be needed with regard to set time, sulfate resistance, and free lime content. The use of pozzolan will depend on required material performance as well as on its cost and availability at each project.

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

In RCC mixtures with a low cement content, pozzolans have been used to ensure an adequate amount of paste for

filling aggregate voids and coating aggregate particles. While the pozzolan enhances the paste volume of these mixtures, it may not enhance the long-term strength development if the pozzolan has a low reactivity.

Class F pozzolan, especially at cool temperatures, generally delays the initial set of RCC mixtures, contributing to low early strength but extending the working life of the freshly compacted lift joint. In high pozzolan-content RCC mixtures, the beneficial reduction in early temperature rise may be partially offset by continued temperature rise after 28 days. Mixtures with high pozzolan content can experience considerable additional heat rise from 30 to 90 days after placement compared with 100% cement mixtures. The fineness and reactivity of Class F pozzolan is critical for strength performance. The 1-year compressive strength of high-pozzolan RCC mixtures at Upper Stillwater Dam decreased 12% when the percentage retained on the No. 325 sieve increased from approximately 24 to 38% (Dolen 2003). The optimum percentage of pozzolan should thus be determined by testing with the job materials.

3.2.2 Aggregates

3.2.2.1 General quality issues—The selection of aggregates and the control of aggregate properties and grading are important factors influencing the quality and uniformity of RCC production. Aggregates similar to those used in conventional concrete and aggregates that do not meet the normal standards or requirements for conventional concrete have both been successfully used in RCC dam construction (Gaekel and Schrader 1992). The use of manufactured coarse aggregate (crushed stone) has been found to reduce the tendency for segregation as compared with rounded gravels.

Marginal aggregates are those aggregates that do not meet traditional standards, such as ASTM C33/C33M. Limits on physical requirements and on deleterious materials for aggregates to be used in RCC for a specific application should be established before construction based on required concrete performance and demonstrated field and laboratory evaluations. The majority of RCC projects have been constructed with aggregates meeting all of the ASTM C33/C33M requirements, with the exception of an increased amount of fines passing the No. 200 (75 μ m) sieve. The mineralogy of fines (for example, fines from aggregates such as limestone and granite) has a significant effect on water demand and workability of RCC. The allowable amount of fines in RCC mixtures for mass placements should therefore be determined based on the most readily available and most economical aggregate that produces RCC meeting the project structural requirements.

Aggregates of marginal quality have been used in RCC on some projects because they were close to the site and thereby the most economical source available. The design of the structure should accommodate any change in performance that may result. On some projects, mixtures that used aggregates of lower physical strength produced RCC with satisfactory creep rates, elastic moduli, and tensile strain capacity. These properties are desirable for mass concrete applications where lower concrete strength can be tolerated.

If practical, lower-quality aggregates are best used in the interior of dams where they can be encapsulated by higher-quality concrete, especially in freezing-and-thawing areas.

RCC can provide a modulus of elasticity equal to or greater than that of a conventional concrete of equal compressive strength. For preliminary design studies, USACE ETL 110-2-343 (USACE 1993) recommends assuming the modulus of elasticity to be equal to $57,000(f'_c)^{1/2}$ increased by 15% for seismic load conditions and reduced by 33% for long-term loading conditions where creep effects are important. A basic objective in proportioning any concrete is to incorporate the maximum amount of aggregate and minimum amount of water into a workable mixture, thereby reducing the cementitious material quantity and reducing consequent volume change of the concrete. This objective is accomplished by using a well-graded aggregate with the largest maximum size that is practical for placement. The proper combination of materials should result in a mixture that achieves the desired properties with adequate paste and a minimum cementitious content. However, in RCC mixtures, the potential for segregation and the means of compaction should also be primary considerations in selecting the maximum size of aggregate. Although early projects in the U.S. used a 3 in. (75 mm) NMSA, a 2 in. (50 mm) NMSA or smaller is less prone to segregation and is becoming more widely used.

The combined aggregate gradation should be selected to minimize segregation. The key to controlling segregation and providing a good compactible mixture is having a grading that is consistent and contains more material passing the No. 4 (4.75 mm) sieve than typical in conventional concrete of similar NMSA. Table 3.2 provides typical combined aggregate grading for various projects.

In conventional concrete, the presence of any significant quantity of flat and elongated particles is usually undesirable. RCC mixtures, however, appear to be less affected by flat and elongated particles than conventional concrete mixtures because vibratory compaction provides more energy than traditional consolidation. Field tests with 40% flat and elongated particles on any sieve and an average less than 30%, as determined by ASTM D4791 with a ratio of 1:5, have had no significant problems. The U.S. Army Corps of Engineers currently has a limit of 25% on the allowable content of flat and elongated particles in any size group (USACE 1994b).

3.2.2.2 Coarse aggregate—The selection of NMSA should be based on the need to reduce cementitious material requirements, control segregation, economize aggregate production, and facilitate compaction. Most RCC projects have used a NMSA of 1-1/2 to 3 in. (37.5 to 75 mm). The U.S. Bureau of Reclamation presently limits the NMSA to 2 in. (50 mm) and requires a minimum of 50% crushed aggregate in mass RCC. There has typically not been enough material cost savings from using aggregate sizes larger than 3 in. (75 mm) to offset the added batching cost and cost of controlling the increased segregation problems associated with the larger aggregates. Coarse aggregate has little effect on compaction when the thickness of the placement

Table 3.2—Combined aggregate gradings for RCC from various projects in U.S.

Sieve size	Willow Creek	Upper Stillwater	Christian Siegrist	Zintel Canyon	Stagecoach	Elk Creek
4 in. (100 mm)	—	—	—	—	—	—
3 in. (75 mm)	100	—	—	—	—	100
2.5 in. (62 mm)	—	—	—	100	—	96
2 in. (50 mm)	90	100	—	98	100	86
1.5 in. (37.5 mm)	80	95	100	91	95	76
1 in. (25 mm)	62	—	99	77	82	64
3/4 in. (19 mm)	54	66	91	70	69	58
3/8 in. (9.5 mm)	42	45	60	50	52	51
No. 4 (4.75 mm)	30	35	49	39	40	41
No. 8 (2.36 mm)	23	26	38	25	32	34
No. 16 (1.18 mm)	17	21	23	18	25	31
No. 30 (0.60 mm)	13	17	14	15	15	21
No. 50 (0.30 mm)	9	10	10	12	10	15
No. 100 (0.15 mm)	7	2	6	11	8	10
No. 200 (75 μ m)	5	0	5	9	5	7
C + P, lb/yd ³ (kg/m ³)	80 + 32 (47 + 19)	134 + 291 (80 + 173)	100 + 70 (59 + 42)	125 + 0 (74 + 0)	120 + 130 (71 + 77)	118 + 56 (70 + 33)
Total fines*, %	20	21	19	21	—	21
Workability	Poor	Excellent	Excellent	Excellent	Good	Excellent

*Total fines = all materials in full mixture with particle size smaller than No. 200 (75 μ m) sieve.

layers is more than three times the NMSA, segregation is adequately controlled, and large vibratory rollers are used.

Grading of coarse aggregate usually follows ASTM C33/C33M size designations. Where close control of grading of coarse aggregate and RCC production are desired, size separations should follow normal concrete practice, as recommended in ACI 304R. Cost savings can be realized by combining two or more size ranges such as ASTM C33/C33M size designations 357 or 467 for 2 in. to No. 4 (50 to 4.75 mm) and 1-1/2 in. to No. 4 (37.5 to 4.75 mm), respectively. Note that as the size range increases, it becomes increasingly difficult to avoid segregation of the larger particles during stockpiling and handling of this aggregate. Aggregates for RCC have been in a single stockpile or have been separated into as many as five aggregate sizes. Some projects simply use a coarse-aggregate and a fine-aggregate stockpile. Other projects have blended products from multiple stockpiles that are not strictly coarse and fine fractions. Pinebrook Dam in Colorado used two base gravel type gradations—one commercially produced and the other produced from site materials. More important than the stockpile split is the resulting combined gradation and the ability to produce a consistent, workable mixture that can be mixed, placed, and compacted. An advantage for coarse aggregate separation arises for projects in hot climates or designs needing precooled aggregates to meet temperature requirements. Fine aggregates or aggregates with fine contents are difficult to cool with chilled water or air-blast methods.

The design engineer should weigh the potential cost savings in a reduction in the number of stockpiles and separate handling and weighing facilities against the potential for increased variation in aggregate grading and its impact on uniform placement and compaction.

RCC mixtures for overtopping protection for embankment dams frequently use a NMSA of 1 in. (25 mm) because the

concrete section is less massive and there are normally no significant temperature concerns. Some designers have used locally available aggregate road base material with grading requirements similar to that contained in ASTM D2940/D2940M. Because the volume of concrete required is normally not substantial, the RCC mixture can be obtained from locally available commercial concrete suppliers.

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

For those mixtures with a sufficient cementitious materials content and paste volume, ASTM C33/C33M fine-aggregate grading can be used. ASTM graded fine aggregates are necessary if an air-entraining admixture is used in RCC.

3.2.2.4 Fines—The primary role of supplemental fines (material passing the No. 200 [75 μ m] sieve) is to lower the volume of voids in fine aggregates without significantly increasing the water demand of the RCC mixture. In low cementitious-materials or low paste-content mixtures, supplemental fines are usually required to fill all the aggregate void spaces. Depending on the volume of cementitious material and the NMSA, the required total minus No. 200 (75 μ m) fines may be as much as 10% of the total aggregate mass, with most mixtures using approximately 3 to 8%. Characteristics of the fines and fines content will affect the relative compactibility of the RCC mixture, and can influence the number of passes of a vibratory roller required for full compaction of a given layer thickness. Regardless of whether it is accomplished by adding aggregate fines, cement, pozzolan, or combination of these, most compactible RCC mixtures contain approximately 8 to 12% total solids finer than the No. 200 (75 μ m) sieve by volume, or 2 to 10% by mass. This is illustrated in Figure 3.2. The fines fill

aggregate void space, provide a compactible consistency, help control segregation, and decrease permeability. Including aggregate fines in low cementitious-paste mixtures allows reductions in the cementitious materials content, provided that they fill voids that would otherwise be filled with cementitious paste in the aggregates. Excessive additions of aggregate fines after the aggregate voids are filled are harmful to the RCC mixture because of decreased workability, increased water demand, and subsequent strength loss.

When adding aggregate fines to a mixture, another consideration is the nature of the fines. Crusher fines and silty material are usually acceptable. Clay fines, which are also called plastic fines, can cause an increase in water demand and a loss of strength, and produce a sticky mixture that is difficult to mix, transport, and compact. Fines, especially clay fines, may coat the surfaces of coarse aggregates and reduce the paste-aggregate bond and reducing strength potential. This problem can be avoided by washing the coarse aggregates either during production or before batching.

3.2.3 Chemical admixtures—Chemical admixtures have been used in RCC mixtures to change the setting properties and, in some cases, to affect a change in water content. The effectiveness of chemical admixtures may depend on the workability of the mixture, the aggregate gradation, and the type of cementitious materials. Chemical admixtures in RCC are commonly used to retard the setting time to reduce cold joints for improving bond between successive lifts (Wenquan et al. 1997). ASTM C494/C494M Types A (water-reducing) and D (water-reducing and retarding) are the most commonly used chemical admixtures. Water-reducing admixtures, used at very high dosages, have been shown to reduce water demand, increase strength, retard set, and promote workability in some RCC mixtures (Hopman and Chambers 1988). As with conventional concrete, the presence of minus No. 200 (75 μ m) fines in many RCC mixtures can impact the dosage rate required to be effective, particularly if the fines content is high or if they include clay. Admixtures should be evaluated with the actual RCC materials before being used in the field.

Air-entraining admixtures are not commonly used in RCC mixtures because of the difficulty in generating the voids of the proper size and distribution when the mixture has a no-slump consistency. Air-entrained RCC has been used on a production basis in China and the U.S. The freezing-and-thawing resistance of RCC is improved with entrained air (Dolen 1991). To entrain air in RCC, however, a Vebe consistency less than approximately 20 seconds is generally necessary, and the aggregates should be free from excessive fines. The dosage of air-entraining admixture has ranged from the normal manufacturers' dosage for clean aggregates to higher than normal for other mixtures.

Entrained air has an additional benefit as a means of improving the workability of the RCC, decreasing the paste volume, and decreasing the Vebe consistency. The total water content of air-entrained RCC can be reduced as much as 12% compared with the same non-air-entrained mixture (Dolen 2002).

In some instances, caution is necessary to avoid reducing the paste volume of air-entrained RCC to less than the minimum necessary to fill aggregate voids without air (refer to Table 3.2). This can cause segregation and difficulties in achieving complete compaction if the air is lost.

The costs of admixtures in RCC include the costs of the admixtures, the batching equipment costs, and the additional cost for quality-control testing. The dosage is normally by mass of cementitious materials, or sometimes by cement only. Unless an unusually high dosage is necessary, the cost of admixtures is similar or less than conventional concrete due to the low cementitious materials content of many RCC mixtures. The cost of batching admixtures ranges from no substantial cost for conventional batching plants to the cost of adding batching devices for continuous batching plants. To control air-entrained RCC, inspectors should perform the necessary air content tests and be able to discern if changes in density in the field (through nuclear density testing) are the result of changes in air content or changes in compaction.

3.3—Mixture proportioning considerations

Optimum RCC proportions consist of a balance between good material properties and acceptable workability for the placement methods. This includes minimizing segregation. In implementing a specific mixture-proportioning procedure, the following considerations regarding plastic and hardened properties should be addressed.

3.3.1 Workability—Sufficient workability is necessary to achieve compaction or consolidation of the mixture. Sufficient workability is also necessary to provide an acceptable appearance when RCC is to be compacted against forms. Workability is most affected by the paste portion of the mixture that includes cement, pozzolan, aggregate fines, water, and air. When there is sufficient paste to fill aggregate voids, workability of RCC mixtures is normally measured on a vibratory table with a Vebe apparatus (Fig. 3.1) in accordance with ASTM C1170. This test produces a Vebe time for the specific mixture and is used similar to the slump test for conventional concrete. RCC mixtures with Vebe consistency of 10 to 45 seconds have a workability sufficient for ease of compaction, uniform density from top to bottom of the lift, bonding with previously placed lifts, and for support of compaction equipment. RCC mixtures, however, have been proportioned with a wide range of workability levels. One test method used for compaction control in earthwork, the modified Proctor test (ASTM D1557), tests a wide range of compaction characteristics and provides an indication of workability for a specific material. The modified Proctor test varies the moisture content of a mixture over a wide range, from extremely dry (Vebe less than 30 seconds) or drier (Vebe greater than 30 seconds). The modified Proctor test is used in earthwork projects to determine an optimum moisture and maximum dry density that is suitable for vibratory compaction, typically with 6 to 9 in. (150 to 230 mm) compacted lift thickness. Some RCC mixtures have contained such low paste volumes that workability could not be measured by the Vebe apparatus. This is particularly true of low paste mixtures proportioned with



Fig. 3.1—ASTM C1170 Vebe consistency test apparatus with 27.5 lb (12 kg) surcharge. (Photo courtesy of U.S. Department of Agriculture, National Resources Conservation Service, 2008.)

very low cementitious materials contents or designed more as cement stabilized fills. Workability of these types of mixtures needs to be judged by observations during placement and compaction, and by compacted density and moisture content measurements.

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

3.3.2 Strength—RCC strength depends on the quality and grading of the aggregate, mixture proportions, and the degree of compaction. There are differing basic strength relationships for RCC, depending on whether the aggregate voids are completely filled with paste or not. The water-cement ratio (w/c) law, as developed by Abrams (1918), is only valid for fully consolidated concrete mixtures. Therefore, the compressive strength of RCC is a function of the water-cementitious material ratio (w/cm) only for fully compacted mixtures, with a measurable Vebe consistency usually in the 15- to 45-second range. Figure 3.2 shows this general relationship. For drier-consistency (all voids not filled with paste) mixtures, compressive strength is controlled by moisture-density relationships. With the same aggregate, the moisture content necessary to produce maximum dry density is less than the moisture required to produce an RCC mixture with a Vebe time in the range of 15 seconds. In general, the optimum moisture content does not vary significantly (on the order of 0.5 to 1%) for a wide range of cementitious contents.

Mixtures that contain less-than-optimum moisture are usually poorly compacted, with a resulting loss in density and strength. In this case, the addition of water to the mixture produces higher compressive strength by increasing the paste volume and filling voids. For fully consolidated mixtures exceeding optimum moisture, slight decreases in

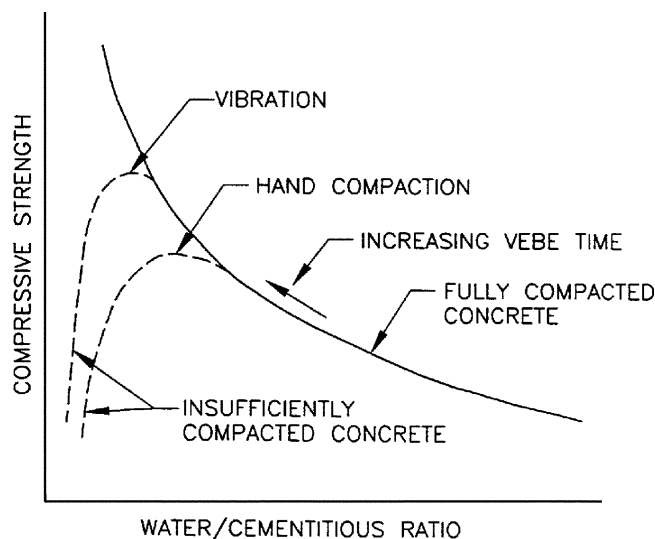


Fig. 3.2—General relationship between compressive strength and w/cm .

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

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

Compressive strength of RCC is usually determined on 6 x 12 in. (150 x 300 mm) cylindrical specimens. Specimens can be prepared using a vibrating table, as described in ASTM C1176/C1176M for more workable mixtures, or can be compacted by a tamping/vibrating hammer, as described in ASTM C1435/C1435M for a wide range of materials, workability, and paste volumes, including drier consistency mixtures. Cylinder molds should be steel or support by a steel sleeve if plastic or sheet metal cylinder molds are used.

These methods use the fraction of the RCC mixture that passes the 2 in. (50 mm) sieve.

3.3.3 Segregation—A major goal in the proportioning of RCC mixtures is to produce a cohesive mixture while minimizing the tendency to segregate during transporting, placing, and spreading. Well-graded aggregates with a slightly higher fine aggregate content than conventional concrete are essential. If not proportioned properly, RCC mixtures tend to segregate more because of the low paste volume of the mixture. This is controlled by aggregate grading, moisture content, and adjustment of fine content in lower cementitious-content mixtures. Higher paste-content mixtures are usually more cohesive and less likely to segregate.

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

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

3.3.6 Durability—The RCC mixture should provide the required degree of durability based on materials used, exposure conditions, and expected level of performance. RCC should be free of damaging effects of alkali-aggregate reactivity by proper evaluation and selection of materials. Recent work indicates that some air-entrained RCC can be produced with adequate freezing-and-thawing resistance (McDonald 2002). If air entrainment cannot be achieved and the RCC is exposed, consideration should be given to increasing the strength for improved durability. RCC surfaces exposed to flowing water performed well where exposure has been of short duration and intermittent. Freezing-and-thawing resistance and erosion should not be a major concern during mixture proportioning if it will be protected with conventional concrete. The durability of RCC

can be significantly reduced if the mixture is not fully compacted. Though this is partially a construction control problem, a mixture proportioned with a paste volume sufficient for compaction can greatly improve its durability.

3.3.7 Construction conditions—Construction requirements and equipment should be considered during mixture proportioning. Some construction methods, placement schedules, and equipment selections are less damaging to compacted RCC than others. A higher workability mixture may result in a compacted RCC surface that tends to rut from hauling trucks and rollers. Wheeled traffic may produce severe rutting and should be restricted from operating on the compacted surface of the last lift of the day before it reaches final set. Rutting of the lift surface at Elk Creek Dam and Upper Stillwater Dam was observed to exceed 3 in. (75 mm). Severe rutting is generally not desirable because ruts inhibit joint cleanup and treatment. Timely finish rolling helps recompact the ruts after the end of the placement. Placing conditions with many obstacles that require smaller compaction equipment benefit from mixtures having a higher level of workability.

3.4—Mixture proportioning methods

3.4.1 General—A number of mixture proportioning methods have been successfully used for RCC structures throughout the world. These methods have differed significantly due to the location and design requirements of the structure, availability of materials, the mixing and placing equipment used, and time constraints. Most mixture-proportioning methods are variations of two general approaches: 1) a *w/cm* approach with the mixture proportions determined by solid volume; and 2) a cemented-aggregate or soils approach with mixture proportions determined by either solid volume or moisture-density relationship. Both approaches are intended to produce quality concrete suitable for roller compaction and mass concrete construction. The basic concepts behind these approaches are covered in ACI 211.3R, Appendix 3. Mixture proportions used for some RCC dams are shown in Table 3.1.

RCC mixture proportions can follow the convention used in traditional concrete practice where the mass of each ingredient contained in a compacted unit volume of the mixture is based on saturated surface-dry (SSD) aggregate condition. A practical reason for use of this standard convention is that concrete properties are the primary control parameters and, hence, conventional concrete practice should reduce the potential for miscommunication. For example, RCC mixing using conventional concrete plants require that mixture constituents be identified based on SSD aggregate conditions for input to the plant control system. This is not necessarily the case for continuous mixing plants, however. Mixture proportions may have to be converted to percent by dry weight of aggregate for RCC mixing in continuous mixing plants. Another reason supporting the concrete approach is that the RCC is typically placed and measured to specified lines, grades, and dimensions. The concrete proportioning method provides a means for establishing if the mixture is yielding properly (batched volume corresponds to the placed volume once compacted and cured). This is much

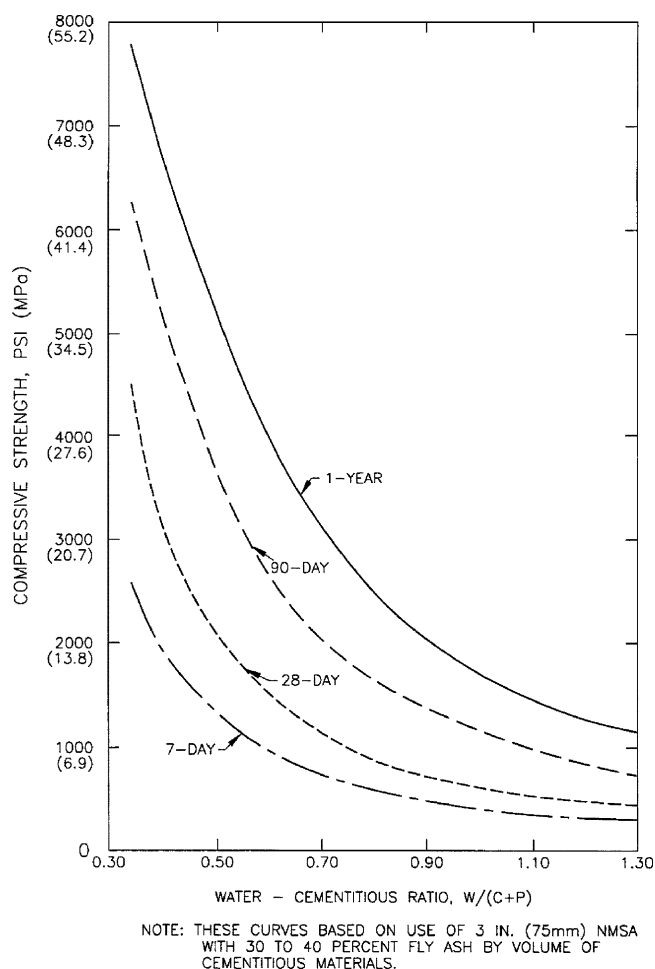


Fig. 3.3—Compressive strength versus w/cm (USACE 1992).

more difficult with a soils approach maximum density method discussed in Section 3.4.5.

3.4.2 USACE method—This proportioning method is based on w/cm and strength relationships and is very similar to proportioning conventional concrete mixtures (Tatro and Hinds 1992; USACE 2000). Appendix 3.6 of ACI 211.3R contains a similar method. Both methods calculate mixture quantities from solid volume determinations, as used in proportioning most conventional concrete. The w/cm and equivalent cement content are established from figures based on the strength criteria using Fig. 3.3 and 3.4. The complete step-by-step procedure for selecting mixture proportioning is presented in Chapter 3 of USACE EM 1110-2-2006 (USACE 2000). The approximate water demand is based on NMSA and desired modified Vebe consistency using a surcharge mass of 27.5 lb (12.5 kg). A recommended fine aggregate content as a percentage of the total aggregate volume is based on the nominal maximum size and nature of the coarse aggregate. Once the volume of each ingredient is calculated, a comparison of the mortar content to recommended values can be made to check the proportions. This method also provides several unique aspects, including ideal combined coarse aggregate grading and fine aggregate grading limits incorporating a higher percentage of fine sizes than permitted by ASTM C33/C33M. Because design

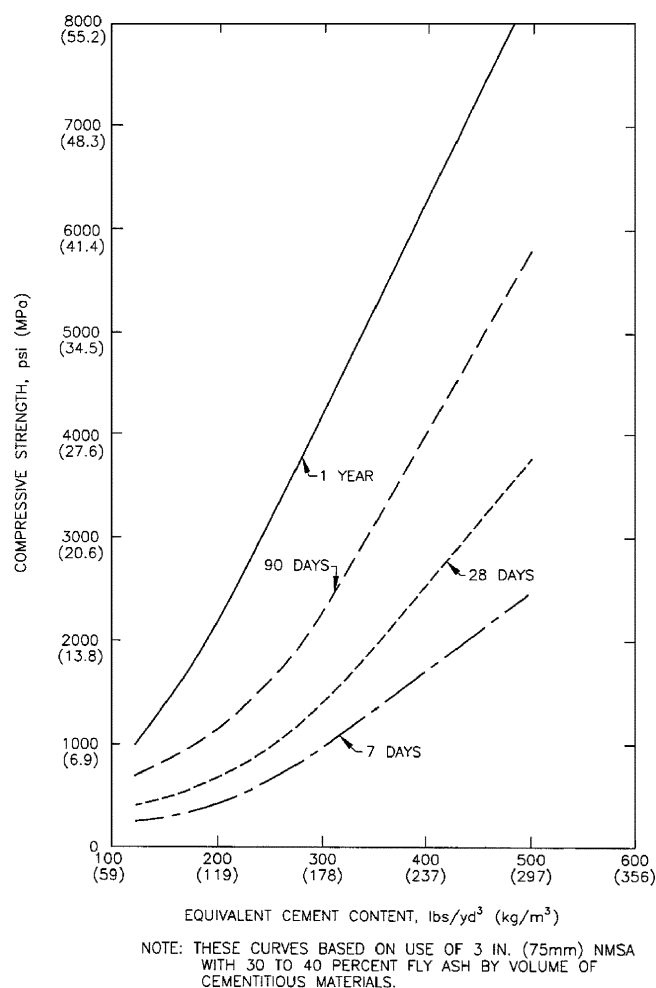


Fig. 3.4—Equivalent cement content versus compressive strength (USACE 1992).

strength for many RCC dams is based on 1 year, a target 90- or 180-day strength may be estimated using Fig. 3.3 and 3.4.

3.4.3 U. S. Bureau of Reclamation high paste method—This mixture proportioning method was developed by the U.S. Bureau of Reclamation for use during the design of Upper Stillwater Dam based on the original concepts of Dunstan (1985). The resulting mixtures from that testing program generally contained high proportions of cementitious materials, high pozzolan contents, clean and normally graded aggregates, and high workability. The purpose of the Upper Stillwater Dam mixtures was to provide excellent lift-joint bond strength and low joint permeability by providing sufficient cementitious paste in the mixture to enhance performance at the lift joints. Thus, the tensile and shear strength controlled the mixture proportions, and the ultimate compressive strength was higher than what was necessary for design purposes.

The proportioning method is summarized in Table 3.3 (U. S. Bureau of Reclamation 2005). The high paste method involves the same method of determining w/cm and fly ash-cement ratios, as described previously (USACE 2000) for the desired strength level and strength gain. The optimum water, fine aggregate, and coarse aggregate ratios are determined by trial batches, evaluating the Vebe consistency

Table 3.3—Methodology for proportioning mass RCC mixtures using consistency tests

Step 1: Determine design/construction criteria		Example
Design strength		3500 psi (24.1 MPa) at 1 year (average of 4250 psi [29.3 MPa])
Consistency		15 to 20 seconds
W/(C+P) ratio (from strength curve)		0.57
Select NMSA (crushed coarse aggregate), percent sand		2 in. (50 mm), 35% (volume of total aggregate)
Entrained air? No (assume 1% air) or Yes (assume 4% air)		1% or 4% by volume
SSD water content		160 lb/yd ³ (95 kg/m ³) for no air, 150 lb/yd ³ (90 kg/m ³) for air-entrained admixtures, add 10 lb/yd ³ (5 kg/m ³) for crushed aggregate
Percent pozzolan (based on design strength age)		60% by mass of C+P
Cement plus pozzolan content (from W/(C+P) ratio)		300 (120 C + 180 P) (180[70 C + 110P])
Sand and coarse aggregate content		Calculate cement and pozzolan content, mortar volume, total aggregate content, sand and coarse aggregate content
Proportioning trials (as required)	Fresh properties evaluation criteria	Hardened properties evaluation criteria
Step 2: Vebe consistency and density versus water content (Vary SSD water content from 150 to 200 lb/yd ³ [90 to 120 kg/m ³] in 10 to 20 lb/yd ³ [6 to 12 kg/m ³] increments in 6 to 12)	SSD water content versus change in consistency and density. Density as a percent of theoretical density. Consistency versus segregation. Note: maintain C+P content, sand-coarse aggregate ratio (adjust total aggregate volume to maintain yield)	W/(C+P) ratio versus compressive strength for constant C+P content. Compressive strength versus compaction. Compressive strength versus age.
Step 3: Vebe consistency and density versus sand content (Vary sand content from 30 to 45% in 3 to 5% increments) (if necessary, adjust water content for 15-second Vebe consistency)	Evaluate consistency and density, segregation. Determine optimum sand:aggregate ratio and if necessary, adjust water content for Vebe consistency of 15 seconds.	Compressive strength versus compaction. W/(C+P) ratio versus compressive strength.
Step 4: Cement plus pozzolan content versus compressive strength (Vary C+P content in 25 to 50 lb/yd ³ [15 to 30 kg/m ³] increments from about 200 to 350 lb/yd ³ [120 to 210 kg/m ³])	Optimum water and sand content selected for 15-second consistency. C+P (paste content) versus consistency. C+P (paste content) versus segregation.	W/(C+P) ratio versus compressive strength for constant water content. Compressive strength versus age. C+P content versus adiabatic temperature rise (optional).
Step 5: Cement-pozzolan ratio versus rate of compressive strength development (Vary C:P ratio for a fixed C+P content in 10 to 25% increments)	Cement : pozzolan ratio versus consistency. Cement : pozzolan ratio versus segregation.	Cement:pozzolan ratio versus compressive strength. Cement:pozzolan ratio versus rate of compressive strength development. Cement:pozzolan ratio versus adiabatic temperature rise (optional).
Step 6: Select optimum mixture proportions and cast test specimens for the final mixture		Strength and elastic properties. Thermal properties; adiabatic temperature rise. Bond strength properties (direct tensile strength, cohesion, friction properties). Durability.
Step 7: Construct laboratory test scale section	SSD water content versus change in consistency and density.	Compressive strength versus density/compaction. Bond strength properties (direct tensile strength, cohesion, friction properties).

Note: Source: U.S. Bureau of Reclamation (2005).

for a range of 10 to 30 seconds. The required volumes and mass of aggregate, cement, pozzolan, water, and air are then calculated, maintaining the yield for each batch.

Laboratory trial mixtures are evaluated to verify acceptable workability, strength, and other required properties for the mixture. The number of mixtures is dependent on the scope of the job, ranging from trials to determine the optimum water content only to laboratory scale test sections for bond strength test specimens. Specific mixture variations may be performed to evaluate their effect on the fresh properties, such as consistency and hardened strength properties to optimize the mixture proportions. Strength specimens are fabricated with a vibrating table using ASTM C1176/C1176M or C1435/C1435M. Typical *w/cm* versus compressive strength relationships for different test ages are shown in Fig. 3.5.

3.4.4 Roller-compacted dam method—The roller-compacted dam (RCD) method was developed by Japanese engineers and is used primarily in Japan (Technical Center

for National Land Development 1981). The method is similar to proportioning conventional concrete in accordance with ACI 211.1 except that it incorporates the use of a consistency meter. The consistency meter is similar to the Vebe apparatus in that the RCC mixture is placed in a container and vibrated until mortar is observed on the surface. The device is sufficiently large to allow the full mixture, often 6 in. (150 mm) NMSA, to be evaluated rather than having to screen out the oversized particles.

The procedure consists of determining relationships between the consistency, called the VC value, and the water content, sand-aggregate ratio, unit weight of mortar, and compressive strength. The proper RCD mixture is the optimum combination of materials that meets the specific design criteria. Because of the consistency test equipment requirements and differences in the nature of RCD design and construction, this method is not commonly used in proportioning RCC mixtures outside of Japan.

Compressive Strength vs. W/(C+P) ratio

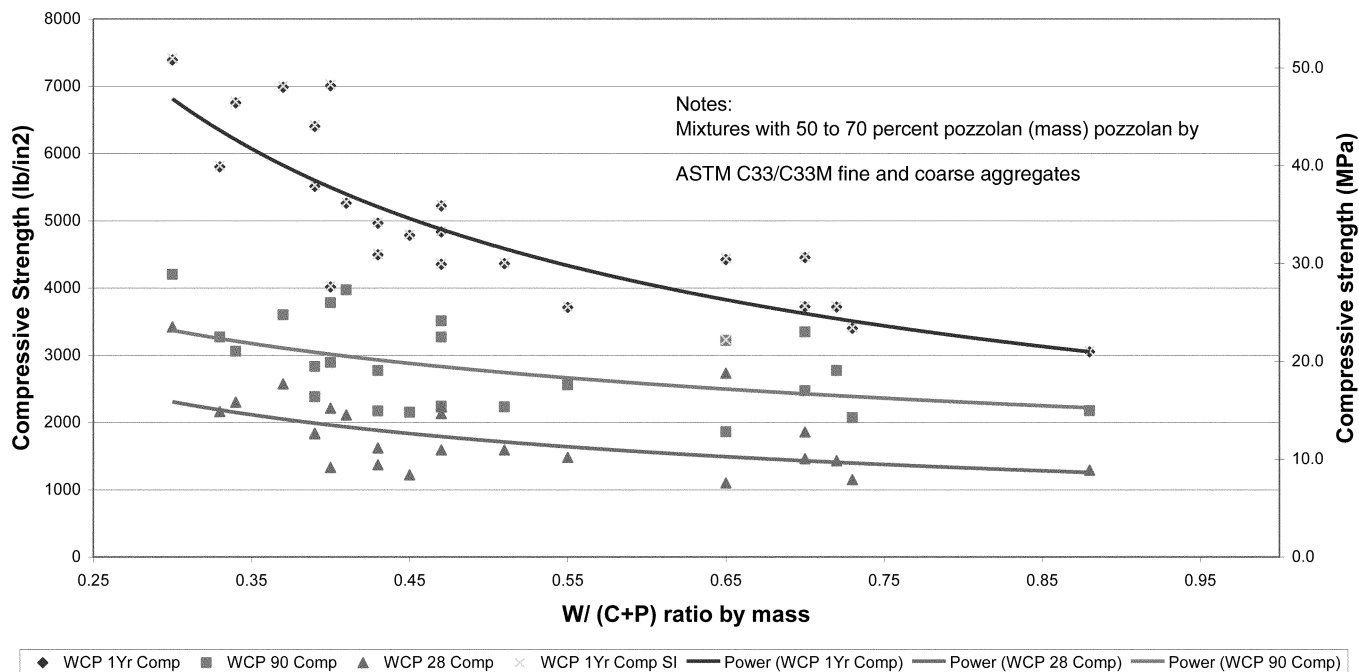


Fig. 3.5—Compressive strength versus w/cm for mixtures with clean graded aggregates.

3.4.5 Maximum density method—This method is a geotechnical engineering approach similar to that used for developing soil-cement- and cement-stabilized base mixtures (Reeves and Yates 1985). Instead of determining the water content by Vebe time or visual performance, the desired water content is determined by moisture-density relationship of compacted specimens using ASTM D1557. Various modifications to the ASTM standard have been found to be desirable because the ASTM D1557 method was not developed for material larger than 3/4 in. (19.0 mm) in diameter (Method D is not included in the current standard), and is not suitable at relatively high levels of workability (Arnold et al. 1992). Proportioning by this approach is also covered in Appendix 3.7 of ACI 211.3R.

3.5—Laboratory trial mixtures

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

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

3.5.3 Testing—Laboratory tests, including temperature, consistency, unit weight, and air content, should be performed by ACI-certified technicians on the fresh RCC produced from each trial mixture. In addition, specimens should be prepared for compressive strength testing at various ages, usually 7, 28, 90, 180 days, and 1 year to indicate the strength gain characteristics of each mixture. These specimens can also be used for determination of static modulus of elasticity and Poisson's ratio at selected ages. Additional specimens should also be fabricated for splitting tensile strength (ASTM C496/C496M) or direct tensile strength at various ages to establish their relationship to compressive strength, and to provide parameters for use in structural analysis.

On major projects, specimens for thermal properties, including adiabatic temperature rise, coefficient of thermal expansion, specific heat, thermal conductivity, and diffusivity are usually cast from one or more selected RCC mixtures. Specimens for specialized tests such as creep, tensile strain capacity, and shear strength may also be cast from these mixtures. Many commercial laboratories are not equipped to conduct these tests, and special arrangements may be required with the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, or universities that have the equipment and facilities for this work. Commercial laboratories used should be accredited in accordance with ASTM C1077 and E329.

3.6—Field adjustments

The primary purpose of laboratory mixture proportioning is to provide proportions that when batched, mixed, and placed in the field, will perform as intended. Laboratory conditions, however, seldom perfectly duplicate field conditions due to ambient temperature and humidity.

batching accuracies, differences in mixer size and mixing action, changes in materials and material grading, compaction equipment, RCC curing, and time between adding water and compaction. In spite of these differences, laboratory mixture proportioning has proven to be an effective means to ensure RCC performance and to minimize field adjustments.

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

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

CHAPTER 4—PROPERTIES OF HARDENED ROLLER-COMPACTED CONCRETE

4.1—General

The properties of hardened RCC are similar to those of mass concrete. Some differences between RCC and conventional mass concrete exist, however, primarily due to differences in required strength, paste volume, and voids content of the RCC mixtures. Most RCC mixtures are not air entrained and may also use aggregates that do not meet the quality or grading requirements of conventional mass concrete. RCC mixtures may also use a higher percentage of pozzolan, which affects the rate of strength gain, workability, and heat generation of the mixture. Because some RCC mixtures may use lower-quality aggregates and lower cementitious contents than conventional concretes, the range of hardened properties of RCC is greater than the range of properties of conventional concrete.

Designers should also be aware of the potential for increased variability of hardened RCC properties due to the potential for greater variations in materials and degree of compaction compared with conventional concrete. Lower-quality aggregates are those that may not meet the requirements for conventional concrete aggregates, either in durability or grading, or those that have been processed without washing. The use of these materials should be carefully considered by the designer and evaluated based on required performance. The rapid placing rates common in RCC construction can place construction loads on concrete before it reaches its initial set; therefore, early-age testing of performance may be needed for the design. The designer should be aware of the potential impact of low early-age strength on construction activities such as form support, vehicle access, and lift surface cleanup.

4.2—Strength

4.2.1 Compressive strength—Compressive strength tests are performed in accordance with ASTM C39/C39M during the design phase to determine mixture proportion requirements, and also to optimize combinations of cementitious materials and aggregates. Compressive strength is used to satisfy design loading requirements and also as an indicator of other strength properties or durability. Tests of cores from trial placement areas may be used to evaluate strength of RCC for design purposes, and also to evaluate the effects of compaction methods on these properties. During construction, compressive strength tests are used to confirm design properties, to evaluate mixture variability, and to provide data for future designs. Cores extracted in accordance with ASTM C42/C42M after construction is complete may be used to confirm design assumptions, construction practices, and may be used to further evaluate in-place properties of the structure. It is important to recognize that the compressive strength test results during construction will lag far behind production, and that maintaining quality can only be achieved as the RCC is mixed, placed, and compacted. Additionally, it is difficult to get reliable compressive strength results from low-strength cores taken too early following construction (though the cores can be used to evaluate compaction).

The compressive strength of RCC is influenced by water content, cementitious content, properties of the cementitious materials, aggregate grading, aggregate quality, and the degree of compaction. For fully-compacted RCC, the traditional influence of *w/cm* on compressive strength is valid. Replacement of cement in an RCC mixture with pozzolan typically delays the early strength development of RCC. Mixtures proportioned for later-age strengths, such as at 180 days or 1 year, often show no loss in strength, resulting in replacement of a significant portion of cement with pozzolan (Dolen 2003).

RCC mixtures with low cementitious contents or poorly-graded aggregates may not achieve anticipated strength levels if aggregate voids are not completely filled. For these mixtures, the addition of nonplastic fines or rock dust has been beneficial in filling voids, thus increasing the density and strength. The use of plastic (clay) fines in RCC mixtures adversely affects strength and workability and, therefore, is not recommended.

Significant differences in compaction have been observed to affect the strength of RCC in both the laboratory and in core samples extracted from in-place construction. For laboratory specimens, the energy imparted to the fresh mixture should be sufficient to achieve full compaction, or strength will not reach the required level due to increased voids. The compactive effort in the laboratory may be compared with cores extracted from a trial placement of simulated construction, provided that the test section has sufficient strength to be cored. The compressive strength of concrete will also decrease due to insufficient compaction that can occur near the bottom of the lift when RCC has poor workability. Not only does this affect compressive strength, but also density, bond strength, and permeability. Compressive strength might also decrease in lifts containing fly ash completing compaction.

Table 4.1—Compressive strength of some RCC dams: construction control cylinders

Dam/project	Mixture type/ ID	Cement, lb/yd ³ (kg/m ³)	Pozzolan, lb/yd ³ (kg/m ³)	<i>w/cm</i>	NMSA, in. (mm)	Cylinder fabrication method	Compressive strength, psi (MPa), at test age				
							7 days	28 days	90 days	180 days	365 days
Al Wehdah	70C60F	118 (70)	101 (60)	0.96	2 (50)	VB	590 (4.1)	1130 (7.5)	2120 (14.6)	2510 (17.3)	3280 (22.6)
	60C70F	101 (60)	101 (60)	1.04	2 (50)	VB	440 (3.0)	800 (5.5)	1420 (9.8)	1750 (12.1)	2730 (18.8)
Camp Dyer	RCC1	139 (82)	137 (81)	0.55	1.5 (37.5)	VB	880 (6.1)	1470 (10.1)	—	—	3680 (25.4)
Concepcion	152C	152 (90)	0	1.03	3 (75)	PT	580 (4.0)	800 (5.5)	1100 (7.6)	1270 (8.8)	—
Galesville	RCC1	89 (53)	86 (51)	1.09	3 (75)	PT	300 (2.1)	580 (4.0)	1020 (7.0)	—	1620 (11.2)
	RCC2	110 (65)	115 (68)	0.84	3 (75)	PT	420 (2.9)	820 (5.7)	1370 (9.4)	—	—
Middle Fork	112C	112 (66)	0	1.43	3 (75)	PT	—	1270 (8.8)	1650 (11.4)	—	—
Olivenhain Trial Placement	100/100-180	100 (59)	100 (59)	0.90	2 (50)	HH	680 (4.7)	1010 (7.0)	1810 (12.5)	—	—
	100/100-195	100 (59)	100 (59)	0.98	2 (50)	HH	450 (3.1)	600 (4.1)	1410 (9.7)	—	—
Olivenhain	11B	127 (74)	204 (121)	0.63	2 (50)	HH	690 (4.8)	1070 (7.4)	1820 (12.6)	2990 (20.6)	—
Santa Cruz	RCCA EA	128 (76)	127 (75)	0.67	2 (50)	VB	1090 (7.5)	2730 (18.8)	3220 (22.2)	—	4420 (30.5)
Siegrist	100/70-162	100 (59)	70 (42)	0.95	1.5 (37.5)	PT	840 (5.8)	1360 (9.4)	2120 (14.6)	2630 (18.1)	2900 (20.0)
Stacey Spillway	210C105P	210 (125)	105 (62)	0.82	1.5 (37.5)	MP	—	2620 (18.1)	3100 (21.4)	—	—
Stagecoach	120C130P	120 (71)	130 (77)	0.93	2 (50)	PT	215 (1.5)	350 (2.4)	—	985 (6.8)	1250 (8.6)
Upper Stillwater	RCCA85	134 (79)	291 (173)	0.37	2 (50)	VB	1560 (10.8)	2570 (17.7)	3600 (24.8)	5590 (38.5)	6980 (48.1)
	RCCB85	159 (94)	349 (207)	0.30	2 (50)	VB	2040 (14.1)	3420 (23.6)	4200 (29.0)	5530 (38.1)	7390 (51.0)
	RCCA	134 (79)	292 (173)	0.39	2 (50)	VB	1080 (7.4)	1830 (12.6)	2600 (17.9)	—	6400 (44.1)
	RCCB	157 (93)	347 (206)	0.33	2 (50)	VB	1340 (9.2)	2230 (15.4)	3110 (21.4)	—	6750 (46.5)
Urugua-I	101C	101 (60)	0	1.67	3 (75)	PT	—	930 (6.4)	1170 (8.1)	—	1390 (9.6)
Willow Creek	175C	175 (104)	0	1.06	3 (75)	PT	1000 (6.9)	1850 (12.8)	2650 (18.3)	—	3780 (26.1)
	175C80P	175 (104)	80 (47)	0.73	3 (75)	PT	1150 (7.9)	2060 (14.2)	3960 (27.3)	—	4150 (28.6)
	80C32P	80 (47)	32 (19)	1.61	3 (75)	PT	580 (4.0)	1170 (8.1)	1730 (11.9)	—	2620 (18.1)
	315C135P	315 (187)	135 (80)	0.41	1.5 (37.5)	PT	2030 (14.0)	3410 (23.5)	4470 (30.8)	—	5790 (39.9)

Note: Cylinder fabrication method: VB = Vebe (ASTM C1176/C1176M); MP = modified proctor (ASTM D1557); PT = pneumatic tamper; and HH = Hilti Hammer.

Table 4.2—Comparison of compressive strengths of RCC: construction control cylinders versus cores

Dam/project	Mixture type/ID	Cement, lb/yd ³ (kg/m ³)	Pozzolan, lb/yd ³ (kg/m ³)	<i>w/cm</i>	NMSA, in. (mm)	Cylinder fabrication method	Cylinder strength, psi (MPa)			Core strength, psi (MPa)			
							28 day	90 day	365 day	Age, days	Strength	Age, days	Strength
Elk Creek	118C56P	118 (70)	56 (33)	1.00	3 (75)	VB	410 (3)	1370 (9)	2380 (16)	90	1340 (9)	730	2450 (17)
Galesville	RCC1	89 (53)	86 (51)	1.09	3 (75)	PT	580 (4)	1020 (7)	1620 (11)	425	2080 (14)	—	—
Middle Fork	112C	112 (66)	0	1.43	3 (75)	PT	1270 (9)	1650 (11)	—	42	2016 (14)	0	0
Olivenhain Trial Placement	100/100-180	100 (59)	100 (59)	0.90	2 (50)	HH	1010 (7)	1810 (12.5)	—	182	1700 (11.7)	—	—
	100/100-195	100 (59)	100 (59)	0.98	2 (50)	HH	600 (4.1)	1410 (9.7)	—	182	1620 (11.2)	—	—
Olivenhain	11B	125 (74)	204 (121)	0.63	2 (50)	HH	690 (4.8)	1820 (12.6)	—	91	2240 (15.4)	—	—
Penn Forest	90/71-155	90 (54)	71 (42)	0.96	1.5 (37.5)	HH	760 (5.2)	1490 (10.3)	2110 (14.6)	365	2015 (13.9)	—	—
Siegrist	100/70-162	100 (59)	70 (42)	0.95	1.5 (37.5)	PT	1360 (9.4)	2120 (14.6)	2900 (20)	335	3200 (22.1)	—	—
Stacey Spillway	210C105P	210 (125)	105 (62)	0.82	1.5 (37.5)	MP	2620 (18)	3100 (21)	—	28	2090 (14)	90	2580 (18)
Stagecoach	120C130P	120 (71)	130 (77)	0.93	2 (50)	PT	350 (2)	—	1250 (9)	180	1960 (14)	365	1920 (13)
Upper Stillwater	RCCA	134 (79)	292 (173)	0.39	2 (50)	VB	1830 (13)	2600 (18)	6400 (44)	180	4890 (34)	365	5220 (36)
Victoria	113C112P	113 (67)	112 (66)	0.80	2 (50)	—	—	—	—	365	2680 (18)	—	—
Willow Creek	175C	175 (104)	0	1.06	3 (75)	PT	1850 (13)	2650 (18)	3780 (26)	365	2120 (15)	—	—
	175C80P	175 (104)	80 (47)	0.73	3 (75)	PT	2060 (14)	3960 (27)	4150 (29)	365	2800 (19)	—	—
	80C32P	80 (47)	32 (19)	1.61	3 (75)	PT	1170 (8)	1730 (12)	2620 (18)	365	2250 (16)	—	—
	315C135P	315 (187)	135 (80)	0.41	1.5 (37.5)	PT	3410 (24)	4470 (31)	5790 (40)	365	3950 (27)	—	—
Zintel Canyon	125CNA	125 (74)	0	1.50	2.5 (63)	—	—	—	—	345	1510 (10)	—	—

Note: Cylinder fabrication method: VB = Vebe (ASTM C1176/C1176M); MP = modified proctor (ASTM D1557); PT = pneumatic tamper; and HH = Hilti Hammer.

retarding admixtures, or both, are less prone to strength loss resulting from delayed compaction. Placing in cool weather also extends the setting time and the subsequent compaction time.

Typical compressive strengths of RCC using field-fabricated cylinders are given in Table 4.1. Table 4.2 presents

a comparison of compressive strength of RCC cylinders versus cores. The design compressive strengths for these mixtures may vary from as low as 1000 psi (7 MPa) to as high as 4000 psi (28 MPa) at an age of 1 year. Strain and creep properties and corresponding compressive strength data from several RCC dam projects are listed in Table 4.3.

Table 4.3—Strain and creep properties of some laboratory RCC mixtures

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

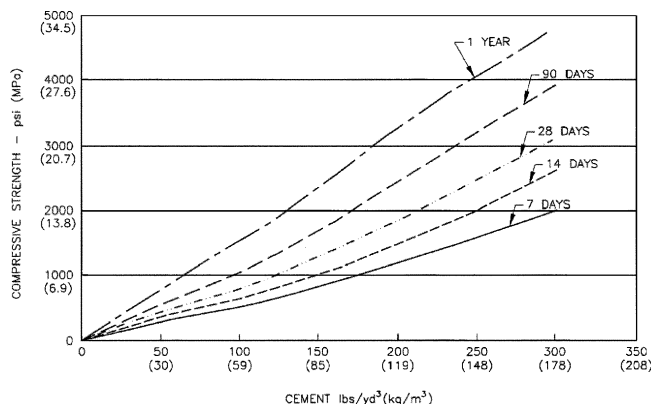


Fig. 4.1—RCC strength curves that can be developed from tests conducted on concretes with varying proportions of cement for high-quality aggregates.

Figures 4.1 and 4.2 show compressive strength curves developed for two different aggregates using a maximum density method for mixture proportioning.

4.2.2 Tensile strength—Tensile strength of RCC is required for design loadings, including dynamic loading and in the thermal analysis. Table 4.4 shows direct tensile strength values for core samples extracted from several projects. The ratios of direct tensile-to-compressive strength for parent (unjointed) RCC mixtures have typically averaged approximately 4 to 8%, depending on aggregate quality,

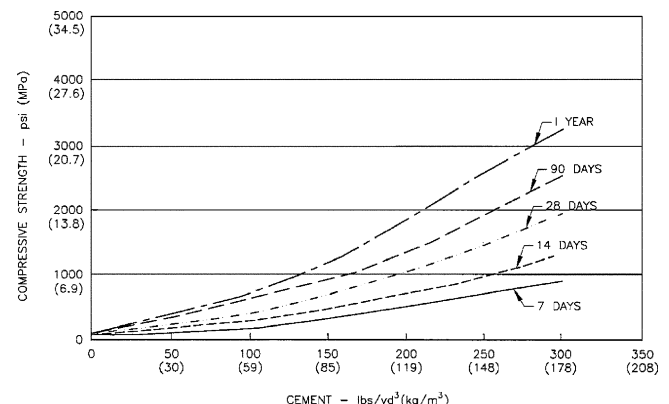


Fig. 4.2—RCC strength curves developed for lesser-quality aggregates.

strength, age, and test method. Mixtures with low cementitious materials content, or those with lower-quality or coated aggregates, or both, will have corresponding lower direct tensile strengths. The ratio of direct tensile-to-compressive strength of both RCC and conventional mass concrete will usually decrease with increasing age and compressive strength (Schrader 1994). The direct tensile strength of concrete is less than the splitting (indirect) tensile strength of jointed concrete. Splitting (indirect) tensile strength is determined in accordance with