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Roller-Compacted Concrete

Ernest K. Schrader, Ph.D., FACI[*]

20.1 Introduction

Roller-compacted concrete (RCC) has rapidly become a commonly used material for dams and massive structures. It is also used for overtopping and erosion protection of embankments and for heavy-duty pavements. This chapter concentrates on mass applications of RCC, primarily for dams; however, many of the concepts, from testing to material properties and mix designs, apply to all uses of RCC. In a sense, RCC dams can be thought of as a series of bonded pavements or parking lots stacked on top of each

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[*] Consultant, Schrader Consulting Engineers, Walla Walla, Washington; expert in the theory and application of roller-compacted concrete, including planning, design, and construction of more than 100 international projects.

FIGURE 20.1 Placing RCC with 110 lb of cement and 54 lb of fly ash per cubic yard using a 24-in. conveyor at Rompepicos Dam, Mexico. (Photograph courtesy of Ernest K. Schrader.)

other. This chapter provides an explanation of what RCC is, how it differs from conventional concrete, what its special properties are, and how to use it effectively. The chapter covers specific technical and construction issues, including aggregates and mixture proportioning, laboratory testing, properties, engineering and design, cost, and construction. Emphasis is placed on areas of controversy and significant interest, such as cost savings, mixture proportions, material properties, watertightness, lift-joint quality, and design options.

20.1.1 What Is RCC?

Roller-compacted concrete is concrete, but it is placed by nontraditional methods. It requires a drier or stiffer consistency than conventional concrete. RCC can have a much broader range of material properties than conventionally placed concrete. It can use aggregates not meeting normal requirements, it can be placed at very high production rates, and it can be much less expensive. By definition (ACI Committee 207.5R, 1999), RCC is concrete that has a consistency that allows it to be compacted with a vibratory roller. Usually a 10-ton vibratory roller intended for compaction of asphalt and granular base is used because of its high compactive energy with high-frequency and low-amplitude vibration. RCC is often mixed in a continuous process rather than in batches. It is delivered with dump trucks or conveyors, spread in layers using a bulldozer, and given final compaction with a vibratory roller. Figure 20.1 shows a typical application of mass RCC on a medium-sized dam, using a 24-in. conveyor delivery system. A condensed summary of the RCC process has been described in earlier literature (Schrader, 1988; Schrader and Namikas, 1988). More thorough summaries have also been published (ACI Committee 207.5R, 1999; Hansen and Reinhardt, 1991; ICOLD, 1989; Jansen, 1989; Schrader, 1994, 1995c,d, 2002, 2003a). Freshly mixed uncompacted RCC generally looks like damp gravel that might be used for a road base, although some mixtures that have a wetter consistency look more like a conventional no-slump concrete. Not until the cement has reached a point near final setting or until the hydrated interior is exposed does RCC have the visual appearance of normal concrete. Portland cement is normally the primary cementing medium, although fly ash or natural **pozzolan** is often used for a major portion of the cementing material. Slag cement has also been used. Low-cement-content mixtures typically use natural nonplastic fines or rock dust as a filler to compensate for the lack of **paste** that would otherwise exist. At times, the fines have cementing abilities.

20.1.2 History

The rapid worldwide acceptance of RCC dams is a result of need, success, and economics. Materials used occasionally 30 to 40 years ago, in hindsight, could be considered to be RCC. These applications were typically stabilized gravel fills, and the material was not viewed as an engineered concrete. In the 1960s, a high-production, no-slump mixture that could be spread with bulldozers was used at Alpe Gere Dam in Italy (Gentile, 1964) and at Manicougan I in Canada (Wallingford, 1970). A similar process was used as late as the 1980s at Burdekin Falls Dam in Australia. These mixtures were almost RCC, but they were consolidated with groups of large internal vibrators mounted on backhoes or bulldozers, a procedure that is currently used at times with conventional low-slump mass concrete—for example, at the Tekeze Arch Dam in Ethiopia.

During the 1970s, a number of organizations were involved with trials, laboratory evaluations, and the development of various philosophies concerning mass RCC. A number of RCC applications for portions of dams and spillways, for temporary structures, and for noncritical uses were completed during this first decade of significant RCC development, including the placement of more than 1 million cubic yards of RCC at Tarbela Dam. In 1974, a preliminary design with extensive laboratory testing was completed by the U.S. Army Corps of Engineers for the Zintel Canyon Dam. This would have been the world's first RCC dam, but because of funding issues the dam was not actually constructed until 1992.

The work with RCC in the 1970s formed the basis for RCC dams as they began to appear in the 1980s. Growth and acceptance of this new process was dramatic. In 1983, only one major all-RCC dam existed in the world (Willow Creek in Colorado) (Schrader 1982a,b). About the same time, Shimijagawa Dam, a rolled-concrete dam (RCD) was completed in Japan. RCDs typically use RCC for the interior portions. By 1996, just 13 years after completion of the first all-RCC dam, about 200 large RCC dams worldwide were completed, under construction, or under design. There are now too many to keep track of, with many hundreds of projects being documented. In the United States alone, about 300 documented uses of RCC in dams can be found, including 46 dams higher than 50 feet, more than 30 dams lower than 50 feet, 126 uses of RCC to allow overtopping of embankment dams, more than 10 uses of RCC for added support of existing concrete dams, several for raising the height of existing dams, and several uses for earth-dam rehabilitation applications, among the many miscellaneous uses.

Although the United States initially had the greatest number of RCC dams, they are now more prevalent in countries such as China, Spain, and Brazil, and their popularity is increasing in Vietnam, India, and elsewhere in Asia and Southeast Asia. RCC dams can be found on every continent except Antarctica. RCC dams are in use, under design, or in the planning stages in countries that have climates ranging from arctic to tropical and are at elevations ranging from sea level to very high mountain regions. Figure 20.2 through Figure 20.9 show examples of completed RCC dams of various mixes, sizes, and locations.

Rolled-concrete dams are now being used extensively in Japan, where over 30 projects have been completed, are under construction, or are in various stages of planning and design; however, RCD has not become popular outside of Japan. The process uses a relatively low-cement-content RCC for the interior portion of the dam, but typically encases the entire mass of RCC with at least 10 ft of conventional concrete. This includes the upstream and downstream faces, the foundation, and the upper portion of the dam, although the current trend seems to use more RCC and less conventional concrete. **Monolith** joint spacings are typically the same as those used for conventional concrete dams. The result is a very attractive dam that looks and behaves like a traditional concrete dam, but the RCD procedure tends to compromise the substantial cost savings and reduction in schedules possible with dams that are almost entirely RCC. The trend in the United States has moved from using RCC primarily for new dams to using it more for rehabilitation and support or the buttressing of existing dams, for raising the height of existing dams, and for providing emergency spillway capacity over existing embankment dams. This trend is expected to develop in other countries as they begin to realize the benefits and additional uses of RCC. Figure 20.10 shows the use of RCC to provide a buttress and an overtopping spillway at the Tongue River embankment dam in Montana.

FIGURE 20.2 Willow Creek Dam in Colorado, which was the world's first major all RCC dam and used mostly 80 lb of cement and 32 lb of ash per cubic yard. (Photograph courtesy of Ernest K. Schrader.)

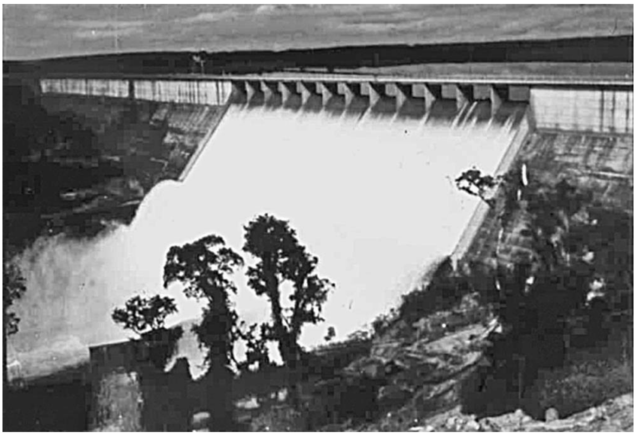


FIGURE 20.3 Urugua-I Dam in Argentina, which used 105 lb of cement per cubic yard (no ash). (Photograph courtesy of Ernest K. Schrader.)

FIGURE 20.4 Balambano Dam in Indonesia, which used 121 lb of cement and 81 lb of fly ash per cubic yard. (Photograph courtesy of Ernest K. Schrader.)

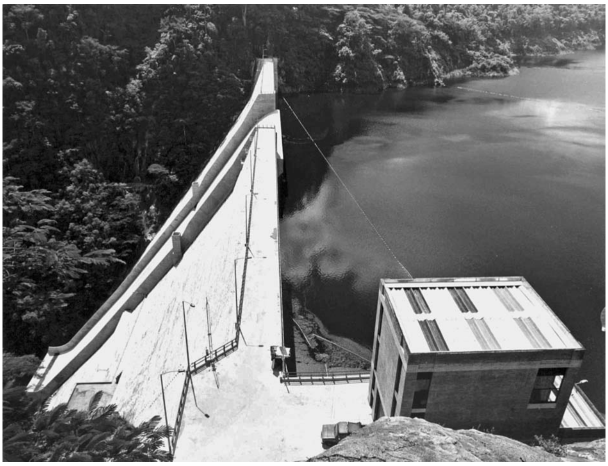


FIGURE 20.5 Miel I Dam in Colombia, which is 620 ft high and used low to medium cement content mixes and no ash. (Photograph courtesy of Ingetec S.A., Colombia.)

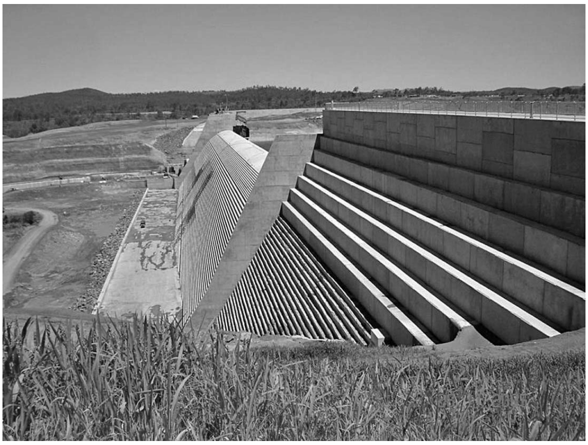


FIGURE 20.6 Burnett River (Paradise) Dam in Australia, which used 106 lb of cement per cubic yard (no ash). (Photograph courtesy of Ernest K. Schrader.)

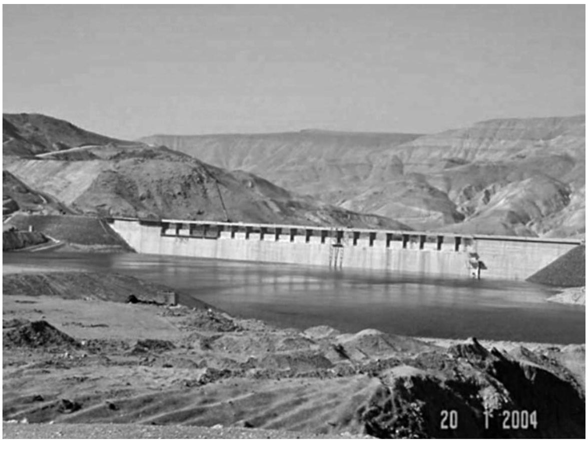


FIGURE 20.7 Mujib Dam in Jordan, which primarily used 143 lb of cement per cubic yard (no ash). (Photograph courtesy of Lahmeyer International, Bad Vilbel, Germany.)

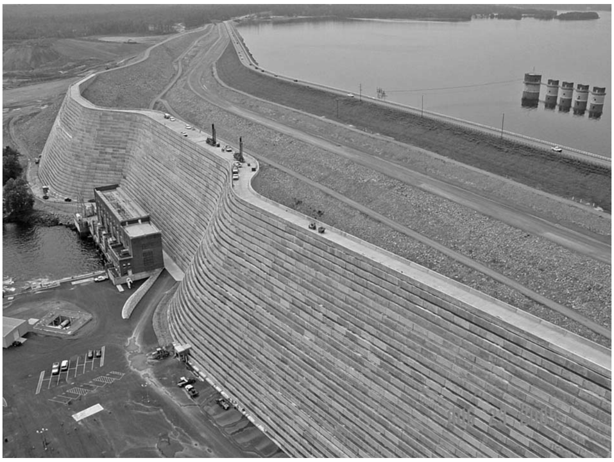


FIGURE 20.8 Saluda Dam in South Carolina, which was built downstream of an existing unstable embankment dam using 150 lb of cement and 150 lb of dumped waste ash per cubic yard. (Photograph courtesy Paul C. Rizzo Associates; Monroeville, PA.)

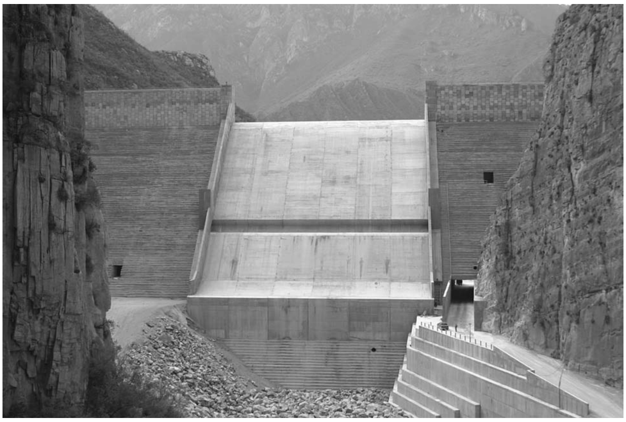


FIGURE 20.9 Rompepicos Dam in Mexico, which is 350 feet high; mostly used 73 lb of cement and 54 lb of waste ash per cubic yard. (Photograph courtesy of Ernest K. Schrader.)

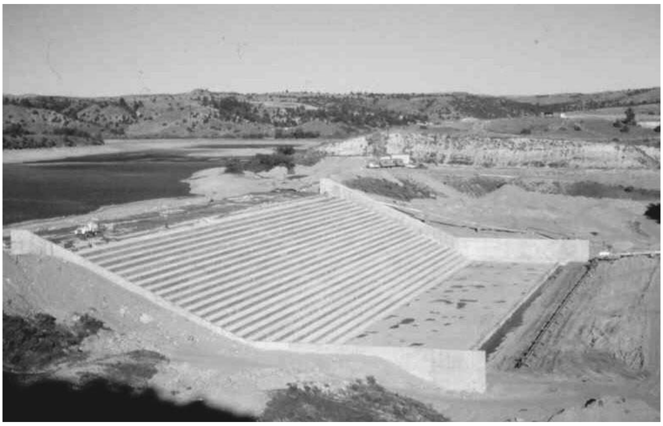


FIGURE 20.10 RCC used to provide a buttress and overtopping spillway for the Tongue River embankment dam in Montana. The mix primarily used 150 lb of cement (no ash) with surface layers of the stilling basin having higher cement content.

As with conventional concrete, there is no known limit to the size or height of dams that can be designed and constructed with RCC. Currently, dams on the order of 300 ft high are common, and dams about 600 ft high are not unusual, such as the 620-ft Miel I dam in Colombia. Very large dams such as Longtan in China and Gibe III in Ethiopia are beginning to emerge. Dams up to about 900 ft high, with nearly 20 million cubic yards of RCC are also being designed, such as Diamer Basha in Pakistan. The performance of RCC dams has been very good, although like other dams some projects have had issues with regard to cracking and seepage (Schrader, 1988, 1994, 1995a,c,d, 2002, 2003a; Schrader and Namikas, 1988). These two specific issues are discussed later in more detail.

20.2 Advantages and Disadvantages

20.2.1 General

The list of RCC dam advantages is extensive, but some disadvantages should be recognized. Some of the potential advantages can only be realized with certain types of RCC mixtures, structural designs, production methods, weather, or other conditions. Likewise, some disadvantages only apply to certain conditions and types of mixtures. One condition that remains constant with RCC is that each job must be thoroughly evaluated on its own. What is advantageous for one project with a given set of conditions may not be advantageous for a different project, and what is a problem at one location may actually be a benefit at another location. No single design, mixture, or construction method is ideal for all projects. Although it is almost routine for efficiently designed RCC dams to be the least costly alternative when compared to other types of dams, in some circumstances RCC may be more costly. A situation in which RCC may not be appropriate is when aggregate material is not reasonably available but an abundance of good material is available for impervious fill. When a large spillway capacity is necessary, RCC dams usually are the most economical because the spillway can be placed over the dam, and the non-overflow portion of the dam can be allowed to overtop in an emergency. Fill and embankment dams typically require a separate, very expensive spillway excavated into an abutment and, because they cannot be allowed to overtop, they usually have added height to ensure that overtopping is avoided.

20.2.2 Cost

Typical reasons for using RCC are the reduced cost and time it offers. Savings can be dramatic, sometimes in excess of 50%; however, in reality, some projects lacking the proper planning, equipment, and supervision have not saved any time, and the potential cost savings have been lost. Some projects have experienced added costs because of design decisions by the engineer or owner that resulted in expensive or time-consuming options—for example, architectural concrete, nonessential extra nonessential galleries, excess conventional facing concrete, elaborate spillways added to the face of the dam after finishing the RCC, and arbitrary decisions to use imported or excessive cementitious materials and expensive aggregates when they really were not necessary. Each project must be evaluated on its own. A trade-off in appearance and other characteristics that may be associated with high costs must be acceptable to the owner and compatible with technical requirements.

It is difficult to obtain final actual cost data for RCC dams, although bid price data for various portions of the RCC are abundant, and several reasonable summaries of approximate overall costs are available in various references (Forbes, 1988; Hansen and Reinhardt, 1991; Schrader, 1988, 1995c,d; Schrader and Namikas, 1988). Apparent discrepancies in costs reported in publications and in costs discussed at various meetings exist for two primary reasons: First, the work and materials included in the costs can be very inclusive (e.g., mobilization, joints, engineering, facings, diversion, spillway, forming, galleries, drains, foundation preparation), or the costs may include only the very basic costs of RCC production (aggregate, cement, mixing, and placing). Second, costs are sometimes based on unit bid prices, which can be unbalanced and not the true prices and do not include subsequent added costs for claims, litigation, time extensions, modifications, and overruns.

TABLE 20.1 Typical RCC Prices (1996 U.S. Dollars)

Volume (yd^3)	Price per yd^3
1000–6000	\$42–94
30,000–100,000	\$34–42
250,000–500,000	\$23–34
1,000,000–7,500,000	\$22–29

Note: Prices include RCC, facings, conventional concrete, and miscellaneous items.

Because of the many interrelated aspects of RCC, a fair way to compare the costs of various designs and projects is to consider the volume and combined cost of applicable mobilization; access and haul roads for RCC and related activities; cement; pozzolan; aggregate; admixtures; mixing; delivery; placing; compaction; grout-enriched or bedding mixtures; lift-surface cleaning; curing and protection; upstream and downstream facings; watertightness; spillways; joints; detailed work at the top of the dam; foundation preparation, including leveling the concrete if used; galleries; drainage; and cooling or crack mitigation, if required. Consideration should also be given to the required quantity of excavation, as well as the length of diversion and outlet structures.

The reason for this comprehensive comparison is that misunderstandings have occurred without it. An example is when comparing a more massive lower strength design to a less massive higher strength design. The low-strength design may have significantly lower RCC unit costs, but high dams may require greater volume, more excavation, and longer conduits. Lower unit costs are usually the result of greater volume, lower strengths, and reduced aggregate, cement, pozzolan, and admixture requirements. High-strength designs typically have greater unit costs. They may also have significantly more foundation treatment, **gallery** requirements, lift-joint requirements, leveling concrete, monolith joints or crack control, and cooling requirements. Another example is a design that requires more costly and complex RCC placing methods but has the benefit of less costly spillway and facing work, whereas a different design may have very simple RCC placing that then requires time-consuming and costly spillway or facing construction.

Even with these problems, general price guidelines can be provided. Typically, the final price of RCC (all ingredients, mixing, delivery, and placing, including joint treatment, drains, cure, facings, and other directly related items) varies from about \$22/yd^3 to \$94/yd^3 (1996 U.S. dollars), depending on the size of the project, strength, and complexity. Table 20.1 provides typical price ranges for different sizes of dams based on historical records of completed projects and estimates for future projects. The table excludes projects in France, where RCC tends to be more expensive than elsewhere (but still locally competitive). Another exception is the relatively high final cost of the high-cementitious-content RCC at Upper Stillwater Dam (Parker, 1992). Exceptions at the other end of the spectrum are Zintel Canyon Dam and Willow Creek Dam, where uncomplicated projects resulted in final real costs less than the range indicated in Table 20.1.

Table 20.2 provides a typical price breakdown (1996 U.S. dollars), showing where the more expensive aspects of RCC typically lie—namely, in aggregate and **cementitious** materials. The table also demonstrates the increased unit cost of RCC with a higher cementitious content, but also the typical lower volume required for a high-cementitious-content dam compared to a low-cementitious-content dam. Historically, and in estimates of future projects, the final cost of an entire dam with all related construction such as outlets, spillway crests and gates, access, foundations, diversion, instrumentation, valves, finishing, and environmental restoration is usually about 1.5 to 2.5 times the cost of the RCC. The reasons are different from job to job, but the range stays the same. Simple designs with unformed faces and more massive sections tend to be less, while more complex designs and smaller sections tend to be more.

A big part of the savings of RCC dams compared to embankment dams comes from incorporating the spillway into the dam rather than having a separate major excavation and structure. Additional major

TABLE 20.2 Example RCC Price Breakdown (1996 U.S. Dollars)

Item	Lower Strength, More Massive ($/yd³)	Higher Strength, Less Massive ($/yd³)
Aggregate	11.45	13.20
Cement + pozzolan	7.25	12.75
Delivery	2.80	3.00
Mixing	1.50	1.60
Cooling	.20	1.40
Place-spread-compact	.55	.60
Cure and protection	.20	.15
Bedding and special mixes	.40	.05
Cleaning and surface prep	.25	.10
Survey, joints, drains, gallery, miscellaneous	.20	.40
Total	24.80	33.25
RCC volume (yd³)	1,000,000	850,000
RCC cost for dam	$24,800,000	$28,262,000
Total dam	$28.60	$38.60
Total volume (yd³)	1,030,000	880,000
Total concrete	$29,461,000	$33,968,000

savings are related to the speed of construction. Often, the dam can be raised in one dry season, thereby greatly reducing the diversion and cofferdam costs when compared to the costs of providing protection during the wet season for other designs. When a large project can be completed with RCC sooner than the completion date for an alternative type of dam or design, the savings resulting from lower interest payments for borrowed money during construction can also be significant. The additional income from earlier completion and earlier water storage can be extraordinary for large hydroelectric and irrigation projects. On the other hand, due to weather, lack of availability of cementing materials, funding limitations, or, more frequently, inappropriate equipment, some RCC projects have finished well after the originally projected completion date. If, however, the factors that impacted RCC production occur with an alternative design, the outcome for the alternative can usually be shown to be even worse than it might have been for the RCC dam.

20.2.3 Schedule

In addition to the cofferdam and diversion benefits, being able to schedule RCC placement for dry seasons improves the efficiency of construction. RCC can occasionally remove the dam portion of a large project with tunnels and powerhouses from the critical path and can allow a delay in the start of dam construction, thereby saving interest on that portion of the work. Typical placing rates for projects having RCC volumes on the order of 10,000 to 25,000 yd^3 are about 50 to 200 yd^3/hr. Medium-sized projects of about 50,000 to 200,000 yd^3 generally achieve rates of about 150 to 400 yd^3/hr. Large projects of about 400,000 to 2,000,000 yd^3 or more can be expected to achieve about 500 to 1000 yd^3/hr. In most cases, especially with medium-sized projects, the time required to mobilize, produce aggregates, and prepare foundations exceeds the time required to place the RCC. Emergency projects have benefited from the speed of RCC construction. Kerrville Dam in Texas utilized RCC for the rapid construction of a new dam downstream of an embankment dam that was in imminent danger of failure due to overtopping; the design and construction were accomplished in a matter of weeks. Concepcion Dam in Honduras used RCC to build a water-supply project after declaration of a national emergency in the capitol city of Tegucigalpa (Giovagnoli et al., 1991, 1992). Burton Gorge Dam was essentially investigated, planned, designed, constructed, and put into operation in less than 1 year (Schrader, 1999b).

20.2.4 Equipment, Materials, and Manpower

The construction equipment required for RCC is usually available, including appropriate mixers and conveyors, which are the more difficult pieces of equipment to locate and may have to be imported. Depending on the approach taken in the design and location of the project, materials required for RCC may be difficult or very simple to procure. For example, the design of Concepcion Dam took into account the poor quality of the aggregate, cement, and pozzolan so local materials and a low-strength mixture could be used for economical construction without delays (Gaekel and Schrader, 1992; Giovagnoli et al., 1992, 1992). These materials could not meet normal requirements for conventional concrete or for RCC requiring medium to high strengths. If the design had not been adapted to materials that were readily available, a much more expensive RCC dam would have resulted that utilized specially produced cement and pozzolan and very expensive aggregates that would have been hauled a long distance. A similar situation developed at Mujib Dam in Jordan, where the original design with higher quality aggregate and imported fly ash was changed to eliminate the need for imported fly ash (or any purchased pozzolan) and to allow for the use of more economical dirty basalt aggregate (Schrader et al., 2002, 2003a). A similar approach was also used at the Burnett River Dam in Australia (Herweynen et al., 2004; Lopez et al., 2005). The redesign of Rompepicos Dam in Mexico also used this approach with regard to both cementitious content and aggregates (Schrader and Bali, 2003). Other examples are discussed in Section 20.3.1.

Roller-compacted concrete dams can be built by labor-intensive methods with reduced equipment requirements, but this should only be considered for smaller projects where economics and political reasons justify it and where relaxed quality can be tolerated. RCC is best suited to high production with large equipment and a small labor force. Even where labor is inexpensive and readily available, experience has shown that it is best to use a small work force. It is essential for supervisory staff to understand RCC as well as the type of dam construction to be used. Laborers do not require special skills other than those found in the general heavy-construction industry, but they should be given an orientation for special concerns when handling RCC. It is common for contractors new to RCC to use the services of a specialist familiar with RCC to assist at the start of placing.

20.2.5 Weather

Rain and hot weather are arguably the biggest problems in RCC production, but they are not insurmountable. For a variety of reasons, including the impact of weather on production or hauling, aggregate supply and the reliable delivery of cementitious materials have also been factors in slowing or stopping RCC production on some projects. Many major RCC projects are located in tropical and desert climates. Hot weather causes higher internal peak temperatures, but if the environment remains warm and does not have a severe cold season, thermal cracking can usually be avoided without extraordinary cooling measures for the mix, at least for mixes designed to have relatively low cementitious contents. Hot weather also reduces the allowable time before the concrete must be delivered, spread, and compacted, as well as the time that a lift surface can be exposed before it starts to suffer a significant loss of quality. Rain can be a significant problem if it is heavy or if equipment drives across the concrete surface when it is wet. Light rain will not significantly damage a compacted surface if conveyor delivery is used and hauling equipment is not driving over and disturbing the surface, but it can be a major problem if haul vehicles are used to deliver RCC on a damp lift surface. Rain problems are minimized by scheduling RCC placing during the dry season, avoiding placing during hours when rains are common, providing rain protection when appropriate, and using very high production rates with high-speed conveyor delivery. Table 20.3, developed by the author based on actual production records of different types of RCC dams in various climates, provides general guidance concerning the probable amount of time that an RCC project will be down as a result of rain. As shown in Table 20.3, downtime is a function of rain intensity and duration as well as the method of delivery. If trucks are used for delivery and they must operate on the RCC surface, rain is a much more significant problem compared to when an all-conveyor delivery system is used. This is because tire traffic on a wet surface causes the surface to develop a slurry that then must be removed before placing the next layer, or the dam must be designed with consideration for the decreased lift-joint quality if adequate cleaning is not done.

TABLE 20.3 Shifts Lost Because of Rain

	Peak Rain Intensity (in./hr)				
Method	0	0 < 0.04	0.04 < 0.08	0.08 < 0.20	<0.20
Haul vehicles on dam	0	0[a]	1[a]	1[a]	2
All-conveyor delivery	0	0	0	0[a]	1[a]

[a] Add one more lost shift if rain duration is greater than 8 hr.

Note: Assumes a two-shift/day work schedule.

20.3 Aggregates and Mixture Proportions

20.3.1 Aggregates

With respect to grading and other properties, aggregates similar to those used in conventional concrete can be used for RCC; however, materials and gradations that would normally be considered totally unacceptable for conventional concrete have been used very successfully in RCC dam construction and can actually be advantageous. Although aggregates meeting normal concrete requirements can be used, they are not necessary in RCC dam construction. Because there were no economical options, Concepcion Dam, discussed earlier in Section 20.2.4, has the unique honor of successfully using probably the worst quality materials in a major concrete dam. Monksville and Copperfield Dams used unwashed gravels with minimal processing. The aggregate included friable particles of decomposed granite in the sand sizes. Middle Fork Dam used marlstone oil shale with a specific gravity of about 2.2, a high Los Angeles abrasion loss, and absorption of 12 to 20%. In this case, an unlimited supply of this rock was available at the dam, whereas the nearest aggregate that met traditional criteria for concrete was expensive and required a long haul, all up steep grades. The marlstone required a slightly increased dam section and volume, but the overall result was a large savings.

Willow Creek Dam was the first of many projects to use dirty overburden and dirty quarry materials that normally would be wasted or require extensive washing. As discussed earlier, the fines that normally would be washed out of traditional concrete aggregate are actually needed to achieve a low cementitious content in the RCC mix. Each project must be evaluated separately to find out how to best use the available aggregate materials. In some cases, such as where a poor foundation controls the design section, a low density may actually be beneficial. In most cases, fines are beneficial, especially if they tend to be pozzolanic and well graded. The fines should be nonplastic. Some low-strength aggregates may produce a low but tolerable strength along with a desirable high **creep** and high strain capacity. High Los Angeles abrasion losses can usually be accepted because of service conditions, the mixing and compacting equipment, and the typical RCC grading.

Roller-compacted concrete mixtures are less affected by particle shape than are conventional concrete mixtures because of the mixing and delivery equipment used and the typical grading. The presence of flat and elongated particles is still undesirable, but amounts up to about 40% on any sieve size with an average below about 30% for all sieve sizes have been acceptable. Both crushed and rounded materials work well, but the ideal combination appears to be angular crushed coarse particles with natural rounded sand. When steep unformed slopes are to be constructed, crushed material becomes more important.

Alkali–aggregate reaction in RCC is a subject in itself. A few comments are made here. Potentially reactive aggregates have been used in RCC without problems for various reasons, including low cement contents and high pozzolan contents in some mixtures and the use of low-alkali cements when available. A nontraditional concept to consider is that a slight expansion due to the alkali–aggregate reaction can actually be beneficial if it offsets thermal contraction.

The key to controlling segregation, minimizing cement contents, and providing a good compactable mixture begins with a grading that is more uniform and contains more material passing the No. 4 sieve than would be common in conventional concrete. Using concepts from conventional mass concrete,

TABLE 20.4 Typical Aggregate Gradations for RCC

	Earlier RCC Projects							Typical Current Practice
Sieve Size	Willow Creek	Upper Stillwater	Christian Siegrist	Zintel Canyon	Stage-coach	Concepcion	Elk Creek	
4 in.	—	—	—	—	—	100	—	—
3 in.	100	—	—	—	—	99	100	—
2.5 in.	—	—	—	100	—	—	96	100
2.0 in.	90	100	—	98	100	94	86	98–100
1.5 in.	80	95	100	91	95	90	76	92–100
1.0 in.	62		99	77	82	80	64	76–88
3/4 in.	54	66	91	70	69	72	58	65–79
1/2 in.	—	—	—	—	—	—	—	56–68
3/8 in.	42	45	60	50	52	56	51	47–59
No. 4	30	35	49	39	40	43	41	36–47
No. 8	23	26	38	25	32	33	34	28–38
No. 16	17	21	23	18	25	25	31	20–30
No. 30	13	17	14	15	15	19	21	15–23
No. 50	9	10	10	12	10	15	15	10–16
No. 100	7	2	6	11	8	9	10	7–12
No. 200	5	0	5	9	5	6	7	3–7[a]
Cement+pozzolan (lb/yd^3)	80 + 32	134 + 291	100 + 70	125 + 0	120 + 130	135	118 + 56	—
Total paste volume (%)[b]	20	21	19	21	—	21[c]	21	21–23
Workability	Poor	Excellent	Excellent	Excellent	Good	Excellent	Excellent	Excellent

[a] Adjust the maximum and minimum percent passing the No. 200 sieve on a combined gradation as follows: up 1% if the cement plus ash content of the RCC is less than 120 lb/yd^3; down 1% if the cement plus ash content of the RCC is more than 240 lb/yd^3.

[b] Total paste is all materials in the full mixture with a particle size smaller than the No. 200 sieve (see text).

[c] Total cementitious materials consists of pozzolanic cement having approximately 15% natural pozzolan.

earlier projects tended to use 3-in. maximum size aggregate (MSA), but the recent trend has been to use smaller MSA, on the order of about 1-1/2 to 2 in. This reduces segregation, improves lift-joint quality, and reduces equipment maintenance. The reduced MSA arguably can cause a minor reduction in strength, but such a reduction is minimal and not as significant as would be expected in conventional concrete.

It is inappropriate to provide a single set of upper and lower gradation limits that could be considered correct for all RCC. A wide range of gradations has been used successfully. Table 20.4 shows some example gradations that have been used in RCC. The mixture-proportioning concept that uses a low cementitious content and requires fines in the mixture ideally has a grading similar to an impervious gravel with nonplastic fines. Mixes with lower cementitious content generally require more fines. The maximum amount of fines that can be added without a reduction in strength, and without causing the RCC to become too sticky to mix, spread, and compact, depends on the plasticity of the fines. Plasticity can be defined in terms of soil mechanics by the liquid limit (LL) and plastic index (PI). Based on the LL and PI, Table 20.5 has been developed and used over the past 30 years as a guide for the maximum amount of fines that can be included for most RCC mixtures.

20.3.2 Mixture Types and Designations

Roller-compacted concrete suitable for use in dams can be made with very low cementitious contents, on the order of 85 to 150 lb/yd^3, or it can be made with very high cementitious contents, on the order of 200 to 425 lb/yd^3. Both options, plus intermediate cementitious contents, have been used quite successfully on low and high dams, both options continue to be popular, and both are expected to be used in the future (Schrader 1994, 1995c,d, 2002, 2004). The decision-making process for selecting the type of mix is not very dependent on the size or height of the dam. Unfortunately, it is often more related

TABLE 20.5 Maximum Fines Content

Liquid Limit	Plastic Index	Maximum Percent Passing No. 200 Sieve (%)
0–25	0–5	8.0
	5–10	6.5
	10–15	5.0
	15–20	3.0
	20–25	2.0
25–35	0–5	7.0
	5–10	6.0
	10–15	4.5
	15–20	3.0
	20–25	1.5
35–45	0–5	6.0
	5–10	4.0
	10–15	3.5
	15–20	2.0
	20–25	1.5
45–55	0–5	4.0
	5–10	3.0
	10–15	2.0
	15–20	1.5
	20–25	1.0

TABLE 20.6 Roller-Compacted Concrete Mixture Designations

Designation	Cement + Pozzolan (lb/yd^3)	Strength (psi)
Low	85–150	700–2100
Medium	140–210	1600–3000
High	200–425	2500–4500

to the simple issue of what the designer or owner has used in the past. The decision should be based on factual information related to foundation quality, the degree of reliable inspection expected, facing techniques, climate, cooling and thermal issues, the age at which the reservoir will be filled, and available materials with their associated costs and quality. The best overall option might be a higher strength, high-cementitious-content mix with less mass in one situation, but it could be a lower strength, low-cementitious-content mix in another situation.

Dams designed with higher cementitious content mixes may have slightly less volume but typically have a much higher unit cost and more stringent cooling and quality-control requirements. Lower cementitious content mixtures typically have lower unit costs and less stringent quality control but may require more mass. They also may require special attention to achieve watertightness along lift joints. Costs and watertightness are discussed elsewhere in this chapter. Higher cementitious content mixtures tend to result in good cement efficiencies (strength per unit of cementitious material) when compared to conventional concrete, but lower cementitious content mixtures tend to have even greater efficiencies, on the order of about 10 to 20 psi/lb of cementitious material in a cubic yard of RCC. Efficiencies on the order of 10 psi/lb are typical for excellent quality conventional concrete.

The American Concrete Institute's subcommittee on RCC has recently completed its proposed latest major update on RCC for massive structures. The new report is intended to identify low-, medium-, and high-cementitious-content mixes by a combination of cementitious content and strength ranges that are consistent with other publications. There is a deliberate overlap for the different cementitious content designations, allowing flexibility in judgment with regard to whether the aggregate fines provide some cementitious or pozzolanic value. Nonetheless, the designations, shown in Table 20.6, provide useful guidance.

TABLE 20.7 Types of RCC Mixtures: Typical Extremes

	Dry, Low Cementitious		Wet, High Cementitious	
	lb/yd³	ft³	lb/yd³	ft³
Cement	100	0.51	150	0.76
Pozzolan (ash)	0	0.00	250	1.60
Water	185	2.96	180	2.88
Air (0.5%)	0	0.14	0	0.14
Aggregate fines (8%)	280	1.80	0	0.00
Total paste	565	5.41	580	5.38
Percent paste	14%	20%	14%	20%

Note: Pozzolans and fines may or may not be cementitious in RCC.

At times, terminology has referred to RCC as being high or low *paste content* rather than having high or low *cementitious content*. This is an inaccurate description of the different types of RCC mixes (Schrader, 1994, 1995c,d, 2002, 2003a, 2004). Although RCC mixtures have high, medium, and low cementitious contents, they should not have high and low paste contents. All RCC mixtures should have at least 20% paste by volume (about 14% paste by weight), with the recent tendency being toward paste contents on the order of about 21 to 23% by volume. Paste is considered to be all of the materials that constitute the pasty portion of the mix. This includes everything smaller than 75 μm—small air bubbles, water, admixtures, pozzolans, cement, and aggregate fines.

If low-cementitious-content RCC is used, aggregate fines are necessary to supplement the otherwise deficient paste content. If a high-cementitious-content RCC is used, clean aggregates are required to keep the paste content from being too high. If the paste content is too low, low strengths, excess water demands, and segregation can be expected. If the paste content is too high, inefficient use of cementitious materials can be expected (i.e., less strength per pound of cementitious material). Mixes with too much paste can also result in lift surfaces with excess paste and laitance at the lift surface after compaction, thereby requiring lift-joint cleaning similar to that used for conventional concrete. Table 20.4 and Table 20.7 demonstrate the concept of constant paste contents for all types of RCC. They compare two extreme examples of RCC mix types and consistency. These examples are from two early RCC projects that used mixes near the extremes: (1) the very dry, lean Willow Creek Dam, and (2) a mix similar to one of the very high-cementitious-content, wet-consistency mixes at Upper Stillwater Dam.

Roller-compacted concrete mixtures can have low or high pozzolan contents. Current use ranges from 0 to about 80% pozzolan. There is no universal optimum. In some cases (such as for Stagecoach Dam), using 100% cement resulted in lower strengths than using essentially the same total cementitious content (cement plus pozzolan) but with 50% of it being pozzolan. In other more common cases, adding pozzolan while keeping the cement constant has actually caused a reduction in strength or no significant strength change. Some examples are the Burnett Dam (renamed Paradise dam) (Herweynen et al., 2004; Lopez et al., 2005), the Mujib Dam (Schrader et al., 2003a), the 358-ft high Rompepicos Dam (Schrader and Bali, 2003), and the recently completed mix studies for Dong Nai 3 Dam in Vietnam. In each case, an initial arbitrary decision had been made that a mix with high pozzolan content would be best and worth the extra cost; however, when the cost and difficulty of obtaining good-quality pozzolan were finally appreciated, tests without pozzolan were done that showed that not only was the use of pozzolan costly and unnecessarily complicated but the pozzolan also caused a reduction in strength compared to some mixes with the same cement content but no pozzolan.

The long-term strength gain of RCC is not necessarily determined by the amount of pozzolan that is used, as would normally be expected with traditional concrete. For example, a lean RCC mix at one project using only 92 lb of cement per cubic yard and no pozzolan resulted in 1-year strengths that were 380% greater than the 28-day strengths, while other mixes with pozzolan at other projects have achieved strength gains of only about 150% over the same time period. Figure 20.11 and Figure 20.12 show the global range of values that have been experienced for different pozzolans with different RCC mixtures.

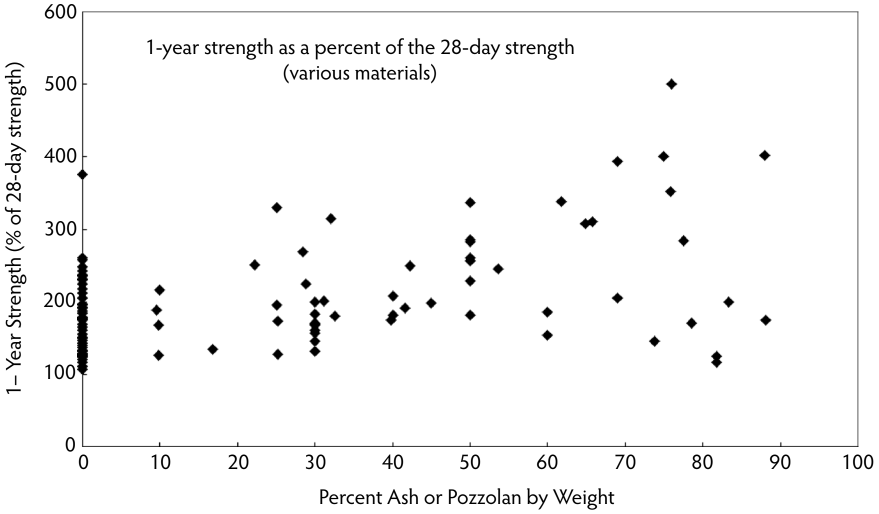


FIGURE 20.11 Efficiency of cementitious material as a function of pozzolan.

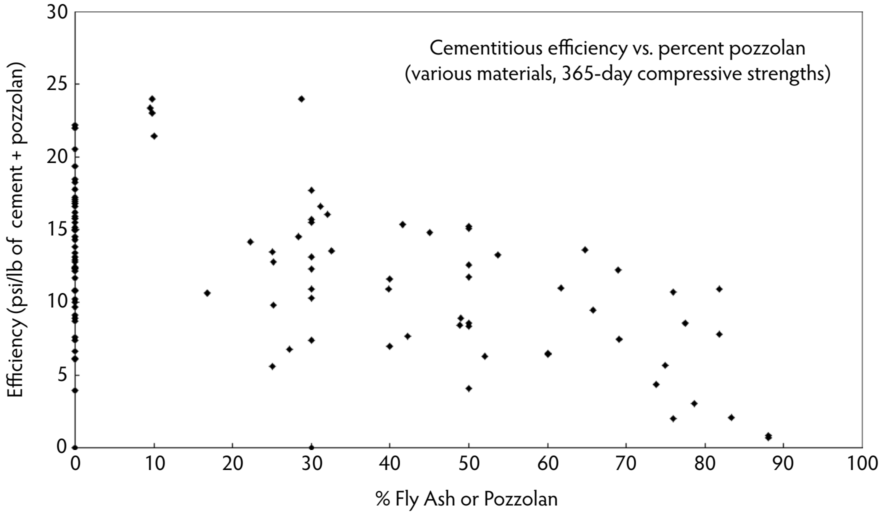


FIGURE 20.12 Long-term strength increase as a function of pozzolan.

Another observation concerning RCC is that some projects have required a minimum cementitious content of about 50 to 100 lb/yd^3 to gain good strength efficiency (strength per pound of cementitious material), whereas at other projects the efficiency has been relatively constant from 0 to about 150 pounds of cement per cubic yard of RCC. Overall, strength efficiency typically tends to decrease at high cementitious contents for the same aggregates and materials at any given project, as shown in Figure 20.13. Strength as a function of total cementitious content is shown in Figure 20.14.

The important point is that RCC does not follow the same rules and trends as conventional concrete with regard to optimum cementitious and pozzolan content. Each project should be evaluated on its own merits, with its own materials, and with a wide range of options during the initial investigations. Open mindedness on the part of decision makers is essential. They should not be misled by old traditional concrete experience or guidelines or experience with only one type of RCC.

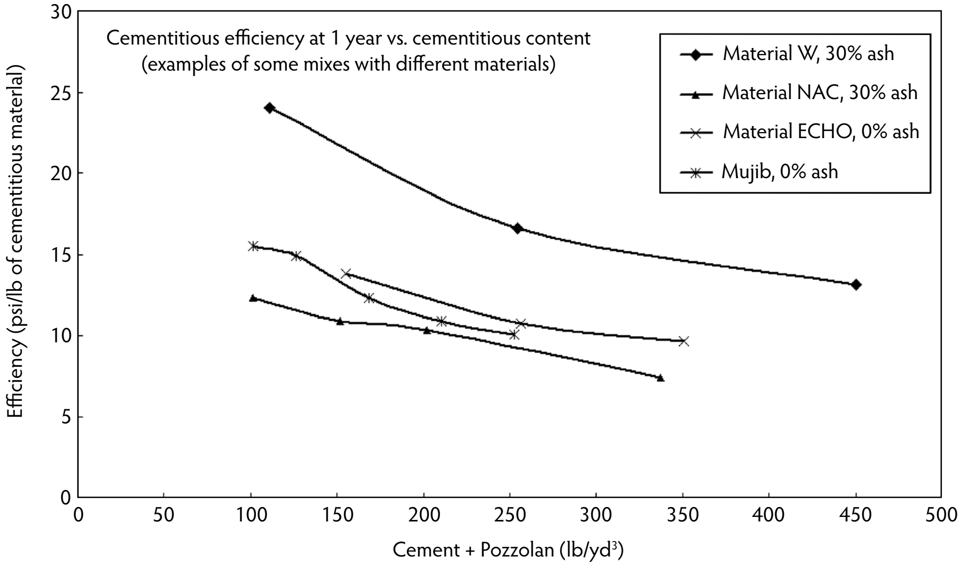


FIGURE 20.13 Reduced strength efficiency as a function of increased cementitious content.

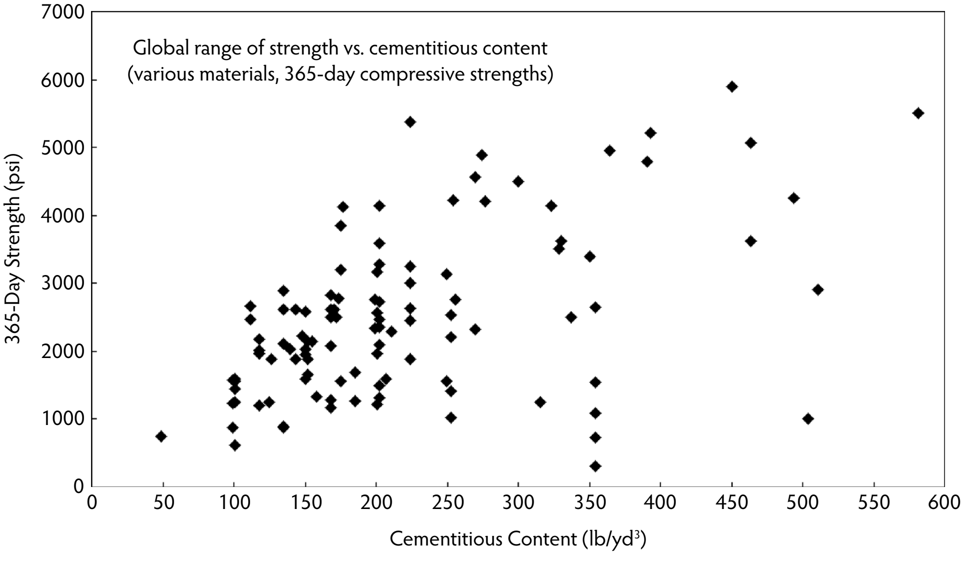


FIGURE 20.14 Example effect of moisture content.

20.3.3 Fresh Mixture Consistency

The terms *wet* and *dry mixture consistency* can be a source of confusion. RCC mixtures have no slump. They must be stiff enough to support a large vibratory roller. By traditional concrete standards, all RCC has a dry consistency; however, within the RCC community, mixtures are referred to as being wet or dry on the basis of their appearance and how they behave in the fresh state during and after compaction. Roller-compacted concrete mixtures that are considered to be wet generally produce a weaving effect or surface waviness as rollers and trucks drive across the freshly compacted RCC. This is due to an excess of moisture or the use of more water than necessary to fill all of the void space. Internal pore pressure develops in the fresh mixture, similar to what occurs in some soils. By contrast, mixtures that are considered to have a dry consistency generally do not weave under traffic after compaction. The terms

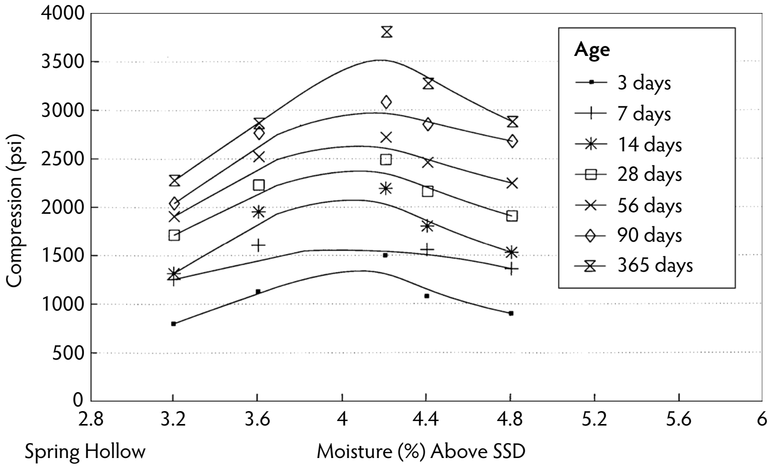


FIGURE 20.15 Example effect of moisture content.

wet and *dry* reasonably describe the behavior of the mixture, but they do not indicate whether the actual water content is high or low. Because of differences in aggregate (texture, shape, and grading) and in cements and pozzolans, the effects of fines when they are included, and the influences of temperature and humidity, a mixture with a higher water content can actually be drier in appearance than another mixture with a lower water content and *vice versa*. This is true when considering water in excess of the water absorbed by the aggregate, and it can be even more exaggerated when total water contents based on oven-dry aggregates are considered. Table 20.7 contains an example.

20.3.4 Water/Cement Ratio and Optimum Water Content

Although it is a somewhat controversial issue, the well-known water/cement ratio rule for traditional concrete does not necessarily apply to RCC. In fact, if what appears to be an excessively high water/cement ratio in a lean mix is decreased too much by simply reducing the water content, it will result in decreased strengths and poor-quality material resulting from inadequate moisture for compaction. As with embankment materials and soils, there is an optimum moisture, as shown in Figure 20.15. At this optimum, both strength and density are maximized. The shapes of the moisture vs. density and moisture vs. strength curves help establish the probable type of mix for a project. If the curve is fairly flat, adding more water will have little harmful effect on the strength of the RCC mass while improving the more important lift-joint quality. In this case, the wetter mix is desirable. If the curve drops off sharply at moisture contents above optimum, a drier-consistency mix is probably best.

For other reasons, the designer may stipulate in advance that a wet or a dry consistency mix is desired. Typically, dry-consistency mixtures are at or near optimum moisture. They typically have modified Vebe times (ASTM C 1170) in excess of 30 sec when that test is used for workability with a surcharge weight. These mixes have very little, if any, deformation under truck and tire traffic after rolling; however, the freshly compacted surface of these mixes can be damaged by truck traffic due to abrasion and turning of the tires. This damage typically can be removed by blowing with an air hose. Dry mixes typically do not have any bleeding problems and are essentially impervious to rain when they are compacted. Rain will simply collect on the surface. If there is any vehicular traffic or other surface disturbance, however, free water on the lift will begin to seriously damage the lift.

Typically, wet-consistency mixtures have modified Vebe times, on the order of about 10 to 15 sec, and they are much wetter than the optimum moisture content. Because they have more moisture than needed for maximum density, there is an excess of water within the compacted RCC. This water has no place to go, so it tends to develop a slight amount of free surface moisture at the lift surface. This can leave a pasty material and surface laitance that requires cleaning. These mixes easily weave under the roller because of

FIGURE 20.16 Surface damage caused by truck tires on wet-mix RCC.

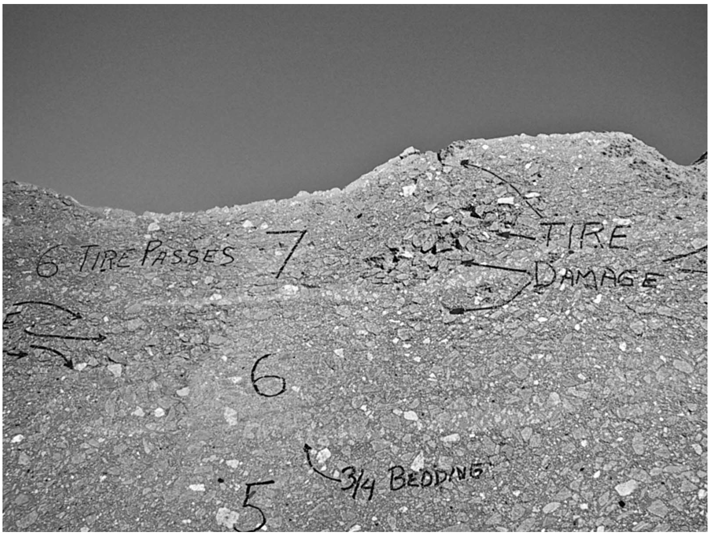


FIGURE 20.17 Interior damage caused by truck traffic on wet-mix RCC.

internal pore pressure caused by the extra water. They also weave under truck or other vehicular traffic until the mix sets sufficiently to support the traffic. A serious issue is when trucks are used to deliver the RCC and must drive across wet mixes, because for a period of time when the mix is between initial and final set when the cement is hydrating and beginning to harden it has insufficient strength to support truck traffic. The result is that the cement paste is disrupted and damaged as it deforms under tire traffic while it is trying to set. This shears and breaks the mortar matrix. The strength loss cannot be regained. The problem can be apparent at times due to cracking at the lift surface next to tire ruts, as shown in Figure 20.16. The more significant problem of internal damage to the RCC can only be seen by saw cutting into the mass afterwards to expose the internal damage as shown in Figure 20.17 (Schrader, 2002).

Because the optimum moisture for RCC is established primarily by the aggregates (there is little or no change in optimum moisture as the cementitious content is adjusted up or down), any major change in water/cement ratio can only be accomplished by increasing or decreasing the cementitious content,

TABLE 20.8 Water/Cement Ratio Examples for Dry-Consistency Roller-Compacted Concrete

Maximum Size Aggregate (in.)	Cement + Fines (lb/yd^3)	Water (% above saturated surface dry)	W/(C + F)	W/C[a]
3	80 + 32	4.4	1.63	1.47
3	175 + 00	4.5	1.06	1.06
3	175 + 80	4.5	0.73	0.65
1-1/2	315 + 135	4.8	0.44	0.39

[a] Water/equivalent cement ratio if the ash volume was cement.

as shown in Table 20.8. When nonapplicable experience from conventional concrete is used to arbitrarily apply a low water/cement ratio requirement to the RCC, the result will be higher cementitious contents with associated higher costs, increased heat and thermal stresses, and a more brittle **elastic modulus** with less stress relaxation due to creep. Attempts to change the water/cement ratio by changing the water content have only minor effects on the water/cement ratio, and such changes can alter the mix consistency and cause deviations from the optimum or desired moisture content and compactability. If the cementitious content is low, the water/cement ratio must be high. Values on the order of 1.0 to 2.0 are common in RCC. This is a major deviation from traditional water/cement ratios in conventional concrete that are more on the order of 0.4 to 0.6. This high water/cement ratio with lean RCC is normal. It does not imply low-quality concrete. It implies a low cementitious content rather than a high water content and wet mix consistency.

Data have been reported implying that a high water/cement ratio automatically causes a major reduction in RCC strength. This erroneous conclusion is the result of incompletely reporting all of the data. As the water/cement ratio decreases, strengths were shown to go up dramatically, but this was primarily because the water/cement ratio was decreased by increasing the cementitious content while keeping the water and mix consistency essentially constant. Figure 20.18 shows the complete picture, with the strength shown as both a function of water/cementitious ratio and as a function of cementitious content.

20.3.5 Approaches to Mixture Design and Proportions

Roller-compacted concrete mixture proportions should follow the convention used in traditional concrete—that is, identifying the mass of each ingredient contained in a compacted unit volume (cubic yard) of the mixture based on saturated surface dry (SSD) aggregate conditions. Moisture contents are then typically converted to a percentage of water above SSD aggregate conditions divided by the compacted

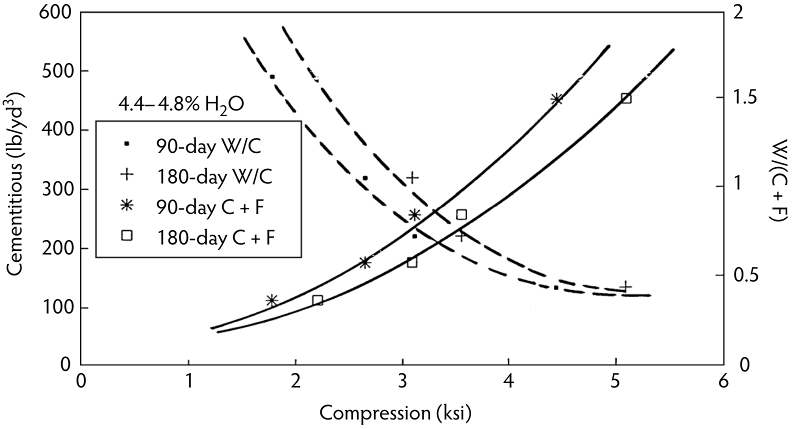


FIGURE 20.18 Strength vs. water/cementitious ratio and cementitious content.

density of the total RCC mixture. Confusion has occurred when some publications and engineers have based the water content on the oven-dry aggregate mass, as done for soils, or on some other parameter. Care should be exercised when reviewing the literature. Mixture proportioning for some earlier projects relied on making many mortar cubes with varying cement, pozzolan, water, and admixture contents in an effort to optimize the mixture without making cylinders of the full mixture. This approach can be very misleading. Experience at several projects has shown that mortar cubes do not necessarily indicate how the full RCC mixture will perform. In some cases, mortar cubes have actually indicated the opposite of what ultimately happened with the full RCC mixture (Gaekel and Schrader, 1992).

Mix designs for RCC can be approached in many ways (ACI Committee 207.5R, 1999; Herweynen et al., 2004; Lopez et al., 2003a,b; Rizzo et al 2003; Schrader, 1994, 1995d; Schrader et al., 2003b; Tatro and Hinds, 1992); see Schrader (2004) for a comprehensive summary. One procedure is based on the concept of water/cement ratio. Another procedure uses a series of lab mixtures to pinpoint the optimum cementitious and pozzolan contents for a given set of aggregates. Other procedures are basically variations of these two themes. No single approach to mix design is best for all situations. All approaches to mix designs ultimately require full-scale job trials and tests, with adjustments based on the results of those tests.

The term *soils approach* has been erroneously used by others to describe a mix-design method developed by the author. This method has nothing to do with soils, and the term is misleading. All methods of RCC mix design, including the one mislabeled as the soils approach, treat the material as a no-slump concrete. They all use a suitable controlled gradation aggregate. They all intend to optimize the amount of pozzolan (if used). They all produce a consistency suitable for RCC construction. They all determine basic concrete material properties such as density and strength.

Whichever procedure is used for mix designs, the method of making test samples must be suitable for the type of mixes that will be made. Some methods, such as the vibrating table, are suitable only for wetter and higher paste mixes, whereas the pneumatic tamper and Kango or Hilti hammer are suited to drier and lower paste mixes. Some laboratories have concluded that a drier or leaner mix is not suitable for a particular project when in reality the mixes were actually quite suitable but the lab had made the samples with the wrong equipment (Schrader, 2003b).

20.3.6 Chemical Admixtures and Grout-Enriched RCC

Chemical admixtures have not been very effective in low-cementitious-content and dry RCC mixes that do not exhibit a fluid paste when subjected to vibration under full consolidation (Gaekel and Schrader, 1992; Schrader, 1984). If enough water is added to cause a fluid paste, retarders have been useful and water reducers have worked, but this may require very high admixture dosages on the order of 3 to 12 times the normal rate. The benefit of retarders and water reducers must be balanced against the cost, the complication of an additional ingredient, and any strength reduction associated with additional water required to provide the necessary wetter paste consistency. Most wetter consistency and higher cementitious content mixes depend on both the high cementitious content and a retarded set time to achieve good lift-joint quality and impermeability for the design. In this case, when the next layer of RCC has to be placed before the previous layer sets, a wetter consistency mix with high doses of retarder and a usually high pozzolan content is usually unavoidable.

As discussed further in Section 20.4.6, field experience has shown good or tolerable resistance to most natural freeze–thaw exposure conditions of mass RCC without air entertainment, but the option of using entrained air has now been achieved with some mixtures. Again, the benefits should be balanced against the disadvantages and cost for each application. Air entraining has been difficult to accomplish with RCC on a routine and consistent basis, but it has been done in the United States using special admixtures such as synthetic air, and it has been accomplished in China (Chengqian and Chusheng, 1991).

Many efforts have been made to consistently entrain air in RCC at facings by using grout-enriched RCC (GERCC). After the mix has been spread, a fluid grout is added to the RCC, with the intent being for the grout to mix uniformly throughout the RCC and turn it into a more fluid mix with higher cementitious content. The result is a zone of material (usually against a form at the face of the dam) that

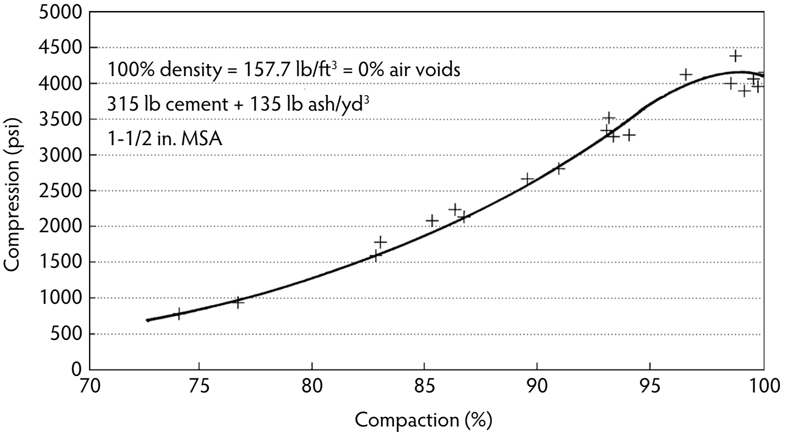


FIGURE 20.19 Twenty-eight-day strength vs. percent compaction.

will have properties and appearance similar to conventional concrete. Various procedures have been used, from simply pouring a hand-mixed grout onto the surface and using an internal poker vibrator to mix and consolidate the RCC with the grout to using sophisticated grout pumps that then inject the grout uniformly throughout the depth of the layer of RCC. Although some results have been promising by including a high dose of air entrainment in the grout, the results are more typically sporadic, with much of the air entrainment being lost by the time the mix is consolidated and sets. Tests and experience, however, have shown that the traditional amounts of air entrainment necessary for good freeze–thaw resistance are not typically required for RCC. Air entrainment is still essential, but a good-quality paste with just a few percent of entrained air has shown itself to be very effective at times (Schrader et al., 2003b).

20.4 Material Properties

20.4.1 Density and Air Content

The density and natural air void content (not entrained air) of RCC depend on the specific gravity of the aggregate, the grading, the moisture content, and the degree of compaction. Fully compacted RCC will typically have less air content and less water than conventional concrete, so its density will be slightly higher. Because RCC has been made with aggregates having a wide range of specific gravities, the specific densities of compacted RCC at different projects varies greatly from about 2.1 to 2.9. Fully compacted RCC with reasonable mixture proportions typically has an air content on the order of 0.5 to 1.5%. Specifications commonly require that field densities must obtain an average of 98% of the maximum practical achievable density (MPAD) at each test location, which is often considered to be 97% of the theoretical air-free (TAF) density, providing that no density at any level within a lift of RCC is less than about 93% of the TAF density. The average density is based on measurements taken at the top, middle, and bottom thirds of the lift. Air contents can be obtained in the laboratory using the pressure method for material compacted by tamping or by the vibrating table method, whichever is appropriate for the mixture consistency. Some of the first RCC projects required greater densities than suggested above, with the thought that densities representing 98 to 100% of the TAF would result in significant increases in strength. This is not correct. Unfortunately, some older specifications and concepts continue to be copied. As shown in Figure 20.19, it is important to achieve a reasonably well-compacted mix with a density of at least 95 to 96% of the TAF, but greater densities provide essentially no increase in strength. Excessive compactive effort can actually be harmful. Excessive compaction can cause a reduction in strength if it begins to break the aggregate particles, and, as with most gravel and sands, overcompaction of RCC can also begin to loosen the material and reduce density.

20.4.2 Coefficient of Thermal Expansion

The **coefficient of thermal expansion** of RCC tends to be slightly higher than the thermal expansion coefficient of the aggregate and slightly less than that for a conventional concrete made with the same aggregate but more cement paste. Because of the wide range of aggregate materials that can be used in RCC, the range of thermal expansion coefficients is much wider than would be expected for traditional concrete. Traditional concrete typically has an expansion coefficient somewhere between 4 and 8 millionths per degree Fahrenheit. Measured expansion coefficients for RCC have varied from about 3 to about 18 millionths per degree Fahrenheit.

20.4.3 Thermal Diffusivity and Conductivity

Thermal diffusivity and conductivity of RCC mixes tend to be similar to the values obtained for the aggregate by itself and similar to conventional mass concrete made with that aggregate.

20.4.4 Poisson's Ratio

Poisson's ratio for RCC tends be similar to values for conventional mass concrete; typical values are on the order of 0.18 to 0.24, depending on the concrete age, aggregate, and strength. At very early ages and very low strengths and for mixtures with soft aggregates or very high contents of noncementitious fines, Poisson's ratio can be much higher. Under these conditions, some RCC mixes have had Poisson's ratio values on the order of 0.3 to 0.5.

20.4.5 Autogenous Volume Change

Autogenous volume change (the increase or decrease in size with no applied load or environmental change) cannot be reliably estimated in conventional mass concrete without at least some test data. This is true of RCC also, especially for mixtures that have peculiar cement, pozzolan, and aggregate. In some cases, there has been early expansion followed by a later period of contraction, or *vice versa*. Typically, the amount of change is minimal and of little consequence, but the potential for expansion or contraction can be important to large mass structures and should be investigated for large projects and for dam projects that use unusual materials. Autogenous volume changes should be considered when determining strain and creep properties and when performing a cracking analysis of large RCC structures.

20.4.6 Freeze–Thaw Resistance

(See also Section 20.3.6.) Resistance to freezing and thawing of non-air-entrained RCC subjected to natural exposure has usually been reasonably good, even when these materials had performed badly in laboratory tests. Examples include projects such as Winchester and Willow Creek Dams, which have unformed and uncompacted downstream faces of exposed RCC with cementitious material contents for the exposed face of 175 and 255 lb/yd^3, respectively. Monksville Dam is another project with an unformed downstream face but with a cement content of only 105 lb/yd^3 (no fly ash or pozzolan). Initially it performed well in freeze–thaw exposure, but after many years it began to show areas of deterioration. Some of this was localized, and attributable to issues during construction, but overall the severe environment has had an effect. Each of these projects receives almost daily cycles of freezing and thawing during much of the winter. Monksville and Willow Creek also have saturation from lift-joint seepage. After more than 25 years, Willow Creek and Winchester have not shown any significant change in the downstream face. Other projects, such as Middle Fork, located in severe climates where temperatures can reach –40°F and that used about 1 ft of conventional concrete facing, have also shown no distress.

Based on test data and observations, the following typical deterioration rates have been developed by the author. These estimates are for cementitious material contents in the range of 85 to 250 lb/yd^3. The deterioration rate for unformed and uncompacted surfaces subjected to freeze–thaw cycles that penetrate about 1 inch is 1 inch of erosion per 100 to 250 cycles of freeze–thaw. Compacted interior RCC is estimated to deteriorate at about 1000 to 2000 cycles per inch of erosion.

As discussed in the sections on aggregates, chemical admixtures, and mix proportions, some projects have been able to achieve sufficient air entrainment to provide good freeze–thaw **durability** even in severe laboratory tests. Early RCC studies indicated that this might be possible only with high-cementitious-content mixtures with very wet consistencies; however, some lower and medium cementitious content mixtures with a relatively dry consistency have also achieved adequate air entertainment and durability using some admixtures. Synthetic air-entraining admixtures seem to offer the best promise, but traditional admixtures have also worked at times. A clear understanding of which admixture will work best is not achieved until after comprehensive testing for each RCC mix and set of materials. A recent example is the set of initial mix studies for the Tongue River project, which is exposed to temperatures ranging from about –40°F to +120°F. Another recent series of interesting tests was done for the proposed Nordlingaalda Dam in Iceland, where very good freeze–thaw resistance was achieved with a normal air-entraining admixture and medium cementitious content at a relatively low entrained-air content (Schrader et al., 2003b).

20.4.7 Cavitation and Erosion Resistance

Cavitation and erosion resistance of RCC have been surprisingly good, and a historical summary has been published (Schrader and Stefanakos, 1995). Very early evaluations of erosion resistance, including full-scale tests at velocities on the order of about 100 ft/sec, were documented by the U.S. Army Corps of Engineers (1981). Based on available data, including two high-velocity and high-head, full-scale trials for a limited duration as well as laboratory and other tests, cavitation and erosion rates have been developed and used with caution to justify exposed RCC spillway surfaces. Assuming good-quality mixtures with cementitious-material contents on the order of 170 to 300 lb/yd^3, an erosion rate of 0.002 lb per square foot of surface per hour of exposure has been extrapolated for a rolled surface and 0.05 lb per square foot of surface per hour of exposure for a rough surface. Field experience confirms that these numbers are either reasonable or conservative.

20.4.8 Compressive Strength

The compressive strength of RCC depends on a variety of factors, including the aggregate, quantity and quality of fines, quantity and quality of cementitious material, degree of compaction, and moisture content. The efficiency, or strength per pound of cement in a cubic yard of RCC, has been discussed in Section 20.3. The wide range of strengths that has been experienced with different RCC mixes having different aggregate, cements, and pozzolans was shown in Figure 20.14. Section 20.3 also included general information about the wide disparity of pozzolan (including fly ash) performance in RCC and the effect of moisture on compressive strength. The relationship between compressive strength and density or air voids content was discussed earlier in Section 20.4.1.

Care must be used when reviewing RCC literature that is based only on one set of site-specific aggregates, pozzolans, mixture proportions, moisture contents, and gradations. Publications occasionally offer misleading global statements about RCC strength when, in fact, the experience used as a basis for those statements has included only one project, one set of materials, and one type of RCC mixture. Because of the wide range of materials and mixture proportions that can be used in RCC, it is very difficult to develop global or general statements or rules about RCC strength relationships. Figure 20.11 through Figure 20.14 show examples of the wide range of strengths, different rates of strength gain, and the wide range in strength performance that can occur with RCC mixes containing fly ash or other pozzolans.

Traditional thinking would limit the amount of fines (material passing the No. 200 sieve) in the aggregate to very small amounts, based on the accepted traditional concept that clean washed aggregates with no fines are best. However, as discussed in Section 20.3, natural or manmade fines are essential in low cementitious RCC mixtures to provide adequate paste and to fill void spaces for control of segregation and for compaction. Nonplastic fines typically increase the strength of low-cementitious-content mixtures. The reasons for this are not entirely clear. In some cases, it is probable that the fines are providing

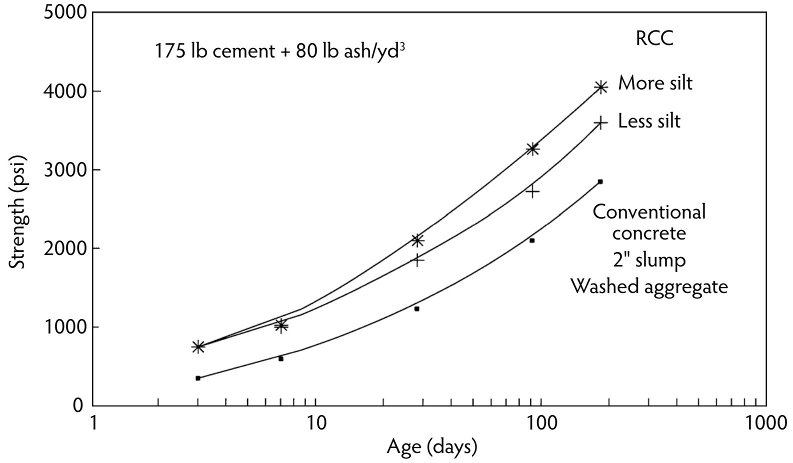


FIGURE 20.20 Effect of fines on strength (Willow Creek Dam).

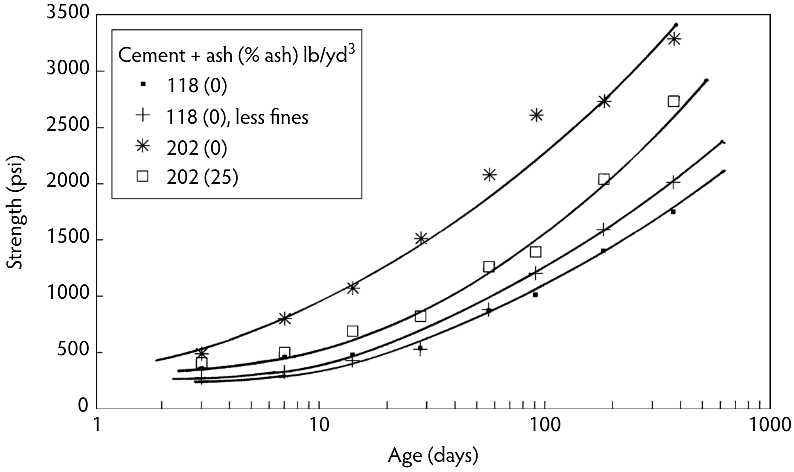


FIGURE 20.21 Effect of fines on compressive strength (Agos Dam).

some degree of pozzolanic strength gain, but it also appears that mechanical benefit is also being provided. Because the fines have substantial surface area and they are used primarily in low cementitious content mixes, the traditional thought that sufficient cementitious material is needed to coat all of the aggregate surfaces obviously does not apply to RCC.

Figure 20.20 shows a case where the addition of fines caused an increase in strength in a medium cementitious content mix. In this situation, the optimum fines content was about 5 to 6%. A slight increase in fines to about 8% resulted in minimal additional strength. At even higher fines contents, the strength could be expected to decrease. The fines were a natural silt with very little plasticity. Figure 20.20 also shows much lower strengths at every age when the aggregate was washed to eliminate all fines, screened to an ideal traditional gradation, and used to make low-slump conventional concrete. Additionally, it shows the strength achieved when the dirty RCC aggregate was washed and sorted to an ideal conventional aggregate gradation. The mix made with this gradation was an excellent quality 2-in. slump mix with a water-reducing admixture. At all ages, the strength of the conventional concrete was substantially less than the RCC concrete made with the same basic aggregate without the expensive washing.

Figure 20.21 shows another project demonstrating nontypical behavior where an increased fines content of a low cementitious content mix caused a slight reduction in strength. The only way this was

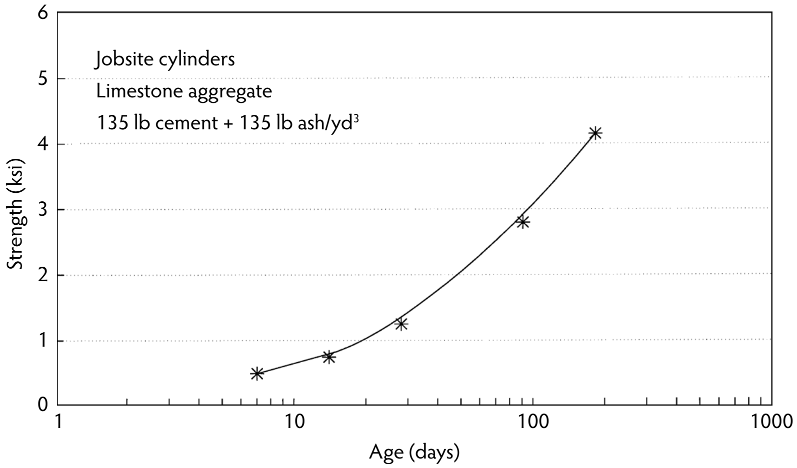


FIGURE 20.22 Compressive strengths (Salt Lick Dam). (Data courtesy of Gannett Fleming Engineers, Harrisburg, PA.)

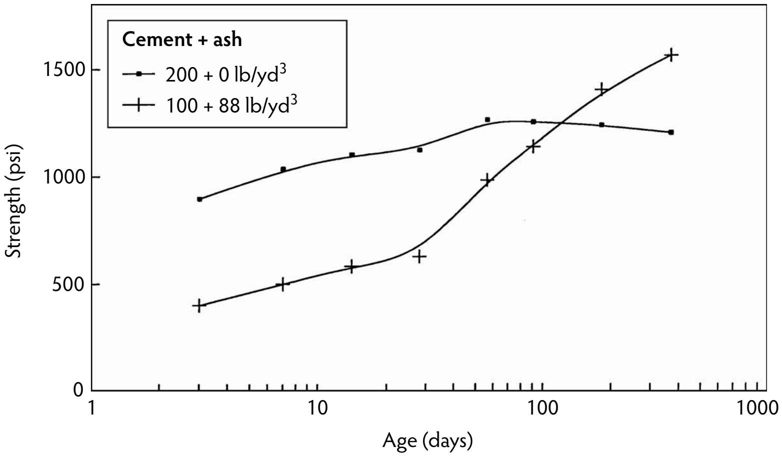


FIGURE 20.23 Strength vs. time (Stagecoach Dam).

detected was by tests. In this case, the fines were siliceous and expected to add substantially to, rather than decrease, the strength. Figure 20.22 shows very good strength gain for a mixture that was used in an application where durability and traditional strength levels of about 4000 psi were important. This was achieved with only 270 lb of cement per cubic yard (135 lb of cement and 135 lb of fly ash). The aggregate was limestone, including the beneficial rock dust which, in the case of limestone, was expected to react somewhat with the siliceous fly ash. Figure 20.23 shows the benefit of fly ash in a low-strength mass RCC made with lower quality aggregates at Stagecoach Dam. In this case, evaluation of the comparative mixtures at ages up to 28 days indicated that fly ash was not beneficial; however, after 28 days the ash performed extremely well, ultimately achieving a strength greater than the mix made with cementitious material that was 100% Portland cement with no ash. In this case, the aggregates were lower quality and the efficiency of the cementitious material was relatively low by RCC standards.

Although Figure 20.22 and Figure 20.23 suggest that fly ash is very beneficial in RCC and can even be better than adding more Portland cement, this is not always the case. Figure 20.21 and Figure 20.24 show mixtures where adding fly ash increased the cost and complexity of the mix while doing essentially nothing for strength. Figure 20.21 shows that when a mix with 202 lb of cement per cubic yard used fly ash for 25% of the cementitious material the strength was reduced by about 25% at all ages, including

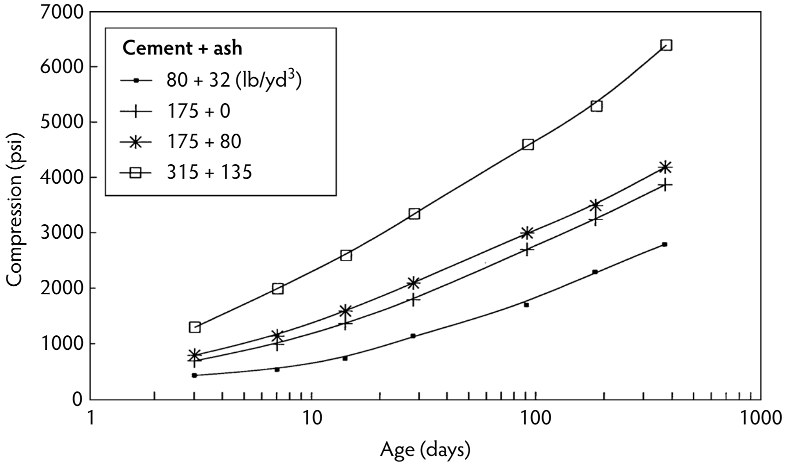


FIGURE 20.24 Strength vs. time (Willow Creek Dam).

the long-term ages up to 1 year. Figure 20.24 indicates that a mix with 175 lb of cement per cubic yard had no significant change in strength when 80 lb of ash per cubic yard was added. In this case, adding silty fines to the mix was found to have the same or better effect as adding fly ash. Figure 20.22 and Figure 20.24 show RCC mixes that achieved relatively high strengths on the order of 4000 and 6000 psi, respectively. This is comparable to very good quality traditional concrete, but the strength was achieved with cementitious contents that are about half that used in traditional concrete. Figure 20.20 through Figure 20.24 represent a wide variety of RCC mixtures, with different aggregate types and gradations, different cementitious and fly ash contents, and different maximum aggregate sizes. In all the examples, the individual data points have been plotted to show that, although the strength gain trends can be different from mix to mix, the strength gain trend for any given RCC mix plots vary predictably with an incredibly small amount of data dispersion. RCC is a reliable engineering material with predictable and dependable properties once a mix design program has been undertaken.

Figure 20.20 through Figure 20.24 plot strength vs. time. Another very useful way to present the data is by plotting strength vs. cementitious content, with different lines representing different ages, as shown in Figure 20.25. From the family of curves shown, the required cementitious content can then be selected

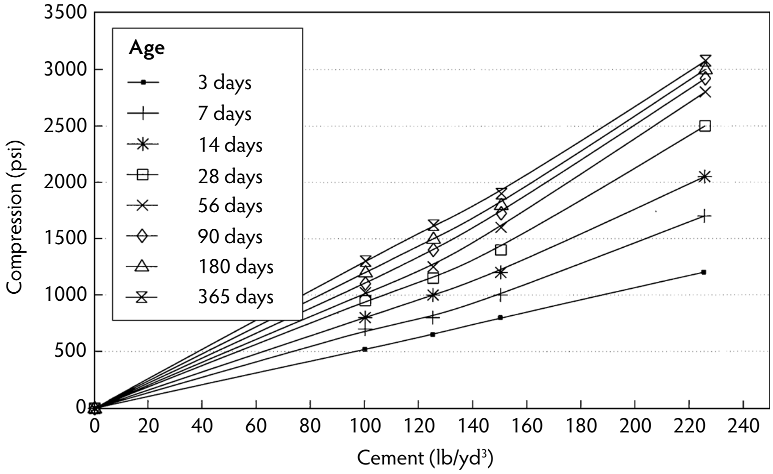


FIGURE 20.25 Compression vs. cement content.

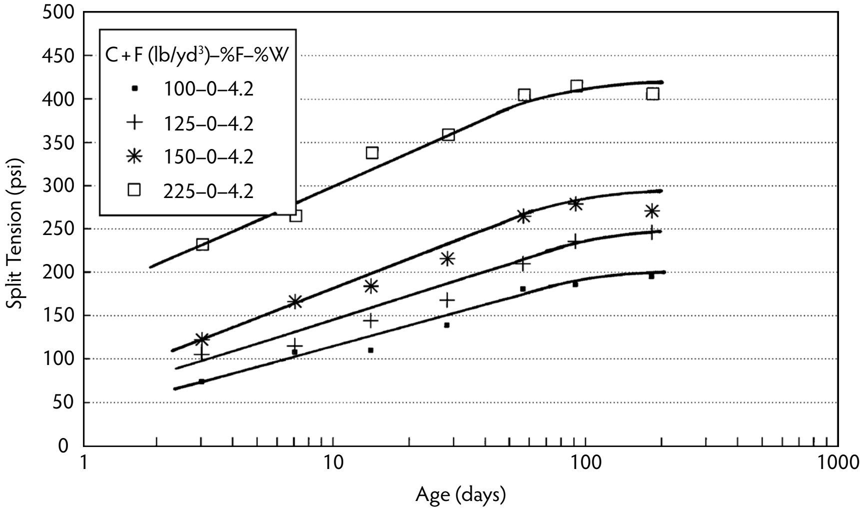


FIGURE 20.26 Split tension vs. time for different cement contents (Big Haynes).

to achieve any strength at any age. The shape of these curves is of particular interest. Figure 20.25 shows a generally linear relationship between strength and cementitious content from 0 to 230 lb of cement per cubic yard; however, other RCC mixes have shown no significant strength gain beyond a certain cementitious content. In other cases, no significant strength was achieved until some minimal amount of cementitious material was used.

The strength data and charts are for projects that range from the start of RCC dams 30 years ago to projects just now being built. Throughout the history of RCC to the present, some projects simply have not benefited from using pozzolan but others have. By relying on an all-encompassing, open-minded approach to mix design studies on both high and low cementitious contents with both high and low pozzolan contents, a project manager can properly evaluate whether or not it is advisable to use pozzolan and how much to use (Schrader, 2004).

20.4.9 Tensile Strength

As with compressive strength, the tensile strength of RCC can vary greatly from mixture to mixture. Cementitious material content is a principal influencing factor, but moisture content and aggregates are also important. Higher cementitious material contents, lower moisture, and crushed coarse aggregates tend to increase tensile strength; however, the tensile *strain* capacity, discussed below, may be more important than the tensile *strength*. A highly deformable mixture with a low elastic modulus can be more desirable than a stronger mixture that is much more brittle and cracks earlier under the same amount of deformation.

The Brazilian split-cylinder test (ASTM C 496) is a simple and economical indirect method of obtaining an indication of the direct tensile strength of concrete. It is frequently used for RCC, but care must be taken when deriving the probable direct tensile strength from indirect split-tension results. This applies to traditional concrete as well, but it is more important for RCC where the relationship of direct to indirect strength can vary from project to project as well as within the range of compressive strengths that might be considered for a particular project. Figure 20.26 and Figure 20.27 show examples of the development of split tensile strength with time for a crushed gneiss aggregate with and without fly ash. The mix designations used in the figures indicate the total amount of cement plus fly ash (in pounds per cubic yard), followed by the percentage of cementitious material that is fly ash, followed by the moisture content as a percentage of the full mix.

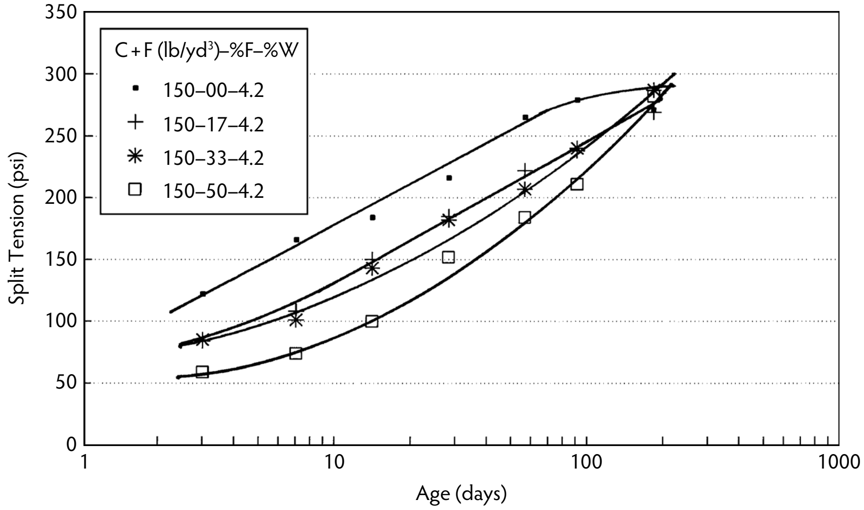


FIGURE 20.27 Split tension vs. percent fly ash (Big Haynes).

The split tensile strength of RCC mixtures with higher cementitious material contents and higher compressive strengths is typically a lower percentage of the compressive strength than what occurs with low-strength mixtures. Some examples of the ratio of split tension to compression strength for various mixes and tests at different projects are 4 to 7% for Upper Stillwater, 7 to 12% for Willow Creek, 9 to 13% for Monksville, 10 to 18%, 13% for Burnett (Paradise), 10 to 18% for Urugua-I, 12 to 17% for Concepcion, 14 to 15% for Mujib, and 13 to 19% for Middle Fork. These have been listed in order from the highest to lowest average strength.

When converting split tensile strengths to direct tensile strengths, a factor should be taken into account based on the compressive strength. Figure 20.28 shows this factor as a function of the logarithm of the compressive strength (Schrader, 1995b). The factor is almost the same when converting from flexural strengths of beams to direct tensile strength and when converting from split tensile strengths to direct tensile strengths. The factor has recently been updated with additional test data (Schrader et al., 2003a). The factor for a particular compressive strength is multiplied by the split-cylinder strength to obtain the derived direct tensile strength.

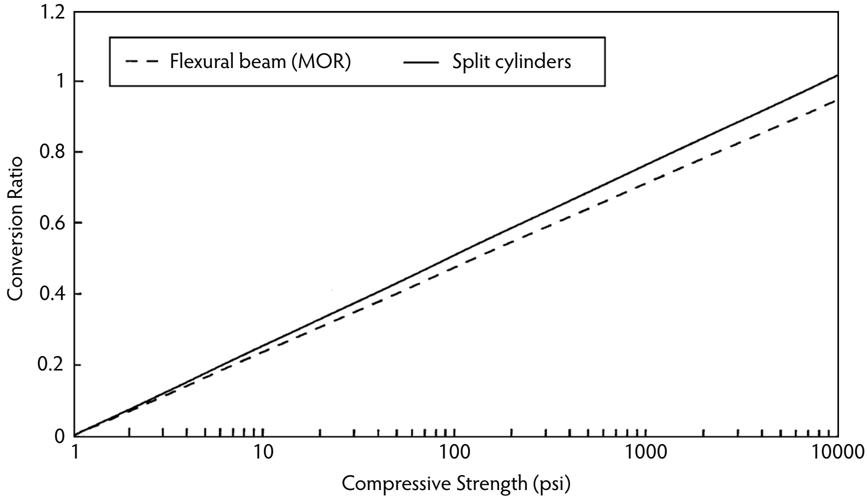


FIGURE 20.28 Tensile strength conversion.

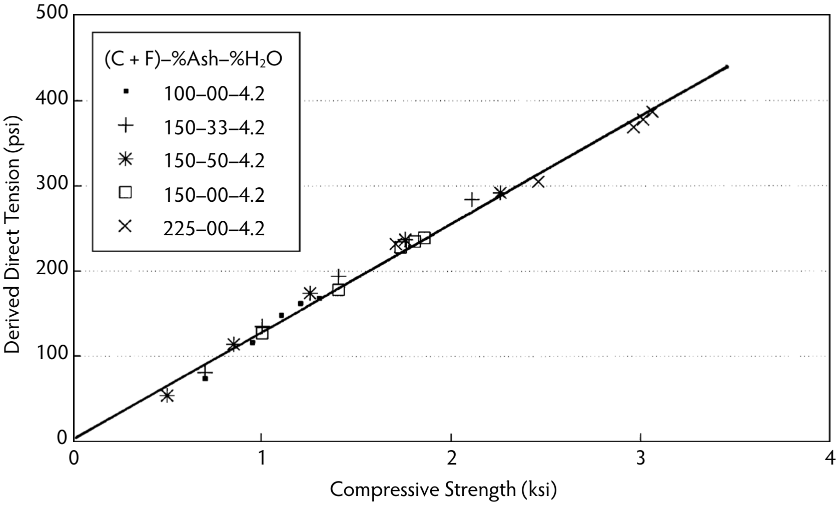


FIGURE 20.29 Derived direct tension vs. compression (Big Haynes).

For metric units in mega-pascals, the updated conversion is:

Direct tensile strength = [0.3 log(10 × compressive strength)] × (split tensile strength)

For units in PSI the updated conversion is:

Direct tensile strength = [0.2 log(compressive strength)] × (split tensile strength)

When all of the adjusting factors are taken into consideration, the final ratio of direct tensile strength to compressive strength typically is nearly a direct linear relationship, as indicated in Figure 20.29.

20.4.10 Modulus of Elasticity

The modulus of elasticity and creep for RCC can have an extraordinary range of values. Mixtures with large amounts of cementitious materials and mixtures made by the water/cementitious materials ratio approach to mixture proportioning usually produce long-term values for the static and sustained elastic modulus and creep similar to conventional mass concrete—namely, modulus values on the order of 3 to 4 million psi and creep values on the order 0.02 to 0.05 ln (time) for loading ages of about 28 to 90 days. Mixtures made with very high pozzolan contents can usually be expected to have lower early-age values of static modulus but higher later-age values.

Low-cementitious-content mixtures can have very low elastic modulus values and high creep rates. The decrease in modulus and increase in creep tends to be exponentially proportional to decreases in strength below about 1500 psi. Each incremental decrease in cement content has much more effect than the previous incremental decrease, but each mixture and aggregate can perform differently. Static modulus values on the order of 0.1 to 1.5 million psi are reasonable for cementitious material contents on the order of 100 to 125 lb/yd^3 at ages of 3 to 90 days. Corresponding ultimate values could be on the order of 0.8 to 2.5 million psi. At Burton Gorge Dam, ultimate elastic moduli were on the order of only 0.15 to 0.30 million psi. This was a quality designed into the mixture. It is attributed mostly to the gradation and use of what might normally be considered lower quality aggregates. A deformable concrete was desired to avoid thermal stress and because the foundation condition had a low and varying mass modulus that could not be accurately predefined. Figure 20.30 shows the typical range of the modulus of elasticity for traditional concrete and extreme values that have occurred with RCC. Although it is an extreme example, it is important to note the substantial increase of modulus (increased stiffness) at later ages for the Agos mix studies. This is attributed to the pozzolanic activity of the added fly ash, plus some

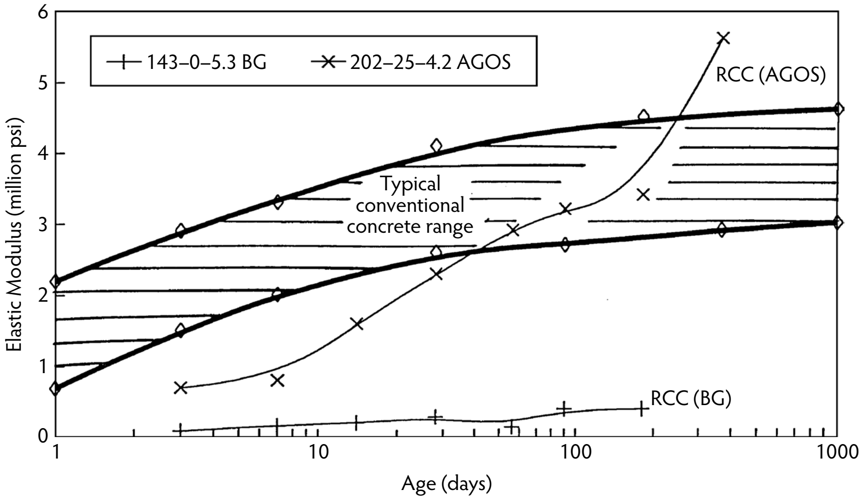


FIGURE 20.30 Modulus of elasticity, typical range.

suspected pozzolanic activity from the natural fines. In this case, a similar increase in strength did not develop; that is, the stiffness increased substantially with time while strength increased at a slower rate. The same occurred for some mixes at the La Miel I project. In both cases, the addition of fly ash caused no noticeable strength gain, although it did cause the RCC to become much more brittle; consequently, the mix in these cases was more susceptible to cracking due to pozzolans.

Figure 20.31 shows the derivation of a new and useful value referred to as the **ultimate modulus**, which is the slope of the secant drawn from the origin to the average peak compressive strength of companion cylinders at failure (Schrader, 1995b; Schrader and Rashed, 2002). It is clear in this typical example that it takes much more deformation and substantial energy to cause the lower strength RCC mixture to fail compared to the higher strength mixture. The mixes were made with identical aggregates and moisture contents and the same source of cement. The only difference was the increased cement content from 100 lb/yd^3 to 225 lb/yd^3. A lower ultimate modulus is associated with more deformation before cracking.

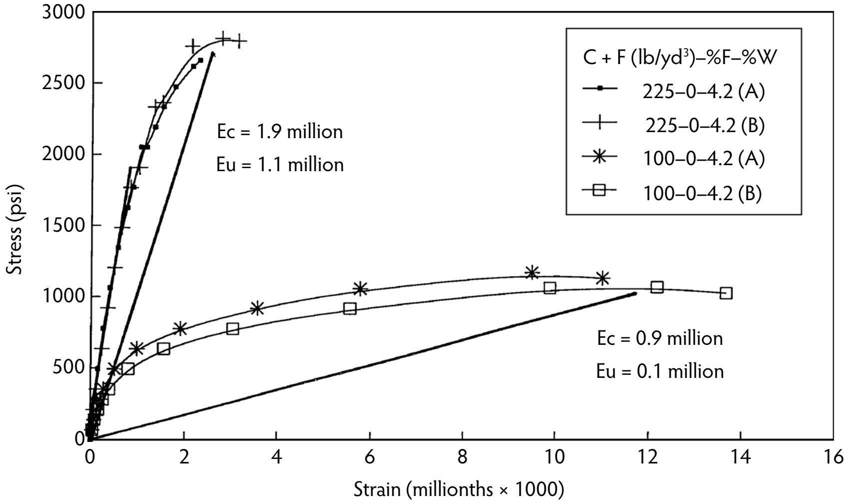


FIGURE 20.31 Modulus of elasticity, elastic and ultimate.

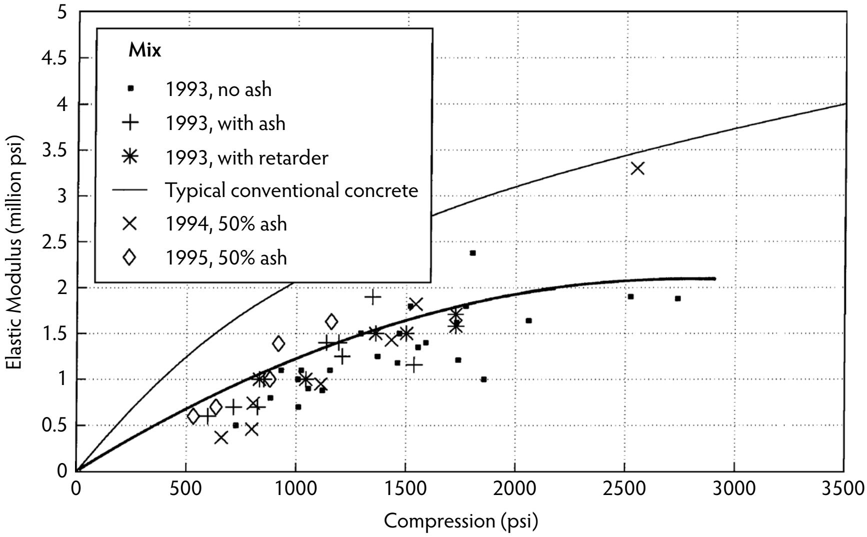


FIGURE 20.32 Elastic modulus at 25% of ultimate load vs. compression.

This is highly desired in a mass structure but may be a detriment in more traditional structures such as bridges. In a cracking analysis of mass concrete, it is the ultimate condition that is critical and that should be studied, not just the elastic condition. As the mix becomes stronger, the elastic and ultimate modulus come closer to the same value, so it is not as important with higher strength mixtures. With lower strength mixtures that are typical of mass placements, using the elastic modulus alone in the cracking analysis can be an extraordinarily conservative approach. The ultimate modulus in compression is a reasonable indicator of the ultimate modulus in tension (Schrader and Rashed, 2002). Figure 20.32 shows the relationship between elastic modulus and compressive strength for a typical RCC mixture with reasonable quality aggregates and about 5% fines. Figure 20.33 shows the relationship between ultimate modulus and compression for the same RCC.

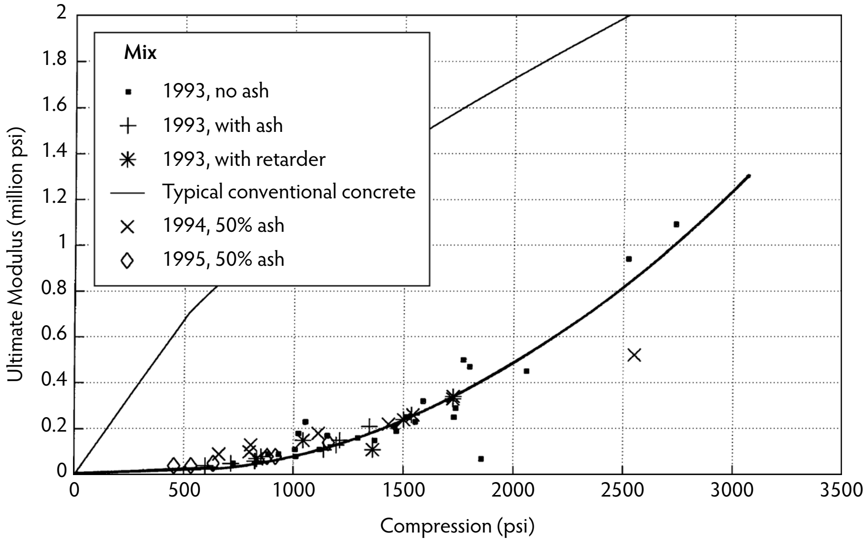


FIGURE 20.33 Ultimate modulus at 100% of ultimate load vs. compression.

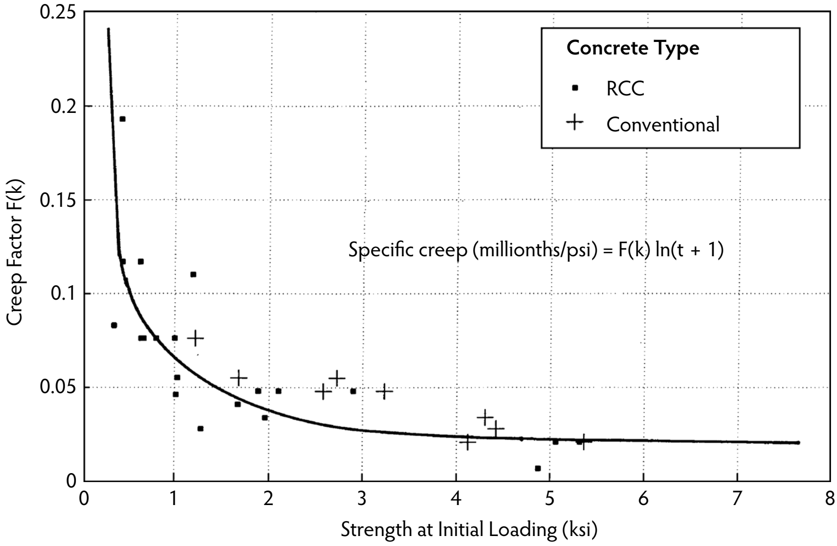


FIGURE 20.34 Specific creep.

20.4.11 Creep

Creep can be thought of in two ways. First, it is the increase in deflection or strain over time due to a sustained load. Second, it is the relaxation of stress over time while maintaining constant deformation or strain. A very high creep rate with associated dramatic reductions in stress over time is possible with low-cementitious-content RCC mixtures. When combined with the initial elastic modulus, creep reduces the **sustained modulus** that is effective over a long time period, thereby improving the crack resistance of massive placements subjected to thermal stresses (Tatro and Schrader, 1992). Figure 20.34 shows the relationship between strength at the time of initial loading and creep. The amount of creep over a selected period of time is the creep factor $F(k)$ multiplied by the natural log of the age in days plus 1 day.

20.4.12 Tensile-Strain Capacity and Toughness

Tensile-strain capacity is related to the modulus of elasticity and tensile strength. Fast-load strain capacities (maximum deformability without apparent cracking) are obtained when the load is applied over a time span of seconds or minutes. However, in dams and other massive structures, the primary concern is for slow-load strain capacity, where the strain due to external forces and internal thermal cooling develops over a long period of time. Because of creep, a dam can usually undergo more deformation without cracking if it is slowly stretched vs. when it is suddenly deformed; therefore, mixtures, with a low elastic modulus during the period of loading and a high creep rate, such as occurs with low-cementitious-material-content RCC mixtures, can have good slow-load strain properties despite low strengths.

Typical slow-load strain capacities for RCC dam mixtures are on the order of about 90 to 150 microstrain (in./in. $\times 10^{-6}$), but values outside of this range are possible. Each mixture should be evaluated, if not by direct slow-load strain capacity tests then indirectly by extrapolation from static modulus of elasticity and creep studies that can be combined to get a sustained modulus value. The tensile strength divided by the sustained modulus will provide a dependable estimate of the slow-load strain capacity over the period of time in question (Ditchy and Schrader, 1988; Tatro and Schrader, 1992; USACE, 1997). The problem with extrapolation is that it assumes that the creep rate in tension will be similar to compression (as tested). This can be conservative, especially for mixtures that contain a relatively large amount of coarse aggregate. Aggregate-to-aggregate contact can decrease creep in compression.

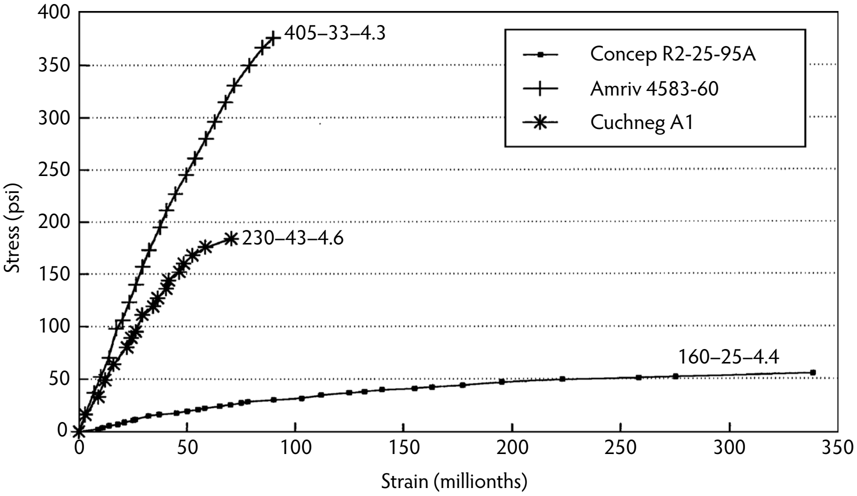


FIGURE 20.35 Tensile-strain capacity and RCC examples.

Because of the low modulus associated with RCC mixtures having lower strength and lower cementitious contents, decreasing rather than increasing the cementitious content and strength of a mixture can actually increase rather than decrease the tensile-strain capacity. This occurs when a decrease in cementitious content results in a greater decrease in modulus than the associated decrease in tensile strength. The ultimate example is the mix that has no cementitious content and insufficient stiffness to define a crack. Obviously, this would also result in an RCC with virtually no strength. Adequate cementitious material is necessary to resist the applied loads, but additional strength does not necessarily mean more crack resistance. Additional strength could result in more cracking. Figure 20.35 is an example of tensile-strain capacity and the tensile modulus of elasticity for mixes with different strengths. The mix numbers next to each tensile stress–strain curve represent the mixture that was used; the first number is the cementitious content, the second number is the percentage of fly ash or pozzolan, and the third number is the moisture content of the fresh mix. In this case, the mix with a cementitious content of 405 lb/yd^3 (with 33% of that being fly ash) had a tensile-strain capacity of about 90 millionths of an inch per inch of length. The mix with only 160 lb/yd^3 of cementitious material also used a very poor-quality aggregate. Its tensile strength was a low 55 psi, but its tensile-strain capacity was very high at about 340 millionths. The structure built with this mix, Concepcion Dam, has been in service for over 8 years with no cracking or distress. Because of the strain capacity of the mix, it was constructed with no cooling to control thermal stresses and contraction.

A very important consideration with lower-strength RCC mixtures is their demonstrated tensile toughness. This is related to ultimate tensile-strain capacity. Substantial toughness is not apparent in higher strength RCC or most conventional concrete. The indication of substantial toughness in lower strength mixtures is a relatively new discovery being demonstrated with time, experience, and assemblage of data. Such toughness can contribute to considerable benefits in dam performance and should be considered as an influencing factor in new dam designs and analyses. Eventually, it may lead to more efficient and economical dams that consider fracture toughness in the design. Toughness can be thought of as the ability to absorb energy. Another way to consider it is as a material property that results in the need for substantial energy to be added to cause the concrete to fail after it has been stressed beyond its elastic range.

20.4.13 Adiabatic Temperature Rise

Major decisions concerning schedule, cost, construction controls, and cracking potential are based on the expected adiabatic temperature rise of the RCC. This should be determined by careful testing using large samples and an experienced laboratory for any large or critical project. Determinations of adiabatic temperature rise based on calculations from the **heat of hydration** of the cementitious materials and the properties of the aggregates have been reasonably accurate for some RCC mixes and quite inaccurate for others. There does not appear to be any good indicator of when they will be reliable. The only way to ensure the proper knowledge of potential peak temperatures as well as the rate of temperature rise for RCC is by proper testing of the full mixture with large samples that have a volume on the order of about 10 ft^3. Companion tests of the heat of hydration of the cement by itself and the heat of hydration of the cement with pozzolan (if used) are useful for later reference.

A review of adiabatic rise for various RCC projects, typically using Type II moderate-heat cement, shows ranges (in degrees Fahrenheit rise per pound of cementitious material in each cubic yard of RCC) of 0.0 to 0.10°F at 1 day, 0.09 to 0.18°F at 7 day, and 0.13 to 0.21°F at 28 day. The adiabatic rise for RCC mixtures, especially those with large proportions of fly ash should also be determined through later ages of 56 to 90 days or more. The assumption that RCC, and other mass concrete, does not produce heat past an age of 7 or 28 days is simply not correct. Exothermic chemical reactions from hydration continue long term, even through one year. The rate of heat generation decreases with time, but it is still there. Also, the thought that fly ash does not produce heat simply is not correct. Depending on its chemistry and reaction with the cement and aggregate fines, this may be a very small amount of heat, or it may be substantial. Proper detailed tests with site-specific materials are necessary to accurately establish just how much heat is produced and when it is produced. Mixtures with lower cement contents tend to produce higher temperature rises per unit of cement. This is even more evident if pozzolan is included.

20.4.14 Thermal Stress Coefficients

Thermal stress coefficients establish how much internal tensile stress will develop in a given mixture for each degree of temperature drop over a specified period of time, assuming the RCC is restrained. RCC can have a broad range of values depending on the mixture proportions and aggregate. It is influenced by creep, coefficient of thermal expansion, and the elastic modulus. Stronger mixtures typically have much higher stress coefficients. For a time period of 28 to 365 days, typical values for low-strength mixtures (800 to 1800 psi) with low cementitious material contents are on the order of 4 to 6 psi/°F. Higher strength mixtures (2000 to 4000 psi) have stress coefficients on the order of 8 to 14 psi/°F.

20.4.15 Shear Strength and Lift-Joint Quality

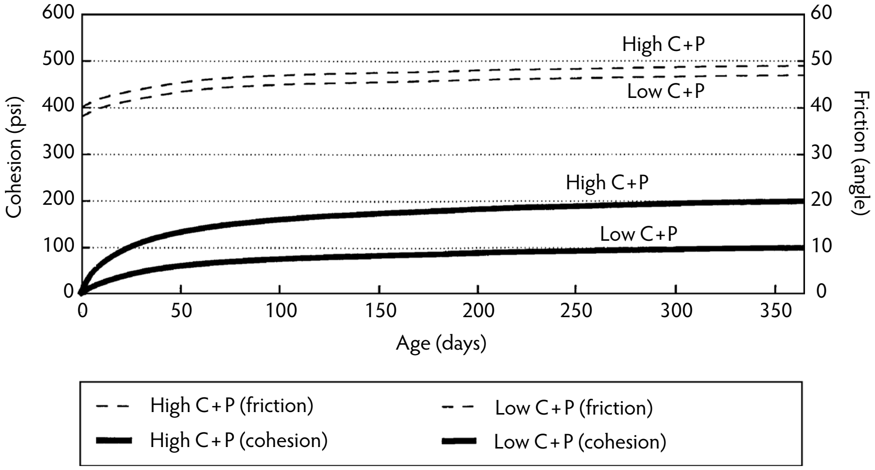
The shear strength of an unjointed RCC mass, of RCC containing joints with strengths similar to the mass and of RCC with the principal load normal to the joints will generally be 10 to 20% of the compressive strength for strengths in excess of 2500 psi, about 15 to 25% for strengths on the order of 2000 psi, and about 25 to 30% for strengths on the order of 1000 psi. Lift joints, or the layer-to-layer interfaces, are the weakest part of RCC structures. Special treatments such as a bedding or mortar mix or high cementitious content mixtures can improve this problem considerably, but these techniques are expensive and time consuming. Lift-joint quality as it relates to shear strength is elaborated below; lift-joint quality as it relates to watertightness is discussed in Section 20.4.16.

The strength of RCC lift joints is primarily dependent on the consistency of the fresh mixture, aggregate characteristics, degree of compaction at the lift surface, cementitious-material content, maturity of the lift surface when it is covered with the next lift, effectiveness of retarding admixtures, condition of the lift surface, and lift-surface treatments. A detailed procedure for assessing lift-joint quality in the field, taking into account the many factors that affect the probable lift-joint strength, has been developed (Schrader, 1995c,d, 1999a). On the basis of clearly defined criteria, the procedure establishes a numerical value (plus or minus) for each of the following factors that influence the *in situ* shear strength: surface segregation, rain, cure, maturity, surface tightness and condition, surface flatness, method of RCC delivery, and miscellaneous factors. The sum of the numerical points assigned in each category is referred to as the **lift-joint quality index** (LJQI). The basis of design corresponds to a LJQI of 0.0. Any positive value implies a slight improvement in quality above the basis of design. A negative value indicates a quality less than the basis of design. A graph provided with the procedure indicates the percentage of the design values for **cohesion** and the percentage of the design value for friction that is associated with various values for the LJQI (Schrader, 1995c,d, Schrader 1999a). As a matter of inspection and field control, the contractor may be penalized for slightly negative but tolerable LJQI work, with a cut-off point at about –4, below which the structure would not perform acceptably and the work is not accepted.

A wide range of possible RCC joint strengths exists, depending on the mix and the above variables, with extremes ranging from about 0 to 400 psi for cohesion and 30 to 60° for friction angles; for example, one early summary of strengths for 35 tests that included 5 projects, 10 mixtures, 8 joint conditions, and 5 aggregate types demonstrated an average cohesion of 155 psi and a friction angle of 50° (Schrader, 1986). Each project should be carefully examined and preferably tested to determine the shear capacity of its joints. Well-proportioned, dry, low-cementitious-content mixtures with reasonable aggregates and construction controls can be expected to produce friction angles on the order of 45°, with cohesion values on the order of 40 to 110 psi. High cementitious content wetter mixtures typically have similar or slightly lower friction angles and cohesion values that may range from about 110 to 300 psi. The reduction of friction with increasing cementitious contents is usually minimal, but it tends to routinely occur when tested. The residual friction after sliding also seems to decrease for higher cementitious content mixes (Schrader, 1995c,d, 1999a, 2003d). The reason appears to be that the fine paste has less friction than the aggregate that it is replacing.

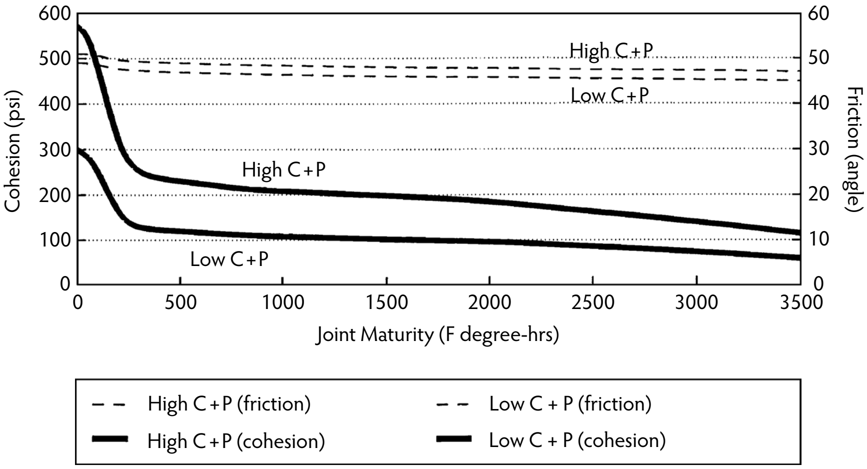
Substantial testing of lift joints reported for a variety of projects provides useful data for those specific mixtures and conditions (ACI Committee 207.5R, 1999; Boggs and Richardson, 1985; Cannon, 1985; Dolen and Tayabji, 1988; Dunstan, 1981; Gaekel and Schrader, 1992; Hansen and Reinhardt, 1991; McLean and Pierce, 1988; Oberholtzer et al., 1988; Schrader, 1982a,b, 1984, 1986, 1994, 1995b,c,d, 1999a, 2003d; Schrader and Rizzo, 2003; Tayabji and Okamotto, 1987). The most comprehensive series of tests on full-scale samples, with emphasis on shear resistance of cracked or debonded lift joints and residual strength after sliding, was done for the Saluda Dam (Schrader and Rizzo, 2003). Care must be exercised not to use one publication or one set of results that is based on one set of conditions at one project as an absolute basis for what will occur at another project. A general idea can be developed based on a compilation of information from other projects and a knowledge of the mixture and materials proposed for a new project, but absolute values should come from testing the specific mixture and conditions in question.

Every job may have its own peculiarities, but generalized observations typical of most RCC follow: Shear strength increases with age. A wetter consistency at the same cementitious material content can slightly decrease the cohesion. Higher cementitious content mixtures achieve higher potential cohesion, but the friction is essentially unaffected. Lift-joint exposure maturity (exposure time × surface temperature) is a major influencing factor in lift-joint quality or strength. Figure 20.36 shows the general trend



Typical trends (approximately 25% ash)
Not retarded, Type I joint

FIGURE 20.36 Friction or cohesion, effect of age.



Typical trends (approximately 25% ash)
No retarder

FIGURE 20.37 Friction or cohesion, effect of joint maturity.

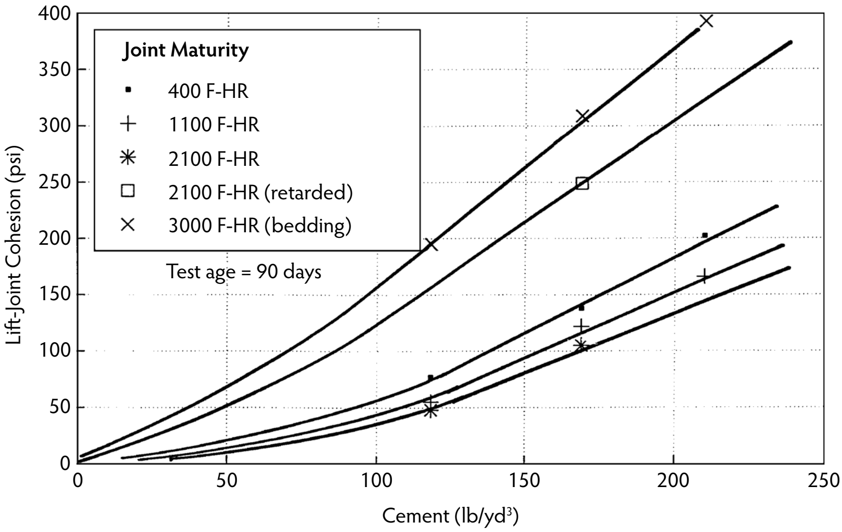


FIGURE 20.38 Miel I lift-joint cohesion vs. cement.

or effect of age on cohesion and friction for mixes with both high and low contents of cement plus pozzolan. Figure 20.37 shows the general trend for lift-joint maturity on cohesion and friction for mixes with both high and low cement and pozzolan content. These figures are intended to show typical or general trends; they should not be used as a basis for design without further consideration for the peculiarities of the RCC specific to each project.

Figure 20.38 is an example of site-specific tests for the Miel I project. The effect of cement content, maturity, admixture, and bedding mix on cohesion is clearly defined for these materials. The mix used only cement, with no fly ash or pozzolan, but it did contain approximately 6% aggregate fines. The bedding mix consisted of a 3/4-in.-thick layer of high-slump traditional concrete with about 45% sand and a high cement content. It was spread just prior to placing the RCC, and the RCC was then compacted over the bedding. Figure 20.39 shows that the friction angle is essentially independent of

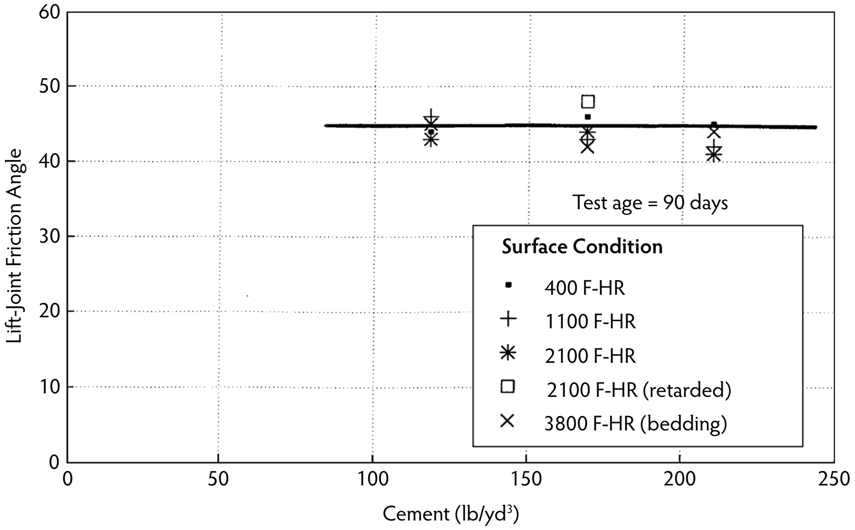


FIGURE 20.39 Miel I lift-joint friction vs. cement.

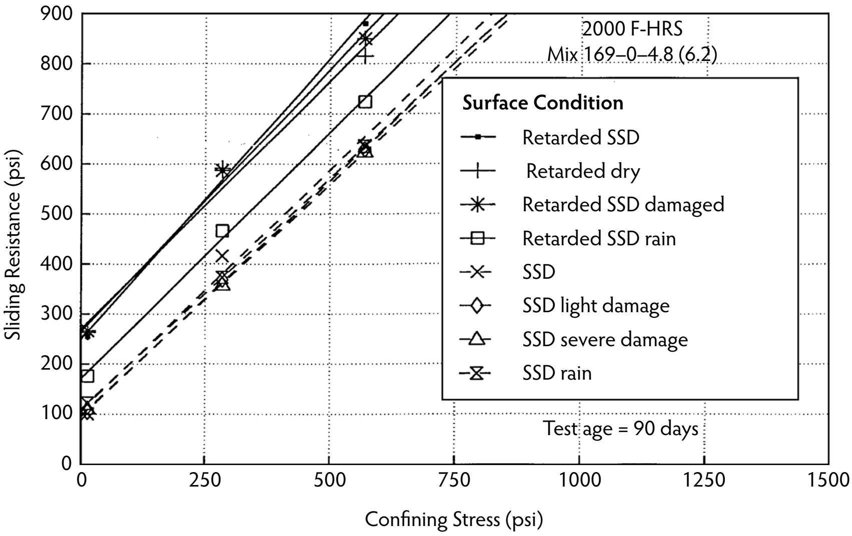


FIGURE 20.40 Miel I lift-joint shear.

maturity, cement content, admixtures, and bedding. It is almost entirely a function of the physical aggregate characteristics.

Figure 20.40 shows a typical plot of total shear stress resistance as a function of the confining stress applied normal to the lift-joint surface. These tests were performed on large blocks saw-cut from the full RCC mix. The mix contained 169 lb/yd³ of cement with no fly ash or pozzolan. It had a relatively dry consistency with 4.8% moisture and 6.2% aggregate fines. A surprising result, similar to those of full-scale tests at other projects with other materials, is that allowing the surface to dry just prior to placing the next layer of RCC had virtually no negative effect on the joint strength. This is contrary to traditional practice for conventional concrete. In the field, allowing the surface to dry just prior to placing the next layer allows efficient and very effective cleaning by blowing the surface with compressed air, thereby achieving an even better joint quality.

20.4.16 Seepage, Permeability, and Watertightness

At the time of early RCC projects, confusion developed concerning **permeability** and seepage in RCC dams because they were sometimes discussed or presented and compared using data that had a very different basis. Any one, or any combination, of the following was used: pressure tests and water-loss results from drill holes in dams; recordings of seepage collected from drain holes drilled into dams that may or may not have included holes that extended into the foundation or **abutments**; recordings of discharges from galleries or stilling basins that may have included water from any combination of sources such as foundation drains, drilled drains in the dam, cracks, monolith joints, local runoff, drains in the RCC, and water from construction activities; tests of cores that may or may not have contained joints that may or may not be oriented with or against the flow path; and permeability tests of laboratory prepared cylinders.

Another problem in reporting seepage data is the lack of a full grasp of the details of internal drains, their construction, their purpose, and how they function; for example, the design for the Urugua-I Dam originally had a grid of face drains behind the upstream membrane so seepage through the membrane could be detected and isolated if it occurred. Because of the 100% effectiveness of liner systems at other dams and confidence that the liner would have no seepage, this was deleted from the work. Only a single drain line was installed. It was located behind the membrane, just above the foundation. Seepage from this drain has been reported as being due to membrane seepage when, in the opinion of the designers and those who were responsible for construction, the seepage is primarily due to two other causes and not the membrane. One cause is poor detail where the membrane is connected to the foundation; water comes under the foundation contact and up behind the membrane to the drain. The other cause is seepage through a portion of the abutment that had questionable grouting; water probably came into the abutment and then traveled to the dam, where some of it migrated upstream to the drain line. When seepage is present, it typically diminishes naturally with time for both conventional concrete and RCC dams. The reduction is especially dramatic with low-cementitious-content RCC dams, where seepage is primarily along lift joints. Typical reductions are on the order of about 85 to 95% within about 1 to 2 years.

Unlike low-cementitious-content RCC, which typically experiences initial seepage along lift joints that do not have special treatment, high-cementitious-content RCC behaves similarly to conventional concrete dams, which typically have negligible seepage along the lift joints. As is the case, for example, with Dworshak Dam (conventional mass concrete) and Upper Stillwater Dam (high-cementitious-content RCC), watertightness problems with these types of dams are more related to leaking monolith joints or leaking cracks. Water loss occurs as high flows or leakage concentrations at fewer isolated locations in high-cementitious-content concrete dams, whereas in the lean RCC dams (without watertight facings or special lift treatment) the unit seepage is smaller but the area of seepage is greater. Two years after their respective reservoirs were raised, leakage through one of the cracks at the very high-cementitious-content Upper Stillwater Dam was greater than all of the seepage from all sources, including foundation drains, local runoff, and lift joints at the very low-cementitious-content Willow Creek Dam (it has no monolith joints or through cracks). This is not to say that all high-cementitious-content RCC dams will have cracks and joint seepage nor that all low-cementitious-content RCC dams will have seepage of lift joints. It is meant to point out general differences and where the emphasis should be placed during design for seepage control with different types of mixtures.

Some projects have been designed to allow seepage and let it pass through the structure without being collected or drained away. Seepage in these projects was the most sensible, economical, and appropriate design. Seepage was not a result of a failed design. On the contrary, the design worked. Going back to one of the first RCC dams, the U.S. Army Corps of Engineers' *Willow Creek Design Memorandum* (USACE, 1981) included a discussion of seepage that could be initially anticipated. Performance of the dam has been almost exactly as predicted. The section or mass of the dam was increased as part of the design to offset uplift pressures along lift joints that were allowed to seep without benefit of an internal uplift reduction drain system. The seepage has reduced naturally over time to about 10% of the initial value. Extensive coring soon after construction and again after years of steady seepage has shown no detrimental

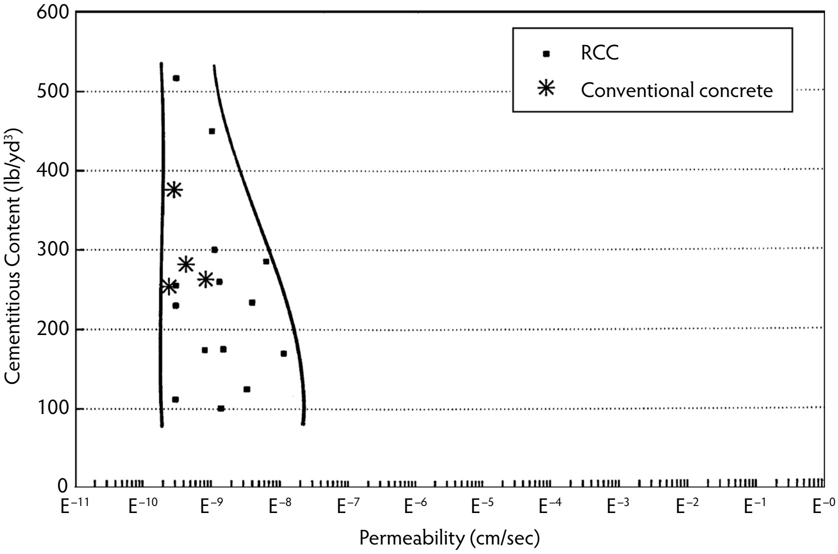


FIGURE 20.41 Sample permeabilities.

effects. This includes tests of joint strength (tension, cohesion, and friction), compression, density, tension, and appearance despite aggressive reservoir water.

Figure 20.41 illustrates essentially no change in RCC permeability (excluding joints) with changing cementitious contents, including very low cementitious contents of only 100 lb/yd^3. The data represent the average permeability values primarily for test samples of RCC actually used on completed dams. For comparison, the figure also shows sample permeability values from tests of conventional mass concrete. The results of the latter are similar to RCC. All of the mixtures have permeability values suitable for dam construction. Table 20.9 shows specific average test results for various RCC mixtures listed in ascending order of cementitious-material content. It is clear from comparing the cementitious-material content to the permeability values that no defined relationship exists between cementitious-material content and permeability within the range of 100 to 450 lb/yd^3. It is also clear from the table that no defined relationship exists between permeability and the proportion of cementitious material that is pozzolan.

Confusion about seepage can be easily clarified and summarized as follows. Properly designed RCC mixtures all have low permeabilities that are similar to conventional mass concrete, about 1 to 10 × 10^9

TABLE 20.9 Roller-Compacted Concrete Permeability: Average of Cores

Project	Cement + Pozzolan (lb/yd^3)	Permeability (cm/sec × 10^{-9})
Urugua-I	101 + 0 = 101	1.4
Willow	80 + 32 = 112	0.3
Zintel	125 + 0 = 125	3.3
Lost Creek	94 + 76 = 170	11.3
Elk Creek	118 + 56 = 174	0.8
Willow	175 + 0 = 175	1.5
Cuchillo Negro	130 + 100 = 230	0.3
Lost Creek	234 + 0 = 234	3.9
Willow	175 + 80 = 255	0.3
Lost Creek	120 + 140 = 260	1.3
Zintel	300 + 0 = 300	1.1
Willow	315 + 135 = 450	1.0
WES	517 + 0 = 517	0.3

cm/sec, regardless of cement and pozzolan content (this statement applies to the compacted mass without joints). A key aspect of properly designed RCC mixtures is that they contain at least 20% by volume of material finer than 75 μm. This includes all materials (water, small air bubbles, pozzolan, admixtures, slag, aggregate fines, and cement). If a low-cementitious-content RCC is made without adding fines to keep the paste volume greater than about 20%, the mixture is poorly proportioned and greater permeability can be expected.

Along with these strong statements about the permeability of unjointed RCC mass, a companion statement is also necessary. If special precautions (such as bedding mixture, upstream membrane, or fast lift placement) are not used, low-cementitious-content RCC dams with a dry consistency will have lift joints that seep. The joints can still achieve good friction and cohesion properties, reasonable tensile strengths, and even look tight, but they will seep. The total quantity of seepage through the joints may be low, but the unit seepage rate along the thin lift joint can be on the order of 1×10^{-3} cm/sec. If this seepage is allowed to penetrate through the dam instead of being intercepted by drains, it may cause uplift and cause the entire mass to look like it is seeping. In numerous applications this condition is tolerable and may be the best overall design, but in other applications special precautions to control seepage or a different type of design are appropriate. If a higher cementitious-content mixture with a wetter consistency is used, lift-joint seepage problems will be similar to those encountered with traditional concrete.

A few clarifications are appropriate. Bedding mixture (a retarded sanded grout or high-slump small-aggregate conventional concrete) will provide watertightness if the bedding mixture extends downstream from the upstream face a distance approximately equal to at least 8% of the hydraulic height above the joint. In the process, the bedding mixture will also provide improved tensile and shear strength. This assumes that the bedding is always placed correctly. In practice, it is reasonable to expect that there will be some less-than-perfect placement of the bedding mixture in any large project; consequently, it is reasonable to assume that some lift joints may have some seepage, just as occurs with traditionally placed mass concrete or high-cementitious-content RCC. This is usually minimal; it can be picked up by drains and will reduce substantially with time. Adding to the width of bedding provides some additional protection, but because of interference with other aspects of the construction it also makes placement of the bedding and achieving good quality more difficult. If total watertightness is desired, regardless of cracks, joints, failed water stops, poor-quality lift joints, or low-cementitious-content mixtures, the impervious upstream membrane system discussed in the next section should be considered.

20.5 Design

20.5.1 General

Efficient RCC designs require balancing considerations including stability of the structure and foundation, stresses from applied loads and dead loads, thermal stresses, construction methods and rates of placement, and mixture proportions including their material properties. Because of the low cost of RCC, the wide range of material properties possible (including properties not possible with conventional concrete), and the ability to use marginal or normally unsuitable materials if necessary, the designer needs to evaluate many more possibilities than would be necessary for conventional concrete. Also, it is necessary to pay more attention to the interrelationship of design with what might otherwise be considered inconsequential decisions with regard to construction. Examples that relate to positioning supports for RCC delivery conveyors and to leveling concrete are discussed in Section 20.6.1. The designer has a more complex task, but he also has greater opportunity to save time and money for the project and maximize the use of available resources and materials.

Roller-compacted concrete has been used for a variety of mass applications. An old example is the base on which structural concrete was placed at the Bellefonte Nuclear Plant, the base on which hydroelectric power plants were constructed at the Tarbela project, and the base under a number of large spillways. Other examples of mass applications are large buttresses or supporting walls for potentially large landslides, as was done along flood channels in El Paso and as was done for the mountainside at the Platanovryssi Dam. Still other mass applications involve erosion protection for enormous plunge pools and stilling basins that would otherwise erode from extreme water flows at both low and high velocity (Schrader and Stefanakos, 1995). The most complex massive RCC structures, and the most common applications, are dams. The remainder of this section on design concentrates on RCC dams, but much of the content applies to other massive applications such as walls and buttresses.

Foundations that are suitable for traditional concrete dams and massive structures are also suitable for RCC dams and massive structures; however, RCC can also use foundations that would normally not be considered acceptable for concrete structures. Because RCC is less expensive than conventional concrete, it is often possible to widen the base or foundation and contact area to reduce bearing pressure and provide added sliding stability. Also, by using a low-modulus RCC, irregularities in geometry and properties of the underlying materials can often be tolerated. A detailed discussion of foundation issues as they relate to RCC is beyond the scope of this chapter, but the topic is well discussed in the literature (Schrader, 2006a,b). Some examples of RCC dams on otherwise unacceptable foundations are Concepcion, Big Haynes, Burton Gorge, Rompepicos, and Buckhorn (Giovagnoli et al., 1991, 1992; Schrader, 1999b, 2002, 2006a,b; Schrader and Bali, 2003).

Structural design of RCC dams uses the same basic criteria and procedures used for conventional concrete dams. After the RCC has hardened in place, it is concrete. The concrete is just placed by a more efficient method than has historically been used, and it may have a design section and material properties that are outside the normal range of conventionally placed concrete structures. These attributes, plus the rapid rate of placement and the minimization or elimination of monolith joints, may require a more in-depth study of the structure. General discussions of structural design of RCC dams can be found in ACI Committee 207 (1989), Jansen (1989) and the U.S. Army Corps of Engineers (1995). Stress analysis of RCC dams, with specific example, has been published by Schrader and Rashed (2002). Recent developments have allowed for three-dimensional analyses of RCC structures that simultaneously consider time-dependent material properties, stress-dependent material properties such as the modulus, different mixes used at different locations in the structure, different times of placement for each layer or group of RCC layers, time-dependent development of thermal stresses, dead and applied loads, and seismic loads (Angulo et al., 1995).

As discussed in Section 20.4.10, RCC mixes can have substantial strain softening. The modulus (stiffness) typically decreases at high levels of loading. This phenomenon begins to occur at stresses as low as about 25% of the ultimate strength for lower cementitious content mixes, whereas it may not be seen until greater levels of load at about 75% of ultimate strength for higher cementitious content mixes. As discussed in Section 20.4.10, the reduction in stiffness can be substantial. This can be very advantageous to RCC dams, and it should be taken into account during design. It can cause localized areas of high stress, such as at the toe and heel of a dam, to redistribute much of the load to adjacent areas of lower stress, thereby reducing what would otherwise be higher peak stresses. This phenomenon can be evaluated using a software program or analysis method that allows the nonlinear stress–strain behavior associated with strain softening to be defined as part of the input. Another way to do this is by using an iterative process that first determines the stresses without strain softening. Then, based on stresses from the first iteration, the modulus is adjusted downward for areas of higher stress, using the actual secant modulus for that area and level of stress. The process is repeated. Usually about four iterations are required before the stresses and associated modulus values are balanced and the true stress distribution evolves (Schrader and Rashed, 2002).

Design should also consider probable uplift and its distribution within the dam. The main issue is uplift pressure due to seepage along lift joints. If seepage can migrate along lift joints to the downstream face but not exit or escape at the face—for example, due to a continuous conventional reinforced concrete face slab at a spillway—then allowance must be made for this trapped uplift or drains will be required under the slab to relieve the pressure.

Seepage and uplift can be reduced at the upstream face by improved lift-joint quality, either by providing a better mix with better binding characteristics or by adding a bedding mix between layers. In theory, this will prevent uplift, but in practice there still will be at least a few lift joints that allow seepage.

Unlike conventional mass concrete, which generally has about 1 lift joint per 2 m of height and special attention is given to every lift joint, RCC typically has about 7 lift joints per 2 m of height, and less time is available to ensure that each joint is carefully cleaned. Consequently, the lift joints typically receive less attention and treatment than do conventional concrete dams, there are many more joints, and there is a greater likelihood of a seeping lift joint regardless of the type of mix and treatment. In addition, even the best of conventional concrete dams usually have the occasional lift joint with seepage. Because the locations where this might occur are not known, uplift should be considered at each joint.

Uplift reduction (usually taken to be 2/3) can be accomplished at a series of drilled drains within the dam, as is done in conventional concrete. As discussed in Section 20.5.4, a common and reliable method of providing watertightness and uplift reduction immediately at the upstream face is to use an impervious upstream synthetic membrane or a properly designed concrete facing, with integral face drains immediately behind the membrane (Scuero and Vaschetti, 2003). Until a reliable track record of field performance under many conditions was established, earlier designs considered that the membrane or facing would provide effective watertightness but that some seepage and resulting uplift could still develop. Based on excellent performance and the concept in the U.S. Army Corps of Engineers manual (USACE, 1995), which suggests that watertightness and uplift assumptions should be based on the site-specific procedure being used and its performance, recent practice has been to consider a proper membrane system to provide essentially total uplift control at the upstream face, providing that it also has a drain system to relieve pressure from any small penetrations that may develop. A conservative design approach is to allow 50 to 75% uplift reduction at the upstream face, with an additional 2/3 reduction at the drilled drains (if used). The impact of this uplift reduction on stresses and the required strength can be very significant (Schrader and Rashed, 2002).

Roller-compacted concrete dams have been constructed with axes that are straight or curved, with two intersecting straight axes, and with a combination of a curved axis with straight tangent axes. Both vertical and sloped upstream faces have been used. The downstream face can be vertical or at any slope. Within a given section, the downstream slope can be infinitely adjusted, curved, or parabolically shaped. Extensions of the toe, deeper excavations, and keys have been used to provide stability over poor rock and bad foundation conditions. RCC dams can be any height, ranging, for example, from 6 ft (Ferris) to 25 ft (Kerrville), 47 ft (Winchester), 125 ft (Copperfield), 160 ft (Monksville), 170 ft (Aulouz), 210 ft (Concepcion), 270 ft (Urugua-I), 300 ft (Trigomil, Rompepicos, and many others), 620 ft (Miel I), 660 ft (Longtan), and approximately 900 ft (Diamer Basah). The primary areas requiring special attention in RCC dams are overdesign strength requirements for variability, design section options, upstream and downstream facings (facings apply also to rooms in RCC masses, facings of RCC walls, and other non-dam applications), and thermal stresses.

20.5.2 Overdesign Strength Requirements

Overdesign average strength requirements for variability are required by most codes for general conventional concrete construction. Sometimes the overdesign is achieved through an arbitrary extra factor of safety applied to the required design strength, but, more appropriately, specific statistical procedures such as those outlined by the American Society for Testing and Materials (ASTM) or the American Concrete Institute (ACI) are used. European practice accomplishes the same thing as ASTM and ACI by using a specified characteristic strength, which is the strength below which not more than a certain percentage of individual strength tests is allowed. Until recently, it was not common to apply these statistical procedures to dam construction. In the earlier days of concrete dam design and construction, various arbitrary methods were employed to provide a reasonable overdesign in dams, or only an average strength was used and nothing was done for overdesign that accounted for variability.

Overdesign is an increase in the average strength requirement to account for the fact that not all cylinders will test at exactly the design strength level. Some will be higher and some will probably be lower. The overdesign factor is a method of limiting the probable number of low strengths to acceptable levels. Special care is necessary when applying overdesign factors in mass concrete, including RCC, because any extra cement used to increase the average strength may result in an unacceptable increase in thermal stresses as well as cooling costs. Also, in high-production RCC where the results of final long-term cylinder tests are not available until the structure is essentially complete, testing of variability in the fresh mixture being placed has developed as a practical method of immediate control rather than using cylinder strengths, which are more for a matter of historical record. The overdesign requirement and its early application to RCC dams are discussed in the early literature (Schrader, 1987). Current recommendations and practice are discussed in detail in recent literature (Schrader, 2007).

Current practice for structural concrete (e.g., in an important beam or column) is to require an average strength sufficiently high so more than a limited number of test samples (typically 1, 5, or 9%) fall below the design strength. ACI Report 214R (ACI Committee 214, 2002) allows different percentages to be used based on the criticality of the incidence of an area of low strength in the structure. Using ACI 214R guidance, traditional accepted practice for mass concrete dams, and a sensible approach, it is reasonable to require the average strength of mass concrete to be sufficiently above the design strength to statistically ensure that not more than 20% of the test samples will fall below the design value. This makes good sense because an area of low strength that represents, for example, 20% of a lift or placement will not normally have a critical impact. Mass concrete dams are typically designed to have a factor of safety of about 3 built into the stress analysis, so being 20% below the design strength is still about 2.5 times more than the applied stress for the normal load condition. More importantly, stresses in an area of low strength (or a void with no strength) will redistribute around that area to adjacent areas of higher strength.

The importance of taking a reasonable approach to overdesign for variability in mass concrete, including RCC, is often overlooked. Requiring a higher average strength requires using additional cementitious materials. Doing so increases costs, but, more importantly, it also increases heat, thermal stress, stiffness of the mix (modulus), and therefore thermal cracking stresses. Arbitrarily increasing the average strength may seem like it would result in a better dam, but the reality is that it can result in a more expensive dam that cracks, rather than a less expensive dam with adequate strength that does not crack.

20.5.3 Design Section Options

Design sections and facing options for large and small RCC dams are summarized in the literature (Schrader, 1993). The variety of basic cross-section options that are generally available for RCC dams are shown in Figure 20.42 and Figure 20.43. The same options could be applied to conventional concrete, but the cost and construction methods used in conventional construction make most of them impractical. Figure 20.42 is a typical section for a low dam or a dam on a gravel foundation. The extra effort and costs required for a formed vertical upstream face usually are not worth the effort in a low RCC dam. It is easier, less expensive, and faster to simply overbuild the dam at the upstream face without forms. In addition to simpler construction, the extra mass provides additional safety within the RCC and may allow less stringent specifications or inspection. It may also justify using mix designs based on the designers' judgment without prior testing and local pit-run aggregate.

Compressive and shear stresses in a low RCC dam are so small they are almost meaningless. If the structure is subjected to overtopping, a reasonable level of bond between the top lift joints is necessary. This can be accomplished by applying a bedding mix between the top several RCC layers. Cement contents for very small dams are usually dictated by exposure conditions, mix workability, gradation of the available

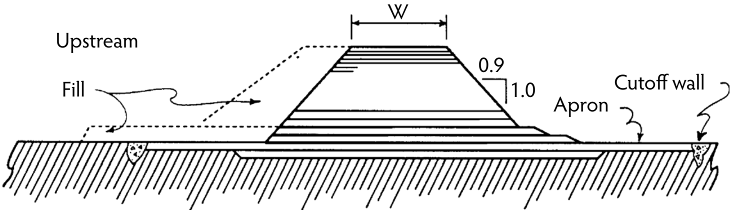


FIGURE 20.42 Small dam section options.

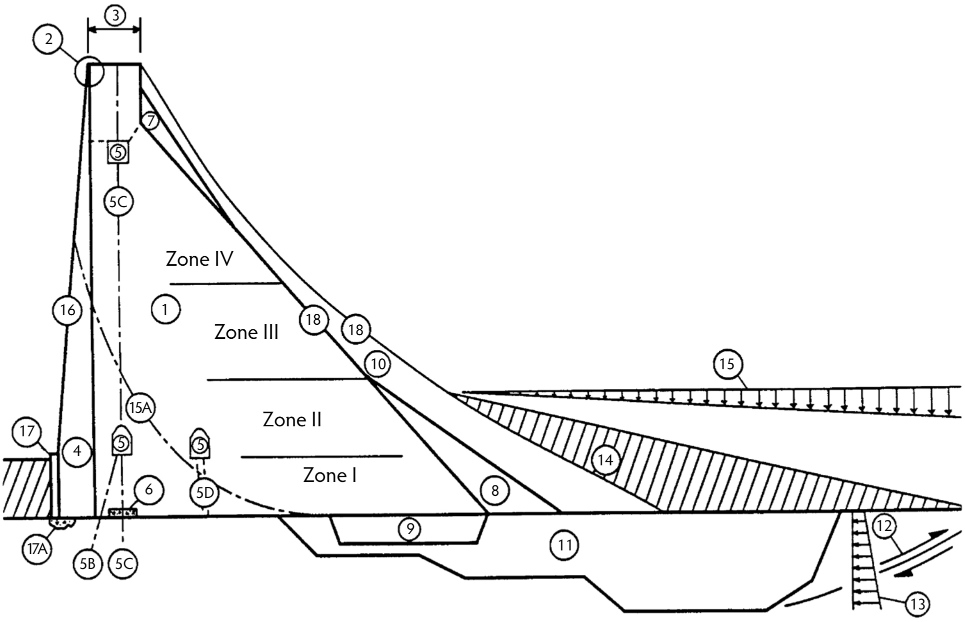


FIGURE 20.43 Large dam section options.

aggregate, quality of the mixing equipment, and degree of inspection. Small dams that may require a cement content on the order of only 50 lb/yd^3 for structural loads should have higher cement contents, usually on the order of 150 to 300 lb/yd^3, to account for these factors. For small dams with volumes on the order of several thousand cubic yards, the cost for the extra cement is insignificant. Extra cement is helpful when placing in cold weather due to the heat it generates. Thermal cracking in a structure of this size and shape normally is not a structural problem. When necessary, watertightness can be provided by using fast construction, a high-cementitious-content wet-mix consistency, an upstream membrane, or a bedding mix between layers at the upstream face. Some structures do not require watertightness.

A downstream slope of 0.9:1.0 (0.9 horizontal distance to 1.0 vertical distance) or flatter is suggested for low dams because it is easy to build with any RCC mix. The extra RCC material involved is negligible. The top width should be selected as the minimum that allows reasonable construction with equipment typical of small projects. The contractor should be allowed to overbuild for his convenience at no additional cost to the owner. A suggested absolute minimum width is 12 ft. Two concerns are required access (if any) after construction and minimum widths for compliance with applicable safety regulations. Fill material can be used at the upstream (or downstream) face of the dam to steepen the slope, narrow the top width of RCC, and save volume if this becomes economical or if the topography requires it. When placed at the downstream face, the fill hides minor seepage and protects the RCC from exposure. If impervious fill is used at the upstream face, it can provide improved watertightness. When fill is used to steepen the RCC slopes of a dam on a non-rock foundation, consideration should be given to the increase in bearing pressure and sliding that will result at the base of the dam.

Small RCC dams on pervious foundations may require a cutoff or grouting for foundation stability or seepage control, but usually it is faster, less expensive, and easier to spread the foundation of the dam out through wider lower lifts and to use apron slabs of RCC. Settlement studies and a slab/beam analysis of the lower lifts establish how far the extension can go without the slab or apron breaking off. The flow path will also influence the apron width. A simple cutoff wall placed into an excavation without forms is recommended. The downstream cutoff and apron normally should have drain holes.

Figure 20.43 illustrates many of the options or variations for a typical gravity dam section that are practical with RCC for larger projects. Variations and options are labeled 1 through 17 in the figure. The basic gravity section with a vertical upstream face, constant downstream slope, and a vertical downstream face at the top of the dam has been used for many RCC dams; however, the low cost of RCC often makes it reasonable to flatten the downstream slope and add more mass than conventional concrete allows. This reduces foundation stress, RCC strength requirements, and lift-joint concerns. Reductions in cement content with related reductions in unit cost and in thermal stresses result. The possibility of using higher cementitious contents with higher strengths should also be investigated if the thermal stresses can be tolerated and the volume reduction offsets the increase in costs due to higher unit costs of the RCC. Influencing factors are the length of diversion, the cost and availability of cement and pozzolan, the quality and production costs of the aggregates, and foundation quality.

A parapet wall (2) can reduce costs by reducing the quantity of RCC. The wall can also act as a personnel barrier and curb. Added height, or *freeboard*, for overtopping waves is not necessary with RCC. Also, by curving the top of the parapet outward, it can return waves by directing them back to the reservoir. The wall can be a continuation of upstream precast panels if that option is used to form the upstream face of the dam. A breakaway parapet (fuse plug) designed to fail during overtopping can be designed. One reason to do this is so water flows over one side of the dam while any downstream powerhouse or access road on the other side remains protected.

The width of the dam (3) should be established after considering a number of factors, such as the cost of additional RCC and downstream vertical facing; the required (not just "nice to have") width for access during operation and construction; inertia (seismic loading) of the laterally unsupported top section of the dam; the effect of the mass on sliding stability due to the added confining load; the effect of the mass on the location of the resultant force for the entire section; the distribution of foundation stresses; and the possibility of causing tensile stress across downstream lift joints for a high dam in the reservoir empty condition.

Adding mass and width to the dam at the base by using a sloped upstream face (4) may efficiently improve stability. An extra benefit is the downward vertical component of the reservoir load on the horizontal projection of the dam face. A condition to check is whether this causes tensile forces to develop or to become unacceptable at the upstream face in both the foundation and lower RCC lifts. Slopes up to about 0.10 (H):1.00 (V) can be practically built in most RCC dams without noticeable effect on the cost, schedule, or construction practicality.

Tension at the upstream face of both RCC and conventional concrete gravity sections is a controversial issue. Each project should be evaluated for its own set of conditions. What may be acceptable for one location and type of mix may be unacceptable for a different location or mix. The majority of designers and regulating codes in most countries consider that gravity sections should have little or no tension at the upstream face in the normal reservoir or normal operating condition. Minor tension is occasionally allowed for severe flood conditions; however, it is reasonable to provide high-cementitious-content mixes or bedding mixes across lift joints near the upstream face to accommodate the need for small but sustained tensile stresses on the order of a few percent of the compressive strength for the normal operating condition, if this is necessary to achieve an economical design in high dams. Allowing for softening of the foundation with a lower tensile mass modulus at the heel of the dam will also reduce this tensile stress. It is reasonable to allow minor tensile stress for flood conditions at isolated areas of good inspection or special construction treatment when necessary. For seismic conditions, tensile stress is usually unavoidable and allowed up to 150% of the expected static tensile strength to account for the increased tensile strength under very fast loading. This increase is referred as the *dynamic increase factor* (DIF). With this allowed stress, a factor of safety just greater than 1.0 is typically accepted under earthquake conditions, with higher factors of safety for flood and normal load conditions. Table 20.10 provides a simplified summary of the required safety factors and allowed stresses for various load conditions under different code or agency requirements.

Galleries (5) in RCC dams should be minimized. There has been a tendency to extend galleries beyond where they are actually needed. This causes higher costs, slower production, and lower overall RCC quality. In large open areas, such as at the base of a high dam section, galleries typically slow production by about 15% for the uncemented fill method of construction. Conventional forming slows production even more. In the upper portions of the dam, where there is less room, the decrease in production at the area of a gallery can be 50% or more, and the quality of placement may decline significantly. Where

TABLE 20.10 Concrete Dam Factor of Safety Examples

Agency	Usual		Unusual		Extreme	
Sliding within the dam and at the foundation contact						
Corps (1995)	2.0		1.7		1.3	
USBR	3.0		2.0		1.0	
FERC (general)	3.0		2.0		1.10	
FERC (low hazard)	2.0		1.25		1.0	
DIN/DVWK	—		1.35		1.2	
Sliding within the foundation						
Corps (limit equilibrium)	2.0		1.7		1.3	
USBR (shear friction)	4.0		2.7		1.3	
USBR (small dams)	4.0		—		1.5	
USBR (small, minimal risk)	2		—		1.25	
FERC (general)	3.0		2.0		1.0	
FERC (low hazard)	2.0		1.25		1.0	
DIN/DVWK	2.0		1.5		1.2	
Resultant location at base						
Corps (1995)	Middle 1/3		Middle 1/2		Within base	
USBR	Middle 1/3		Middle 1/3		Within base	
FERC (general)	Middle 1/3		Middle 1/3		Middle 1/2	
DIN/DVWK	Middle 1/3		Middle 1/2		Within base	
Maximum stress within the dam						
	Comp.	Tension	Comp.	Tension	Comp.	Tension
Corps (1995)	$0.3f_c'$	0	$0.5f_c'$	$0.6f_c'^{2/3}$	$09f_c$	$1.5f_c'^{2/3}$
USBR[a]	$0.33f_c'$	—[a]	$0.5f_c'$	—[a]	$1.0f_c$	—[a]
FERC (general)	$0.33f_c'$	$0.10f_c'$	$0.5f_c'$	$0.10f_c'$	$1.0f_c$	$0.10f_c'$
FERC (low hazard)	$0.5f_c'$	$0.10f_c'$	$0.8f_c'$	$0.10f_c'$	$1.0f_c$	$0.10f_c'$
DIN/DVWK	—	0	—	Yes		Yes
Maximum stress at the foundation contact						
Corps (1995)	Allowable bearing	—	Allowable bearing	—	1.33 × allowable bearing	—
USBR factor of safety (FS)[a]	4.0	—	2.7	—	1.3	—
FERC (general)	0.33 × ultimate bearing	0	0.5 × ultimate bearing	0	Ultimate bearing	0
FERC (low hazard)	0.5 × ultimate bearing	0	0.8 × ultimate bearing	0	Ultimate bearing	0
DIN/DVWK	—	0	May open	—	May open	—

[a] Maximum $f_c < 1500$ psi (usual) < 2250 psi (unusual). USBR allows f_t and allows cracked sections for extreme load.

Note: The information shown applies to general conditions. Exceptions may apply or be allowed for special conditions based on the amount of investigation, field conditions, extent of analysis or design, hazard potential or risk, and whether the dam is new or existing. Corps, U.S. Army Corps of Engineers; DIN/DVWK, European standards; FERC, Federal Energy Regulatory Commission; USBR, U.S. Bureau of Reclamation.

a gallery is actually needed high in a dam for uplift, an open graded rock drain of coarse aggregate should be considered (6). If placed about four lifts high, it is possible to excavate the drain for access if necessary in the future. The vertical distance between galleries is usually determined by the accuracy with which equipment can drill from the floor of the top gallery to intersect the roof of the gallery below. This typically is about 100 feet for a gallery 6 feet wide, using rotary percussion drilling equipment operating from the floor of the upper gallery. In addition to interfering with construction, a gallery high up in a dam can also be a point of weakness in a seismic event (7). Designers of low- and medium-height dams should consider simply overbuilding the dam enough so galleries and drains are not even necessary. The unit cost of the RCC decreases, and construction, operation, and maintenance are simplified. An example of this is Winchester Dam. Using a bedding mix between lifts or a high-cementitious-content RCC is suggested upstream of galleries and between the first three layers in the area above and below the gallery floor and ceiling. This provides watertightness, bond against uplift below the floor, and added sliding resistance against reservoir pressure at the upstream gallery wall.

A **grout curtain** (5B) can be installed prior to the RCC or can be installed afterward from a gallery. The gallery should be large enough to accommodate suitable production equipment, especially at interior corners and intersections. Internal drains (5C) can be easily drilled with track-mounted rotary percussion equipment. Nominal 3-in. holes at spacings of 10 to 15 ft are adequate. These holes can be drilled at high production rates with an accuracy on the order of ±3 ft in about 120 ft. A very efficient way to drill these holes is immediately after placing the RCC lift that is the gallery floor. When a long gallery with holes beginning at the same elevation is called for, it is effective to stop RCC for a day while several track drills drive onto the lift and drill the holes. The area is then cleaned, treated as a cold joint, and the RCC placing resumes. High dams, dams with wide bases, dams with high heat (due to high cement contents, use of high-heat cement, or hot placing conditions), and dams with high elastic modulus values may require longitudinal joints (5D) that can be grouted from a gallery or from outside of the dam. A practical way to make this joint is to simply place open-graded coarse aggregate at the joint location as each RCC lift is spread. The RCC is then compacted with the aggregate (5D). Grout tubes are installed in the aggregate as it is placed. Before raising the reservoir but after sufficient cooling of the mass, the joint is pressure grouted from the bottom up with expansive grout. A continuous monolithic concrete mass results instead of two masses connected by a thin grout line.

Using a **fillet** (7) in the upper part of the dam at the downstream face provides additional weight that improves sliding stability and offsets some uplift pressures. On a high dam, it moves the resultant force of the entire dam section slightly upstream, whereas on a low dam it shifts the force downstream. The distribution of stress under the dam, the amount or existence of tensile stress, and the maximum compressive stress are slightly affected. The fillet also reduces the height of the section at the top of the dam. A downstream toe extension (8) can provide additional stability for a high dam where sliding stresses increase significantly with a minor addition in height. It adds both weight and total cohesion, but only in the bottom portion of the dam, which is usually where it is needed. The fillet (7) increases the mass across the full length of the dam, including the upper portions of the foundation where it usually is not needed. The fillet also adds to foundation bearing and RCC compressive stresses, whereas the toe extension reduces the bearing and maximum RCC stresses. The extended toe requires extra excavation and foundation preparation but only in the deepest section of the dam and not for much of its length. It is possible that an extended toe in a high dam will result in tension across downstream lift-joint areas at the maximum height for an empty reservoir condition. This can be overcome by an early partial reservoir filling.

A **key** (9) is an effective way of providing additional sliding stability when it is needed in the foundation but not in the RCC. Although adding the key near the upstream face may seem like a good idea because of its potential to act as a cutoff, the downstream location will typically be better. If analyzed for local stresses, an upstream key of a high dam may have tensile forces that could negate sliding friction resistance because there will be little or no vertical stress at the key and a full reservoir. A downstream location has the benefit of maximum vertical confining stresses and the resulting friction. To minimize the width of the key (upstream–downstream) and to ensure that the required load is transferred to the foundation without slippage across a weak RCC lift surface, bedding mix should be placed between RCC layers in the key or a high-paste-content mix should be considered. The key provides added foundation stability by extending the foundation failure plane (12) and by the related horizontal component of the downstream foundation-bearing capacity (13). A relatively simple consolidation grouting program in the area downstream of the key may significantly improve stability. A key is usually required only in the deeper portion of a high dam (if it is on medium- to poor-quality rock), at isolated locations where the foundation condition is bad, or for a medium-height dam on an unsuitable foundation.

When the bearing and sliding strengths of a foundation are poor, a conventional concrete dam usually is not economical, but RCC can be a viable option. Using a low-strength and low-cost RCC with a parabolically curved downstream face (10) is one approach. At the PC-1 project, a preliminary design with this concept was prepared for a tailings dam on a clay and weathered-rock foundation. The dam was composed of large monoliths that could undergo significant independent movements caused by time-dependent consolidation of the foundations. Each monolith sat on its own excavated foundation, with steps in the foundation matching the location of monolith joints. The abutments were tied in with embankments that would undergo deformation as required. The foundation for this project was so poor that a massive key was required to provide sliding resistance and to lower the bearing pressure. Because **foundation restraint** is minimal for this type of foundation and cement contents are low due to the low strength requirements, thermal stresses are minimized; however, the thickness of the key (distance from the downstream surface to the foundation under the key) should be analyzed as a cantilevered beam to ensure that it will not break from the rest of the dam. If bearing pressures under the key can accept the added weight (15), then a fill (14) can be placed over a portion of the toe to offset some of the cantilever forces. The fill also provides extra sliding stability if it is extended downstream beyond the RCC key. Regardless of which option is used to widen a dam base, a reduction in bearing pressure and maximum stress occurs in the RCC. Reduced strength requirements lead to less cement being used, lower costs, and less thermal stress. Stresses at the lower levels are closer to stresses higher up in the dam, so fewer zones requiring different quality RCC at different heights are necessary.

Although structural requirements for strength reduce to zero at the top of a dam, some minimum strength is needed for erosion and weathering protection, impermeability, and making the mix cohesive enough to be placed and compacted. The minimum RCC strength should be based on factors such as exposure conditions, function of the dam, risk level, and economics. What is appropriate for one project, owner, and location may not be appropriate for another project, owner, and location. There is some disagreement, but minimum strengths at 1-year values of about 1000 psi have been considered acceptable for the mass. Early RCC dams used higher strength mixes for the upstream and downstream regions and lower strength RCC at the interior. This proved to be a more serious construction and inspection problem than anticipated. The practice is now generally avoided. In addition, other factors have influenced this trend, including the good field performance of low-strength RCC exposed at the downstream face under severe weather. If needed, RCC can be protected at the upstream face by constant immersion in the reservoir, by an unbonded impervious membrane (with or without protective precast facing panels), and by conventional concrete placed using one of many possible techniques. The downstream surface can also be protected.

It is usually best to use one mix throughout an entire section for small- and medium-sized dams up to about 120 ft in height. Due to thermal and economic considerations, higher dams are usually separated into horizontal zones, with higher strength mixes being used in the lower part of the structure. Generally, these zones are on the order of 30 to 60 ft thick, with increases in strength of about 100 to 500 psi per zone. Initial planning for the 340-ft-high Binongan Dam used four zones. The design for the 620-ft-high Miel I dam used eight zones. In addition to the higher compressive strengths required for higher **principal stresses** in the lower portion of high dams, stronger mixes in the lower zones also provide additional lift-joint tensile strength, added cohesion, and usually a slight increase in friction.

When a mix in a lower zone has adequate strength for compression but not for sliding stability, several options are available. Increasing the mass or weight of the dam and widening the base have been discussed. Increasing the paste content of the mixes is another option, if it is economical and does not cause thermal cracking due to added heat from hydration or a higher elastic modulus. Another option uses bedding between RCC layers. As discussed in Section 20.4, this dramatically increases cohesion and moderately increases friction. This technique is especially useful when cold joints occur in low-paste mixes. Contract drawings can simply show where bedding mix is necessary for both cold joint conditions and, in some cases, with weak RCC mixes for fresh joints (15A).

20.5.4 Upstream and Vertical Face Options

Design options for the upstream face are detailed in the various sections of Figure 20.44 labeled 16A through 16M. If the upstream face is sloped (16A), the unformed face may be left exposed when it is aesthetically acceptable and when lift-joint seepage is either tolerable or controlled with bedding or higher cementitious content RCC. If total watertightness is required and special mixes with rigorous lift-joint inspection are not utilized, a flexible geomembrane can be placed over the sloping face (16B) (Schrader, 1999b). Where the membrane is exposed, it can be protected from removal by vandals by hanging a chain link fencing over it or by other methods. Below grade, it has been protected from damage by a layer of sand.

Reinforced conventional concrete placed after the RCC (16C) uses the same design concept as an upstream face on a rockfill dam. If the wall is thick enough, it is feasible to construct it ahead of the RCC with traditional slipformed or jump-formed construction. This allows the RCC to be placed rapidly as a trailing activity, with the RCC placed directly against the wall. There is no forming to delay the RCC operation. The wall is the form. It also acts as a thermal shock protection for the RCC. The wall will provide an attractive and watertight facing when properly designed and constructed. This requires slabs with water stops in the vertical and horizontal joints. A *plinth*, or watertight tie-in to the foundation and abutments, is required. Two-way reinforcing distributes shrinkage cracks throughout the slab so cracks are small and closely spaced. By limiting the crack width to about 0.006 inches, the cracks will be essentially watertight and typically undergo autogenous healing or calcification with time, even under hydraulic head. A drain system is necessary between the slabs and the RCC. Anchors are required to hold the slabs to the dam. These should be designed for the force due to horizontal acceleration in an earthquake. It is possible but difficult to position the anchors in the RCC when it is placed; drilling and grouting them afterward is the alternative. This concrete-facing method is often considered but is seldom designed or used. An extension of the concrete-faced option (16D) includes a second facing of porous concrete that acts as a total drain between the RCC and the upstream face. This also isolates the RCC from shrinkage and potential cracking or joint requirements in the facing, and it acts as thermal insulation to reduce gradients near the face. It was included as an option for the RCC design option at Kapachira Dam.

Roller-compacted concrete can be placed directly against conventional forms, but without a conventional concrete bedding or facing the degree of compaction and appearance will be compromised. Threaded anchors to the forms can be compacted into the RCC. After the RCC has been placed high enough so the next form panel can be positioned and anchored, the lower form can be slid out along the anchor and away from the RCC mass (16E). The void between the RCC and form can then be filled with conventional concrete that bonds to the young RCC and is mechanically held by the anchor. Instrumentation has shown that, by controlling the rate of placement and set time of the concrete with this type of procedure, form pressures can be developed that will stress the anchors and prestress the face in place.

Precast panels (16F) make an attractive, economical, and crack-free facing, but the panel joints are not watertight. Anchors are minimal, usually about 75 ft^2 of panel per in.^{2} of steel anchor area. Watertightness can be provided with a flexible PVC membrane (about 0.08 in. thick with welded field seams) attached to the back of the panel. A nut and washer tightened against the membrane with epoxy provides a watertight seal where the anchor penetrates the membrane. This procedure has been very successful in construction, operation, and tests to a head of 600 ft. A small amount of bedding is recommended between the membrane and RCC. Drains should be provided behind the membrane to collect seepage if it occurs and to provide additional stability by creating extra uplift reductions.

Roller-compacted concrete can also be placed against a conventional form that is later removed. A small amount of bedding against the form has helped to seat the form and provide a better surface. When done properly, this will result in a conventional concrete appearance, with RCC immediately behind the face; however, it requires a mix and technique that not everyone has been able to accomplish with total success. At times, difficulties have been encountered when the bedding has not squeezed up the form face, resulting in a boney look to the RCC at the exposed face. Another way to accomplish the appearance of a conventional concrete face is to use grout-enriched RCC (GERCC), with or without an air-entraining admixture as discussed in Section 20.3.6.

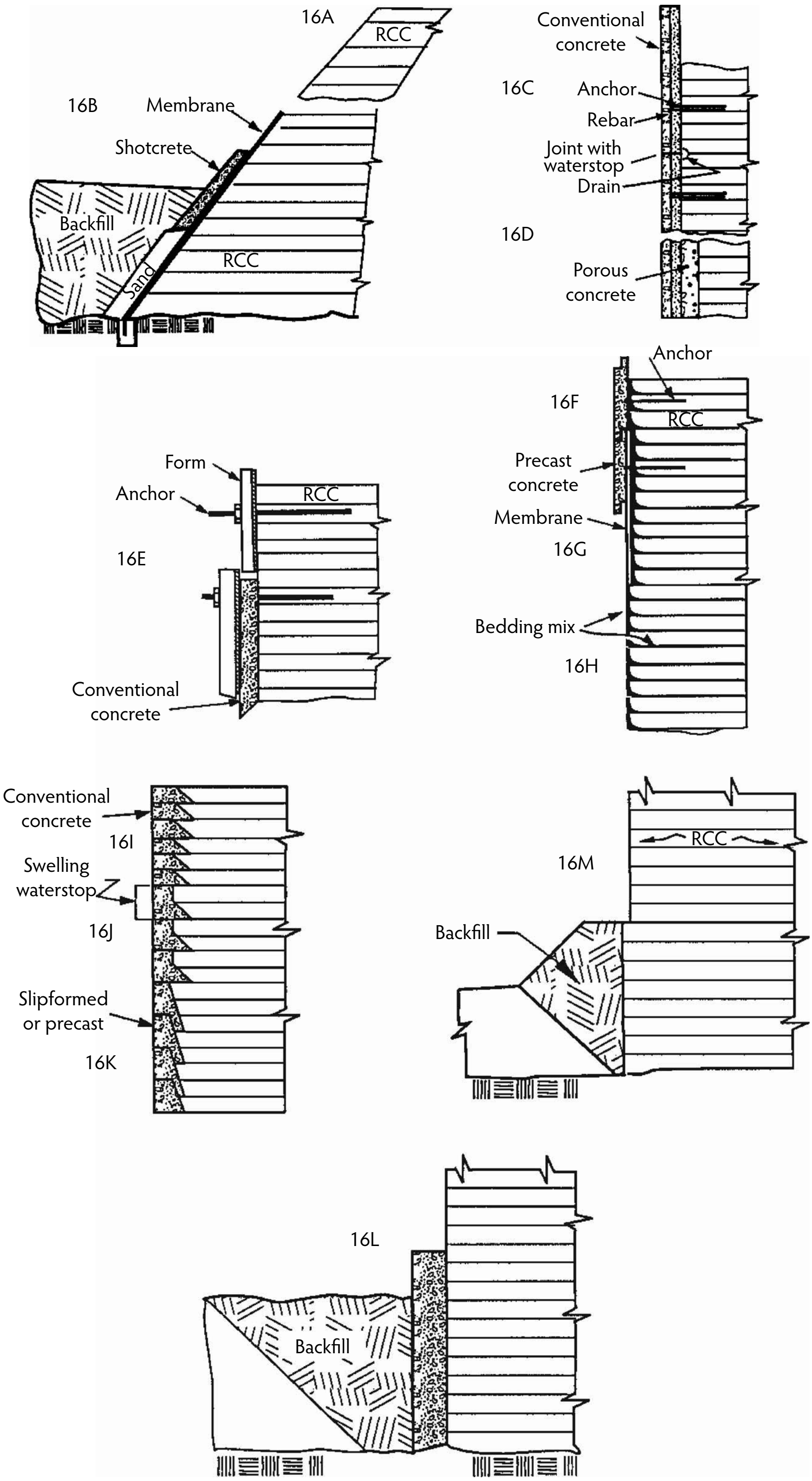


FIGURE 20.44 Upstream face options.

Watertightness can be established with an exposed polyvinylchloride (PVC) membrane placed directly against the dam face (16G) (see Section 20.4.16). The membrane requires an anchored but unbonded procedure specifically developed for concrete dam facings. A variety of synthetic membranes was used in earlier projects, either with drains or without drains These systems worked satisfactorily, but were not entirely successful. A specially formulated PVC membrane produced and installed by the Carpi company was then adapted to RCC, using technology and proven performance from its application to provide watertightness at older conventional concrete dams with seepage and permeability problems. This membrane has routinely provided total watertightness at the upstream face. The installations include a face drain system. The Carpi exposed-membrane system has been installed with 100% success for more than 20 years on a number of RCC dams and for much longer in the rehabilitation of leaking old conventional concrete (Scuero and Vaschetti, 2003). Drains between the membrane and RCC improve stability through additional uplift reduction, as discussed in Section 20.4.16. Simply extending the bedding mix downstream along the lift joint (16H) for a distance equal to at least 8% of the hydraulic height will provide watertightness if it is done 100% correctly 100% of the time. In practice, this is not possible. Normal construction with good inspection results in about a 95% reduction in seepage; this may be technically but not aesthetically adequate.

A number of RCC dams, and the facings of rooms and walls on other RCC mass applications, have been built that using the procedure labeled 16I in Figure 20.44. The procedure results in an attractive conventional concrete face that is completed with the RCC. Usually, the facing has no anchors to the RCC and no reinforcing bars. If a low-water/low-cement/low-shrinkage conventional concrete mix containing a high-range water reducer is carefully used and controlled, a virtually crack-free facing can result—even without vertical joints. The mix should not be thicker (horizontal dimension) than about 1 ft, or thermal and shrinkage cracks will probably result. Excellent curing must be provided. Without these precautions, tight cracks at spacings of about 4 to 10 ft can be expected. Normal construction with a reasonable mix will be crack free if joints are provided in the facing about 25 ft apart. The problem with joints in a facing is that it is very difficult to install water stops. Various projects that have attempted this have had less than watertight joints. The facing does not make the horizontal lifts watertight. If placing proceeds very quickly (about four to six lifts per day), the fact that the successive layers are placed before the previous layer has fully set will improve watertightness of these joints.

A modified procedure (16J) uses a temporary blockout near the upstream face at every other RCC lift. The blockout is removed prior to placing conventional facing and the next RCC lift. Each face placement covers two RCC lifts. Added watertightness can be achieved by using a simple *swelling-strip* water stop that is impregnated with chemical grout and laid along the facing mix lift surface. If seepage penetrates the lift joint, moisture causes the strip to swell, thus creating watertight pressure against the adjacent lift surfaces.

Interlocking upstream-facing elements (16K) have been precast and slipformed. As precast pieces, the upstream area covered by each piece is only about 10 ft^2 of exposed surface area, so production and placing becomes labor intensive and slow. The small area is a result of the weight of the thick and overlapping shape. The joints are not watertight, and there is some concern regarding the stability of the facing if it is not anchored to the RCC. Horizontally slipformed facing can slow production of RCC on dams with a short axis, but the procedure and equipment are better suited to long dams with a large volume of RCC per lift. Careful control of the mix and its delivery is critical, and the facing will develop small shrinkage cracks. RCC can be placed against the facing the same day it is slipped. Consideration should be given to the bond between the unanchored facing and RCC. This may require a high-paste RCC mix against the slipformed facing. Sandblasting may be necessary to achieve a bond if the facing is old before the RCC is placed against it. The possibility and consequences of saturation and freezing at the bond line should be evaluated.

Dams in steep canyons, and some large projects, can benefit from an upstream wall (16L) placed across the valley. Such a wall acts as an upstream form for the RCC or as a starting wall for concrete facing and membrane systems. It protects the foundation by containing water and debris, and it allows fill to be placed against the upstream side of the wall, thereby creating a practical work area that extends to the

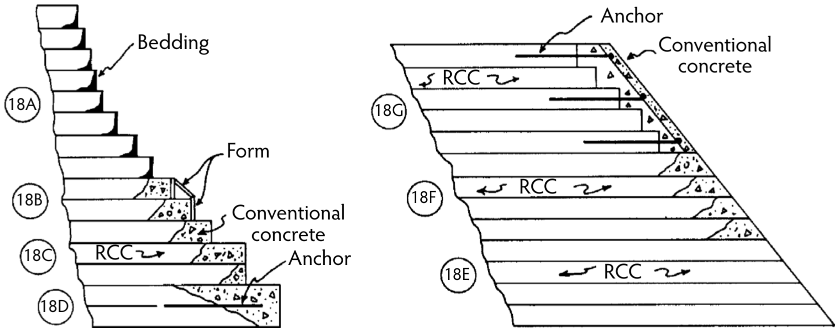


FIGURE 20.45 Downstream face options.

face of the dam. Projects such as Copperfield have saved time and money by placing backfill lift by lift with the RCC to create a vertical upstream face without forms (16M). This is fast and effective and provides a long level surface upon which subsequent forms can be set when the maximum practical height of backfill is reached. Regardless of what procedure is used for watertightness, a tight contact is essential at the interface between the upstream face and foundation. Details regarding this contact and how it varies from one upstream facing or water barrier method to another are beyond the scope of this chapter.

20.5.5 Downstream and Sloping Face Options

The downstream face of the dam, or any other sloping face, can be designed using any one of the many options shown in Figure 20.45 and labeled 18A through 18G, as well as with GERCC as discussed in Section 20.3.6. A common, economical, and practical method uses steps with a small amount of bedding placed against reusable-form panels (18A). The panels are one to three lifts high, moveable without equipment, and held by simple methods such as pins hammered into the RCC after compaction. By changing the width of the steps, any average or changing downstream slope can be achieved. If a conventional concrete appearance or protection from weather is desired, conventional concrete can be used for the facing (18B). Larger steps (e.g., if needed in a spillway) can be built with variations of this method (18C and 18D). Reinforcing steel and anchors are not required with a monolithic construction procedure, but with low-cementitious-content mixes it is essential that the conventional concrete be placed first with a mix that will have lost its slump but not reached initial set by the time the RCC is spread against it and compacted down into it. If the RCC is placed first, the result will look good at the surface, but there will be no reliable contact or interface between the two mixes. Anchorage is then necessary and the RCC should first be compacted at the edge (18D). Smooth spillways and downstream sloped surfaces have been designed and constructed using no treatment except for hand trimming (18E), unreinforced and unanchored conventional concrete facings with about a 1-ft minimum width (18F), and slipformed concrete with anchors and two-way reinforcement placed after completion of the RCC and after substantial chipping or preparation of the RCC (18G).

20.5.6 Thermal Considerations

Concrete produces heat when it hydrates and hardens. This is of little consequence to small placements, but it is of major concern to massive placements. If heat from hydration is trapped within the mass, the internal portion of the mass will harden and stiffen at an elevated temperature. Later, as this heat slowly escapes, the mass will try to contract as it cools. If the mass is restrained (e.g., by being bonded to a rock foundation), it is prevented from contracting. The attempted thermal strain is therefore converted into tensile stress. If the thermal stress is greater than the tensile strength, cracking will occur. Because massive structures typically have little, if any, reinforcement, the stability of the structure usually depends on an uncracked section with internal tensile stresses less than the cracking strength of the concrete.

Roller-compacted concrete provides several opportunities to reduce internally developed thermal stress. Its lower cement content reduces the total hydration heat in almost a direct proportion to the cement reduction. If the mix has a very low cementitious content, the stiffness or brittleness (modulus) of the concrete can be low, and substantial stress relaxation due to creep can occur. Although it can be done, it is not very practical or economical to provide forced post-cooling; some of the traditional methods of precooling, as with ice and chilled water, are also not very economical or effective. Producing aggregates in cold winter months and storing them in large stockpiles until they are used in warmer months has resulted in reduced placing temperatures. This has the same overall impact as using a submerged chilled wet belt or cold air to precool the aggregate, but it is essentially free, and it applies to both fine and coarse aggregate, whereas submerged wet belts can only be used on the coarse aggregate. In addition to controls on aggregate production, the rate of placing, hours of placing (night vs. day), and the schedule for starting and finishing placing are critical factors for thermal stress analysis. The designer must pay attention to these details and consider them in the thermal evaluation.

Thermal evaluations for RCC mass placements require much more attention to detail than is necessary with traditional mass concrete. There are several reasons for this, but the most important is the large exposed surface area for each thin layer of RCC mass that is placed in each lift. Conventional concrete uses a much smaller exposed surface area with a thick layer of concrete mass for each lift. The heat transfer, either by heat lost to the atmosphere or by heat gained from exposure to the sun, is consequently a much more critical aspect of RCC thermal studies. The time of placement of each layer or lift of RCC can also be a very significant factor, whereas the time of day for placement of conventional concrete is not as important. A low-cement-content RCC mixture may have an adiabatic temperature rise that is less than the heat absorbed from the sun before the layer is covered with the next layer of RCC. In this case, placing at a faster rate can result in lower temperatures—exactly opposite of what would occur with normal placing of conventional mass concrete. Details of thermal analyses are beyond the scope of this chapter. Various references contain examples and suggested methods for analysis (Ditchy and Schrader, 1988; Hirose et al., 1988; Tatro and Schrader, 1985, 1992; USACE, 1997).

When properly accomplished with detailed input of the time-dependent construction schedule, finite-element method (FEM) temperature analysis can accurately predict the temperatures of any RCC mix at any location in a structure at any time. This usually requires consideration of the time of day for placement of each layer of RCC, the variable temperature throughout the day, the movement of air across the lift surface, and an accurate determination of the adiabatic temperature rise of each mix. It also requires knowing the physical thermal properties of the materials, considering the type of cure and evaporative cooling, and considering probable interruptions to the placing schedule.

Thermal FEM studies can be simplified by using one-dimensional, heat-flow studies for the more massive sections of a structure, with two-dimensional analysis being reserved for areas of smaller dimensions on the order of about 20 ft wide. The results of the individual studies can then be combined to create a three-dimensional time-dependent result. Using multiple one-dimensional heat-flow analysis where possible can actually be better using than two- and three-dimensional studies because it allows better detailing of the FEM mesh, with nodes at the interface of every lift. This typically is every 12 in. throughout a structure that extends hundreds of feet in each direction. The exact time of placement of each lift can then be taken into account. Large two- and three-dimensional models that are suited to traditional concrete placements with a large mass being placed only every few days typically have much larger node spacings and are unable to account for the detailed placing of RCC in 1 ft layers every 3 to 16 hr.

Figure 20.46 provides a conceptual approach to using one- and two-dimensional models to properly study a large RCC mass. Figure 20.47 shows the results of a study performed with this methodology and gives an idea of the temperature distributions within a structure that used RCC ranging from very lean cement contents in the center of the structure to higher cement contents in the outer 9 ft of the dam. The thermal contours are based on actual field measurements. The temperatures in square boxes indicate the predicted temperature for that mix, location, and time. Predictions were within a degree or two of the actual conditions.

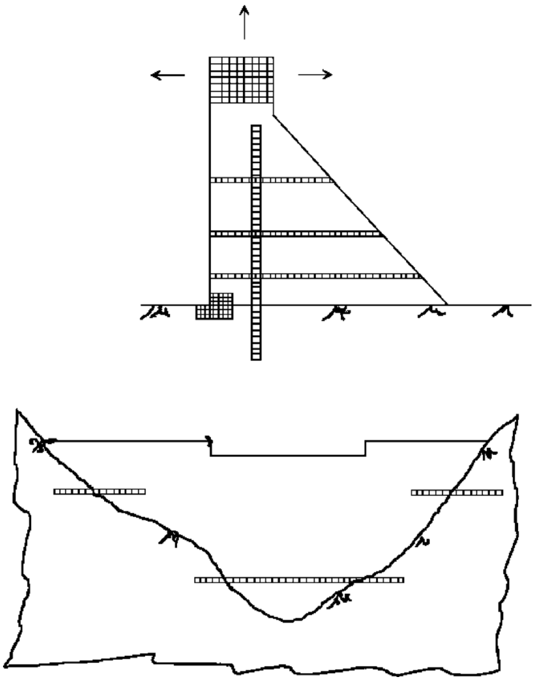


FIGURE 20.46 Sample finite-element method (FEM) mesh for thermal studies.

20.6 Construction

20.6.1 General

Construction is discussed in general in ACI Committee 207 (1989), Oury and Schrader (1992), and Schrader (1991, 1992, 1995a,c,d, 1999b, 2002). There are many examples in the literature of RCC construction methods used at specific projects and their interrelationship with RCC design issues at, for example, the Burton Gorge, Rompepicos, and Burnett dams (Schrader, 1999b; Schrader and Bali, 2003, Lopez et al., 2005). Because of the interrelationship between mix designs, structural design, material properties, and construction, many aspects of construction have been discussed, at least in part, in the previous sections of this chapter. It is important for the contractor to understand that construction equipment and methods have a direct effect on design and that some procedures, production rates, and equipment may not provide the quality or characteristics required for a particular design. What is acceptable for one design and set of conditions may not be acceptable for a different design or set of conditions. Some examples of the interrelationship of design and what may seem like simple construction decisions follow with regard to positioning of supports in the dam for RCC conveyors and how RCC is started at the foundation.

Many RCC dams are constructed using an all-conveyor system, with the conveyor being supported on posts within the dam. The posts are pulled up and raised as the dam is built. Before sufficient RCC has been placed to support the posts, they require a substantial footing. Without proper design considerations, these footings represent fixed rigid blocks protruding into the dam with vertical faces that could initiate cracking both from the perspectives of restraint to thermal contraction and the tendency for the formed vertical face to propagate into the RCC as a crack.

One way to deal with the restraint from objects such as these is to place them at the center of monoliths, or so one face of the footing is flush with a monolith joint. Because thermal contraction is toward the center of the monolith, movement will be from the free face of the monolith joint toward the center, which is already the position of maximum restraint. Footings located here should be bonded to the adjacent RCC. Ideally, footings near the middle of a monolith should be circular, without corners. If the

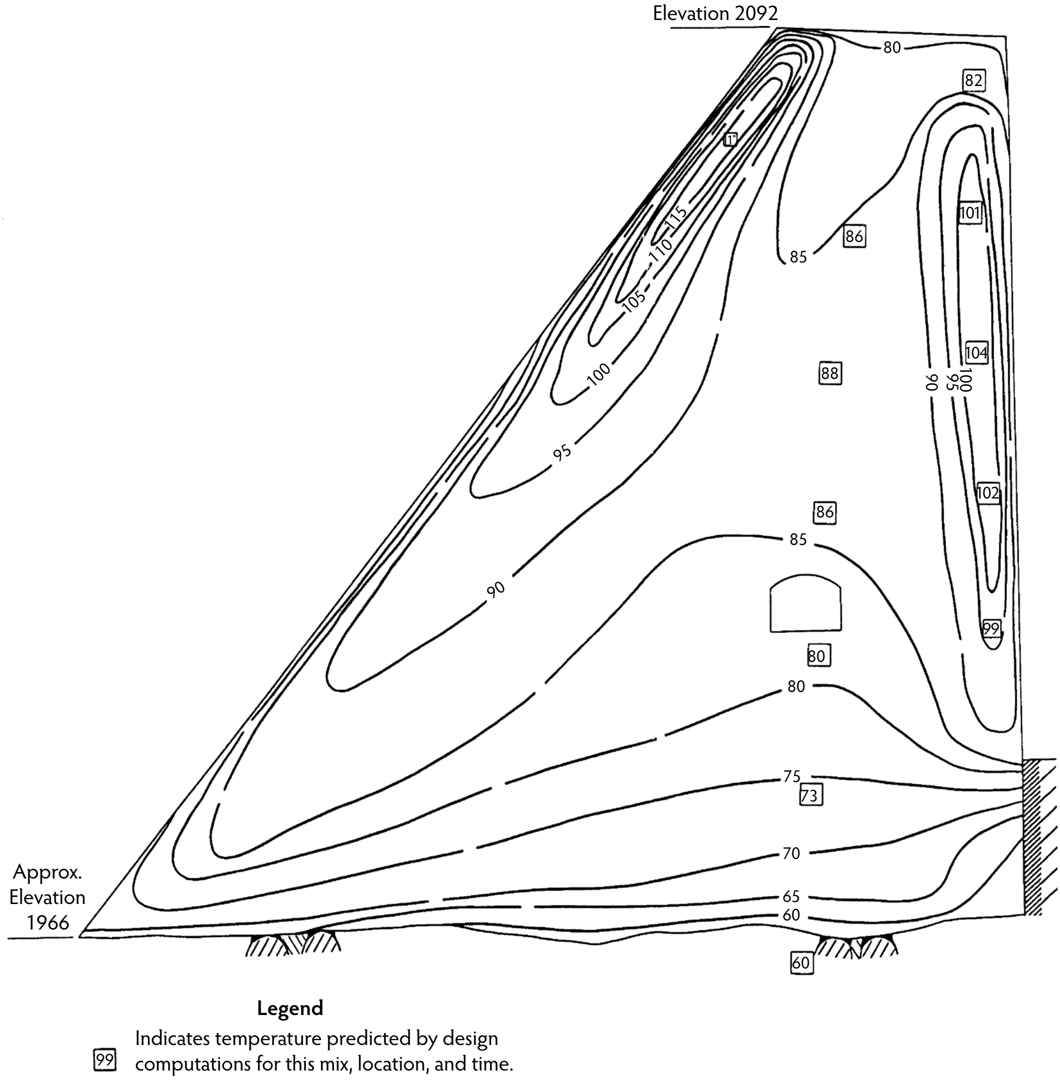


FIGURE 20.47 Predicted vs. actual internal temperatures.

footings have corners, they should be rounded or chamfered. In addition, consideration should be given to reinforcing the RCC in front of corners by dropping bars into these lifts as they are placed. If the footings are located at monolith joints, square footings can be used. In this case, the faces of the footings should be debonded from the RCC (e.g., with curing compound) so the monolith can contract away from the fixed rigid restraint of the footing.

A much preferred approach to footings above the foundation is to avoid them by setting the posts into the foundation. This can be done by drilling large-diameter holes into which the posts are placed. Another procedure that has been used is excavating into the foundation with careful blasting or hydraulic hammer excavation and then filling the hole with dental concrete. The top of the dental concrete is finished flush with the top of the surrounding foundation. The dental concrete block becomes part of the foundation. The post is embedded within the dental concrete. Because this approach eliminates the problem of a rigid block protruding into the foundation, it allows placing the posts at almost any location, with a general guide that they should not be closer than about 2 m from a monolith joint. The posts jack-up out of the foundation as RCC is placed.

Similar to the issue with massive footings above the foundation, concrete (including RCC) ramps should also be avoided within the RCC, unless their impact on design, including thermal restraint and potential for propagation of a ramp face as a crack into the RCC, is adequately addressed. If ramps are to be constructed and left in place, they should use RCC of similar quality to the RCC in the dam, and the position of the ramp should usually be toward the middle of a monolith. Because of restraint, ramps on the foundation require more attention than ramps that are within the RCC, above the foundation.

Some RCC projects have used leveling concrete to cover the foundation and provide a smooth base from which to start RCC, whereas other projects start with RCC directly on the foundation. There are arguments for each approach. Considerations for and against the use of leveling follow. Leveling concrete simplifies the start of RCC placing and its initial production rate, but it requires considerable time to construct, and it uses concrete that is more expensive than RCC, with different properties than the RCC. If the RCC or foundation has a high tensile mass modulus similar to conventional concrete, the leveling concrete will simply be another material with properties similar to what is above or below it, so this is of less concern. If conventional concrete is used for leveling on a foundation with substantial undulations and slopes, it will be very thick in most locations. This will require thermal controls that usually involve forced cooling of the leveling mix. If the project already has ice capability for other purposes, the problem is not difficult to overcome, but if no cooling capability would otherwise be necessary then this becomes a major expense. In addition to thermal cracking, consideration should be given to drying shrinkage. This requires the leveling mix to be continually cured until it is covered with RCC.

Formed vertical and clearly defined joints should be avoided in leveling concrete unless they coincide with contraction joints in the RCC. This applies to both the transverse and longitudinal directions. A formed joint represents the start of a crack off the foundation and a stress riser (restraint) where thermal stresses are usually maximum. Some projects that have used leveling concrete and could not avoid extra joints due to concrete plant and placing capacity issues have later injected the joints with epoxy after they opened and before placing the RCC. Leveling concrete typically has long-term stiffness (modulus) values on the order of 20 to 35 GPa (3 to 5 million psi) with low creep. If this concrete is placed on a foundation with lower tensile mass modulus, it creates added restraint and therefore higher thermal stresses.

Any type of RCC mix can be placed directly onto foundation rock without leveling concrete. This is accomplished by first spreading a thin layer of high-slump bedding mix (with or without coarse aggregate) onto the rock and then spreading the RCC over the bedding and compacting it while the bedding is still fresh. This has been one of the most common procedures for placing RCC on foundations, and it has been very successful. The RCC compacts into the bedding so the two materials become one concrete, while the grout and mortar portion of the bedding conforms to the rock and provides total glued contact to it. No distinctly different material lies between the foundation and the RCC, which avoids the separate leveling mix and its concerns.

If the foundation is relatively poor and it would deteriorate from exposure prior to placing the RCC, it is common to use shotcrete or a thin mud mat of high-slump concrete to seal and protect it. The shotcrete typically is on the order of 50 to 100 mm (2 to 4 in.) thick, and the mud mat is 100 to 150 mm (4 to 6 inches) thick. Clearly defined formed edges should be avoided. The material will be subject to some cracking, but the cracks will be random. By keeping the mud mat thin, cracks will likely mirror the joints in the foundation rock and not propagate up into the RCC. Where shotcrete is placed against abutments and there is a tendency for the foundation underneath to still deteriorate or where the abutment could not be cleaned to sound material before shotcreting, grout pipes have been used to ensure a seal between the shotcrete and foundation. Each grout pipe should be an individual line, usually PVC, that is routed through the dam to a convenient location such as the downstream face for later grouting. It is imperative to maintain identification of each pipe so they can be grouted in a planned pattern after the RCC has been placed to a substantial height above the location. The pipes should not be interconnected.

Rapid construction is important to quality, simplicity, and profit in RCC projects. It is more difficult to produce quality construction at low production capacity than at high production rates. In general, RCC mixtures that do not contain a retarder should be delivered within 10 minutes of when mixing started, spread within 10 minutes of when they are delivered, and compacted within 10 minutes of when they are spread. Typical specifications require that the elapsed time from the start of mixing until the end of compaction should not exceed 40 minutes. The exposed edge of RCC lifts should also be compacted or advanced within about 40 minutes of when the material was mixed. These time limits are good guides, but consideration should be given to the particular characteristics of each mixture, the temperature, whether the mix is placed in a critical part of the structure, and the practicality of construction.

A common characteristic of profitable and technically successful RCC dams is good communication between the contractor and designer, with decisions being made promptly and with authority in the field. Interruptions and slowdowns result in reduced joint and RCC quality as well as increased costs. Interruptions to a continuous RCC construction operation are bad for both the engineer and the contractor. Direct communications and procedures for on-site problem resolution are essential, without excess personnel, management, or administration. This sounds basic and simple, but it is amazing how many projects have suffered from insufficient authority, responsibility, and responsiveness in the field—from both the contractor and engineers. When problems develop at the placing area, they must be resolved quickly. In RCC construction, there usually are no alternative monolith blocks where work can progress while the problem is studied. When contingency plans for added monolith joints are approved in advance, it may be possible to raise a portion of a structure or massive placement ahead of the rest of the structure, but this can result in placing difficulties and the design implications must be considered.

Profitable and efficient RCC construction is machine intensive, with minimal labor per cubic yard of placed RCC. Equipment should do the majority of the work, not labor, even for smaller projects. The rare exceptions are special projects designed to be labor intensive in developing countries with the intent of employing a large unskilled labor force at low wages. Fueling, form work, and assembly of embedded items should all be scheduled and planned so the majority of this work is accomplished off the lifts and during shift changes or scheduled downtime. All unnecessary vehicles and personnel (including visitors and inspector trucks) should be kept out of the placing areas and equipment paths. It is essential for all materials, access, embedded parts, foundation excavation and preparation, and similar work to be planned and readied well ahead of time.

20.6.2 Aggregate

The location, size, and withdrawal of aggregate from stockpiles must be coordinated with the RCC plant location and method of feed to minimize segregation and variability. At the very high production rates possible with RCC, several loaders or a conveyor system may be required to keep feed bins full. The length of haul and size of turnarounds must be considered so loading equipment can operate rapidly, efficiently, and safely. Aggregate stockpiles and the concrete plant location can be even more important than in the production of conventional concrete. Typically, very large stockpiles that could easily be half the material needed for a season of placement are provided prior to starting RCC placement. Some of the reasons for this are as follows:

- Technical design requirements may require producing aggregate during the winter so it can be stockpiled in the cold for later use. At Middle Fork and Monksville Dams, winter stockpiling resulted in aggregates that still had occasional frozen areas when the material was withdrawn during the summer, although ambient temperatures exceeded 80°F. At Burton Gorge Dam, instrumentation showed that producing RCC aggregate at night resulted in a 10°F lower aggregate stockpile temperature than producing similar aggregates during the day.
- It may be relatively easy to mobilize aggregate production to full operation while work for the rest of the project is just beginning. It is customary to pay for aggregate in a stockpile at the job site if it is tested and found to be acceptable. Payment should be based on an appropriate percentage of the in-place cost of RCC, including some profit.
- The rate of aggregate use during RCC placing may exceed the aggregate production capacity. With large stockpiles, material that occasionally is produced out of specifications may be spread throughout the acceptable material to produce a blend that is within specification. Larger aggregate stockpiles also have the benefit of more stable moisture contents which reduces fluctuation in RCC consistency.

FIGURE 20.48 A large "all-in" aggregate stockpile with no segregation at Burnett Dam.

Although many RCC dams have been constructed with numerous aggregate size groups and stockpiles, many others have been very successfully constructed with just two size groups. Usually this is +3/4 in. and –3/4 in. Some projects have used a single, all-in size group. Figure 20.48 shows an all-in, 2-in. MSA aggregate pile at Burnett River Dam. As cost and production benefits are demonstrated on more and more projects, with excellent control of moisture and variability, minimizing stockpiles is becoming more popular. Fewer size groups mean less area for storage and less equipment for loading and transportation. Fewer aggregate bins are required, and less complicated mix designs are possible. A major benefit that is often overlooked is what happens if an aggregate feed bin malfunctions. If a plant has four bins and each bin carries a separate material, production stops if one bin malfunctions. If the same four-bin plant is used to carry only two size groups, at least one of the size groups would be fed with more than one bin. When a bin malfunctions, production can proceed, though at a slower pace, with the operating bins while repairs are made to the bin that is down.

When low-cementitious-content RCC mixes are used, it is necessary to include nonplastic fines (passing 75-µm or No. 200 sieve) to compensate for the otherwise low paste content. When fines are included with a size group of –3/4 in., the material is similar to a road base. It has minimal tendency to segregate, especially if it is damp. Also, the moisture content in the pile tends to stay very uniform because the material is not free draining. This is not the case with traditional washed concrete aggregates. Very large and high stockpiles of –3/4-in. RCC aggregate containing nonplastic fines have been built in layers. The aggregate is later removed without segregation by a front end loader. A potential disadvantage of handling an RCC aggregate with nonplastic fines is its tendency to compact in bins and bridge small gate openings unless special precautions are taken.

20.6.3 Mixing

A comprehensive discussion of RCC mixing and delivery philosophies and specific concerns about handling RCC is available in Oury and Schrader (1992). This reference also includes details and experiences, beyond the scope of this chapter, that are pertinent to a wide range of RCC mixing and delivery equipment types. The concrete plant location should be selected to minimize energy requirements and be appropriate for the terrain, whether the RCC is transported by conveyor or haul vehicle. It should be selected to minimize overall haul distances, vertical lift, and exposure of the fresh mixture to sun and weather. The plant should be located on a raised area so spillage and wash water drain away without creating a muddy area, especially if vehicular haul is used. The plant location for dams will generally be in the future reservoir area just upstream of the dam and above the cofferdam level or on one of the abutments. The plant should have a bypass or belt discharge that allows wasting rejected RCC without first delivering it onto the dam. This bypass can also be used for sampling, for delivery to trial sections, and for other construction uses.

Both continuous mixers and batch mixers have been used to produce RCC; continuous **pugmill** mixers are the most common. Batch operations with drum mixers tend to cause the most difficulties and concerns. They should not be used. For the same space requirements, continuous mixers generally provide greater capacity than batch-type plants. Continuous pugmill mix plants specifically intended for RCC and properly operated and maintained routinely achieve good production rates and uniformity. This applies to plants that operate with volumetric controls as well as to those that operate on weight controls.

Although some RCC has been successfully produced with conventional batch-type plants having drum mixers, problems with low production, bulking, sensitivity to the charging sequence, mixture variability, slow discharge, and buildup in the mixer have been common. This does not mean that acceptable RCC cannot be produced by batch methods and drum mixing, but special attention is needed and low productivity can be expected. Equipment that is well suited to normal high-production conventional concrete is not necessarily suitable for all RCC mixtures and the typically higher production rates.

Roller-compacted concrete mixtures can be very harsh, and some can cause the buildup of fines. Drums should be designed or coated to resist buildup that tends to result from the high fines content of some RCC mixtures. Even with these precautions, experience has shown that substantial buildup can develop in drum mixers. If the buildup is not removed, a loss in mixer effectiveness results. Except for special small applications with higher cementitious contents, clean conventional-type aggregates, and aggregate sizes limited to about 3/4 in., transit trucks and mobile batch plants should be avoided. Even with these types of mixtures, slow discharge and high mixture variability should be anticipated.

Pugmill mixers that were originally intended for cement-treated base, asphalt, or moisture conditioning of soils have presented difficulties with maintenance and variability when they have been used to construct RCC dams; however, pugmill mixers of both the batch and continuous-mix type have performed well when they are specifically designed and intended for RCC. Typical individual plant capacities range from about 150 to over 400 compact cubic meters per hour. It is generally better to have multiple smaller plants than a single larger plant. If one plant is down, the others can usually continue placing while repairs are made. Also, it is easier to find subsequent uses for smaller plants than for very large specialized plants.

The theoretical or rated peak capacity of the plant should be well above the desired average production. As a general guide, the average sustained placing rate usually does not exceed about 65 to 70% of the peak or rated plant capacity when haul vehicles are used for delivery on the dam and 75% when an all-conveyor delivery system is used. These values tend to be lower on smaller projects and higher on uncomplicated larger projects. Table 20.11 shows the average efficiency that can be expected throughout each placement shift for different work schedules and methods of delivery with a properly managed project. These values have increased only a slight amount in recent years compared to early RCC projects.

Mixers for RCC must accomplish two basic functions: They should provide sufficient capacity for the high placing rates typical in RCC, and they should thoroughly blend all ingredients. Typical average placing rates are on the order of about 50 to 150 yd^3/hr for small projects, 200 to 500 yd^3/hr for medium projects, and 500 to 1000 yd^3/hr for large projects. The mixer should operate with little or no downtime. Scheduled maintenance must not be neglected, and repairs should be accomplished rapidly.

Variations in the free-moisture content of the aggregates can be particularly troublesome when the plant starts up. Some plant operators make the error of overestimating free moisture and provide too little water in the initial mixtures. This is particularly undesirable because most initial mixtures will be used for covering construction joints or foundation areas where the RCC should be slightly on the wet side for improved bond. It is better to start on the high side for moisture and subsequently reduce it to the desired consistency than to start with a mixture that is too dry.

TABLE 20.11 Probable Average Sustained Production through Full Shifts

Shifts Worked	Days Worked	All-Conveyor Delivery (%)	Haul on Dam (%)
Two, 10-hour Two, 8-hour	6 on, 1 off *or* 12 on, 2 off	76	66
Three, 8-hour Two, 12-hour	6 on, 1 off *or* 12 on, 2 off	73	63
Three, 8-hour Two, 10-hour Two, 12-hour	Continuous up to 28 days	70	61
Three, 8-hour Two, 10-hour Two, 12-hour	Continuous over 28 days	65	55

Note: Assumes Aran continuous pugmill and Rotec or equal proven conveyor. Reduce efficiency by 10% if multiple shifts per day do not overlap. Although Rotec conveyors and Aran mixers (or proven equivalent) may be capable of 80 to 90% efficiency by themselves, the above efficiencies are realistic overall shift values when total maintenance, all types of other equipment breakdowns, aggregate feeding/delivery, raising and moving forms or facings, and slowdowns at abutments are considered.

Mixture uniformity must be maintained for all the production rates used. Continuous mixers typically work efficiently above a minimum production rate and up to production levels that are two to four times that of the minimum rate. A consistently uniform mixture must still be provided even when slowing production by, say, 50% near abutments and when increasing it again after leaving confined areas. Large projects with multiple mixers can simply shut down one or two mixers until the higher production rate is needed again. On smaller projects with one mixer, the mixer must be capable of uniform production at varying outputs. Mixture variability is discussed in more detail in Schrader (1987, 1988, 2003a). Table 20.12 provides a summary of what can be expected with regard to the variability of RCC mixtures at different levels of quality control.

Accurate and consistent control of cement and pozzolan feed is particularly important with continuous-mix plants. This is especially true at lower cement-feed rates. Feeders designed to operate at the high cement-feed rates typical of soil cement or conventional concrete usually do not operate well at the low cement rates required for some RCC mixes. Maintaining sufficient head in the silos, using air fluffers, and using vane feeders or positive-displacement cleated belt feeders have been necessary to provide accurate feed. Proper ribboning or sequencing and feed rates of the aggregates and cementitious material as they are fed into the mixer are critical to minimizing mixing time. Each plant and RCC mixture seems to have its own peculiar requirements that can only be determined by trial and error. Properly designed pugmills have handled 3 in. and larger nominal maximum size aggregate (NMSA), but experience has shown that the amount of material larger than 2 in. should never exceed about 8%, and the maximum size should not exceed 4 in. The preferred NMSA for most mass applications of RCC is 2 in.

Accurately introducing the correct quantities of materials into a mixer is only one part of the mixing process. Uniformly distributing and thoroughly blending them throughout the mixture and then discharging them in a continuous and uniform manner comprise the other part of the process. This can be more troublesome with some RCC mixtures than with conventional concrete mixtures. The accuracy of the concrete plant and methods for control of the mixture during production should be studied for cost effectiveness. If exacting quality control and low variability are necessary, they can be provided in RCC mixtures. Typical coefficients of variation for RCC compression tests are shown in Table 20.12.

20.6.4 Delivery

The volume of material to be placed, access to the placement area, availability of rental or lease equipment, capital cost for new equipment, and design parameters generally are the controlling factors for selection of equipment and procedures to be used for transporting RCC from the mixing location to the placing area. Essentially, the three methods for transporting RCC are by batch, continuously, or

TABLE 20.12 Quality Based on Variability for Roller-Compacted Concrete

		Coefficient of Variation				
Description		Excellent	Very Good	Good	Fair	Poor
Overall	General construction, sampled from the placement	0–11	11–14	14–18	18–23	>23
Within batch	General construction	0–4	4–6	6–8	8–10	>10
Within batch	Lab trial batches	0–3	3–5	5–7	7–9	>9

Source: Schrader, E.K. et al., in *Roller Compacted Concrete Dams*, Berga, L. et al., Eds., Swets & Zeitlinger, Lisse, 2003, pp. 355–362. With permission.

using a combination of both—typically, via a continuous conveyor feed to a hopper on the dam from which vehicles take batches for final delivery to the spreading area. To some extent, transportation may be influenced by the type of mixing equipment used; however, with proper controls and accessories, such as holding hoppers designed to control segregation, continuous mixers can be used with batch transportation and batch mixers can be used with continuous-flow transportation equipment.

The type of transporting equipment used to move RCC from the mixing plant to the placement area will also be influenced by the largest aggregate size in the mixture. Experience indicates that 1.5-in. NMSA concrete can be transported and placed in nonagitating haul units designed for aggregate hauling and earth moving without substantial uncontrollable segregation. Mixtures with large 3-in. NMSA aggregate have more of a tendency to segregate when they are dumped from this type of equipment onto hard surfaces, but with care and proper procedures these mixtures can be hauled and dumped successfully. Problems with segregation during the transportation and placing of 6-in. NMSA mixtures have been severe. Typical current practice is to require that 100% of the aggregate be smaller than 3 in., with only 1 or 2% allowed above 2 in., and allowing 100% to pass 1.5 in.

The entire system of mixing, transporting, spreading, and compacting should be accomplished as rapidly as possible and with as little rehandling as possible. The time lapse between the start of mixing and completion of compaction should be considerably less than the initial set time of the mixture under the conditions in which it is used. A general rule for nonretarded mixtures with little or no pozzolan is that placing (depositing), spreading, and compacting should be accomplished within 40 minutes of mixing, preferably, within 30 minutes of mixing. This time limit is applicable at mix and ambient temperatures of about 70°F. It can be extended for colder weather and should be reduced in warmer weather. It also can be extended for mixtures that are proven to have extended set times because of high pozzolan contents, slags, or effective admixtures with wet RCC consistencies. A simple test to establish the tolerable time for any particular mix and temperature is to compact two cylinders from the same batch every 15 minutes, beginning immediately after mixing. The cylinders are all tested for compressive strength at the same age, at about 14 or 28 days. A plot of strength vs. time of compaction will quickly indicate the age at which compressive strength becomes seriously affected. Tests have shown that tensile strength and the modulus of elasticity will begin to decrease at about the same time and at the same rate as compressive strength.

The two primary methods of transporting RCC are by conveyor and hauling vehicle. Transport by bucket or dinky has been used, but this slows the rate of production and is more prone to cause segregation; however, if such a system is already available or necessary for large volumes of conventional concrete, it can also be used for the RCC. Pipe delivery has been tried on a few projects with varying degrees of success. If pipe delivery is considered, it should be designed specifically for the mix to be used and potential pressures, it must have a steep slope, the technical issues of moisture loss and temperature gain must be addressed, the length of time in the pipe and its effect on the age of the RCC when compacted must be considered, and sustained satisfactory operation should be proven in full-scale trials.

Transporting RCC by continuous high-speed conveyors directly to the dam is generally preferred. The overall economics, including all direct and indirect costs of alternative delivery systems as well as reliability, the final quality, and schedule should be considered when deciding whether to use or require an all-conveyor delivery system. All aspects of the conveyor system should be specifically designed for RCC of the type used on the project. The advice of personnel experienced with the type of mixture and equipment proposed should be solicited. Conveyor systems that may work well with conventional structural concrete, aggregates, coal, or other materials may not work well with RCC. Conveyor systems that work well with a high-cementitious-content, wetter, small-aggregate, or no-fines RCC may not work well with a low-cementitious-content, drier, larger aggregate, or high-fines RCC. Clogged transfers, segregation at the discharge, severe wear at transfers, segregation over rollers, slow belts, not being able to start or stop a loaded belt, drying, loss of paste, and contamination of the RCC lift surface by material dropping off the return side of belts are the most common problems. A detailed discussion of conveyor equipment and methods can be found in the literature (Oury and Schrader, 1992).

Where equipment is readily available for lease or rent, an all-conveyor system can be as economical and practical for small projects as it is for larger projects. The 4000-yd^3 Echo Lake Dam in California is an example. The project utilized a highway-mobile, all-conveyor delivery system that was driven to the job site and erected in one day. It was used the next two days for RCC placement where haul units could not possibly work and was then driven off to the next project. It was fed from an equally mobile RCC continuous-mix pugmill.

A written agreement stating that the schedule and design are based on a required predeveloped conveyor delivery system is an approach that can be used at the time of the design so the engineer can confidently base the design on the better quality, cleaner, and faster lifts placed by specialized RCC conveyors, rather than relying upon the slower production and lower quality lift surfaces typical when haul vehicles are used on the surface. The supplier guarantees availability of the equipment, the required production capability, "not to exceed" reasonable downtimes, and availability of field technicians to assist the contractor. The supplier also guarantees a "not to exceed" price that will be quoted to all qualified bidders. The agreement should address an appropriate allowance for downtime and on-site spare parts.

Allowance is made for contractors to submit a more elaborate conveyor system, whereby, at their option, their costs may be greater but they purchase rather than lease the equipment or they achieve faster production rates. This approach has been used on public projects in at least two countries, with legal documents being created that satisfy all public entities as well as the designer, supplier, and contractors. This approach has proven to be good for owners, designers, and contractors. It reduces risk, ensures a low, preestablished cost, guarantees placement methods that are compatible with design, and helps maintain the planned construction schedule.

All-conveyor delivery systems can be supported and arranged in several ways. One approach that has been used for many years, including on projects such as the Cuchillo Negro Dam, Lake Robertson Dam, Loyalty Road Dam, and others, utilizes vertical posts embedded in, and raised with, the dam to support and raise the conveyors. Conveyors reach from the posts to essentially anywhere on the dam surface. Seigrist and Spring Hollow Dams are examples where conveyors were used that were supported from smaller pipe posts anchored to the upstream face of the dam with a long conveyor that extended the full length of the upstream face of the dam and that raised with the dam. This approach was successful, but the procedure has not become popular because other methods have been more effective and adaptable to changing field conditions. The conveyor feeds a tripper that runs along the main belt at the upstream face to feed a crawler-mounted mobile conveyor placer on the lift surface. The crawler placer can drive on the surface, extend or retract its conveyor, lift it, or swing it similar to the boom on a hydraulic crane. This allows the operator to deposit the RCC in a layer at its final location. Smoothing the layer with a bulldozer and compaction can follow immediately after the RCC has been deposited from the conveyor. A similar procedure was used for much of the San Rafael Dam in Mexico. The crawler placer, with a different setup for the conveyors that fed to it, was used at Concepcion Dam in Honduras and is being used at the Pangue Dam in Chile and other RCC dams.

For Echo Lake and Big Haynes Dams, wheel-mounted conveyors, called *creter cranes*, and swingers reached from outside the dam to the lift surface to deposit the RCC in layers; however, this method is only suitable for small dams or for the smaller upper abutment portions of larger dams, as was done at Burnett River Dam. Burton Gorge Dam in Australia utilized a partial conveyor system with a belt feeding

FIGURE 20.49 Tower belt with 320-ft reach at Miel I dam in Colombia.

continuously from a pugmill mixer to a hopper on the dam. Trucks then hauled the RCC from the hopper to the placing area. Problems with this type of system include continual raising of the hopper, segregation at the edges of each load dumped into and out of the trucks, damage to the surface caused by the truck tires, and insufficient room at the top of the dam for the hopper and trucks.

Large dams now typically use a *tower belt*. The largest towers may stand more than 200 ft above the surface of the dam and raise with it. They also can reach as high as 300 ft. The tower supports a horizontal boom with a line and hook that virtually hang a large conveyor out in space, or it can be used to lift very large loads at long reaches when used as a traditional crane. The tower itself can also be rigged to support connected segments of conveyor belt in space, leaving the crane available for other tasks. The conveyor belts typically feed a large *crawler placer*. This equipment is essentially a crawler-mounted crane with another belt for a boom. The belt can extend in or out, swing left or right, and angle up or down to deposit RCC in even windrows at essentially any location on the dam. Within a couple minutes of mixing, fresh RCC is typically delivered and placed on the dam with this type of system at rates ranging from about 200 to 1000 yd^3/hr. The Miel I dam in Colombia is one example (Figure 20.49). Exposure time on conveyors should be as short as practical, with a maximum typically of about 5 minutes. Belt speeds should be on the order of about 10 to 30 ft/sec. Covering the conveyor to protect the mixture from drying and from rain should be required for all long sections and preferably for the entire system.

A well-designed conveyor system can also be capable of handling conventional concretes concurrently with RCC; however, this may complicate the placing operation unless separate parallel conveyors for the RCC and conventional concrete are provided. On the Elk Creek project, a larger belt was used for RCC while a parallel smaller one was used for conventional concrete, bedding mixes, facing mixes, and grout. It is especially important that conveyors do not allow RCC or other material to fall onto the compacted RCC surface along the conveyor path. Because of the rapid rise of RCC dams, conveyor systems should

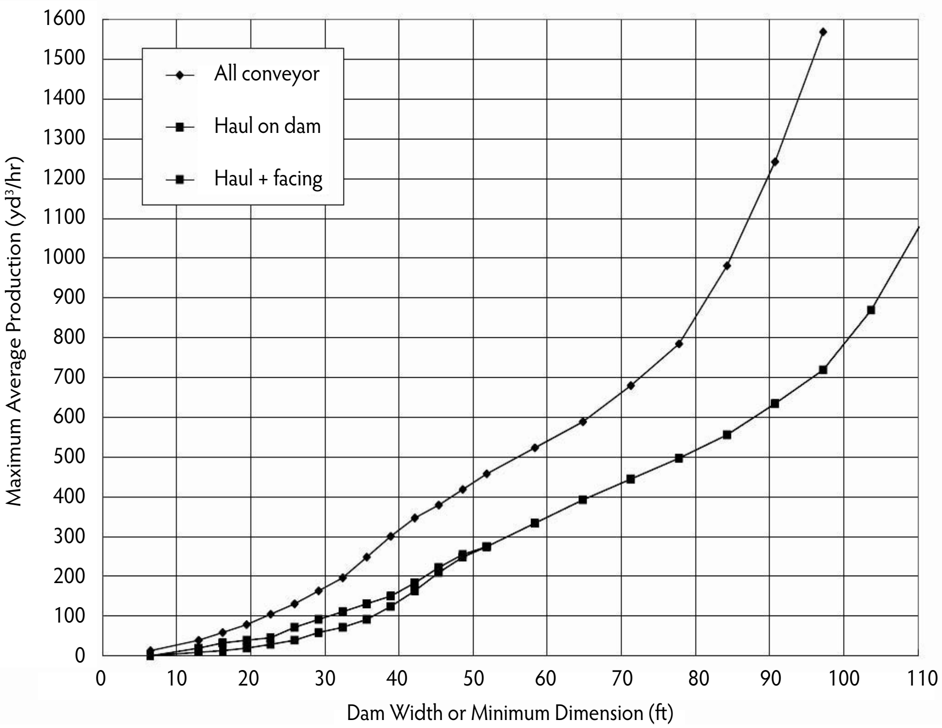


FIGURE 20.50 RCC production in confined work areas.

be designed to be raised quickly. When conveyors are located above the lift surface, provision must be made for clearance of equipment operating under them.

As with conventional mass-concrete conveyor systems, special attention should be given to belt widths, speed, protection, maintenance, incline angles, backup systems, and spare parts. Belt scrapers should be provided to clean return belts, which typically require frequent attention for adjustment and wear. Special attention is necessary to prevent segregation at transfer points and at any interim hoppers or bins.

A continuous belt running from the mixer to the final placement area can substantially increase placing rates and significantly reduce other equipment needs and their related labor requirements. Figure 20.50 compares typical average achievable productivities for reduced dam widths when delivery is totally by conveyor and when haul vehicles are used on the dam. Without a conveyor, productivity decreases to very low rates in narrow sections such as at the top of a dam. Figure 20.50 is based on a compilation of actual data at various projects and from computed round-trip delivery times at other projects.

In addition to the benefits of full-conveyor delivery (no hoppers, fast delivery, less congestion, no haul roads, less maintenance, less labor, elimination of lift-surface damage from haul vehicles, and improved productivity), the conveyor can also serve as an access walkway and as a support for lights, water, air, and electric lines to the placement area. A plan has even been developed to use the conveyor as a support for a roof or enclosure to protect the placement area from rain, sun, and wind.

When haul units are used to distribute RCC that is conveyed to the lift surface, a hopper arrangement that continuously loads them will be necessary at the end of the main conveyor. The objective is to allow the mixers and conveyors to operate and discharge without interruption or waiting for haul vehicles. The recommended minimum size of the hopper is at least twice the size of the haul vehicle. Because of the relatively high unit weight of freshly mixed RCC compared to the loose unit weight of soil, rock, or gravel normally hauled in these vehicles, weight rather than volume normally controls the amount of material hauled per trip. Bottom-dump trailers and scrapers minimize segregation, spreading requirements, and the distance the RCC drops, but they are difficult to use near abutments and obstructions. Scrapers have better mobility than bottom-dump trailers of the highway type. Scrapers and bottom-dumps trailers have the advantage of depositing material in the layer to be spread as they are moving. This was common method of placement in some early RCC projects, but it has lost favor to large articulated trucks with special tailgates that minimize segregation or to all-conveyor delivery.

Front-end loaders have been used to deliver RCC from a central feed point on the placement to the location where it is spread. This is generally not suitable and should not be done on large projects or in critical areas. The method has resulted in problems with contamination of joint surfaces, limited productivity, and segregation. In special cases, however, where the mixture is not susceptible to segregation, spillage can be avoided, and tire tracking is not a problem, this method may result in the most economical situation that is also technically acceptable. Principle candidates for this approach are smaller dams in tight canyons where the distance for loader travel is minimal. Also, the projects should preferably have a smaller maximum size aggregate, excellent gradation, and a tendency for a higher paste and cementitious content. In addition, each layer should be placed and compacted before the set time of the previous layer. Extra cleaning or special grout or bedding mixtures may be appropriate between layers when they are not placed and compacted before the previous layer reaches its final set. If vehicles are to be used for transporting RCC, a thorough study should be made of the haul route. Problems that may prevent hauling by road include steep and rough terrain, availability of road-building material, plant location, schedule, and environmental considerations. If the concrete plant is located upstream of a dam, it may not be practical to bring the road through or over the upstream face system. Raising the roads to keep up with the rate of rise of the dam may require so much time that it becomes an inefficient system at higher elevations. To avoid slowing down the mixing and placing operations, raising the roads during a 2- to 4-hr/day shutdown period while maintenance and other work is being done should be considered. Roads must be kept at slopes consistent with the capabilities and safety requirements of the equipment.

Haul roads should make the transition onto the lift surface at a shallow angle if possible (plan view) so turning and damage by tires are minimized. If an immediate right-angle turn is necessary (from roads that enter directly onto the dam perpendicular to the face), significant scuffing and lift-surface damage will result. Operators should move slowly while turning and use the largest turning radius possible. The road should be constructed with clean, free-draining rock or gravels, if possible.

The last portion of the road prior to entering the lift should be surfaced with large aggregate or clean rock material that minimizes contamination of the RCC surface from truck tires. Simply extending the RCC onto the road will not provide cleaning action. To prevent lift contamination, it may be necessary to use water sprays to wash vehicle wheels before they are allowed on the lift surface, but excess water dripping from the truck and its tires can become a problem. To minimize adverse effects on the surface, hauling equipment should not travel in a concentrated path on the lift. Even with all of the above precautions, experience, including observation and cores, has shown that damaged lift surfaces should be expected where haul roads onto the dam are used.

When the RCC is hauled to the placing location and dumped, it should generally be deposited on previously spread but uncompacted material and pushed forward onto the compacted lift surface. This provides remixing action and minimizes clusters of coarse aggregate that otherwise would tend to occur at the lift interface. When RCC is dumped in large piles, larger aggregates tend to roll down the outside of the piles and create clusters. A general rule is to limit the height of a pile to 5 ft. Correcting this kind of segregation is nearly impossible if the rock has already rolled onto a previously compacted lift. Where this condition occurs, the segregated large aggregate must be removed, broadcast onto the RCC layer being spread, or wasted.

20.6.5 Placing and Spreading

A preferred technique for placing RCC is to advance each lift from one abutment to the other. An exception is where the distance from abutment to abutment is smaller than the distance from the upstream to the downstream face, such as at the bottom of dams in narrow canyons. In this case, placing can begin by working in the upstream–downstream direction. Large dams, where the distance from abutment to abutment is long and where all of the foundation may not be ready at the time RCC placement starts, can benefit from placing between forms within any group of monolith blocks if the area is large enough for efficient production. This will also reduce the time of exposure of each lift, thereby improving lift-joint quality. The practice from embankment construction of limiting the direction in which rolling equipment can operate does not apply to RCC.

Some early RCC projects considered, recommended, approved, or required placing RCC in paving lanes, typically going from abutment to abutment. This initially seemed like a logical approach, but the practice is now discouraged or prohibited. The problems with it are more serious with low-cementitious-content, dry-consistency, and large aggregate mixtures. Although they may work well with paving mixtures and paving operations, spreader boxes attached to dump trucks, Jersey spreaders attached to dozer equipment, and paving machines lack mobility and occupy important space in narrow areas of the dam. They can be difficult to maneuver at the abutments. Paving lanes tend to leave segregation along the edge of the lanes with dam mixtures. The edges can also become too old to be well mixed and compacted into RCC of the adjacent lane by the time the adjacent lane is placed. The edge also tends to dry out while exposed prior to placing the adjacent lane. This has resulted in concerns over poor quality and weakened or permeable planes through the dam at the interface of paving lanes. For a high-cementitious-content mix with smaller aggregate, a wetter consistency, and a retarded set time, concerns about placing using pavement lanes are reduced.

Tracked dozer equipment has proven to be best for spreading RCC. It is fast and sufficiently accurate and contributes to uniformly compacted RCC. By careful spreading, a bulldozer can remix RCC and minimize segregation that results from dumping. Careful attention should be given to ensure that remixing is occurring and that the dozer is not simply burying segregated material. At Elk Creek Dam, retarded RCC mixtures with a Vebe time of 15 to 25 sec were end dumped in piles at least 35 ft from the advancing face. Dozers knocked down the piles and spread the RCC forward into thin, unsegregated, 6-in.-thick layers until a full lift thickness of 24 in. was reached. The entire surface of each layer was traversed by at least two passes of the dozer tracks. This dozer action produced an average density of 147 pcf. Only the top of the 24-in. full thickness of the lift then required additional compaction by the roller. Similar results have been achieved with other RCC mixtures having a wet mixture consistency. At Nickajack Dam, wet-consistency, air-entrained RCC was spread in two 12-in.-thick layers, with the second layer following behind the first layer. The second layer was compacted before the first reached initial set. The advancing layer was about 100 ft in front of the following layer.

At Burton Gorge Dam in Australia, 100% compaction was achieved using a small dozer in the top portion of the dam by modifying the mixture with retarder, using a wetter consistency, placing rapidly (one lift every 1 to 4 hours), and rigorously tracking the 12-in.-thick layers as they were spread. This resulted in densities that reached the theoretical air-free density of the mixture. Thorough dozer tracking the same mixture at a dry consistency and without retarder, but while the mixture was less than about 30 minutes old, achieved densities on the order of about 96% of the theoretical air-free values. This was followed by roller compaction to achieve a higher final density.

Typically, two rollers and one D6 dozer with a backup smaller dozer can spread and roll nonretarded RCC at a rate of about 300 to 500 yd^3/hr in 12-in.-thick layers. The dozer should operate on fresh RCC that has not been compacted. All turning and crabbing should be done on uncompacted material. Operating the dozer on a compacted surface will damage the surface, unless the dozer is equipped with rubber tracks and the operator uses special care. Recently a device has been developed with rubber tires that attaches to the dozer. The device is lowered to lift the tracks off the surface so the dozer can drive across the RCC form one end to the other without causing damage. When it is necessary for the dozer without this device to drive onto compacted RCC, the operator should limit the movement to straight back-and-forth travel. Track marks made prior to the mixture reaching initial set can be recompacted by the vibratory roller without significant loss of joint quality; however, damaged surfaces that are recompacted after the mixture has set or if it has dried will have little or no strength, even though they may have acceptable surface appearance. Damaged material can be easily removed by blowing with an air jet, even many hours later. Material that is recompacted early enough will remain cemented in place if blown with an air jet.

A relatively recent development in RCC spreading is the *slope-layer method*. Starting from a previous level lift surface, the RCC layer is placed on a slope of about 10 (H):1 (V), more or less. The first layer is then just a small fillet of RCC. A second layer is immediately placed over this at the same slope followed by a third, fourth, and subsequent layers, until the vertical depth of the multiple layers at the high end is some preestablished height on the order of about 6 ft, more or less. This becomes the total lift height for the multiple layers. Because of the slope of the layers, the length of each layer is minimized. In the case of a 10 (H):1 (V) slope and 6-ft lift depth, the distance is only 60 ft. This allows each layer to be placed before the subsequent layer approaches its setting time. Lift-joint cleaning is not really required except when contamination is an issue, and the layers will bond together in one mass without noticeable layer joints lines. The final top surface requires special attention afterward for cleanup before starting the next lift of multiple layers. The procedure must be coordinated with forming and form supports, so it has places where it is beneficial and places where it is not advantageous.

Spreading equipment should leave a flat or plane surface of the proper thickness before the roller does its compaction. The roller should not bridge over high points and miss providing full compaction at low points of freshly spread lift surface. Depending on the workability of the mixture, ridges or steps between adjacent passes of the dozer blade can result in uneven compactive efforts and variable quality in the RCC. As a general rule, having a flat surface ready to roll in the least amount of time is more important than having an exact grade with delayed rolling. Typical tolerances for lift thicknesses are on the order of ±2 in., except for the exposed final lift surface in a structure, which typically has a much smaller tolerance.

Where special mixtures are specified (e.g., at the upstream or downstream face), special procedures are required. If conventional concrete is used against a formed face with a dry-consistency RCC mass behind it, the conventional mixture should be placed first and the RCC immediately spread against and on top of the sloping unformed face of the conventional concrete. The conventional mixture should be designed to lose slump rapidly but not set rapidly. This allows the RCC to be compacted into the conventional concrete before either mixture sets. If the conventional concrete does not lose slump soon enough, the roller will sink into it resulting in a variety of construction problems. If rolling is delayed while waiting for the conventional mixture to stiffen, the RCC can become too old for proper compaction. If the roller operator simply stays back from the conventional concrete far enough to avoid sinking into it or shoving it up, the two mixtures will not adequately compact or join together. Using more of the conventional concrete makes the problem worse. Usually, only 12 in. of conventional concrete is used, but some projects have been successful with only a few inches of facing. If the facing concrete is wider than about 18 in., the mixture is usually consolidated with immersion-type vibrators while the adjacent RCC is rolled.

If the RCC has a wetter consistency, and especially if it has a delayed set, it is possible to place the conventional concrete mixture after the RCC. The facing concrete still needs to have a relatively low slump when RCC compaction is performed, but it can still be possible to immersion vibrate the interface region of the RCC and conventional concrete. With this procedure, the width of conventional concrete has typically been wider than when conventional facing mixtures are used with drier consistency RCC; however, experience, coring, and internal destructive investigations have shown that a poor interface of the two mixtures has often resulted with this procedure, even when the two mixtures appeared to respond well to immersion vibration and the exposed top surface of the layers looked well consolidated.

The most common compacted lift thickness has been 12 in. Typically, large, dual-drum vibratory rollers can develop full compaction of this thickness with only four to five passes. A factor influencing lift thickness is the maximum allowed exposure time before covering one lift with the subsequent lift. Each project should be studied to optimize the benefits of thicker or thinner lifts. Thicker lifts mean longer exposure times but fewer lift joints and fewer potential seepage paths. Thinner lifts result in more potential joints but allow the joints to be covered sooner with better bonds.

At the start of extremely rough foundations and where the foundation has deep holes that have not been filled with dental or leveling concrete, a front-end loader or excavator bucket can sometimes be used to reach the placement site to deposit material. This is a slow operation but may be the only practical solution for some locations. The problem is eliminated with the all-conveyor delivery system or with mobile conveyors that reach across and into areas of rough terrain.

The equivalent of a Cat D-4 Case 550 rubber track or a JD-450 is required to start the foundation and for tight conditions. With an all-conveyor delivery system, a Cat D-4 is generally capable of spreading RCC at a rate of about 300 yd^3/hr. Dozers should have hydraulic tilt and angle capability. It is common to underestimate the value of good spreading equipment and operators. Graders have been used on some RCC projects, but they generally are not necessary and can actually become a problem. They are difficult to maneuver in small areas, and the tires can damage otherwise good compacted surfaces. There also is a tendency to overwork and rework the surface as if it were soil instead of concrete with a limited working time.

20.6.6 Compaction

Maneuverability, compactive force, drum size, frequency, amplitude, operating speed, and required maintenance are all parameters to be considered in the selection of a roller. The compactive output in volume of concrete per hour obviously increases with the physical size and speed of the roller, but larger size rollers do not necessarily give the same or better density and compactive effort as smaller rollers with a greater dynamic force per unit of drum width. Job size, workability, lift depth, the extent of consolidation due to dozer action, and space limitations will usually dictate roller selection. Large rollers cannot operate closer than about 6 in. to vertical formwork or obstacles, so smaller hand-guided compaction equipment is usually required to compact RCC in these areas. If a slipformed or precast facing system that has an interior face sloping away from the RCC is used, the large rollers can operate all the way to the facing.

The dynamic force per unit of drum width or per area of impact on tampers is the primary factor that establishes effectiveness of the compaction equipment. Most experience has also shown that rollers with a higher frequency and lower amplitude compact RCC better than rollers with high amplitude and lower frequency, although suitable results have been achieved on some projects using rollers with both high frequency and amplitude. The typical compactor is a 10-ton double- or single-drum roller with a dynamic force of at least 475 lb of force per inch of drum width. These rollers are typically used for asphalt and roadway compaction. Larger 15- and 20-ton rollers of greater mass and size, typically used with rockfill construction, have been used with RCC, but they usually have larger amplitudes and lower frequency and are less suited to the aggregate gradings used in RCC. Achieving density and a good lift–joint interface is more difficult with these larger rollers.

In tight areas such as adjacent to forms and next to rock outcrops, large tamping foot-type compactors are most suitable. They are mobile and can provide high-impact energy to produce good density; however, they usually do not leave a smooth surface and they can sink when tamping RCC that has been placed over an excessive thickness of wet bedding mixture, when tamping RCC with excess water, or when tamping next to a conventional concrete mixture that has not lost its slump. One-man vibrating plate compactors intended for sands are not very effective, but the more recent massive plate compactors intended for deep lifts of gravel are effective, although they may require multiple passes. Walk-behind rollers are not very effective in most cases unless they can produce a dynamic force on the order of about 250 lb/in. of drum width. Four to six passes of this type roller on fresh RCC not deeper than 12 in. usually results in suitable compaction for tight areas, with densities about 98% of those achieved with the large roller. This reduced density is often considered acceptable, except for special areas that are identified as critical and truly in need of greater compaction.

The appearance of fully compacted RCC is dependent on the mixture proportions. Mixtures of wetter consistency usually exhibit a discernible pressure wave in front of the roller. If the paste content is equal to or less than the volume required to fill all the aggregate voids, rock-to-rock aggregate contact occurs and a pressure wave may not be apparent. This can also occur if the mixture is simply too dry to develop internal pore pressure under the dynamic effect of the roller. Mixtures that have more paste than necessary to fill aggregate voids and a wetter consistency will result in visible paste at the surface that may pick up on the roller drum, depending on the constituents and plasticity of the paste. The fresh mixture surface should be spread in such a way that the roller drum produces a consistent compactive pressure under the entire width of the drum. If the uncompacted lift surface is not reasonably smooth, the drum may overcompact high spots and undercompact low spots.

Minor damage from scuff marks and unavoidable dozer tears in the surface of a freshly compacted lift can usually be immediately rolled down with the vibratory drum in a static mode or with a rubber tire roller. If the mixture was sufficiently fresh and moist when rerolled, a suitable rehabilitation of the damage will result. If the mixture is too old, severely damaged, etc., the rerolled RCC may look acceptable, but it can and should be easily blown off by an air hose used for general cleanup of loose debris on the lift. For sliding stability, joint tension, or watertightness, designs usually require clean and relatively fresh joint surfaces with good bond. This is typically achieved by the use of a suitable large vacuum truck or air blowing. Some tests have shown sandblasting at 24 and 72 hr can actually reduce bond.

20.6.7 Joint Treatment and Inspection

Lift-joint damage from free surface water (rain or overcuring) was discussed in Section 20.3.4 as it relates to the different types of RCC mixes (i.e., wetter or drier consistency and inspection). Lift joints should be kept from drying or freezing continuously, 24 hr per day, 7 days per week, prior to the next layer of RCC. Tests and experience have shown, however, that allowing the surface to dry back to just under an SSD condition, as indicated by a change in color from darker to lighter, will greatly facilitate cleaning by air blowing and will not reduce joint quality for most RCC. Some tests have even shown a slight increase in joint strength. Rewetting the surface after final cleaning and just prior to spreading RCC over it is considered prudent. In addition to the benefit of cure, keeping the surface from drying out provides evaporative surface cooling, thus reducing internal temperatures and providing a lower joint maturity value. If the surface is more than about 2 days old and it has become sufficiently hard, water washing may be necessary if air blowing alone does not adequately clean off any damage, contamination, and general laitance that may be present. Water washing can only be used after the surface has hardened. Sandblasting is generally not advised or necessary.

Roller-compacted concrete mixtures generally do not bleed or develop laitance at the surface. An exception is very wet mixtures and some cases of dry mixtures after days of moist cure. If there is no weak laitance or other contamination at the surface, the lift-joint cleaning typically required with conventional concrete is not necessary. Although it is the subject of some debate, minor intermittent laitance that may occur in some situations is generally not removed.

If the construction joint is less than about 1500°F degree-hr old and if it has been kept clean and moist throughout its exposure, no joint treatment is required under most conditions. If the surface has been contaminated by dirt, mud, or other foreign elements, the contamination should be removed. The degree-hr maturity is the sum of the temperatures of the lift surface measured every hour during the time that it is exposed. If the surface has been allowed to dry out, exceed about 1500°F degree-hr of maturity, or became damaged, it should be cleaned and may require a full or partial bedding mixture prior to placement of RCC. The 1500°F degree-hr used here is an example. It may be 900 at one project and 2100 at another. These variables make specifications for RCC lift surfaces difficult to write, and they leave inspection of this most critical item to the judgment of both the designer and contractor.

20.6.8 Curing and Weather Protection

After the RCC has been placed and compacted, the lift surface must be cured and protected, just as for concrete placed by conventional methods. The surface must be maintained in a moist condition, or at least so moisture does not escape. It should also be protected from temperature extremes and freezing until it gains sufficient strength. When haul vehicles are used on the lift surface, RCC placement typically must immediately stop with even the slightest rainfall; otherwise, the tires will turn the surface into a soft damaged material that then will require waiting for the RCC to harden so extensive cleanup can be undertaken. When conveyors are used for delivery and little or no vehicular traffic is required on the RCC, construction can continue in slight rainfall. This may require a gradual and very slight decrease in the amount of mixture water used because of the higher humidity and lack of surface drying. Table 20.3, based on data covering various types of mixes and delivery methods throughout the world over the past 15 years, provides guidance with regard to the effect of rain on RCC placing operations. Immediately after an RCC lift has been compacted, it is essentially impermeable and will not become damaged by light to moderate rain if there is no hauling or traffic on the surface. After a rain, hauling on the lift can resume only after the surface has begun to dry naturally to a SSD condition. A slightly sloped surface will aid in draining free water and speed resumption of placing operations.

Cure during construction has been accomplished with modified water trucks on larger projects and with hand-held hoses for all size projects. Trucks should be equipped with fog nozzles that apply a fine mist that does not wash or erode the surface. Trucks can be augmented with hand-held hoses that reach areas that are inaccessible to the water truck. Provision must be made for maintaining the damp surface while the trucks are fueled, maintained, and refilled with water. Care should be exercised that the trucks do a minimum amount of turning and minimally disrupt the surface. Maintaining access on and off every lift during construction can be a problem that makes trucks impractical; consequently, the recent trend has been to use hand-held hoses rather then water trucks.

The final lift of RCC should be cured for an appropriate time, generally in excess of 14 days. Curing compound is unsuitable because of the difficulty in achieving 100% coverage on the relatively rough surface, the probable damage to the surface from construction activity, the low initial moisture in the mixture, and the loss of beneficial surface temperature control that is associated with moist curing. Unformed sloping surfaces such as the downstream face of a dam are very difficult to compact and can be considered sacrificial and unnecessary to cure provided this has been incorporated into the design. Uncompacted exposed RCC will be subject to raveling. Whereas the outside several inches will be incapable of achieving any significant strength or quality, they will serve as protection and a moisture barrier for the curing of the interior RCC.

Defining Terms

Abutment—The foundation along the sides of the valley or gorge against which a dam is constructed.

Autogenous volume change—The change in volume produced by continued hydration of concrete exclusive of effects external forces, water changes, and temperature changes.

Cementitious material—The fine solid-particle material in concrete that reacts in solution with water and at times other fine solid particles to create a hardened concrete with strength; Portland cement, sometimes with pozzolan, is usually used.

Coefficient of thermal expansion—The change in linear dimension per unit length divided by the temperature change.

Cohesion—The adhesion of concrete or mortar to other concrete, rock, and other materials.

Creep—Deformation over a long period of time under a continuous sustained load; also, the relaxation or reduction of stress over a long period of time under a sustained deformation.

Durability—The ability of concrete to resist weathering action, chemical attack, abrasion, and other service conditions.

Gallery—A long, narrow passage in a dam or concrete mass used for access, inspection, grouting, drilling drain holes, and collecting seepage.

Grout curtain—A row of holes filled with grout under pressure near the heel of a dam to control seepage under the dam.

Heat of hydration—Heat generated by chemical reactions of cementitious materials with water, such as the heat evolved during setting and hardening of Portland cement.

Lift-joint quality index (LJQI)—A numerical designation indicating the quality of a concrete lift joint, derived from evaluation of the factors affecting the quality of the joint.

Modulus of elasticity (elastic modulus)—The ratio of stress to strain in the elastic region of behavior prior to development of nonrecoverable microfracturing.

Monolith—A section or block of a large structure such as a dam that is bounded by free faces or contraction joints.

Paste—That portion of a fresh concrete mixture that is composed of a mixture of all particles that will pass through a No. 200 or 75-μm sieve (namely, cement, pozzolan or fly ash, water, small air bubbles, admixtures, and aggregate fines).

Permeability—The rate of flow of water through a unit cross-sectional area under a unit hydrostatic gradient.

Poisson's ratio—The ratio of transverse strain to axial strain resulting from a uniformly distributed axial stress.

Pozzolan—A finely divided powder that is composed of siliceous and other minerals that react with the byproducts of Portland cement hydration to form additional cementitious materials.

Principal stress—Maximum and minimum stress occurring at right angles to a principal plane of stress.

Pugmill—A mixing chamber usually composed of two horizontal rotating shafts to which mixing paddles are attached.

Restraint—Internal or external restriction of free movement of concrete in one or more directions.

Roller-compacted concrete (RCC)—A relatively dry concrete mixture that can be compacted by vibratory rolling, usually by a 10-ton roller.

Sustained modulus of elasticity—The modulus of elasticity of concrete that occurs under constant sustained load, including the effects of creep.

Theoretical air-free density—The density corresponding to a concrete that has been compacted to 100% solids with no air.

Ultimate modulus—The ratio of stress to strain that occurs at the maximum load beyond which concrete loses strength and fails.

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(a)

(b)

(c)

(a) Impact testing to determine the stress-wave speed in concrete; (b) polarization resistance testing to determine the corrosion rate of reinforcing steel in concrete; and (c) testing for internal voids in concrete pipe by the impact-echo method. (Photographs courtesy of Germann Instruments, Inc.)