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15 January 2000

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Roller-Compacted Concrete

ENGINEER MANUAL

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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

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Manual
No. 1110-2-2006

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Engineering and Design
ROLLER-COMPACTED CONCRETE

1. Purpose. The purpose of this manual is to provide information and guidance on the use of roller-compacted concrete (RCC) in dams and other civil works structures. Elements discussed include investigation and selection of materials, mixture proportioning, material properties, design and construction considerations, construction methods and equipment, Government Quality Assurance/ Contractor Quality Control, and performance. This manual is intended to serve as a companion to Engineer Manual (EM) 1110-2-2000, "Standard Practice for Concrete for Civil Works Structures." The user of this manual should have a copy of EM 1110-2-2000 and the references listed therein. This manual does not cover RCC for pavements.

2. Applicability. This manual applies to all USACE Commands having civil works responsibilities.

3. Distribution Statement. Approved for public release; distribution is unlimited.

FOR THE COMMANDER:

RUSSELL L. FUHRMAN
Major General, USA
Deputy Commander

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Chapter 1
Introduction

1-1. Purpose

The purpose of this manual is to provide information and guidance on the use of roller-compacted concrete (RCC) in dams and other civil works structures. This manual does not cover RCC for pavements. Elements discussed include investigation and selection of materials, mixture proportioning, design and construction considerations, construction equipment and techniques, inspection, and performance. This manual is intended to serve as a companion to Engineer Manual (EM) 1110-2-2000, "Standard Practice for Concrete for Civil Works Structure." The user of this manual should have a copy of EM 1110-2-2000 and the references listed therein.

1-2. Applicability

This manual applies to all USACE Commands having civil works responsibilities.

1-3. References

Required and related references are listed in Appendix A.

1-4. Definition

The American Concrete Institute (ACI) 116R[1] defines RCC as "concrete compacted by roller compaction; concrete that, in its unhardened state, will support a roller while being compacted." Properties of hardened RCC can be similar to those of conventionally placed concrete. However, RCC can also be made with hardened properties that are outside the range of typical properties of conventionally placed concrete. The term "roller compaction" is also defined by ACI as "a process for compacting concrete using a roller, often a vibrating roller." The terms "rollcrete" and "rolled concrete" are no longer to be used.

1-5. Applications

RCC may be considered for application where no-slump concrete can be transported, placed, and compacted using earth and rock-fill construction equipment. Ideal RCC projects will involve large placement areas, little or no reinforcement, and little or no embedded metal work or other discontinuities such as piles. Application of RCC should be considered when it is economically competitive with other construction methods. It may be considered in lieu of gabions or riprap for bank protection, especially in those areas where riprap is scarce. It may be considered for large work pads, aprons, or paved areas, massive open foundations, base slabs, cofferdams, massive backfill, emergency repairs, and overtopping protection for embankment dams. It may be used in lieu of conventionally placed concrete in concrete gravity and arch-gravity dams. RCC may be considered for use in levees where foundations are adequate and may also be used in caps for jetties to reduce the amount of required rock. For many dam projects, the use of RCC may allow a more economical layout of project features such as an over-the-crest spillway as opposed to a side channel spillway for a comparable embankment dam. A comprehensive summary of RCC dams with heights greater than 15 m (50 ft) has been compiled by Dunstan (1997). A wide range of performance objectives is possible with RCC. Structures designed in a manner similar to those utilizing conventional concrete can be constructed using RCC with many of the same characteristics. It is also possible to design structures requiring less demanding performance, consequently making them more economical.

[1] All ACI references are listed with detailed information in Appendix A.

1-6. Objective of RCC Operations

RCC was initially developed to produce a material exhibiting the structural properties of concrete with the placing characteristics of embankment materials. The result was a material that, when properly designed and constructed as a gravity structure, should be more economical than comparable earth-rockfill and conventional concrete structures. To achieve the highest measure of cost effectiveness and a high-quality product similar to that expected of conventional concrete structures, the following RCC design and construction objectives are desired: RCC should be placed as quickly as possible; RCC operations should include as little manpower as possible; RCC design should avoid, as much as possible, multiple RCC mixtures and other construction or forming requirements that tend to interfere with RCC production; and RCC design should minimize complex construction procedures. RCC structures have been designed for a wide range of performance conditions, from low-strength more massive structures to high-strength less massive structures. It is critical that the design of the structure be coordinated with the performance requirements for the RCC material and the specification requirements for construction.

1-7. Major Advantages

RCC construction techniques have made RCC gravity dams an economically competitive alternative to conventional concrete and embankment dams due to the following factors.

a. Costs. Construction-cost histories of RCC and conventional concrete dams show the unit cost per cubic yard of RCC is considerably less than conventionally placed concrete. Approximate costs of RCC range from 25 to 50 percent less than conventionally placed concrete. The difference in percentage savings usually depends on the cost of aggregate and cementing materials, the complexity of placement, and the total quantities of concrete placed. Savings associated with RCC are primarily due to reduced forming, placement, and compaction costs and reduced construction times. Figure 1-1 shows the relationship of the cost of RCC to the volume of the RCC structure based on RCC projects constructed in the United States.

b. Rapid construction. Rapid construction techniques (compared with those for concrete and embankment dams) and reduced material quantities (compared with those for embankment dams) account for major cost savings in RCC dams. The RCC construction process encourages a near continuous placement of material, making very high production rates possible. These production rates significantly shorten the construction period for a dam. When compared with embankment or conventional concrete dams, construction time for large RCC projects can be reduced by several months to several years. Other benefits from rapid construction include reduced administration costs, earlier project benefits, possible reduction or deletion of diversion facilities, and possible use of dam sites with limited construction seasons. Basically, RCC construction offers economic advantages in all aspects of dam construction that are related to time.

c. Integral spillways and appurtenant structures. As with conventional concrete dams, spillways for RCC dams can be directly incorporated into the structure. A typical layout allows discharging flows over the dam crest and down the downstream face. In contrast, the spillway for an embankment dam is normally constructed in an abutment at one end of the dam or in a nearby natural saddle. An embankment dam with a separate spillway and outlet works is generally more costly than the comparable RCC dam with an integral spillway and outlet works. For projects requiring a multiple-level intake for water quality control or for reservoir sedimentation, the intake structure can be readily anchored to the upstream face of the RCC dam. For an embankment dam, the same type of intake structure would be a freestanding tower in the reservoir or a structure built into or on the reservoir side of the abutment. The cost of an RCC dam intake is considerably lower than the cost of an intake structure for an embankment dam, especially in high seismic areas. The shorter base dimension of an RCC dam, compared with that of an embankment dam, reduces the required size and length of the conduit and penstock for outlet and hydropower works and also reduces foundation preparation costs.

d. Minimized diversion and cofferdam. RCC dams provide cost advantages in river diversion during construction and reduce damages and risks associated with cofferdam overtopping. The diversion conduit for RCC dams will be shorter than for embankment dams. With a shorter construction period, the probability of high water is less, therefore the size of the diversion conduit and cofferdam height can be reduced from that required for both embankment and conventional concrete dams. These structures may need to be designed only for a seasonal peak flow rather than for annual peak flows. With the high erosion resistance of RCC, the potential for a major failure would be minimal, and the resulting damage would be less, even if overtopping of the cofferdam did occur. Significant advantages can be realized using RCC for the construction of cofferdam structures. It offers the benefits of rapid construction, small footprint, and continued operability after overtopping.

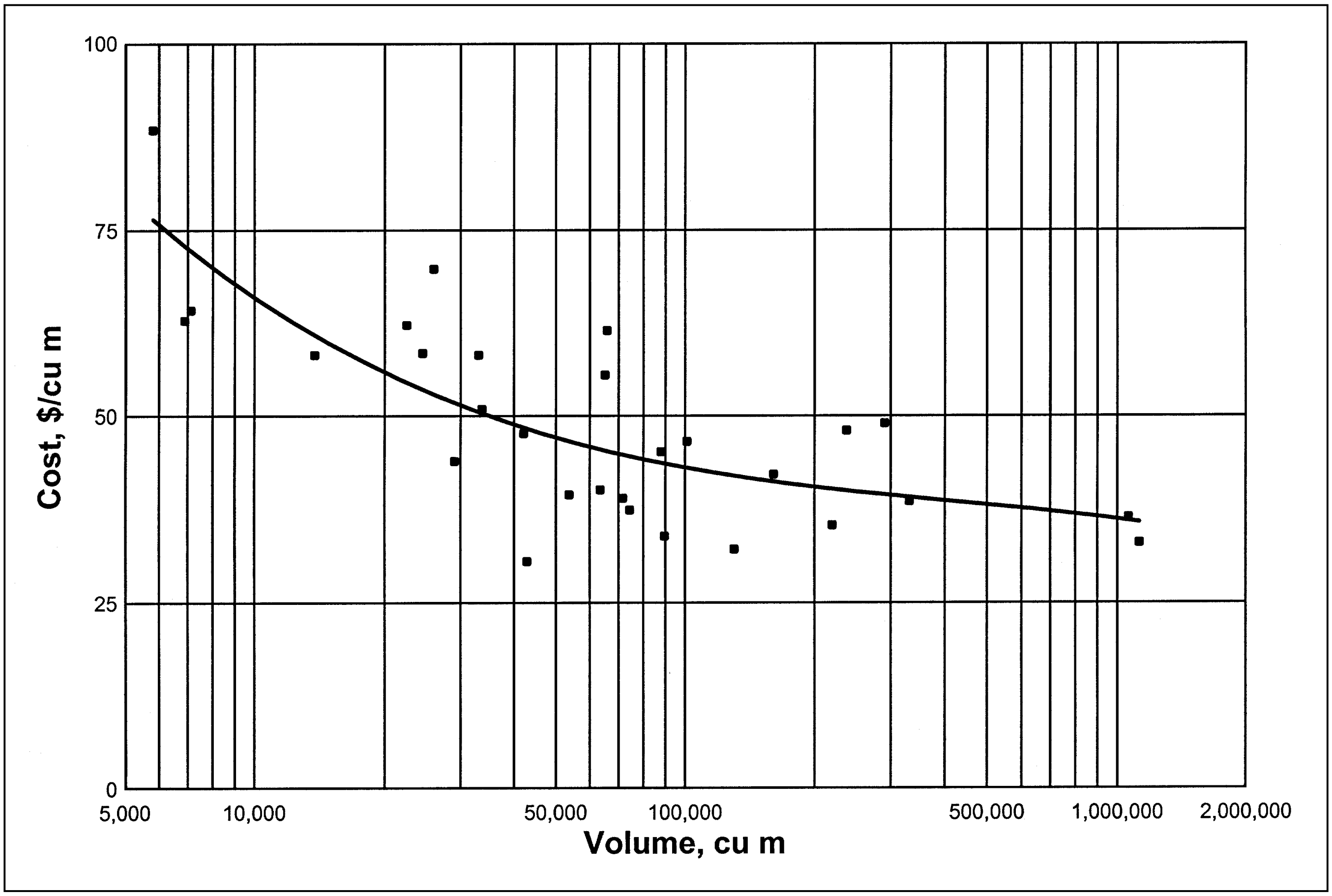

Figure 1-1. RCC costs (1998 price level)

e. Other advantages. When compared with embankment dams, the smaller volume of RCC gravity dams makes the construction material source less of a driving factor in site selection. Furthermore, the borrow source will be considerably smaller and may be more environmentally acceptable. The RCC gravity dam is also inherently more resistant to internal erosion and overtopping.

1-8. Engineering Responsibilities and Requirements

The duties and responsibilities identified in EM 1110-2-2000 apply to RCC structures. During the feasibility stage it may be advantageous to perform a preliminary thermal study to establish gross performance of the structure. Guidance is provided in ETL 1110-2-542, "Thermal Studies of Mass Concrete Structures," for performing these preliminary thermal studies. Later, during the preconstruction engineering and design phase, a more detailed thermal study may be performed to better identify crack control features of the structure. The design team for an RCC project may include many disciplines. As with other mass concrete structures, it is critical that a geologist, engineering geologist, or geotechnical engineer evaluates the foundation conditions, a hydraulic engineer evaluates the spillway and outlet structures, a structural engineer designs the structure, and a materials engineer designs the RCC mixture and coordinates the requisite construction requirements. Coordination by the design team of design requirements, materials requirements, and construction requirements is critical to achieve a cost-effective design.

Chapter 2
Investigation and Selection of Materials

2-1. Policy

Policies for RCC dams regarding the investigation of concrete materials and the scope of the required investigation are the same as for a conventional concrete dam and are discussed in detail in EM 1110-2-2000. It is necessary to assess the availability and suitability of the materials needed to manufacture RCC with qualities meeting the structural and durability requirements. An availability investigation should particularly emphasize the need to meet any high RCC production and placement rates. Additional investigations may be needed for RCC in various applications, as appropriate.

2-2. Cementitious Materials

a. General. The method of investigating cementitious materials for RCC is similar to that used for conventionally placed concrete and should be in accordance with EM 1110-2-2000. The selection of cementitious materials significantly affects the rate of hydration and strength development. The use of pozzolan is quite common for RCC projects and generally provides for reduced cost and lowered heat generation. Pozzolan contents ranging up to 80 percent by volume of the cementitious material have been used by many design organizations.

b. Cement. Type II portland cement is more commonly used with RCC because of its low heat generation characteristics at early ages and its longer set times. The use of Type III portland cement is not practical for most RCC applications because it shortens the time available for compaction and increases heat evolution at early ages. The slower rate of strength development of some cements generally results in greater ultimate strength for a given cement content.

c. Pozzolan. The use of a pozzolan or ground slag may be especially beneficial in RCC as a mineral filler and for its cementitious properties, as well as providing a degree of lubrication during compaction. Pozzolan occupies some of the paste volume otherwise occupied by cement and water. Class F fly ash is most commonly used as a pozzolan or mineral filler for RCC but Class C fly ash has also been used. Class F fly ash contributes to lower heat generation at early ages, may be used to replace cement (generally up to approximately 50 percent by volume), reduces cost, acts as a mineral filler to improve workability, and delays final set. Therefore, RCC mixtures containing Class F fly ash benefit from increased placement time and increased workability. Laboratory testing should be conducted to verify and evaluate the benefits of using pozzolan.

2-3. Aggregates

a. General. One of the most important factors in determining the quality and economy of concrete is the selection of a suitable source of aggregate. This statement is as true for RCC as for conventional concrete. The investigation of aggregates will follow the procedures described in EM 1110-2-2000.

b. Aggregates for RCC. As with conventional concrete, aggregates for RCC should be evaluated for quality and grading. Aggregate for RCC should meet the standards for quality and grading as required by the desired properties for the design structure. The use of lesser quality aggregate may be appropriate for certain circumstances, such as construction during an emergency situation, when the use of a poorer quality aggregate does not affect the design requirements of the RCC, or where specific material properties can be achieved with the use of such aggregates. Changes from the grading or quality requirements must be supported by laboratory or field test results included in a design memorandum. The design memorandum should identify that the concrete produced from the proposed materials fulfills the requirements of the project for strength, durability, water tightness, and economy. The typical nominal maximum size of aggregate (NMSA) particle which has been handled and compacted in Corps of Engineers RCC construction is 75 mm (3 in.). However, the gradings may be significantly different than those normally used for conventional mass concrete. While larger sizes have been successfully used in Japan and at Tarbela Dam, the use of NMSA larger than 75 mm (3 in.) will seldom be technically justified or economically viable in most Corps of Engineers structures. Use of larger aggregate greatly increases the probability of segregation during transporting and spreading RCC and seldom significantly reduces the RCC cost. A proposal to use aggregate larger than 75-mm (3-in.) nominal maximum size should be included in a design memorandum and should be accompanied by results from an investigation showing that the larger aggregate can be handled without segregation, can be compacted, and that its use will actually result in lower costs.

c. Fines in aggregate. When low cementitious material content RCC is used, the required amount of material passing the 75-μm (No. 200) sieve is greater for RCC than is acceptable for conventional concrete. The larger percentage of fines is used to increase the paste content in the mixture to fill voids and contribute to workability. The additional fines are usually made up of naturally occurring nonplastic silt and fine sand or manufactured fines. Although the greatest benefit from the use of fines is the control of segregation, in many cases the use of fines increases water demand, thus lowering strength. Care should be exercised when selecting aggregates with plastic versus nonplastic fines. When plastic fines exist in aggregate, an evaluation of the effects of strength loss, water demand, and durability should determine the feasibility of meeting the structural design requirements. When pozzolans are used to replace natural fines, workability improves while w/(cm) ratios decrease and long-term strength may increase.

2-4. Water

Criteria for assessing available water supplies as sources of mixing and curing water are given in EM 1110-2-2000. Experience has shown that the source of water (groundwater vs. surface water) can have a significant effect on RCC performance. Times of setting and strength development can vary significantly. Caution should be exercised when accepting a water supply, and acceptance should be contingent on appropriate verification of performance.

2-5. Chemical Admixtures

a. General. Chemical admixtures have been effective for modifying RCC mixtures proportioned for workability levels in the 10-20 sec Vebe range. Admixtures can be used to improve workability, delay time of setting, and improve durability of such mixtures. Larger quantities of admixtures are typically required for RCC than for conventional concrete, thus increasing the relative cost.

b. Water-reducing and retarding admixtures. The use of a water-reducing and retarding admixture or a retarding admixture, Type B or D, according to CRD-C 87[1] (American Society for Testing and Materials (ASTM) C 494), should be considered for any RCC placement. The use of a water-reducing and retarding admixture has proven to be beneficial for extending workability of RCC and increasing the initial and final times of setting, thereby enabling a better bond and increasing the likelihood of a watertight joint. The extended workability is especially beneficial during warmer weather, during RCC startup activities, for transporting RCC from distant sources, and for placement of 600-mm- (24-in.-) thick lifts. The addition of the water-reducing and retarding admixture will normally increase the workability of the RCC mixture and result in a decreased water content. Dosages of water-reducing and retarding admixtures can be several times as much as recommended for conventionally placed concrete because of the drier consistency of RCC; however, in some instances, excess dosages of water-reducing and retarding admixtures for lean RCC mixtures can result in minimal improvement in or, at times, detrimental impact on short-term and long-term performance. Dosage should be based on results of laboratory tests where the effect of varying dosages are evaluated.

c. Air-entraining admixtures. Air-entraining admixtures have been added to RCC mixtures in attempts to entrain an air-void system with proper bubble size and spacing to resist damage to the concrete when it is subjected to repeated cycles of freezing and thawing while critically saturated. Experience indicates that the dosages of air-entraining admixtures required for RCC may be considerably higher than those required for conventionally placed concrete; however, the air content required to achieve significant freeze-thaw protection may be lower and the air bubble shape may not be as critical as for conventional concrete. As with conventional concrete, the workability of the RCC may be visibly improved by the addition of air-entraining admixtures, resulting in a reduction of the amount of mixing water required. The fines content, type of fines, and water content of RCC mixtures significantly influence the effectiveness of air-entraining admixtures. An examination of air-entrained RCC cores obtained from the RCC dam at Fort Ritchie, MD, revealed an air-void structure different from that normally observed in conventional concrete. The air voids in the RCC exhibited very irregular shapes compared with

[1] All CRD-C designations are to *Handbook for Concrete and Cement*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

conventional concrete, but the bubble spacing factors were comparable. Testing of various RCC mixtures at the U.S. Army Engineer Waterways Experiment Station (WES), though limited in scope, indicates that certain brands of air-entraining admixtures perform significantly better than others, although frost resistance was moderate at best. Laboratory and field evaluations should be performed to determine the effectiveness of various brands of admixtures and the quantities required to meet design criteria. In most instances, the development of air-entrained RCC in the laboratory has proven less difficult than producing and controlling air-entrained RCC under field conditions. A relatively new approach to entrainment of air into exposed RCC facings is to pour air-entrained, cementitious grout over about a 0.4-m (1.3-ft) strip of the RCC lift surface along the vertical formwork. Once the grout soaks into the RCC, the mixture can be successfully consolidated with internal vibrators to form a homogenous, impervious facing of air-entrained RCC (Forbes 1999). The grout-enriched RCC technique has been successfully used in nearly all of the RCC dams constructed in China during the 1990's. The method has also been used with similar success at the recently completed Cadiagullong Dam in Australia and Horseshoe Bend Dam in New Zealand and is currently in use at the Beni Haroun Dam in Algeria.

Chapter 3
Mixture Proportioning

3-1. General

The proper selection of mass or structural RCC mixture proportions is an important step in obtaining an economical, durable concrete and should be accomplished in the laboratory under the direction of a materials engineer with previous RCC mixture proportioning and project experience. RCC mixture proportions depend largely upon the strength and durability requirements of the structure. However, RCC proportions may also be greatly influenced by project-specific requirements such as material availability, hauling and conveying methods, spreading and compaction equipment, etc. The RCC mixture proportioning procedure that is presented in paragraph 3-3 of this chapter is one of several methods that have been used successfully covering a broad range of mixtures and performance requirements.

3-2. Basic Considerations

a. Durability. RCC durability is dependent on strength, cementitious material content, aggregate quality, and percent compaction. With hard, dense aggregates and an appropriately selected type and quantity of cementitious material, RCC exhibits excellent resistance to abrasion and erosion, alkali-aggregate reactivity, and sulfate attack. However, the resistance of RCC to the effects of aggressive waters, chemicals, gases, or simple leaching of soluble constituents by water is primarily a function of the permeability of the concrete, and, since lean mass RCC mixtures are designed with low cementitious contents, they are relatively permeable. For lean interior mass mixes, durability protection is often enhanced by the use of exterior zone mixes with higher cementitious contents, incorporation of conventional concrete facings, use of impermeable membranes, and sometimes oversized sections allowing for some deterioration. The frost resistance of non-air-entrained RCC is poor when exposed to freezing and thawing while critically saturated. However, when RCC is not critically saturated, it is relatively frost resistant, even in areas of severe climate. In laboratory applications, significant improvement in resistance to freezing and thawing of RCC has been realized by use of certain air-entraining admixtures. However, consistent production of air-entrained RCC in actual production conditions has been less reliable. If air entrainment is specified for the RCC, laboratory and field testing should be performed using project materials to determine: (1) the effectiveness and proper dosage rates of the selected air-entraining admixtures, (2) the effects of air on RCC workability and water demand, (3) the effects of RCC handling and compaction operations on the air-void system parameters, and (4) the effects of aggregate and cementitious material fines on entrained air content. The pressure method described in ASTM C 231 is typically used to measure the air content of RCC. Since the RCC cannot be consolidated by rodding or internal vibration, it is consolidated in the air meter bowl by external vibration (using the Vebe table) or tamping (using a pneumatic tamper, electric hammer, etc.). The top surface of the consolidated or compacted RCC can be struck off while the specimen is still on the Vebe table using a steel plate, or it can be leveled off using a plywood plate and tamping. After the RCC is consolidated or compacted and struck off flush with the top of the air meter bowl, the unit weight and air content of the sample may be determined following the procedures of ASTM C 138 and C 231. The unit weight of mixtures containing NMSA greater than 37.5 mm will require a larger unit weight measure, and electric or pneumatic tamping may be the only means to effectively consolidate the RCC.

b. Strength. As with the design of conventional concrete structures, the required RCC strength is determined by the design of the structure. RCC is different than conventional concrete in that material properties are affected by the workability level of the mixture, the fines content, and the moisture content relative to the optimum moisture content. Consequently, it is extremely difficult to state general relationships. In most situations, for any given combination of concreting materials, strength is largely dependent on cement content. The moisture content of the mixture is a function of the aggregate and the desired RCC workability level. The necessary proportions of materials, including cement and pozzolan, must be determined by laboratory evaluation. Figures 3-1 and 3-2 and Table 3-3 provide a starting point for establishing cement contents and water contents, respectively. The effect of pozzolan on RCC strength development cannot be assumed; it must be determined in the laboratory. Figures 3-1 and 3-2 provide relationships between cement content and compressive strength for various equivalent cement contents with and without pozzolan. These curves represent average data from a variety of RCC mixtures ranging from 19.0- to 75-mm (3/4 to 3 in.) NMSA and batched with and without Class F fly ash. Values estimated from the curves should be verified by trial batches to ensure that the required average compressive strength (f_{cr}) is achieved.

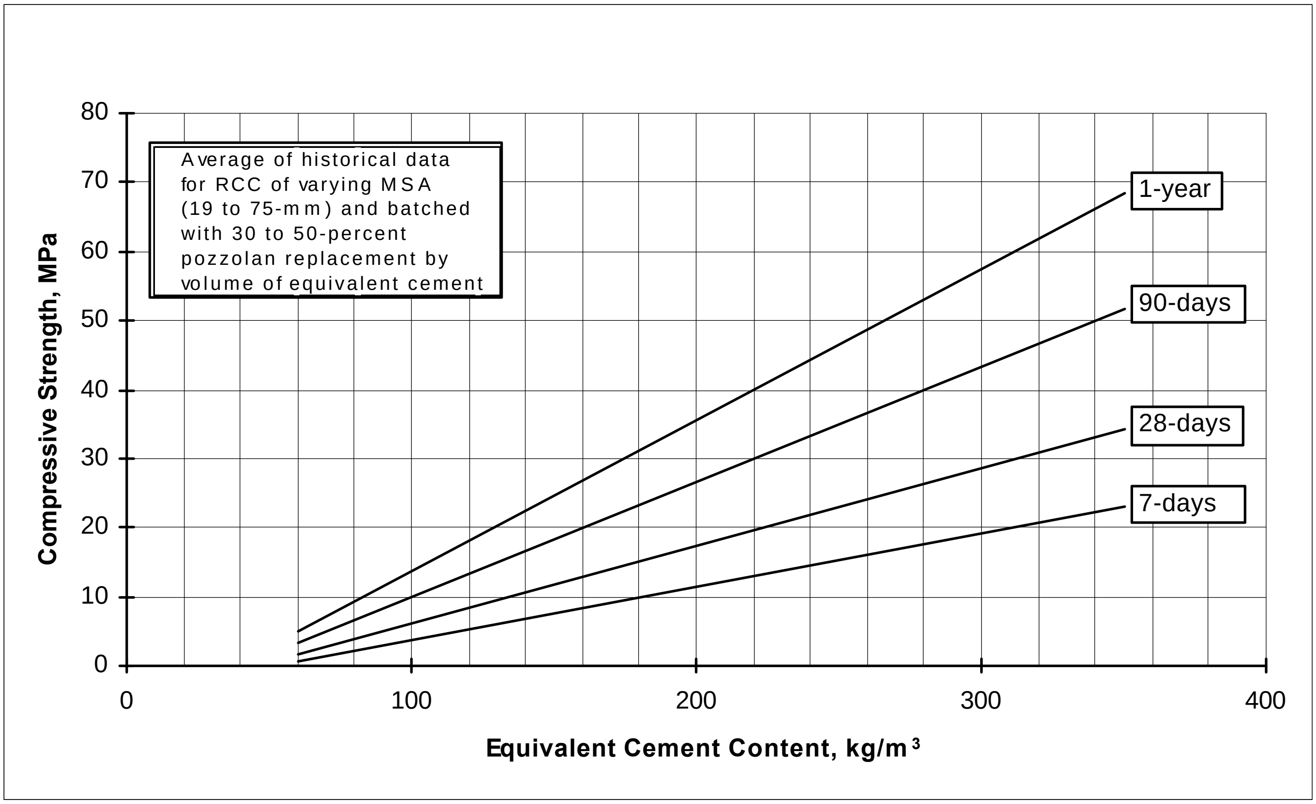

Figure 3-1. Equivalent cement content versus compressive strength; average historical data for RCC batched with pozzolan

(1) Calculating equivalent cement contents. The calculation of equivalent cement contents used in this manual is based on the absolute volume equivalency computation method commonly used throughout the Corps of Engineers. Using the volume equivalency method, the equivalent cement content is calculated using the equivalent mass of cement that would occupy the same volume as the cement and pozzolan combined. Many commercial laboratories calculate this in a slightly different manner using a mass equivalency method as described in ACI 211. The materials engineer should be aware that the different methods used for computing cement equivalency will result in slightly different values.

(2) Compaction. CRD-C 10 (ASTM C 192) describes a procedure for molding cylinders by using external vibration and surface surcharge for concretes that have low water contents. For RCC mixtures designed at a Vebe consistency of less than 30 sec, the RCC can be easily consolidated on the Vebe table using plastic cylinder molds and a surcharge as described in CRD-C 10. For RCC mixtures designed at Vebe consistencies greater than approximately 30 sec, tamping procedures are required to fabricate specimens. Tamping can be performed using pneumatic pole tampers or electric tamping hammers, and either steel molds or plastic molds with steel sleeves that can resist pressures exerted by the tamping equipment can be used for fabrication. Be aware that the selection of the appropriate compaction method is dependent on the workability level of the mixture.

c. Workability. The workability of RCC is the property that determines the RCC's capacity to be placed and compacted successfully without harmful segregation. It embodies the concepts of compactability and, to some degree, moldability and cohesiveness. It is affected by the same factors that affect the workability of conventional concrete (i.e., cement content, water content, the presence of chemical and mineral admixtures, and the grading, particle shape, and relative proportions of coarse and fine aggregates). However, the effect of each factor will not be the same for RCC as for conventional concrete. The workability of RCC cannot be measured or judged in the same way that the placeability of conventional concrete is indexed to the slump test. The slump test is not meaningful for concrete intended for roller compaction since the correct mixture has no slump. A critical step in the design of RCC mixtures is to establish the desired workability level of the RCC.

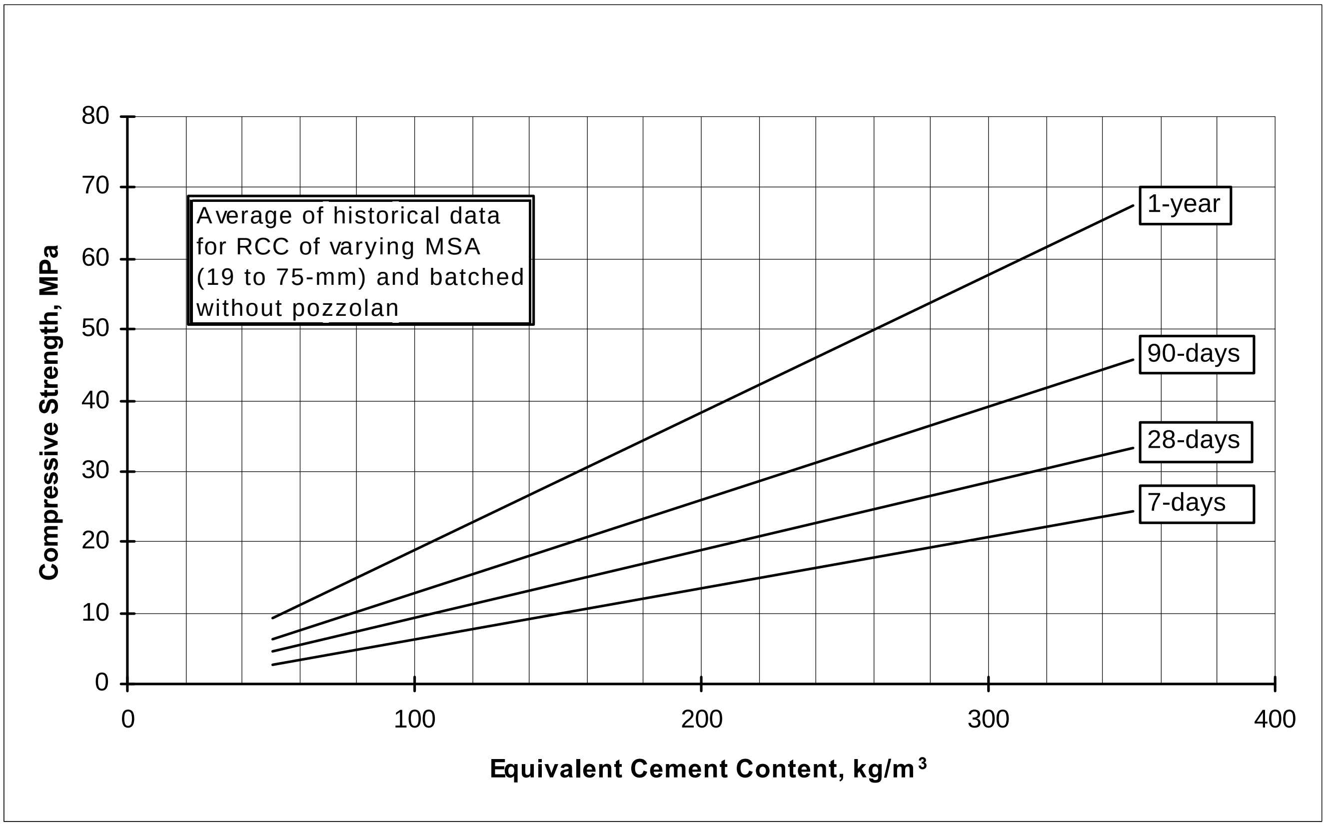

Figure 3-2. Equivalent cement content versus compressive strength; average historical data for RCC batched without pozzolan

For more workable mixtures, consistency of the mixture may be measured using a modified Vebe apparatus. The apparatus and test method are described in CRD-C 53. Most Corps of Engineers mass RCC applications have used RCC mixtures proportioned with Vebe consistencies ranging from approximately 12 to 25 sec. Within this range of Vebe consistency, RCC is generally very workable, is easily placed, and can be fully consolidated, especially at lift joints. However, RCC mixtures with Vebe consistencies of greater than approximately 30 sec have also been used successfully. Advantages of the drier consistency mixtures include somewhat greater economy through more efficient use of cementing materials and less surface rutting and deformation during placement. A walk-behind roller is useful to evaluate mixture workability in small laboratory test sections. On larger test sections, the use of full-size transporting, spreading, and compaction equipment is required. These test strips and sections must be large enough to accommodate the full-size equipment and also have sufficient area for the operation to stabilize. Mixture proportions may then be further adjusted, if necessary, and, final modified Vebe times may be established to control RCC production.

d. Generation of heat. Low water contents associated with mass RCC make possible the use of very low cement contents. The maximum amount of pozzolan or ground slag consistent with strength, durability, and economic and construction requirements should be used to further minimize the portland cement content. During the preconstruction engineering and design (PED) stage of the project, the designer and laboratory personnel must work together in close co-ordination to ensure that parameters used for mixture proportioning studies necessary at this stage agree with the design assumptions selected. From these studies, a range should be selected for the total cementitious material content as well as the amount of pozzolan or slag or both to be used. Later, the project specifications will be based on the range of selected cementitious material content, and the laboratory will make the final contract mixture proportioning studies using materials supplied by the contractor. Placement temperatures, which are expected to affect the fresh and hardened properties of the RCC, should be taken into consideration as much as possible during the mixture proportioning studies.

e. Aggregate. The largest practical NMSA should be used in RCC. However, the larger the aggregate size used in the RCC mixture, the more likely that problems related to segregation during handling, spreading, and compaction operations will occur. The number of aggregate stockpiles used is usually determined based on a variety of factors, including: (1) the available space at the batch plant, (2) the aggregate sizes normally produced and available in the local area, (3) the inherent tendency for the specific aggregate to segregate, and (4) the number of individual materials that can reasonably be handled at the batch plant. In general, any number of aggregate stockpiles may be used as long as the aggregates are batched accurately and are not allowed to segregate. The grading limits of individual coarse aggregate size fractions should comply with those used for conventional concrete for civil works structures. Individual coarse aggregate size groups should be combined to produce gradings approaching the ideal gradings shown in Table 3-1. For mass RCC mixtures, fine aggregate will normally contain somewhat higher percentages of sizes smaller than the 600-μm sieve. This is primarily to reduce the volume of voids within the mortar matrix, decrease the tendency for bleeding, and generally produce a more cohesive and workable mixture. The addition of supplemental material, primarily material finer than the 75-μm sieve, is sometimes needed to supplement the locally available project materials that may not contain sufficient fines. This supplemental fine material may consist of fly ash, natural pozzolan, ground slag, or natural fine blend sand. The use of fly ash, natural pozzolan, or ground slag as supplemental fine material may provide added benefits as a result of a reduced overall water demand, lower cement content, and higher ultimate strength. Fine aggregate gradings within the limits shown in Table 3-2 have performed satisfactorily; approximate fine aggregate contents, expressed as a percentage of the total aggregate volume, are given in Table 3-3. RCC containing softer aggregates, and perhaps clayey or excessive fines, will generally have a greater water demand, be less durable, achieve lower compressive strengths, and experience less bond between lifts. Marginal or minimally processed pit-run aggregates may result in poor concrete performance and should not be used unless laboratory results indicate that all project technical and economic requirements are met.

Table 3-1
Ideal Coarse Aggregate Grading

	Cumulative Percent Passing		
Sieve Size	4.75 to 75 mm (No. 4 to 3 in.)	4.75 to 50 mm (No. 4 to 2 in.)	4.75 to 19.0 mm (No. 4 to 3/4 in.)
75 mm (3 in.)	100		
63 mm (2-1/2 in.)	88		
50 mm (2 in.)	76	100	
37.5 mm (1-1/2 in.)	61	81	
25.0 mm (1 in.)	44	58	
19.0 mm (3/4 in.)	33	44	100
12.5 mm (1/2 in.)	21	28	63
9.5 mm (3/8 in.)	14	18	41
4.75 mm (No. 4)	--	--	--

Table 3-2
Fine Aggregate Grading Limits

Sieve Size	Cumulative Percent Passing
9.5 mm (3/8 in.)	100
4.75 mm (No. 4)	95-100
2.36 mm (No. 8)	75-95
1.18 mm (No. 16)	55-80
600 μm (No. 30)	35-60
300 μm (No. 50)	24-40
150 μm (No. 100)	12-28
75 μm (No. 200)	6-18
Fineness modulus	2.10-2.75

f. Water content. Approximate mixing water requirements and entrapped air contents (for non-air-entrained RCC) are shown in Table 3-3 for various NMSA. The water contents shown are averages from structural and mass concrete mixtures made with both natural and manufactured aggregate. Unit water demand for RCC containing a specific aggregate combination will generally show little change over a wide range of cementitious material contents. Also shown in Table 3-3 are approximate ranges of modified Vebe times corresponding to ranges of water contents and approximate mortar contents for RCC mixtures having varying nominal maximum aggregate sizes.

Table 3-3
Water Content, Sand Content, Mortar Content, Paste-Mortar Ratio, and Entrapped Air Content for Various Nominal Size Aggregates. Typical Values for Use in Estimating RCC Trial Mixture Proportions

	Nominal Maximum Size of Aggregate[a]					
	19.0 mm		50 mm		75 mm	
Contents	Average	Range	Average	Range	Average	Range
Water content[b], kg/m^3						
a) Vebe <30 sec	150	133-181	122	107-140	107	85-128
b) Vebe >30 sec	134	110-154	119	104-125	100	97-112
Sand content, % of total aggregate volume						
a) crushed aggregate	55	49-59	43	32-49	34	29-35
b) rounded aggregate	43	38-45	41	35-45	31	27-34
Mortar content, % by volume						
a) crushed aggregate	70	63-73	55	43-67	45	39-50
b) rounded aggregate	55	53-57	51	47-59	43	39-48
Paste: mortar ratio, Vp/Vm, by volume	0.41	0.27-0.55	0.41	0.31-0.56	0.44	0.33-0.59
Entrapped air content on -1 1/2 in. (37.5-mm) fraction, %	1.5	0.1-4.2	1.1	0.2-4.1	1.1	0.5-3.3

[a] Quantities for use in estimating water, sand, mortar, and entrapped air content for trial RCC mixture proportioning studies.
[b] Lower range of values should be used for natural rounded aggregates and mixtures with low cementitious material or aggregate fines content.

3-3. Procedure for Selecting RCC Mixture Proportions

Laboratories should proportion RCC mixtures using materials that are representative of those to be used on the project. RCC mixture proportioning procedures are very similar to those of conventional concrete. The primary differences are due to the relatively low water content and no-slump consistency of RCC. An RCC mixture must be stable enough to support the weight of a vibratory roller and other heavy equipment, yet workable enough to allow some aggregate reorientation. This reorientation allows the voids between aggregate particles to become filled with paste or mortar during the compaction operations. The following is a step-by-step procedure for proportioning RCC for structural or mass concrete applications. After proportions are established for a proposed mixture, it is intended that the workability and strength of the RCC mixture be verified in the laboratory by trial batching. All of the data presented in the figures and tables are a compilation of over 150 RCC mixture proportions formulated in the laboratory and used on various projects throughout the world. After proportions are selected, minor adjustments during laboratory trial batching are normally required and should be expected.

Step 1: Determine all requirements related to the properties of the RCC mixture, including:

a. required/specified strength and age

b. expected exposure time and condition

c. cementitious materials limitations

d. admixture requirements

e. maximum size, source, and quality of aggregate

Note: Special concrete properties, such as stress-strain characteristics, thermal properties, creep, etc., should be considered during the material selection process and ultimately evaluated after the concrete proportions are established. A comprehensive laboratory test program would normally include a series of mixtures spanning the specified strength requirements with specialized tests on selected mixtures in order to provide a comprehensive evaluation of the materials. The mixture proportioning procedure herein is based on the assumption that the concrete materials are suitable for the intended use. For structural applications, the required average compressive strength (f_{cr}) should be determined using procedures described in EM 1110-2-2000 or ACI 214. However, for normal mass concrete applications, these procedures may be somewhat overly conservative, and a modified approach to establishing an over design factor and the required average strength may be considered.

Step 2: Determine the essential properties of the materials. Obtain representative samples of all materials in sufficient quantities to provide verification tests by trial batching. For estimating purposes, a single RCC mixture proportion will require sufficient materials in the laboratory to produce approximately 0.5 m^3 (0.7 yd^3) of concrete. Proportion RCC with the determined (Steps 3 and 4) or specified amount of pozzolan or cement replacement materials that will satisfy strength, durability, and economic requirements. From the materials submitted for the test program, determine the grading, specific gravity, and absorption of aggregates and the specific gravities of the cementitious materials. The grading of the aggregates submitted for mixture proportioning studies should also be verified to ensure that the aggregate is truly representative of the source.

Step 3: From Table 3-3, estimate the water requirement and entrapped air content for the maximum size aggregate being used.

Step 4: Compute the required equivalent mass of cement from the required compressive strength shown in the relationship on Figure 3-1. If the use of pozzolan is anticipated, compute the cement and pozzolan mass based on the equivalent absolute volume of required cement.

Step 5: Compute the required coarse aggregate proportions that best approximate the ideal coarse aggregate grading shown in Table 3-1.

Step 6: Compare the available fine aggregate grading to the recommended fine aggregate grading shown in Table 3-2. If the fine aggregate is lacking minus 75-µm (No. 200) fines, pozzolan or other nondeleterious natural fines may be used as a supplement. From Table 3-3, select the fine aggregate (sand) content for the maximum size and type (crushed or rounded) aggregate being used.

Step 7: Compute the absolute volumes and masses for all of the mixture ingredients from the information obtained in Steps 2 through 6.

Step 8: Compute the mortar content and compare with values given in Table 3-3. Mortar volume includes the volume of all aggregate smaller than the 4.75-mm (No. 4) sieve, cementitious materials, water, and entrapped air. Adjust fine aggregate content, if required, to increase or decrease mortar volume of the mixture.

Step 9: Compute the volume of paste and the ratio of paste volume to mortar volume, Vp/Vm. For paste, include the volume of all aggregate and mineral filler finer than the 75-µm (No. 200) sieve, cementitious materials, water, and entrapped air. The minimum Vp/Vm ratio should be greater than approximately 0.42 to ensure that all voids are filled. If required, adjust cementitious material content or increase quantity of aggregate and mineral filler finer than 75-µm (No. 200) sieve.

Note: The minimum Vp/Vm ratio of 0.42 is recommended to ensure that voids are filled. However, RCC has been proportioned satisfactorily with a Vp/Vm as low as approximately 0.30 (Table 3-3). Paste to mortar volume (Vp/Vm) ratios less than 0.42 may indicate that the mixture has insufficient paste to fill voids. This condition may adversely affect strength and result in higher entrapped air content, increased permeability, and decreased workability.

Step 10: Evaluate the workability and strength of the RCC mixture by trial batching. For RCC containing large aggregate, test for density ("unit weight") and then wet sieve over the 38-mm (1-1/2 in.) sieve and test for modified Vebe time (if applicable) and air content. Mold specimens for compression and other strength tests as appropriate. All RCC laboratory cast and in situ specimens should meet the minimum size and dimensional requirements as specified in the ASTM testing standards for conventional concrete. In general, cylinders, cores, beams, and blocks will preferably have a minimum dimension of at least three times the nominal maximum size of coarse aggregate in the concrete. All RCC laboratory-cast specimens should be moist cured, and in situ samples should be moisture conditioned the same as for conventional concrete.

Note: For RCC mixtures proportioned at Vebe consistencies greater then approximately 30 sec, the Vebe apparatus and external vibration do not provide sufficient energy to fully consolidate the concrete. For these mixtures, consolidation is accomplished by tamping with pneumatic or electric rammers.

3-4. Example Problem

RCC is required for a flood control structure in a moderate climate. The required average compressive strength is 17.5 MPa (2500 psi) at 1 year, and the required minimum shear cohesion is 193 kPa (28 psi). Placement conditions allow for the use of large aggregate, and a quarry that can produce 75-mm (3-in.) NMSA is nearby. A Class F fly ash is available.

Step 1:

a. The required average compressive strength is 17.5 MPa (2500 psi) at age 1 year. RCC is for mass placement with no limiting requirements for cement content.

b. The mixtures are to be proportioned at a modified Vebe consistency of 15 to 25 sec.

c. Portland cement Type II, low alkali, will be specified. Class F fly ash is available and will initially be used at 40 percent replacement by volume of equivalent cement to reduce cement costs and lower heat generation. Later, supplemental mixture proportioning studies may be conducted to evaluate the performance of mixtures with 30 and 50 percent cement volume replacement.

d. Service records indicate good to excellent performance for concrete batched with aggregate from the local quarry source. Aggregate quality tests indicate the rock is a hard, dense, durable basalt that is well suited for use as concrete aggregate. The aggregate meets conventional concrete grading requirements, but the producer is not able to meet the recommended RCC fine aggregate grading. The fine aggregate must be supplemented to meet the recommended RCC grading band shown in Table 3-2.

e. Adjacent to the local quarry source is a deposit of very fine sand. Petrographic examination indicates the material is primarily ash and pumice fragments. Tests on the fine sand indicate that it is suitable for concrete and can be used to supplement fine aggregate in order to meet the required RCC grading band.

f. It has been determined that a Type D admixture will be used at the rate of 0.3 L per 50 kg of equivalent cement to retard the RCC mixture in order to facilitate placing and bonding at lift joints. Later, supplemental mixture proportioning studies may be performed to evaluate the effect of varying admixture dosage.

g. The mixture proportioning program will consist of selecting initial proportions for the mixture, then making additional mixtures at higher and lower cementitious material contents. Selection of final mixture proportions will be based upon compressive strength versus equivalent cement content curves. Shear strength tests will be performed on laboratory-simulated lift joints after properties of the RCC mixture are established.

Step 2:

Density of the Type I-II cement and Class F fly ash are determined to be 3.15 and 2.26 Mg/m^3, respectively. Samples from the project rock quarry and from the fine sand deposit are available for RCC mixture proportioning studies. Gradings, specific gravities, and absorption tests on the aggregate samples are performed and detailed in Table 3-4.

Step 3:

For the 75-mm (3-in.) maximum size aggregate, a water content of 107 kg/m^3 (180 lb/yd^3) and an air content of 1.0 percent are selected from Table 3-3.

Step 4:

For the required average compressive strength of 17.5 MPa (2500 psi) at age 1 year, Figure 3-1 indicates the required cement content is approximately 120 kg/m^3 (200 lb/yd^3). Class F fly ash is to be used at 40 percent replacement by volume of equivalent cement. Densities of cement and fly ash are from Step 2. Volume and weight of the cement and fly ash are calculated as follows:

$$\text{Volume of equivalent cement} = \frac{120\ \text{kg}}{(3.15)\ (1000\ \text{kg/m}^3)}$$

$$= 0.0381\ \text{m}^3$$

Table 3-4
Summary of Aggregate Grading Blend Used for Example RCC Mixture Proportions

	Percent Passing, Nominal Size Groups									
	Coarse Aggregate					Fine Aggregate				Total
Sieve Size	75 to 38 mm	38 to 19.0 mm	19 to 4.75 mm	RCC[a] Blend 40-26-34	Table 3-1 Ideal	Sand	Fine Sand	RCC[a] Blend 88-12	Table 3-2 Ideal	Aggregate[a] Blend 66-34
75 mm	100			100	100					100
63 mm	90			96	88					97
50 mm	46	100		78	76					85
37.5 mm	4	95		60	61					74
25. 0 mm		34	100	43	44					62
19.0 mm		8	98	35	33					57
12.5 mm		1	59	20	21					47
9.5 mm		1	29	10	14	100		100	100	41
4.75 mm			4	1		98		98	95-100	34
2.36 mm			1			85		87	75-95	30
1.18 mm						67		71	55-80	24
600 µm						42	100	49	35-60	17
300 µm						22	98	31	24-40	11
150 µm						8	86	17	12-28	6
75 µm						2.6	72.1	10.9	6-18	3.7
Fineness modulus						2.78		2.47	2.10-2.75	
Specific Gravity, BSSD	2.79	2.77	2.76			2.77	2.56			
Absorption, (%)	0.7	1.0	1.4			1.6	1.9			

[a] Blend proposed for RCC trial mixture proportions as follows:
coarse aggregate: 40% 75 to 38 mm, 26% 38 to 19.0 mm, and 34% 19.0 to 4.75 mm size groups
fine aggregate: 88% fine aggregate and 12% fine sand sizes
total aggregate: 66% coarse aggregate and 34% fine aggregate

Volume of fly ash = (0.40) (0.0381)

= $0.0152\ m^3$

Volume of cement = (0.60) (0.0381)

= $0.0229\ m^3$

Mass of fly ash = $(0.0152\ m^3)\ (1000\ kg/m^3)\ (2.26)$

= $34.4\ kg/m^3$

Mass of cement = $(0.0229\ m^3)\ (1000\ kg/m^3)\ (3.15)$

= $72.1\ kg/m^3$

<u>Steps 5 and 6</u>:

Ideal coarse aggregate gradings for several maximum size aggregates and the recommended fine aggregate grading band are shown in Tables 3-1 and 3-2. From Table 3-3, a total sand content of 34 percent is selected. Results of the calculations for proportioning coarse and fine aggregates are shown in Table 3-4. The total coarse and fine aggregate is blended to provide the desired 34 percent fine aggregate content in the overall total aggregate grading. The proportions of each individual nominal aggregate size group is calculated:

75 to 37.5 mm = 0.40 (0.66) (100) = 26.4%

37.5 to 19.0 mm = 0.26 (0.66) (100) = 17.2%

19.0 to 4.75 mm = 0.34 (0.66) (100) = 22.4%

Fine aggregate = 0.88 (0.34) (100) = 29.9%

Fine sand = 0.12 (0.34) (100) = <u>4.1%</u>

Total aggregate = 100.0%

<u>Step 7</u>:

Compute absolute volumes and masses for each mixture ingredient:

a. From Steps 3 and 4:

Cement = $72.1\ kg/m^3$ = $0.0229\ m^3$
Fly ash = $34.4\ kg/m^3$ = $0.0152\ m^3$
Water = $107.0\ kg/m^3$ = <u>$0.1070\ m^3$</u>
Total = $0.1451\ m^3$

b. Air content is estimated to be 1.0 percent of the minus 37.5-mm portion of the mixture. The determination of air content volume is a trial and error procedure as follows:

Air content of total mixture = $0.0085\ m^3$ (estimate)
Volume of air, cement,
fly ash, and water = 0.0085 + 0.1451
= $0.1536\ m^3$

Volume of aggregate = 1.0000 - 0.1536
= 0.8464 m^3

From Steps 5 and 6 and Table 3-4; 74 percent of total aggregate is minus 37.5 mm, 26 percent is plus 37.5 mm (Table 3-4); therefore, the volume of the minus 37.5-mm portion of the mixture is:

1.0000 - (0.26)(0.8464) = 0.7799 m^3
or
(0.74) (0.8464) + 0.1536 = 0.7799 m^3

Estimated air content = 1.0% of minus 37.5-mm portion of mixture
= (0.01) (0.7802 m^3)
= 0.0078 m^3

Change estimated air content and repeat computation until estimated value and computed value converge, as follows:

Air content of total mixture = 0.0078 m^3 (changed estimate)
Volume of air, cement,
fly ash, and water = 0.0078 + 0.1451
= 0.1529 m^3

Volume of aggregate = 1.0000 - 0.1529
= 0.8471 m^3

Again, from Steps 5 and 6 and Table 3-4; 74 percent of total aggregate is minus 37.5 mm, 26 percent is plus 37.5 mm (Table 3-4); therefore, the volume of the minus 37.5 mm portion of the mixture is:

1.0000 - (0.26) (0.8471) = 0.7798 m^3
or
(0.74) (0.8471) + 0.1529 = 0.7798 m^3

Estimated air content = 1.0% of minus 37.5-mm portion of mixture
= (0.01) (0.7798)
= 0.0078 m^3

Therefore, estimated air content volume (1% of minus 37.5-mm portion of mixture) is 0.0078 m^3.

c. Absolute volumes and weights for each mixture ingredient, including total aggregate volumes, can now be calculated as shown in Table 3-5.

<u>Step 8</u>:

Compute mortar volume:

Mortar volume = volume cement + volume fly ash
+ volume water + volume air
+ volume minus 4.75-mm aggregate

= 0.0229 + 0.0152 + 0.1070 + 0.0078
+ (0.04) (0.1898) + (0.98) (0.2533)
+ 0.0347

= 0.4434 m^3 = 44.3%

From Table 3-3, mortar content is within typical limits.

Table 3-5
Summary of Example RCC Mixture Proportions

Material	Aggregate, %	Volume, m^3	Specific Gravity	Weight, kg/m^3
Coarse aggregate				
75 - 37.5 mm	26.4	0.2236	2.79	624
37.5 - 19.0 mm	17.2	0.1457	2.77	404
19.0 - 4.75 mm	22.4	0.1898	2.76	524
Sand	29.9	0.2533	2.77	702
Fine sand	4.1	0.0347	2.56	89
Cement		0.0229	3.15	72.1
Fly ash		0.0152	2.26	34.4
Water		0.1070	1.00	107.0
Air		0.0078	--	--
Type D admixture		--	--	(0.72 ℓ/m^3)[a]
		1.0000		2556.5

[a] (120 kg/m^3 cementitious material) (0.3 ℓ/50 kg cementitious material).

Step 9:

Compute paste volume:

Paste Volume = volume cement + volume fly ash
+ volume water + volume air
+ volume minus 75-µm aggregate fines

= 0.0229 + 0. 0152 + 0.1070 + 0.0078
+ (0.026) (0.2533) + (0.721) (0.0347)

= 0.1845 m^3

Check paste/mortar volume ratio:

$$\frac{Vp}{Vm} = \frac{\text{Volume Paste}}{\text{Volume Mortar}} = \frac{0.1854\ m^3}{0.4434\ m^3}$$

$$= 0.416$$

The ratio is within typical limits, Table 3-3.

Step 10:

Compute masses for a trial batch from mass and volume information in Step 7 and as shown in Table 3-5. Results of tests on the trial batch are as follows:

Air content = 0.9%
Vebe consistency = 8 sec

The mixture appears well proportioned but slightly wet as indicated by the low Vebe time. Air content is close to the 1.0 percent assumed and does not require adjustment. For adjustment in mixing water, assume ± 3 percent change in mixing water = ± 10-sec change in Vebe consistency. Therefore, recompute second trial mixture following same procedures as outlined in Steps 2 through 10, making the following adjustments:

Mixing water: decrease approximately 3 percent to 103.8 kg/m^3 (175 lb/yd^3).

Cementitious material content: maintain equivalent cement content of 120 kg/m^3 (200 lb/yd^3).

Aggregate: maintain coarse and fine aggregate relative proportions, but increase total aggregate volume equal to the water volume decrease.

Strength performance: evaluate required strength parameters and make further mixture proportion adjustments if necessary.

3-5. Field Adjustment of Mixture Proportions

The mixtures developed using the steps listed have proven to be placeable; however, minor field adjustments to the proportions should be expected. Advantage should be taken of the preliminary and project test sections to make the necessary field adjustments. They should be made on the basis of visual observation, the modified Vebe, and nuclear density test results. Once a determination is made that a mixture is too dry or too wet, the adjustment is made only by adding or deleting water in the mixture until the concrete can be completely compacted in three or four passes of the vibratory roller with the vibrator on. Routine minor adjustments in water content will be required daily or more often due primarily to changes in the aggregate moisture condition. Minor adjustments to cement content can be made using mixture proportioning concepts described in the preceding paragraphs and verified by observed performance.

Chapter 4
Properties

4-1. General

The properties of hardened RCC are similar to those of conventionally placed mass concrete (CMC). Where differences exist, they are generally due to the lower water content in RCC, differences in void content, or slight aggregate or other material differences. The range of possible RCC properties may be wider than for CMC due to the wider range of aggregate qualities used in RCC, the use of lower cementitious material contents, and the use of significant amounts of mineral filler on some projects. The variation of RCC properties for some projects may be greater than that for CMC if greater variation exists than usual for materials quality or compaction. This chapter provides information on hardened RCC properties including strength, elastic properties, tensile strain capacity, creep, volume change, thermal properties, permeability, density, and durability. ACI 207.5R, "Roller Compacted Mass Concrete," presents additional data and information on these properties.

a. Testing. Some properties will be determined by laboratory testing and some will be assigned by the engineers. Some properties, like modulus of elasticity, creep, and, to some degree, tensile strain capacity, are difficult to estimate without testing. When thorough laboratory tests cannot be performed, the best approach is to use results of more easily performed laboratory tests in conjunction with published information in ACI documents, technical publications, and engineering handbooks for similar concrete materials and mixtures from other projects. Properties that are determined in laboratory tests should be representative of concrete mixtures containing project-specific materials. Whenever possible, material properties should be obtained from tests on core samples taken from test RCC placements made with the proposed design mixes. Variations in material properties due to scatter of test data, differences in behavior of the material between actual and that predicted by a numerical model, and expected differences between the laboratory mixture and the actual mixture used during construction can be accounted for by performing parametric studies using combinations of the upper and lower bound values of critical properties. Test data should be included in the concrete materials reports. The rapid construction time of RCC structures, and the general practice of using a 1-year-age design strength, can lead to a structure's being loaded prior to the RCC attaining the required design strength. This serves to emphasize the need for materials engineers and structural engineers to be closely involved in the selection of RCC properties.

b. Strength and elastic properties. The strength and elastic properties of RCC vary depending on the mixture components and mix proportions in much the same manner as for CMC. Aggregate quality and cementitious content are the principal factors affecting strength and elastic properties, but these properties may be as much dependent on field control of mixing and placing operations as on mixture ingredients or mixture proportions. Properties important to the seismic analysis of RCC dams include compressive strength, tensile strength, shear strength, modulus of elasticity, Poisson's ratio, and density. Except for density, all these properties are strain-rate sensitive, and the strain rates that occur during major earthquakes are on the order of 1,000 times greater than those used in standard laboratory testing.

4-2. Strength

The following sections provide information and guidance on compressive, tensile, and shear strength. Tensile strength is further subdivided into topics of direct tensile strength, lift joint direct tensile strength, splitting tensile strength, flexural strength, and dynamic tensile strength. Shear strength is subdivided into subsections on parent shear strength and lift joint shear strength. Strength of RCC is measured using the identical methods employed for CMC, with the only differences being the methods of consolidating specimens. Strength properties of RCC are heavily dependent on degree of compaction, aggregate quality, and cementitious content. RCC strength tests may be conducted using compacted specimens or specimens cored or sawn from structures or test sections. As with CMC, suitable factors should be used to account for the natural variability of not just compressive strength but tensile strength and shear strength as well. RCC differs from CMC due to the more frequent horizontal planes of weakness (construction joints) created during placement, each with tensile and shear strength generally less than that of the parent concrete. Adequate compaction is essential for all RCC. For a properly proportioned mix, compaction is often considered sufficient if the RCC has no more than 1.5 percent air voids. Five percent air voids due to incomplete compaction can result in a 30 percent loss of strength, while 20 percent air voids can produce a strength loss of 80 percent (Kaplan 1960). The more difficult an RCC mixture is to compact, the more likely it is that incomplete compaction will occur and that strength will be less than desired. In some instances, adding water to a very dry mix may produce a strength gain, because the added water increases workability and compactibility of the mix, thereby reducing air voids. Aggregates that produce high strength are not always the ideal material for RCC or CMC dams. On some projects, the use of aggregates of lower physical strength has produced RCC with desirable (high) creep rates, low elastic moduli, and good tensile strain capacity. However, the same aggregates may also produce low tensile strength and low shear properties which are important for structures in seismic areas. Caution should be exercised in using early strength results to predict long-term strength and when using marginal aggregates or other unusual materials since some materials may unexpectedly limit long-term strength properties. As in CMC, the use of significant quantities of pozzolan may result in slower strength gain but, often, higher ultimate strength. Some RCC mixtures, depending on the shape and grading of the aggregates and the degree of compaction and segregation present in the RCC, may exhibit stronger anisotropic properties than CMC. Strength tests on several RCC projects indicate that in some cases cores drilled vertically yield higher strengths than companion horizontally drilled cores (also observed in conventional concrete) (Kogan and Fedossov 1995, Dunstan 1981, Cannon 1995). In a few cases the opposite result has been observed. For conventional concrete, the anisotropic behavior is usually attributed to accumulation of bleed water under aggregate particles. For RCC, the observed anisotropic behavior may be due to the distribution and orientation of aggregate particles resulting from spreading and compacting the horizontal RCC layers. The orientation of cores can influence tensile strength results by as much as 20 percent. If tensile strength is of structural importance, drilled cores of both vertical and horizontal orientation should be tested. In at least one international RCC dam project, the anisotropic nature of the RCC strength properties was accounted for in adjustment factors for design strength (Tejada 1995). Tensile strength (also referred to as bond) and shear strength at lift joints are affected by degree of compaction, aggregate quality, and cementitious material content, but also by the lift joint preparation and condition. The chance of obtaining the desired bond and shear strength at lift joints is less likely with RCC mixtures that are too dry to be easily consolidated or with RCC mixtures that are designed with inadequate paste volume. Lift joint bond as well as shear strength, to a lesser degree, and the overall variation of these properties in a structure will generally be improved with use of a bedding mortar or concrete and rapid placement of successive lifts. The bond strength at the lift joints for properly proportioned, well-compacted RCC will approach that achieved at the prepared lift joints of CMC. The design values for joint bond and shear strength should be based on a laboratory test program that includes evaluation of joint strength using core or sawn block samples from test placements constructed under anticipated field conditions. A comprehensive laboratory test program will ensure a greater degree of certainty and, in some cases, may eliminate overly conservative or redundant design assumptions. The use of various strength properties derived from coring test pads, test sections, or actual structures must be done with care. A sufficient number of specimens must be tested to yield statistically significant results. The process of coring specimens has possible effects that must be taken into account by the materials engineer. These include the variety of strains imposed on the specimens by the coring action and by core removal. These effects are especially troublesome when extracting cores from lift joints for lift joint strength testing.

a. Compressive strength (f_c'). As with CMC, compressive strength is used as a gauge of the overall strength of RCC, as well as a gauge of other properties such as durability. It is rarely a concern for design loading; tensile strength is generally the principal concern for design. Compressive strength for RCC is measured from cylinders fabricated as described in paragraph 3-2b(2) as well as from drilled cores (ASTM C 42), with the size of the specimens determined using conventional practice with respect to aggregate size. Compressive strength can be measured during construction to monitor mixture variability, to confirm achievement of design properties, and for historical purposes. Compressive strength is primarily affected by cementitious material content, type of cementitious materials, aggregate quality and grading, and degree of compaction achieved. For well-compacted RCC mixtures, these influences are similar to those for CMC. For RCC mixtures either poorly compacted or lacking sufficient paste to fill all voids, the degree of compaction will generally control the level of strength achieved. Typical RCC compressive strength values for a wide range of projects are shown in ACI 207.5R. RCC with high-quality aggregates will produce compressive strength equal to conventional concrete. RCC, due to the use of sometimes marginal aggregates, can provide an even wider range of strength than CMC. Common RCC mixtures may produce compressive strength ranging from 6.9 MPa (1000 psi) to over 27.6 MPa (4000 psi) at 1-year age. Most RCC projects have used mixtures producing an average compressive strength between 13.8 and 20.7 MPa (2000 to 3000 psi) at 90-days to 1-year age. RCC mixtures may be designed for a minimum strength of 13.8 MPa (2000 psi) for durability reasons alone. For seismic areas, higher design compressive strength is often required in order to achieve the higher tensile and shear strength necessary. Compressive strength from cores of RCC follows the standard relationship of core strength to cylinder strength from conventional concrete (ACI 318R), but may vary more widely depending on mixture workability, compaction effectiveness, cylinder preparation methods, and other factors. Core and cylinder testing on a number of RCC dams (ACI 207.5R, McDonald and Curtis 1997) provides an overall average of core compressive strength equal to about 75 percent of the equivalent age cylinder compressive strength. On some projects where low workability RCC mixtures were used, the cylinder strengths have been lower than the core compressive strengths due to difficulty in adequately compacting test cylinders. Coefficient of variation (V) of RCC compressive strength specimens cast during construction has varied widely, depending primarily on the mixture workability. Coefficient of variation (V) is more generally used than standard deviation, due to the commonly low-strength mixtures used on dams. Like CMC, V tends to decrease with later ages of testing. Values of V reported for RCC dams (Schrader 1988, Andriolo 1995) have varied from 10 to 28 percent, with the lower values (< 20 percent) generally representing more workable mixtures. Although there has been little testing of RCC in rapid load compression, there is no reason to expect results much different from test results for conventionally placed mass concrete. Dynamic strength testing is normally performed at rapid load rates to simulate seismic loading. During seismic events, strain rates are related to the fundamental period of vibration of the dam, with the peak stress reached during a quarter cycle of vibration. For a typical gravity dam, this may mean loading the specimens to ensure failure occurs at about 75 msec, depending on the period of the structure. Results from laboratory tests on conventional concrete, indicate an approximate 30 percent increase for compressive strength of moist specimens under rapid loading conditions. The use of moist specimens for the normal load rate or "static" strength tests is critical for this test procedure. The use of dry specimens will generally increase static compressive strength but will not affect the rapid load tests. Such test results will then suggest there is no increase in strength from normal to rapid load rates.

b. Tensile strength. Tensile strength can be measured by several methods, including the direct tension method (CRD-C 164), the splitting tensile method (ASTM C 496), and the flexural test or modulus of rupture method (ASTM C 78). All tensile strength tests are age dependent, load rate dependent, and moisture content dependent. Each of these test methods produces different results, as described by Raphael (1984). The tensile strength of RCC is dependent on cementitious material content, aggregate strength and bond characteristics with the paste, degree of compaction of the mixture, and lift surface condition and treatment. The tensile strength is more dependent on aggregate bond than compressive strength, hence the relationship between the tensile strength and the compressive strength of concrete not only varies with the method of test, but also varies with the type and maximum size of aggregate. Raphael (1984) discusses the tensile and compressive strength of concrete for dams, the various test methods used for measurement, the differences in test measurements, the effects of rapid load testing, and the resulting trends in strength results. ACI 207.2R discusses tensile strength in some detail. Lift joints are the weakest locations in RCC, as in CMC, structures. Hence, the tensile strength at the lift joints is the critical tensile property for RCC. Direct tensile strength (called "bond") is the pertinent tensile test for lift joint tensile strength. Split tensile testing of horizontal cores has been used to establish joint strength; however, identification and location of the joint in the central portion of the core, for correct performance of the test, is very difficult. Prediction of tensile strength based on compressive strength is generally not particularly reliable. The ratio of tensile to compressive strength is of interest to designers, especially for smaller structures where tensile testing may not be conducted. The ratios of tensile strength to compressive strength for RCC mixtures have typically ranged from about 5 to 15 percent, depending on aggregate quality, strength, age, and test method. Cannon (1995) and others have compared these ratios and found them to be widely varying. No single equation can fit existing data, even when only one tensile test method is involved. Cannon found a trend of changing ratios with strength level, with the ratio of tensile to compressive strength decreasing as strength level increased. These ratios depend primarily on aggregate characteristics and strength level. When testing for a specific aggregate, more meaningful ratios may be obtained. As with compressive strength, core tensile strength will generally be lower than equivalent cylinder tensile strength. The ratio of core to cylinder tensile strength can vary widely depending on the tensile test method, the handling of the specimens, and the method of cylinder compaction.

(1) Direct tensile strength (f_{dt}). Direct tension test results for RCC, similar to those for CMC, are lower than for splitting tensile tests (often about 25 to 30 percent lower than splitting tensile strength) and may be assumed to represent the minimum tensile properties of concrete. Direct tension tests are more difficult to conduct for parent concrete than splitting tensile tests, are more affected by drying and microcracking of specimens, and produce higher variability test results when compared with splitting tension tests. Because of the problems involved with the direct tension test, the splitting tensile test has historically been more commonly used to evaluate the parent tensile strength of RCC mixtures. However, the direct tension test is used to evaluate the tensile strength of the lift joint, the tensile property of most interest for RCC structure design. The parent direct tensile strengths from a number of projects, using both cores and cylinders, have ranged from 3 to 9 percent of the compressive strength, with most values between 6 and 8 percent. The ratio of f_{dt} / f'_c varies with strength level and age. The relationships expressed in Tables 4-1, 4-2, and 4-3 were developed to accommodate the apparent reduction in this ratio with increasing strength. The tensile strength of parent RCC should be based on direct tensile test strengths or a maximum of 75 percent of splitting tensile strengths (Cannon 1995). If test strengths are based on wetscreening and removal of aggregates larger than 38 mm (1.5 in.), test values for the full mixture should be reduced by 10 percent.

(2) Lift joint direct tensile strength. Tables 4-1 through 4-3 present a means to determine preliminary lift joint direct tensile strengths for design from splitting tension tests conducted on the parent RCC. The factors used in these tables are based on historical data (Cannon 1995). Lift joint direct tensile strength tests should be run on cast specimens and/or cores from test placement sections to provide values for final design. As with CMC, direct tensile strength at the lift joint will generally be less than in the parent RCC. Lift joint direct tensile strength of RCC is sensitive to the maximum size of aggregates, workability of the mixture, degree of compaction, and age and condition of the lift joint surface. Due to the varying nature of lift joint strength, statistical concepts should be applied in the selection of design values for lift joint tensile strength based on the probability of attaining anticipated joint strengths with the mixtures anticipated, the method of construction, and whether bedding mortar or concrete is applied to the lift surfaces. Inadequate lift surface cleanup, segregation, or poor consolidation can drastically reduce the direct tensile strength across lift lines. Good-quality aggregates, good mixture workability and compaction effort, rapid covering of lift joints by subsequent lifts, and the use of bedding mortar are required to obtain good bond strength at the joint. The mortar bedding ensures that there is adequate paste at the lift surface boundary to provide bond and to fill any rock pockets at the lift surface. When test data are not available, Tables 4-2 and 4-3 represent a range of acceptable preliminary design values for RCC mixtures based on mixture workability, aggregate size and type, and lift joint preparation. Low values of lift joint direct tensile strength are based on natural, low-strength aggregates and unbedded lift joints. High values of lift joint direct tensile strength are based on all crushed, high-strength aggregates and bedded lifts.

(3) Splitting tensile strength (f_{st}). Splitting tensile tests are easier to perform, can be less sensitive to drying and microcracking, and can provide more consistent results than direct tensile tests. However, splitting tensile test results tend to overpredict actual tensile strengths and should be adjusted by a strength reduction factor of 0.75 (Cannon 1995) to reflect results that would be obtained from direct tensile tests. CMC splitting tensile strength typical ranges are shown in Table 4-1. RCC splitting tensile strength varies similarly as shown in Tables 4-2 and 4-3. For preliminary design, Tables 4-2 and 4-3 can be used to develop estimated RCC lift joint tensile strength from splitting tensile tests on the parent RCC. Tests should be conducted to provide values for final design, especially for critical structures. Like direct tensile strength, the ratio of splitting tensile to compressive strength varies with aggregate type, strength level, and age. In the splitting tensile test, the failure plane is normally forced to occur through a narrow area along the specimen's longitudinal axis. This is one explanation for the splitting tensile test's producing values higher than the direct tensile test.

Table 4-1
Conventional Mass Concrete (from Cannon 1995)

NMSA mm (in.)	Max/Min	Split Tensile Strength[a] ≤ 20.7 MPa (≤ 3000 psi)	Split Tensile Strength[a] > 20.7 MPa (> 3000 psi)	Conversion Factor[b]	Design Lift Joint Tensile Strength ≤ 20.7 MPa (≤ 3000 psi)	Design Lift Joint Tensile Strength > 20.7 MPa (> 3000 psi)
≤75 (1.5)	Max	0.15 f'_c	0.664 $(f'_c)^{1/2}$	0.56	0.085 f'_c	0.3735 $(f'_c)^{1/2}$
	Min	0.10 f'_c	0.498 $(f'_c)^{1/2}$	0.56	0.055 f'_c	0.2822 $(f'_c)^{1/2}$
> 75 (1.5)	Max	0.15 f'_c	0.664 $(f'_c)^{1/2}$	0.50	0.075 f'_c	0.332 $(f'_c)^{1/2}$
	Min	0.10 f'_c	0.498 $(f'_c)^{1/2}$	0.50	0.050 f'_c	0.249 $(f'_c)^{1/2}$

[a] Splitting tensile strength of parent material (cylinders).
[b] Includes factors for conversion to direct tensile of 0.80, for joint strength and probable percent of bonded joint of 0.70, and of 0.90 for NMSA >75 mm (1.5 in.).

Table 4-2
Roller Compacted Concrete, Workable Consistency ≤ 30 Seconds Vebe Vibration (Cannon 1995)

NMSA mm (in.)	Use Bedding Mortar? Y	N	Max/Min	Split Tensile Strength[a] ≤ 24.1 MPa (≤ 3500 psi)	Split Tensile Strength[a] > 24.1 MPa (> 3500 psi)	Conversion Factor[b]	Design Lift Joint Tensile Strength ≤ 24.1 MPa (≤ 3500 psi)	Design Lift Joint Tensile Strength > 24.1 MPa (> 3500 psi)
≤ 75 (1.5)	-	-	Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.53	0.090 f'_c	0.3735 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.53	0.040 f'_c	0.2407 $(f'_c)^{1/2}$
> 75 (1.5)	Y		Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.47	0.080 f'_c	0.3320 $(f'_c)^{1/2}$
	Y		Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.47	0.040 f'_c	0.2158 $(f'_c)^{1/2}$

[a] Splitting tensile strength of parent material (cylinders).
[b] Includes factors for conversion to direct tensile of 0.75, for joint strength and probable percent of bonded joint of 0.70, and 0.90 for NMSA 75 mm (1.5 in.).

Table 4-3
Roller Compacted Concrete, Less Workable Consistency > 30 Seconds Vebe Vibration (Cannon 1995)

NMSA mm (in.)	Use Bedding Mortar? Y	N	Max/Min	Split Tensile Strength[a] ≤ 24.1 MPa (≤ 3500 psi)	Split Tensile Strength[a] > 24.1 Mpa (> 3500 psi)	Conversion Factor[b]	Design Lift Joint Tensile Strength ≤ 24.1 MPa (≤ 3500 psi)	Design Lift Joint Tensile Strength > 24.1 MPa (> 3500 psi)
≤ 75 (1.5)	Y		Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.35	0.060 f'_c	0.2490 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.35	0.030 f'_c	0.1577 $(f'_c)^{1/2}$
> 75 (1.5)	Y		Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.32	0.055 f'_c	0.2241 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.32	0.025 f'_c	0.1411 $(f'_c)^{1/2}$
≤75 (1.5)		N	Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.18	0.030 f'_c	0.1245 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.18	0.015 f'_c	0.0830 $(f'_c)^{1/2}$
> 75 (1.5)		N	Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.16	0.025 f'_c	0.1162 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.16	0.015 f'_c	0.0747 $(f'_c)^{1/2}$

[a] Splitting tensile strength of parent material (cylinders).
[b] Includes factors for conversion to direct tensile of 0.75, for joint strength and probable percent of bonded joint of 0.70, of 0.90 for NMSA >75 mm (1.5 in.), and for bedding mortar (0.67 if bedding mortar is used, 0.33 if not used).

(4) Flexural strength. Flexural strength, or modulus of rupture, is a measure of tensile strength. Although flexural strength can be applied directly in analysis as described by Raphael (1984), it is seldom measured due to the difficulty in casting specimens with mass concrete and especially with RCC. In addition, the flexural strength does not evaluate the tensile strength at lift joints, which is the critical tensile strength property for RCC dams. Hence, flexural strength is generally not used in analyses for RCC dam structures. The variation of this test is higher than other tensile tests and higher than that of compressive strength. Some flexural strength beam specimens have been sawn from test sections, but this requires substantial effort and time, with results that may be difficult to interpret. Available RCC data indicate that the Raphael (1984) relationship of flexural to compressive strength is valid for RCC as well (Hess 1995; Omran, Nayak, and Jain 1995). This relationship may be used for planning purposes where necessary, but should be confirmed by testing for significant structures.

(5) Dynamic tensile strength. Although there has been little testing of RCC in rapid load tension, there is no reason to expect results much different from test results for conventionally placed mass concrete. Raphael (1984) discusses the effects of dynamic loading on the tensile strength of concrete. Like compressive strength, tensile strength of concrete is strain-rate sensitive. High strain-rate testing produces tensile strengths at least 50 percent higher than those produced during tensile strength testing where the strain rate is very slow. For this reason, the dynamic tensile strength of RCC is considered equivalent to the direct tensile strength multiplied by a factor of 1.50 (Cannon 1995, Raphael 1984). This adjustment factor

applies to both the tensile strength of the parent material and to the tensile strength at the lift joints, whether tested in direct tension, splitting tension, or modulus of rupture. As with compressive strength specimens, the use of moist specimens for the normal load strength tests is critical for this test procedure.

c. Shear strength. Shear strength is one of the most important concrete properties for RCC dams and is generally represented by a Mohr envelope relationship of a combination of cohesion (bond) and frictional resistance:

$$S = c + \sigma \tan \phi \qquad (4\text{-}1)$$

where

S = shear strength, MPa (psi)

c = cohesion , MPa (psi)

σ = normal or confining stress, MPa (psi)

ϕ = friction angle, deg

CRD-C 90, “Method of Test for Transverse Shear Strength Confined, Single or Double Plane,” can be used to measure this property on cast specimens or drilled cores, for parent RCC and at lift joints, with tests conducted usually at a minimum of three confining pressures. The upper confining pressure selected for dams should represent at least the maximum height of the structure. The shear strength along lift surfaces is always less than the parent concrete. Therefore, as for tensile strength, the strength at lift surfaces will govern the design. Shear strength of the parent or lift joint RCC can be developed from cylinders cast in the laboratory, from blocks of RCC sawn or cored from test sections, or from cores extracted from the RCC structure. For preliminary design, values of parent shear strength can be developed from historical data or tests and then modified to represent lift joint shear strength. Final design shear strength parameters for important structures, such as moderate to high dams or dams in high seismic zones, should be developed from laboratory testing of cores from test sections. Use of “over-design factors” to account for the natural variation of strength results should be applied to shear strength, as are routinely used for compressive strength. Until specific data are available for shear strength test variation, normal coefficient of variation used for compressive strength may be applied.

(1) Parent shear strength. Cohesion varies with the mixture proportions, especially the amount of paste and cementitious content, and with age. The friction angle is primarily dependent on aggregate type and shape and is relatively independent of factors affecting cohesion. Generally, the friction angle does not change significantly with mixture proportions or age. Shear strength properties for RCC are similar to those for CMC. Values of cohesion for the parent RCC have ranged from as little as 0.5 MPa (75 psi) and less to over 4.1 MPa (600 psi) (McLean and Pierce 1988). Values of c / f_c' for workable parent RCC mixtures have ranged up to 20 percent of the compressive strength. Mixtures with Vebe consistency times greater than 30 sec may have cohesion values under 10 percent of the parent compressive strength. RCC friction angles have varied from 40 to 60 deg.

(2) Lift joint shear strength (from cores). The shear strength at the lift joints is generally the critical value for design. RCC shear strength for lift joints can be lower than for CMC and may be more variable on some projects. Cohesion varies a great deal from lift surface to lift surface, while the shear friction angle is usually quite consistent. Cohesion generally varies based on the amount of paste, cementitious content, and lift joint preparation and exposure. Cohesion can be improved by correcting these problems and by application of a bedding mortar or concrete. Shear friction angle is relatively unaffected by factors affecting cohesion and is more dependent on the aggregate type and shape. McLean and Pierce (1988) found that use of ϕ = 45 deg for preliminary design was generally conservative, while use of $c = 0.1\ f_c'$ was unconservative, due partly to the natural variation of all strength properties. For unbedded lift joints, c / f_c' has varied from 0.03 to 0.06. For bedded lift joints, c / f_c' has varied from 0.09 to 0.15. Friction angle for bedded and unbedded lift joints has been essentially unchanged. Evaluation of shear strength from cores requires caution when interpreting results since joint core recovery can vary dramatically depending on drilling and extraction procedures. Core specimens tested are invariably the best samples, while unbonded or poorly bonded RCC generally debonds during coring or extraction and is not tested further. Hence, the percent

joint recovery in a core testing program must be considered when evaluating test results and determining RCC lift joint shear strength design properties. This can be done by reducing the cohesion by a suitable factor representing the percent bonded lifts based on the percent bonded lift joint recovery, similar to that applied for the determination of lift joint direct tensile strength (bond). Bonded lift joint recovery has varied from 2 to 38 percent for projects with unbedded lift joints, while bonded lift joint recovery for projects with bedded joints has varied from 65 to 85 percent. A preliminary design value of c = 0.05 f_c' is recommended for lift joint surfaces that are to receive a mortar bedding; otherwise, a value of 0 should be assumed. A value of ϕ = 45 deg can be assumed for preliminary design or for small projects, for both parent and lift joint shear strength. Design values should also take into account the expected percentage of the joint which will be adequately bonded, as indicated by the testing of cores from test sections and later from the completed structure. Assumed values must be verified for final design by tests performed on samples prepared in the lab and on cores taken from test fills. At a number of RCC projects, joint shear tests, at different confining pressures, have been performed on a series of large blocks of the total RCC mixture cut from test placements compacted with walk-behind rollers or small to full-scale roller compactors. Shear strength under rapid loading may or may not behave like rapid load tensile strength. Until testing of RCC shear specimens under dynamic loading conditions has been accomplished, designers should use values of shear strength conducted using the normal load rate.

4-3. Elastic Properties

a. Modulus of elasticity (E). The modulus of elasticity is defined as the ratio of normal stress to corresponding strain below the proportional limit. For practical purposes, only the deformation which occurs during loading is considered to contribute to the strain in calculating the normal load rate modulus of elasticity (also called “static” or “instantaneous” modulus). Subsequent strain due to sustained loading is referred to as creep. Properly proportioned and consolidated RCC should provide a modulus of elasticity equal to or greater than that of CMC of equal compressive strength made with similar materials. E is dependent on age, strength, and aggregate type, and the same modulus-strength relationships used for CMC may be used for RCC. The modulus of elasticity is determined according to ASTM C 469 (CRD-C 19), “Standard Test Method For Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression,” or CRD-C 166, “Standard Test Method for Static Modulus of Elasticity in Tension,” which are both procedures for a chord modulus. Three methods of modulus measurement are seen in the literature (chord, secant, and tangent). Hence, for critical analyses, the engineer may need to determine which method has been used when using published data. Generally the differences between the methods are small compared to the overall variations in material properties and uncertainties in analysis. The modulus of elasticity may exhibit some anisotropic behavior due to the coarse aggregate particle alignment; however, the effects on the modulus will be small and can generally be ignored. To model the time dependency of the modulus of elasticity, tests should span the duration of analysis. Test ages of 1, 3, 7, 28, 90, 180, and possibly 365 days, as well as the design age, may be considered.

(1) Modulus of elasticity of CMC is about 6.9 GPa (1×10^6 psi) at 1 day and ranges from about 21 to 38 GPa (3 to 5.5×10^6 psi) at 28 days and from about 30 to 47 GPa (4.3 to 6.8×10^6 psi) at 1 year. Lower quality aggregates have been successfully used in RCC, often resulting in very low E at all ages. Hence, RCC values of E tend to have a wider range than for CMC. A low modulus of elasticity is generally beneficial in reducing apparent stress and strain in the structure. Low-strength mixtures will generally produce low moduli.

(2) Tensile E_c is assumed to be equal to the compressive E_c. For critical seismic structures, this assumption should be evaluated more closely, since the stress/strain relationship becomes nonlinear after concrete stresses reach approximately 60 percent of the peak stress (Raphael 1984). In compression this does not cause a problem because, in general, concrete compressive stresses, even during a major earthquake, are quite low with respect to the peak stress or ultimate capacity. In tension, it is a different matter since tensile stress can approach and exceed the peak tensile stress capacity of the concrete, and, in some cases, cracking will occur. For critical projects in seismic areas, the static and dynamic modulus should be determined by testing, using the range of materials and mixtures expected to be used. For rapid strain-rate loading, the dynamic modulus of elasticity may be 15 percent higher than the static modulus (Bruhwiler 1990, Hess 1992).

(3) Sustained modulus of elasticity (E_{sus}) includes the results of creep and can be obtained directly from creep tests by dividing the sustained load on the test specimen by the total deformation. ACI 207.1R and ACI 207.4R include values of static and E_{sus} for CMC. E_{sus} for tests conducted on specimens loaded at early ages for a period of one year will be about 2/3 that of the static E. E_{sus} for tests conducted on specimens loaded at 90 days or later ages for a period of 1 year will be a slightly higher percentage of the static E.

(4) ACI formulas for the modulus are not based on mass concrete mixtures and are generally not accurate estimates of mass concrete modulus. The static modulus of elasticity, in the absence of testing, for planning purposes only, may be assumed equal to the following formula (ACI 318R). Many CMC and RCC tests have indicated modulus values higher than the ACI formula predicts. Because most structural analyses use the modulus to calculate values of stress from strain, the use of the ACI modulus formula may be unconservative for some projects. Caution should be exercised in the use of this formula for critical projects, and actual test results should be used for final design.

$$E = 57{,}000\ (f_c')^{1/2} \tag{4-2}$$

where E = static modulus of elasticity, psi × 10^6, and f_c' = static compressive strength, psi.
Preliminary design studies may assume the modulus of elasticity to be increased by 15 percent for seismic load conditions and reduced by one third for long-time load conditions where creep effects are important.

b. Poisson's ratio. Poisson’s ratio is defined as the ratio of the lateral to the longitudinal strain resulting from a uniformly distributed axial stress and is determined according to ASTM C 469. Poisson's ratio for RCC is the same as for CMC. For static loads, most values range between 0.17 and 0.22, with 0.20 recommended when testing has not been performed. Poisson's ratio is also strain-rate sensitive and the static value may be reduced by up to 30 percent when evaluating stresses due to seismic loads (Bruhwiler 1990). This should be confirmed by testing for critical projects where this property may significantly affect design results. Some testing has suggested that Poisson’s ratio is not significantly sensitive to the strain rates normally considered for mass concrete dams (Hess 1992).

4-4. Creep

Creep is defined as time-dependent deformation (strain) due to sustained load. Specific creep is creep under unit stress, or strain per MPa (psi). Creep from long-term loading results in an increase in strain, but at a continually decreasing rate, under a state of constant stress. Creep is dependent on the material properties and proportions, is closely related to the modulus of elasticity and compressive strength of the concrete, and is thus a function of the age of the concrete at loading. Concrete with a high modulus of elasticity and high strength will generally have relatively low creep. Low strength, low moduli mixtures have larger creep values. Higher creep properties are generally desirable to slowly relieve stress and strain buildup due to foundation restraint and thermal and exterior loadings. Creep is determined according to ASTM C 512, “Standard Test Method For Creep of Concrete in Compression.” Creep tests for mass concrete should always be conducted with sealed specimens to avoid drying shrinkage effects. The test method recommends five ages of loading between 2 days and a year to fully define creep behavior. ASTM C 512 represents creep by the following formula. The first part of the formula, (1/E), represents the initial elastic strain from loading, and the second part represents the long-term effects of creep after loading:

$$\epsilon = (1/E) + F(K)\ln(t+1) \tag{4-3}$$

where

ϵ = specific creep , or total strain per MPa (psi)

E = static modulus of elasticity, MPa (psi)

$F(K)$ = creep rate

t = time after loading, days

Creep values for a number of RCC projects are reported in ACI 207.5R. *F(K)* values for RCC have ranged from 1.5 to 29 millionths per MPa (0.01 to 0.2 millionths per psi), with the higher numbers corresponding to lower compressive strength mixtures. For significant structures, creep tests should be conducted using the materials, proportions, and loading ages applicable to the structure. The effects of creep can also be considered by using the sustained modulus of elasticity of the concrete measured during the period of loading (ACI 224R, ACI 207.1R).

4-5. Tensile Strain Capacity

Tensile strain capacity (TSC) is the change in length per unit length that can be sustained in concrete prior to cracking. Tensile strains can be developed by external loads as well as by volume changes induced through drying, reduction in temperature, and autogenous shrinkage. TSC is dependent on time and rate of loading, type of aggregate, and aggregate shape characteristics (angular as produced by crushing versus natural rounded) and is strongly dependent on strength. Tensile strain capacity is determined according to CRD-C 71. The Corps of Engineers introduced TSC testing of concrete several decades ago to provide a basis for evaluating crack potential for strain-based thermal studies of MCS (Houghton 1976). This property is also used to compare different aggregates and different concrete mix proportions in MCS. TSC is determined in a series of tests that include normal and slow loading of beams. The slow-load test was designed to simulate the strain conditions in a mass concrete structure during long-term cooling. Normal load rate tests were designed to simulate strain conditions near the surface of a mass concrete structure where cooling occurs more rapidly. The test method requires a minimum of three beams for each test, and, generally, a minimum of three tests is recommended for each test set to allow for variation in the test results. A TSC test series usually contains a suite of rapid- and slow-load tests to failure typically initiated at 3, 7, 28, and/or other ages. The differences in TSC capacity from the slow and normal load rate beams provide an indication of the cumulative creep strain during the slow-load test. The strains measured in the slow-load beam test containing both elastic and creep strains are expressed in millionths (1×10^{-6} mm/mm (in./in.)). Houghton (1976) previously described the test procedure for normal load rate tensile strain capacity (TSC_n) and use of the data. TSC test results can vary widely. Use of test results for the specific materials and mixtures to be used in an MCS should be used whenever possible. Typical ranges of TSC for CMC and RCC are shown in Table 4-4. Ratios of CMC slow load TSC to normal load rate TSC tested at the same age as the slow load specimen ranges, from 1.0 to 2.0 and an average of 1.4. This average is relatively insensitive to age. ACI 207.5R provides TSC values for some RCC projects.

Table 4-4
Typical TSC Ranges (millionths)

TSC load rate - Age of loading	CMC	RCC[a]
Slow load rate - 7 to 90 days	88 – 237	--
Normal load rate - 7 days	40-105	20-140
Normal load rate - 90 days	73 –136	--

[a] (Hess 1995, Andriolo 1995)

4-6. Volume Change

a. Drying shrinkage. Drying shrinkage is governed primarily by the water content of the mixture and the characteristics of the aggregate. RCC drying shrinkage is similar to or lower than that of CMC due to the lower water content of these mixtures. Drying shrinkage is tested according to ASTM C 157, “Length Change of Hardened Hydraulic-Cement Mortar and Concrete.” The effects of drying shrinkage are generally ignored for analysis of MCS, since the interior of MCS generally remains moist, except for possible application to surface cracking.

b. Autogenous volume change. Autogenous volume change, commonly called “autogenous shrinkage,” is a decrease in volume of the concrete due to hydration of the cementitious materials without the concrete gaining or losing moisture. This type of volume change occurs in the interior of a large mass of concrete and can be a significant factor. It is primarily related to the material properties and proportions in the mixture and especially the type of aggregate. Autogenous shrinkage occurs over a much longer time than drying shrinkage. Although no specific test method exists, autogenous shrinkage can be determined on sealed creep cylinder specimens with no load applied in accordance with ASTM C 512, “Standard Test Method For Creep of Concrete in Compression,” or from sealed “rapid load” beams fabricated for tensile strain capacity tests. Autogenous volume change cannot be reliably predicted without laboratory testing. Unusual behavior has been occasionally observed with this property, including essentially zero values, as well as positive values denoting expansion. The effects of this property can generally be ignored for small, shorter length structures.

4-7. Thermal Properties

Thermal properties for CMC and RCC are generally similar and are discussed in EM 1110-2-2000. Scanlon and McDonald (1994) describe thermal properties, test methods, ranges of test values and significance of these properties, including coefficient of thermal expansion, adiabatic temperature rise, specific heat, thermal diffusivity, and thermal conductance. The actual property values can vary significantly depending on aggregate, cement and pozzolan type, and content. For this reason, testing the full mixture is recommended. Thermal properties are seldom employed to make final selection of materials for detailed study. These properties are normally determined for the concrete materials selected for use (selection based on other factors). There may be exceptions to this general rule for some large projects where there is a variety of available aggregate sources from which to choose. For these projects, the selection of aggregates based on thermal properties like coefficient of thermal expansion may yield significant cost reductions. ACI reports 207.1R, 207.4R and 207.5R and many WES reports provide a wide range of laboratory determined concrete thermal properties. If likely aggregate sources are known, an improved estimate of thermal properties can be made based on the aggregate rock type and previous testing of CMC or RCC mixtures made with similar aggregate. The coefficient of thermal expansion is usually slightly smaller for RCC (because of higher aggregate content) than for conventional concrete. The coefficient of thermal expansion for CMC and RCC varies between 7 and 14 millionths per °C (4 and 8 millionths per °F). A value of 9 millionths per °C (5 millionths per °F) can be used for preliminary RCC design studies. The ratio of TSC/coefficient of thermal expansion is a rough indicator of the temperature drop required to produce cracking and can be used to compare the ability of various materials combinations (particularly aggregates) to resist thermal cracking.

4-8. Permeability

Permeability of the RCC mass and of the horizontal lift surfaces are key elements for hydraulic RCC structures. The permeability of RCC is largely controlled by mixture proportioning, placement method, use of bedding mortar on lift surfaces, and the degree of compaction. Concrete with low permeability generally has a low water-cementitious material ratio, is well mixed and consolidated, is proportioned with adequate paste and mortar to sufficiently fill all voids, and has been properly cured to allow for the continued hydration of cement. High cementitious material content mixtures have lower permeability than low cementitious material content mixtures. RCC permeability, particularly for lift joints, is discussed in Chapter 5, Design and Construction Considerations. Permeability of RCC cylinders and cores can be tested using CRD-C 163, "Test Method for Water Permeability of Concrete Using Triaxial Cell." This test method produces a value of intrinsic permeability (k) which must be converted to the more commonly used coefficient of permeability (K) using the formula in the test method. In general, an unjointed mass of RCC proportioned with sufficient paste will have permeability values similar to CMC. Test values for well-compacted, workable RCC mixtures typically range from 1.5 to 150×10^{-8} mm/sec (0.3 to 30×10^{-9} ft/min). Measured RCC permeability values have a very large range (Dunstan 1988) because of the wide range of mixtures used and the wide range of density achieved in structures and test specimens due to the use of cores and cylinder specimens and the variety of permeability tests used.

4-9. Density

Density is defined as mass per unit volume and is determined according to CRD-C 23. Density of RCC depends primarily on aggregate density and the degree of compaction. Typical values of density for CMC range from 2240 to 2560 kg/m^3 (140 to 160 lb/ft^3). The lack of entrained air and lower water content of many RCC mixtures result in a slightly higher density when compared to conventional air-entrained mass concrete made with the same aggregate. For some projects in seismic areas, density plays a significant role in structural design and on cost.

4-10. Durability

RCC, like CMC, is subject to potential deterioration due to the effects of abrasion/erosion, freezing and thawing, and other factors such as alkali-silica reaction expansion and sulfate attack. Chapter 8, Performance, discusses historic performance of RCC hydraulic structures subject to deterioration from some of these factors. Water-cementitious material ratio guidance for conventional concrete is given in EM 1110-2-2000, including maximum permissible water-cementitious material ratios for various anticipated structure exposure conditions. Due to the nature of RCC these water-cementitious material ratios cannot be applied easily to RCC but should be followed whenever possible.

a. Abrasion/erosion resistance. Abrasion/erosion resistance is primarily governed by compressive strength of the RCC and quality of the aggregate. ASTM C 1138, "Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)," has been used to evaluate the erosion resistance of both conventional concrete and RCC. This procedure results in values of concrete volume (or average depth) loss at 12-hr increments up to conclusion of the test at 72 hr. Abrasion-erosion percent loss after 72 hr (ASTM C 1138) can be expected to range from about 3 to 15 percent (higher values for lower strength mixtures) for workable RCC mixtures with good to excellent quality aggregates. Sufficient data and field experience with high velocity flows over RCC is not yet available to provide guidance on correlation of test results to field performance. A variety of other observational tests have been run on RCC (Schrader and Stefanakos 1995) to evaluate resistance to abrasion/erosion. These have generally confirmed good to excellent RCC resistance for moderate to high velocity flows. RCC mixtures with a low water-cementitious material ratio and large-size aggregates are expected to provide erosion resistance equal to a conventional concrete with similar ingredients.

b. Resistance to freezing and thawing. RCC mixtures do not normally have intentionally entrained air and consequently will not have a high resistance to freezing and thawing in a critically saturated moisture condition. However, many examples of good field performance exist for RCC that is not critically saturated. RCC subjected to ASTM C 666, Procedure A, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," typically performs poorly. Air-entraining admixtures are available and have been used to successfully entrain air in RCC mixes in the laboratory and on a few RCC projects. Entrained air has been successfully incorporated in RCC mixtures for Zintel Canyon Dam, Nickajack Dam, Santa Cruz Dam, Lake Robertson Dam, and others, as well as in a number of test sections. For workable RCC mixtures, laboratory investigations and field applications have shown certain air-entraining admixtures can effectively establish an air-void system with good performance, even when subjected to ASTM C 666 testing. Most RCC mixtures require a high dosage of air-entraining admixture to be effective, and percentages of air entrained in RCC will usually be more variable when compared with CMC.

Chapter 5
Design and Construction Considerations

5-1. General Design Considerations

a. Introduction. This chapter provides considerations and recommendations for selecting and designing features for RCC structures. In general, most design considerations and recommendations related to RCC construction mirror those that apply to projects built using CMC-type construction. However, RCC design and construction do introduce a number of design considerations unique to this construction method. At no time should the approach to RCC design allow for less than safe performance of the structure. The design parameters should be clear, the design should provide for safe performance, and construction operations should not be compromised. References on the design of RCC structures and related features from several organizations are included in Appendix A.

b. Project considerations. Numerous factors are critical in selecting the features of an RCC structure. Obvious selections are to establish the size and location of the structure, type of structure, available materials, and specific project features and ultimately to determine the cost of the project. Other considerations in selecting features are the annual maintenance required for the completed project, the impact of construction on local residents, industries, and other activities, the impact of the length of the construction season, and the concerns of the public. The functional requirements of the project should be selected with due consideration given to the needs of the customer. The structure must perform in a manner suitable to customer needs. Project managers and designers should consider all these issues when selecting features for the project.

c. Design team. The design team should include the project manager who has direct contact with the customer, the various designers involved in formulating the project features, and, where possible, the construction staff. Once the team establishes the features to be considered in the design, the structural designer determines the strength and serviceability requirements for a proposed RCC structure in concert with the materials engineer who is responsible for developing mixtures that will achieve the desired strength and serviceability properties. The materials engineer should indicate if the desired properties are achievable with the type of construction to be used and the quality of aggregates available. Compressive, shear, bond, and tensile strengths in RCC construction may be as dependent on the method of mixing and placing as on mixture ingredients or mixture proportions. Therefore, the design team must jointly develop project features, balancing the design of each feature with the performance of available materials and with the specification of construction requirements.

d. Simplicity of design. A key element in selecting RCC project features is to keep them as simple as possible. The quality of RCC improves and the cost of RCC decreases when the material can be placed as quickly as is practical. Slow or interrupted placements result in RCC with lower density and poor-quality lift surfaces. Placements should be configured to minimize manual labor and to minimize locations where placing, spreading, and compacting equipment must slow down or be replaced by smaller equipment. Complex designs with consequent complex construction operations have a higher probability of problems resulting in project delays and increased costs. Where such operations are necessary, the design team should carefully coordinate the design and the contract documents to anticipate and eliminate potential problems.

e. Broad applications for RCC structures. A wide range of structure types are possible using RCC. Dams may have straight or curved axes, the faces may be vertical, sloped, or stepped, a variety of seepage and drainage systems may be used, and a range of material properties are possible. Various facing methods using form systems, precast concrete systems, membranes, and RCC are available to construct the RCC faces. Structures have been constructed on rock foundations of various qualities as well as on nonrock foundations. In all cases, the design of the RCC structure must accommodate the site conditions and appropriate construction requirements developed to implement the design. A realistic balance of structural requirements and material performance is necessary, and construction requirements must be tailored to provide the required performance.

f. Other design functions. Detailed guidance on many issues relating to the design of instrumentation systems, foundations, spillways, intake structures, and outlet works is provided in the appropriate EMs and ETLs on the respective subjects.

5-2. Special Structural Design Requirements for RCC Gravity Dams

a. General. The principles of design specified in EM 1110-2-2200, "Gravity Dam Design," apply to RCC gravity dams. However, there are differences in the requirements for uplift within the body of the dam, and there are additional testing requirements to ensure adequate safety factors to protect sliding. RCC structures are generally unreinforced and must rely on the concrete strength in compression, shear, and tension to resist applied loads as well as internal stresses caused by non-uniform temperatures (gradients). The compressive strength of RCC can be high and is seldom a limiting factor in structural design. Unreinforced RCC, as is the case with unreinforced conventional concrete, has limited capacity to resist shear and tensile stresses. Therefore, RCC structures are generally designed so that tensile stresses do not develop under normal operating conditions during the life of the structure. However, under certain unusual and extreme load conditions (e.g., seismic loading), some tensile stress is permitted. Tensile stresses can also develop due to volume changes resulting from long-term and short-term temperature gradients.

b. Uplift within the body of an RCC dam. Uplift within the body of an RCC dam constructed with mortar bedding on all lift joint surfaces can be assumed to vary in accordance with the requirements for conventional concrete gravity dams. When mortar bedding is not used, uplift within the body of the dam shall be assumed to vary from 100 percent of headwater at the upstream face to 100 percent of tailwater (or zero, as the case may be) at the downstream face. The use of impermeable membranes at or near the upstream face of a dam may provide some uplift reduction. Some membrane systems incorporate a drainage layer immediately downstream of the membrane that should be considered. Uplift reductions may be possible based on adequate consideration of the foundation conditions and treatment, the membrane connections, and the reliability of the drainage system. For major dams of substantial height where a foundation gallery is incorporated in the design, drilled face drains in the RCC are recommended to ensure that seepage along lift joints is controlled and that uplift is minimized.

c. Minimum sliding factors of safety for RCC gravity dams. The minimum factors of safety required for sliding stability of RCC gravity dams will be as required in EM 1110-2-2200 for conventional concrete gravity dams. However, because of the uncertainties and variability of cohesive strength at RCC lift joint surfaces, the selection of cohesive strengths used in sliding analyses must be made carefully. A preliminary cohesion design value of 5 percent of the compressive strength is recommended for lift joint surfaces that are to receive a bedding mortar; otherwise, a value of 0 should be assumed. The angle of internal friction can vary from 40 to 60 deg. A value of 45 deg may be assumed for preliminary design studies. Assumed values must be verified by tests performed on samples prepared during laboratory design of RCC mixtures and on cores taken from design stage test sections. These tests must demonstrate that the shear resistance of a typical lift joint meets or exceeds the design requirements. Some minor increases in shear resistance can be achieved by sloping lift surfaces down from downstream to upstream. Requiring inclined lift surfaces is not recommended if the primary goal is to improve shear resistance.

d. Reinforcement in RCC placements.

(1) Anchorage reinforcement. It becomes necessary at times to embed reinforcing steel in RCC for the purpose of anchoring various structural features. These structural features could be outlet works structures, training walls for spillways, parapets, etc. The anchorage of these features to the RCC structure can be accomplished either by installing the reinforcement during RCC placement or by drilling and grouting the reinforcement in place following RCC placement. Although it is common practice to install anchorage reinforcement during RCC placement, this practice has some disadvantages. First, it is difficult to position the reinforcement so that it meets location requirements with respect to the appended structural feature. Second, it is difficult to support the reinforcement during RCC placement so that it will not be displaced, and often it is difficult to devise a reinforcement support system that does not interfere with formwork and construction activities. Holes must be provided in the formwork to accommodate the anchorage extension and must allow enough flexibility so the reinforcement can be placed at an RCC lift surface where mortar bedding will be provided to ensure complete reinforcement encapsulation. Reinforcement to be installed during RCC placement should be provided with a development length at least twice that required for top bars per ACI 318 in order to ensure full bond strength development. As an alternative, anchorage reinforcement can be installed after RCC placement by drilling and grouting. This procedure is more costly but does allow for more accurate positioning of reinforcement and does promote bar encapsulation and bond development.

(2) Structural reinforcement. RCC can and has been placed incorporating steel reinforcing. An example is the spillway chute surfacing and apron for the Toutle River Sediment Retention Dam. The RCC for the spillway chute and apron was

reinforced with heavy welded wire mats. These mats were provided in the RCC placement to (a) prevent the formation of wide cracks that might make the RCC susceptible to deep abrasion-erosion from ash-laden flood flows, (b) provide bending resistance to limit cracking due to differential settlement, and (c) provide shear-friction resistance across cracks to prevent blocks of RCC, formed by perimeter cracking, from being dislodged by flood waters. The welded wire fabric is one innovative way of bringing the strength and serviceability advantages of reinforced structural concrete to an RCC placement.

5-3. Seepage Considerations

a. General. An important design consideration for RCC dams is the control of seepage. Excessive seepage is often undesirable because of the adverse effects on structural stability, possible long-term adverse effects on durability, adverse appearance of water seepage on the downstream face, and the economic value associated with lost water. The joints between RCC lifts can be a major pathway for potential seepage through an RCC dam. Cracks resulting from thermal volume changes, foundation irregularities, and poorly consolidated RCC along the foundations, abutments, and embedded features are the other potential major pathways for seepage. Properly proportioned, mixed, placed, and compacted RCC should make as watertight a structure as conventional concrete. Seepage can be controlled through appropriate design and construction procedures. They include proportioning proper RCC mixtures, installing impermeable membranes, placing bedding mortar over a portion or all of the area of each lift joint, installing contraction joints with waterstops, and draining and collecting seepage water. Collected water can be channeled to a gallery or to the toe of the dam. Collection methods include vertical drains with waterstops at the upstream face and vertical drain holes drilled from within the gallery near the upstream or downstream face. Good practice dictates that any RCC dam, regardless of its intended use or structural or environmental conditions, should be designed and constructed to minimize seepage. Note that some measures can be implemented at little or no extra cost while others may require a significant additional cost.

b. Membrane systems. Impermeable membranes installed at or near the upstream face of a dam provide a method to minimize seepage through an RCC structure. Membranes are thin layers of PVC, polyethylene, or other flexible material that are “plastic welded” to form a continuous sheet. Often, these membranes are attached to precast concrete panels used to construct the vertical upstream face of the dam. Membranes are attached to panels by an adhesive or embedded features. Special provisions must be made to prevent seepage through penetrations in the membrane, interties with the foundation and adjacent structures, and movement of the structure.

c. Drainage systems. Most RCC structures must include provisions for internal and foundation drainage. Drainage is required to stabilize the structure and to capture abutment, joint, crack, and lift joint seepage. Stability provisions for larger structures often require uplift reduction by providing proper foundation drainage. Intercepting seepage water through a structure eliminates visible seepage on the downstream face and the associated maintenance actions that follow. Foundation drainage can be captured in a gallery, a manifold system, or downstream piping systems. Internal drainage is often captured by using face drains, which are a pattern of closely spaced vertical or angled drill holes located near the upstream face of the dam, drilled soon after completion of RCC placement. Joint drains are usually installed downstream of and concurrently with waterstop joints during placement of the RCC and joint assemblies. Various configurations of half-pipes, gravel zones, geotextiles, and perforated tubing are used to intercept seepage water along RCC lift lines and RCC-to-rock interfaces. All of these measures provide secondary containment of seepage water. In all cases, primary containment should be provided by good quality RCC, properly constructed and using bedding mortar or bedding concrete.

d. Considerations for “dry” dams. Dry dams are structures that usually impound no reservoir except for those rare instances where a catastrophic flooding is captured. The purpose of a dry dam is to meter out the volume of water at a rate appropriate for the discharge channel. Generally, such structures are designed for full uplift, and there is minimal treatment of exposed surfaces. These structures are intended to be very low-cost, safe dams. The installation of a foundation grout curtain, foundation drains, and internal drains is not always necessary. When considering dry dams, designers should anticipate future project uses for a flood control structure. A later change of project purpose to a water supply reservoir where a permanent pool will exist may not be possible without extensive and costly modifications.

5-4. Layout of RCC Construction Operations

Several issues specifically related to RCC construction may influence the location of various permanent and temporary project features.

a. Aggregate usage during RCC placement is generally very high because of the continuous placement of RCC at maximum practical production rates. This usually requires large aggregate stockpiles to be used during RCC placement since aggregate production occurs at a slower rate. Normally, large areas for aggregate stockpiles must be provided in order to have adequate quantities of aggregate. Access to these areas is necessary for time periods in advance of RCC placement or during off hours. The alternative to constructing large onsite stockpiles is to utilize extensive truck hauling or extensive conveying at a rate to match the RCC placement rate.

b. The RCC production plant location is often located in the upstream reservoir or on or near an abutment. Obviously, a location near the aggregate stockpiles is advantageous to minimize the transportation of aggregates from stockpiles to the plant. The nature of the stream or river may affect the location of the plant and stockpiles if flooding during the construction season is likely or significant. The plant must be accessible and provide the required staging area for trucks hauling cementitious materials. Such material handling can be an extensive and continuous operation during production of RCC at moderate to high production rates. Access for the resupply of other materials, service vehicles, and auxiliary hauling, such as loaders or dump trucks, should be considered.

c. In populated areas, the impacts of construction traffic, noise, and dust can be a public relations concern and a potential public safety problem. Locating offensive operations in areas that screen the view and the noise may be advantageous. High intensity truck traffic during construction, and the subsequent maintenance and repair of roadways, is always a major concern.

5-5. Testing Programs

a. Approach to testing. A critical part of the design and later construction of any RCC project is the testing and evaluation of materials and construction techniques. The timing and extent of such testing depends on several factors. As with conventional concrete, projects utilizing materials not previously used require a responsible level of quality evaluation. Aggregates, cementitious materials, admixtures, and other constituent materials must be evaluated to ensure basic quality performance. Some of these physical properties are specific to RCC and need not be evaluated the same as for conventional concrete. Projects where optimization of material properties by material selection, mixture proportioning, or structural design changes can result in significant cost savings will benefit from more intensive testing. Less testing may be acceptable where testing yields no such benefits. Projects with only a minor quantity of RCC, where structural performance is easily achieved without extensive testing and evaluation, may benefit from a conservative approach to mixture proportioning. The experience of the design and construction staff may dictate the level of required testing. More experience with local materials in RCC placements may provide a sound basis on which to design the project. Field staff with previous RCC placement experience may be a factor in determining how field placement trials are conducted.

b. Materials testing. Testing of materials for RCC mixtures should be performed in the manner described in EM 1110-2-2000. Chapters 2, 3, and 6 of this EM provide specific recommendations for such testing as it applies to RCC mixtures.

c. Design stage test section. During the design phase of any major project, a preliminary test section should be completed at a convenient location to confirm RCC mixture proportion characteristics and to allow observation of placement and compaction characteristics of RCC. This will provide a means of evaluating mixture proportions, aggregate characteristics, time intervals between lift placements, lift thickness, and placement and compaction techniques. The test section placed during the design phase should be constructed by an experienced contractor hired especially to construct the test section. For smaller projects, it may be more practical to incorporate the gathering of test section data into the construction stage test section. Contracts should be crafted to allow test section construction to be closely controlled by the designer and materials engineer, and appropriate testing should be performed. Each test section should be sufficiently large to permit use of full-size production equipment and to provide a shakedown period to establish and refine procedures and controls. Funds expended on the test sections are nearly always returned manyfold in increased quality and production during later construction. Construction of any test section should use batching and mixing equipment, vibratory compactors, and dozers similar to those anticipated for use on the project. The in situ testing program should address: (1) the type and number of tests necessary to ensure that the required properties are uniformly attained throughout the placement, (2) the sampling procedures required to provide representative samples, and (3) the type of tests and sampling procedures required to test potential planes of weakness such as those that occur at lift joints.

d. Construction stage test section. For any major project, construction of a test section by the project contractor is essential even if a preliminary test section was completed during the design phase. Such a project test section will provide an opportunity for a contractor to develop and confirm techniques and equipment for efficient placement of the required RCC. A project test section should also be designed to demonstrate the contractor's capability to produce the quality and quantity of RCC required by contract specifications. A project test section should be constructed sufficiently early in the contract period to allow the contractor time, if it is necessary, to increase the size of his batching/mixing system to meet project requirements or to modify placing, spreading, and compaction techniques or to modify any other operation that is considered essential to the success of the RCC construction. The designer must consider the size of the test placement when formulating the evaluations to be performed. Contractors cannot meet tight placement rates and time limits if concurrent testing and evaluations interrupt operations.

e. Construction stage test strips. Often it is necessary to quickly evaluate the performance of an RCC mixture. The placing of test strips is a convenient practice to accommodate this. RCC is placed at some designated location in lanes approximately two dozer widths wide and three to six roller lengths long. One or two layers of RCC are typically placed and evaluated. These mini-test sections allow the evaluation of mixture performance and performance of other items of equipment.

5-6. Facing Systems and Techniques

a. Reasons for facing systems. Most RCC structures use some form of facing system to construct one or more of the RCC faces. Natural RCC slopes, that is RCC placed at a slope equal to or less than the natural angle of repose of the material, have been used satisfactorily on many RCC dams. Facing systems are used with RCC structures for several reasons;

(1) Form for RCC face. RCC placed as a granular material cannot stand vertically. Facing systems provide a vertical or sloped form against which RCC is placed. Generally this practice reduces the volume of RCC that would otherwise be required.

(2) Provide a durable surface. As expected, the resistance to freezing and thawing of critically saturated, nonair-entrained RCC is poor. Improvements in the resistance to freezing and thawing of RCC have been achieved using certain admixtures for specific mixtures. However, performance equaling that of conventional concrete is yet to be realized. Until such time that an adequate and consistent air-void system can be introduced into the RCC in the field, unprotected RCC should not be used in portions of a structure subjected to many cycles of freezing and thawing in a critically saturated state. Conventional cast-in-place or precast air-entrained concrete facing elements of adequate thickness should be used to protect the nonair-entrained RCC from damage due to freezing and thawing.

(3) Control seepage. Some facing systems provide a means to control seepage. Panel systems with embedded or attached membranes provide a barrier to seepage. Conventional concrete facing can limit seepage into the structure.

(4) Hydraulic performance. Spillway or outlet surfaces constructed of RCC may not provide the erosion resistance or the dimensional control to serve as high-velocity surfaces. Facing systems are used in this case to provide a cast-in-place concrete surface on the designated slope. Slip-formed elements have been used to provide a stepped spillway surface at some projects.

(5) Aesthetics. In some cases, concerns over the appearance of the upstream or downstream face may dictate whether a facing system or a surface treatment is necessary.

b. Type of facing systems. It may be necessary to clad vertical and near-vertical exposed surfaces of RCC with precast or cast-in-place conventional concrete to provide a more durable exposed surface and to provide a restraint against which the outside edge of each lift of RCC is placed. This is particularly likely to be required for the upstream face of RCC dams and is sometimes used on the downstream face or on spillway or stilling basin training walls. Cast-in-place conventional concrete may also provide increased watertightness for the upstream face and will provide increased resistance to erosion and damage by freezing and thawing. The design for any water-retaining structure constructed using RCC, however, should not put primary reliance on an upstream facing system to protect against seepage. The design for providing watertightness of the structure should rely primarily on the RCC itself; on proper mixture proportions, lift surface treatments, and RCC placement, spreading, and compaction techniques. The conventional concrete facing also provides a medium for installing contraction joints with waterstops and joint drains, as well as thermal or seismic reinforcement, form-tie anchors, and instrumentation which cannot be installed practically in RCC.

c. Simultaneous placement of RCC and conventional concrete facing or abutment foundation bedding. When cast-in-place conventional concrete is placed on the upstream face of a dam constructed of RCC, or when conventional concrete is placed against rock abutments, care must be taken that the interface between the conventional concrete and the RCC is thoroughly consolidated and intermixed. Consolidation should take place in a sequence so that the entire interface area is intermixed and becomes monolithic without segregation or voids in the material or at the interface itself. Paragraph 6-7*b* details the preferred method of placing a low-slump facing concrete against formwork followed by the placement of RCC. This method has proven to provide RCC-conventional concrete joints superior to joints placed in reverse order.

d. Slipform curbing system. Cast-in-place air-entrained conventional concrete elements constructed by slipform methods have been used to form both the upstream and downstream faces of RCC dams. The slip forms move across the dam extruding curb-facing elements. Grade and alignment are maintained using laser control. After each lift of the facing elements (curbs) on each side of the dam achieves sufficient strength, the RCC is placed in 300-mm (12-in.) lifts across the width of the dam between the facing elements before the next lift of curbing is placed. With this procedure, there is no intermixing of the conventional concrete and the RCC; however, this system provides a straight, aesthetically pleasing facing, both upstream and downstream. A concern related to this system is the condition of the interface between the RCC and the extruded curbing. At the interface there may not be any bond, thus creating a plane of weakness between the facing and the RCC. Also there may be segregation and rock pockets in the RCC at the interface. The use of the extruded curb system may be limited to structures where lift thicknesses do not exceed 300 mm (12 in.) because 600-mm (24-in.) lifts would require 1.2- to 1.35-m- (4- to 4.5-ft-) high extruded curb shapes to maintain a reasonable placing rate. As lift volumes decrease, extruding of the curbing often limits the rate of RCC placement.

e. Precast facing systems. Precast panels of conventional concrete have been used as a means of forming the upstream face at several dams. Some were not intended to cut off seepage while others were lined with a continuous polyvinyl chloride (PVC) membrane to completely block passage of water. The membrane-backed precast panel can be a reliable method of eliminating seepage in an RCC dam, provided it is properly and carefully installed. However, care should be exercised in selecting the proper membrane material appropriate for the field conditions. The cost of the system will be high because of the cost of the membrane and the care required to seal all the joints and avoid damage during handling and placing. Whether membrane lined or not, the precast panels serve as stay-in-place forms that provide a finished appearance to the face of the dam as well as a durable air-entrained concrete surface. Precast panels have been used only on vertical faces because the overhang of the panels interferes with the RCC placement and compaction on inclined faces.

f. Uncompacted slope. If little or no attempt is made to compact the edges of an RCC placement, the sides will assume a natural angle of repose ranging from 45 to 65 deg. Dams with a slope of this steepness may use uncompacted RCC for the non-overflow downstream face without special equipment or forms. The uncompacted slope will have a rough natural-gravel appearance with limited strength. When uncompacted slope is used, the structural cross section should include a slight overbuild (at least 300 mm (12 in.)) to account for deterioration and raveling of material loosened from weathering over the project life. The uncompacted outer sections (i.e., sacrificial concrete) should not be included as a portion of the dam cross section for structural purposes. It is recommended that natural slopes that will be exposed to view be trimmed to grade during construction of the dam. This removes the loose material and, if properly done, results in a uniform appearance of the surface. Compaction of the unformed downstream slope using specially designed compaction equipment has been attempted at several projects with varying degrees of success.

g. Formed RCC surfaces. In some situations it may be advantageous to place RCC directly against forms. Without special treatment, formed RCC surfaces may provide a poor-quality surface exhibiting voids and segregated aggregate. However, the use of bedding mortar or concrete against formwork and extra care in compaction can yield very attractive formed RCC surfaces. Grout-enriched RCC has been used on some recent projects to provide durable RCC surfaces with reduced permeability. In this approach, cementitious grout is poured over about a 0.4-m (1.3-ft) strip of the RCC lift surface along the vertical formwork. Once the grout soaks into the RCC, the mixture can be successfully consolidated with internal vibrators to form a homogenous, impervious RCC facing (Forbes 1999). The grout-enriched RCC technique has been successfully used in nearly all of the RCC dams constructed in China during the 1990's. The method has also been used with similar success at the recently completed Cadiagullong Dam in Australia and Horseshoe Bend Dam in New Zealand and is currently in use at the Beni Haroun Dam in Algeria.

5-7. Lift Surfaces

a. Design. The design and constructed quality of lift surfaces are critical to the stability of a structure and to the seepage performance of a structure. The design of a structure will dictate the shear and tensile strength required at the lift joints. The formulation of the mixture proportions and subsequent testing programs are the first steps in ensuring that required performance is attained. Proper specification of construction procedures and field control of construction operations are just as vital to ensuring that required performance is attained. The design team must balance the structural requirements, the material performance, and the required and allowable construction activities in preparation of a viable project design. The considerations discussed below should aid the design team in selecting the appropriate project features related to lift surface quality.

(1) In general, the lift surfaces should provide a clean, bondable surface against which the next lift of RCC can be placed, spread, and compacted so the interface attains the required shear and tensile strength and inhibits the seepage of water. Design values should be selected and conditions should be controlled so that the design values are reasonably attainable and consistently attained.

(2) RCC is often placed in layers measuring 250-400 mm (10-16 in.) in thickness and subsequently compacted. The process is then repeated for the successive lifts. Bedding mortar can be applied to part or all of the lift surface just prior to placement of the next lift of RCC. Partial lift placements of bedding mortar, to minimize seepage through lift joints, are often limited to a width of bedding equal to 8-10 percent of the hydraulic head acting on the lift surface in the zone against the upstream face of the dam. This method is often the most economical means of placing RCC.

(3) A later development, intended to reduce the number of lift joints, increase shear strength of the lift joints, and decrease lift joint seepage, was the placement of four layers of RCC to form a lift. In this method, RCC is placed and spread in approximately 150-mm (6-in.) layers. Each layer is completely tracked with the spreading dozer for compaction. After placement of the fourth layer, the entire surface is compacted with the vibratory roller. This surface later receives a bedding mortar just prior to placement of the next four layers of RCC. This method has the advantage of minimizing the number of lift joints and strengthening the full joint by use of bedding mortar on the full joint.

(4) A bedding mortar or bedding concrete over the upstream zone of each lift joint is recommended for providing watertightness for any dam that will impound water for extended periods. The application of bedding mortar over the full lift surface may be necessary for dams where appreciable bond strength between lifts is necessary (such as those built in earthquake zones where more tensile and shear strength across the lift joints is required than is available without bedding mortar). Tests show that the use of a bedding mortar for low-cementitious materials content mixtures can significantly increase the tensile strength and cohesion value at the joints when compared with lift joints using no bedding mortar. The composition of the bedding mortar and method of application are described in Chapter 6. The need for a bedding mortar or bedding concrete for other structures such as massive foundations, dam facings, sills, and cofferdams should be based on the need for a specific level of bond or watertightness, or both.

(5) Testing of various bedding materials has shown that bedding concrete incorporating coarse aggregate provides slightly better shear performance on lift joints than similar joints bonded using a bedding mortar with no coarse aggregate. Bedding mortar is less labor intensive to apply and should be the preferred material if large areas are to receive bedding. A designer may consider eliminating the full-area bedding mortar on lift joints for dams with no permanent reservoir and where structural analysis does not require the added joint strength. However, possible future uses of the structure should be considered before eliminating features that are irreversible (e.g. the future conversion of a dry dam to a water storage project).

b. Quality. Many factors serve to reduce the quality of the lift surface. A major factor is exposure, i.e., the length of time and the temperature to which a lift is exposed. Lift quality, measured by the cohesion value of the contacting surfaces, tends to decrease as the time between lift placements increases. It also decreases if the temperature is higher during that exposure. Designers of RCC structures must ascertain the probable exposure conditions and develop design and construction requirements appropriately. Specification requirements may limit the time lifts are exposed or limit the maturity of the lift.

Maturity is the integration of the temperature history of the exposure over the time of exposure. This is usually expressed in degree-hours. Excessive exposure is usually treated by varying degrees of cleaning of the lift surface and ultimately by application of a bedding mortar or bedding concrete. For applications where high lift performance is required, cohesion reductions for a range of exposure conditions should be evaluated under controlled laboratory conditions.

5-8. Control of Cracking

a. Cracking of RCC structures. As is the case with most concrete structures, cracks do occur in RCC structures, and, if the structure involved is a dam or other water-retention structure, the results can range from simple leakage to instability of the structure. Cracking is often the result of mass volume changes resulting from long-term cooling of the structure or from short-term cooling of the RCC surfaces. Other cracking may result from abrupt changes in foundation grade and from high stresses generated by re-entrant corners of structures embedded in the RCC. Cracking may occur in spite of preventative measures. The possibility of thermal and restraint-based cracking should be anticipated in design by incorporating appropriate jointing, as well as secondary features such as drainage conduits and sumps, where necessary, to remove water from the structure. The consequences of such cracking may range from destabilization of the structure to operational and maintenance problems. Remedial measures can be extensive and costly.

b. Temperature-related cracking. Analytical methods to determine the potential for cracking of RCC structures are presented in ETL 1110-2-542, "Thermal Studies of Mass Concrete," and ETL 1110-2-365, "Nonlinear Incremental Structural Analysis of Massive Concrete Structures." The means to control such cracking are to: (1) limit the heat gain of the RCC material and thereby limit the volume change, (2) accommodate the volume change by providing an adequate number of contraction joints, or (3) select materials and mixture proportions that yield advantageous elastic and thermal properties. The designer must consider a reasonable program of materials use and temperature controls during construction and balance these with the cost of additional jointing of the structure.

(a) Temperature control. Temperature-control measures for RCC typically will be similar to those used for conventional concrete. These measures include limiting heat evolution of the mixture, limiting placing temperatures, using insulation, requiring nighttime placement, and limiting placement to seasons or periods of cool weather.

(b) Precooling techniques. The postcooling technique of using cooling fluids circulated through pipes is rarely considered for RCC placements because of the high cost interference with high production. Precooling techniques of replacing mixing water with ice may not always be practical for RCC placements because of the relatively small amounts of mixing water used. This precooling technique, however, may have merit where drier aggregates and mixture proportions with higher water contents are used. Precooling of the RCC within the mixer, using liquid nitrogen, has been very effective in reducing peak RCC temperatures at some projects. Liquid nitrogen is expensive and is practical only for reducing peak RCC temperatures for short periods during extremely hot weather. Manufacturing and stockpiling aggregate during cold weather, combined with aggregate retrieval from the cold interior of aggregate stockpiles, can be successful in precooling RCC. However, contract specifications should clearly indicate where aggregate retrieval is to occur and during which season aggregate production and stockpiling is permitted.

c. Transverse contraction joints. Placing vertical transverse contraction joints in dams constructed with RCC and installing waterstops in these joints near the upstream face should be a primary consideration for control of thermal cracking. Several different methods of joint installation have been successfully used in many dams. Given the practicality and cost of many of the thermal controls discussed in the preceding sections, the addition of transverse contraction joints may be the most economical solution to adverse thermal conditions.

d. Foundation-induced cracking. Generally, abrupt changes in foundation grade require that a transverse contraction joint be positioned at the offset to prevent propagation of an uncontrolled crack through the structure. Abrupt changes in foundation grade should be avoided.

e. Re-entrant corner cracking. Various special features can be built in RCC dams. These include drainage and access galleries, outlet conduits, intake towers, and spillways. Where possible, the detrimental effect of the re-entrant corner should be minimized by geometric consideration, use of reinforcement, or installation of a transverse contraction joint.

f. Waterstops and membranes. If transverse contraction joints are used for water-retaining structures, standard waterstops should be installed in an internal zone of conventional concrete at the joint near the upstream face. This zone is monolithic with the conventional concrete facing, if such is used. Waterstops and joint drains are installed in a manner similar to that for conventional concrete dams. Structures using upstream membrane systems do not generally also use waterstops at planned contraction joints. Recent implementations of membrane systems have incorporated features that allow movement at the joint locations without damage to the continuous membrane surface. Details such as double membrane layers and expansion folds should be considered for all applications using membrane systems.

5-9. Galleries for Grouting and Drainage

a. Galleries. For many dams that are greater than 30 m in height, galleries are included in the design. A gallery is necessary to provide a location from which to drill drain or grout holes, provide drainage for leakage, and provide access for inspection. Several different gallery designs have been used in RCC construction. They include construction of a gallery with gravel or sand fill followed by excavation of the fill after the surrounding RCC has hardened, construction using a slip form curbing system for walls with precast reinforced ceiling elements, and construction using conventional forming systems for walls with precast reinforced ceiling units. All of these methods have both advantages and disadvantages.

(1) Excavation of fill material gallery. This method provides a means to construct a gallery with minimal interruption to RCC placement. Uncemented materials are placed in the gallery zone, and placement proceeds. Only after RCC placement has progressed sufficiently above the gallery can excavation of the fill material commence. The major disadvantages of this method are that gallery sidewalls and ceilings can be very rough and irregular and the method requires a mining and excavation operation. Timber plank forms have been effectively used to better confine the fill material and provide a smoother gallery sidewall.

(2) Slipform or precast concrete gallery units. This method provides a good quality gallery and a relatively rapid means to form a gallery. Slip forming should only be considered if gallery lengths are very long and RCC placement advances at a rate of only 1 lift per 24-hr period or less. These gallery systems tend to hide observation of the RCC walls. RCC cracking and seepage water are difficult to detect.

(3) Conventional forming method. This method is often the method of choice for structures where the extent of the gallery is minimal and forms can be constructed easily. This provides a gallery where the RCC is uniformly shaped and visible. It tends to interrupt RCC placement during the placement of the gallery elevation lifts. A form removal operation follows after RCC progresses above the gallery.

b. Elimination of galleries. For lower-head structures, designers should consider eliminating galleries from the design. This action will require alternate measures to be implemented to provide the required foundation cutoff, foundation drainage, and instrumentation access. Grouting can be performed in advance of the RCC placement as it is for embankment dams or at the upstream heel of the dam. Drainage can be accomplished by numerous means that do not include a gallery. Galleries should be limited to the specific zones in the dam where personnel access is required; other means should be used where only drainage and instrumentation are necessary.

5-10. Outlet Works

Outlet structures and conduits can provide obstacles to RCC placement. The preferred practice in placement of outlet works in RCC design is to attach an intake structure to the RCC structure and locate the conduits in or along the rock foundation to minimize delays in RCC placement. Independent, rather than concurrent, construction of these features is often the best approach. Conduits are usually constructed of conventional concrete prior to initiating RCC placement. Locating the intake structure upstream of the dam and the control house and energy dissipator downstream of the toe also minimizes interference with RCC placement. The avoidance of large embedments in the dam simplifies the construction, minimizes schedule impacts, and may maximize savings. The conduits are usually in trenches beneath the dam or along an abutment. Routing outlets through diversion tunnels is a possible configuration. In situations where conditions dictate that waterways must pass through the dam, the preferred approach is to locate all penetrations in one conventionally placed concrete block prior to starting RCC placement. This minimizes the treatments of each embedded feature and ensures less seepage through the structure.

5-11. Spillways

a. General. The hydraulic design of spillways for RCC structures is comparable to that of spillways for conventional concrete structures. The function of the dam structure and the magnitude, frequency, and duration of spill allow certain option selections. Typical spillway options for RCC structures include: (1) natural RCC sloped spillways, (2) stepped RCC spillways, (3) stepped conventional concrete spillways, and (4) sloped conventional concrete spillways. RCC materials for spillway surfaces are appropriate for low-head or infrequent-use spillways. Spillways surfaced with anchored conventional concrete as a chute or steps are preferred for more critical-use situations. Similarly, stilling basins, endsills, roller buckets, and other related features are designed with RCC or conventional concrete.

b. *Erosion*. Concrete erosion is a major concern and must be considered when designing spillway aprons, stilling basin channels, and other concrete surfaces subject to high-velocity flows, or when designing concrete surfaces exposed to the action of abrasive materials such as sand, gravel, or other waterborne debris. Erosion damage of concrete surfaces can be caused by cavitation or abrasion.

(1) Cavitation erosion. Cavitation from surface imperfections has been known to cause surface damage at flow velocities as low as 12 m/sec (40 ft/sec). RCC surfaces cannot be held to the same close tolerances as conventionally placed concrete with formed, slipformed, or screeded surfaces. Therefore, a conventional concrete topping or facing may be required over RCC placements where the surface will be exposed to significant flowing water. Duration of flow, however, is also a factor. For structures with infrequent, short-duration, high-velocity flows, it may be economically prudent to accept some cavitation damage in lieu of strict surface tolerance requirements.

(2) Abrasion erosion. Spillway aprons, stilling basins, and many other hydraulic structures may suffer surface erosion due to abrasion. Concrete, whether RCC or conventionally placed, cannot withstand continued abrasive action from silt, sand, gravel, rocks, construction debris, or other waterborne debris without experiencing severe erosion problems. RCC mixtures with a low water-cement ratio and large-size aggregates are expected to provide erosion resistance equal to a conventional concrete with similar ingredients. In circumstances where abrasion erosion or cavitation erosion is severe, a steel lining may be chosen to minimize maintenance and repair work. The embedments or anchorages required with steel linings do not lend themselves to RCC construction. Therefore, when steel linings are used, conventional concrete, placed to a depth sufficient to encapsulate the liner anchor system, is used over the RCC.

c. Surface treatment for high-velocity flow conditions. RCC can be used for paving open channel inverts, for bank stabilization and erosion protection, and for other flow channelization projects, provided flow velocities are less than 8 m/sec. The surface tolerance control obtained with RCC construction is not suitable when flow velocities exceed 8 m/sec. RCC construction may be considered for spillways, stilling basins, and other flow channelization projects where velocities exceed 8 m/sec; however, a conventionally placed surface concrete screeded and floated to meet specified tolerance requirements must be used if high-velocity flows are expected to occur frequently. Typical conventional concrete applications in RCC dams include spillways, spillway caps, spillway buckets, and stilling basins.

Chapter 6
Construction Methods and Equipment

6-1. RCC Production Controls

The concerns regarding production of RCC can be divided into two main issues, those affecting the quality of RCC and those affecting RCC production rates. The information provided in this manual focuses primarily on determining and achieving the necessary RCC quality for a specific RCC design. However, designers are reminded that one of the primary advantages of RCC over other materials is the relative economy of the final product. This economy is a direct result of the high production rates that are possible with RCC.

a. RCC production rates. One of the cost-saving features of RCC is the rapid rate at which it can be placed and consolidated by earthmoving and compaction equipment. Generally, as with most other construction processes, the faster the placement is made, the less expensive the RCC becomes. In the case of a dam, the faster placement will mean less time between placement of lifts, resulting in lift joints with improved strength and seepage performance. Typical production rates may range from 35 to 150 m^3/hr (50 to 230 yd^3/hr) for a small RCC project, 150 to 350 m^3/hr (230 to 460 yd^3/hr) for a moderate-size RCC project, and 350 to 750 m^3/hr (460 to 1000 yd^3/hr) for a large RCC structure. At Elk Creek Dam in southwest Oregon, a maximum rate of 765 m^3/hr (1000 yd^3/hr) was achieved with an average placement rate of 450 m^3/hr (600 yd^3/hr). High production rates might not be needed or even obtainable on smaller structures where working space is limited. Regardless of the size of the project, the capacities of the batching, mixing, and transporting system must be balanced to keep pace with the placement and compaction operations.

b. System coordination. The production rate for RCC is the result of the concurrent, coordinated operation of several systems: aggregate production; material batching and mixing; RCC transportation, placing, spreading, and compacting; quality control testing; and other related operations. These related operations include bedding placement, facing system placement, gallery construction, and intake works and spillway construction. It is generally necessary to accumulate large aggregate stockpiles before starting RCC placement so that adequate stockpile reserves are available at all times during production. Adequate stockpiles are especially important if the aggregate requires additional processing or transportation from offsite sources. The potential for rapid RCC placement also provides the designer the option of limiting placement to specific time periods to take advantage of cool or warm weather to aid in controlling the temperature of the RCC. It also provides the opportunity to reduce the extent of cofferdam and diversion requirements. The designer must consider the relationship of each of these systems and balance specifications in such a way that the individual system requirements are compatible with the overall production requirements. Whenever possible, the contractor should be given the flexibility to manage the RCC production rates as long as overall schedules are met. This will allow the most economical match of material, equipment, and labor resources. However, required schedule dates must be clearly defined in the specifications, with workable controls to enforce them.

c. Segregation. Segregation is one of the most detrimental conditions that can occur in the production and placing of RCC. Handling of materials must be controlled during each phase of the operation to minimize or prevent segregation of the aggregate. Many of the preferred procedures and equipment used for RCC construction are based, in part, on favorable performance with regard to segregation.

6-2. RCC Production Plants

The RCC plant includes the aggregate stockpiles, the materials feed system, the mixer, and the discharge system. Recommended practices for each of these systems are contained in the guide specifications as well as in the references listed in Appendix A. Many of the practices recommended for conventional concrete production apply to the production of RCC. Some of the notable exceptions are discussed below.

a. Aggregate stockpiles. Segregation is the primary condition to avoid when handling aggregates. Specifications should include provisions to control operations to prevent the occurrence of segregation. Aggregates for conventional concrete are traditionally grouped into specific size groups to prevent segregation. Unlike conventional concrete, RCC aggregates are often grouped in nontraditional size ranges. This practice is intended to take advantage of the natural grading of some in situ materials in order to limit processing of the aggregate. Another intention is to minimize the number of stockpiles and, consequently, the number of handling systems. The presence of 75-µm (No. 200) fines in some fine aggregates for RCC may allow the combination of size groups without segregation. Some projects have used a single stockpile for the full aggregate grading although this is not recommended for most applications. Reducing the number of aggregate size groups and stockpiles may increase the variation in total aggregate grading and, consequently, increase the variation of properties of the RCC produced.

b. Aggregate feed system. Aggregates are usually supplied to the proportioning and mixing plant by one of three methods. The simplest method, usually employed for low-production projects, is the use of a front-end loader to charge aggregate feed bins at the plant. The loader removes aggregate directly from the stockpile and deposits the aggregate in feed bins. Standard implementation ranges from one bin for feeding a single aggregate group or two bins for feeding a fine and coarse aggregate to three bins for feeding one fine and two coarse aggregate groups. A variation of this process is to use remote feeders and conveyors to charge the plant feed bins. Again, front-end loaders haul the aggregate from the stockpile to the bin that feeds the batch plant. This is more typical of projects where the loader haul distances must be minimized. A reclaim tunnel is advantageous for large projects requiring higher volumes of aggregate. This option eliminates the use of front-end loaders by directly feeding the stockpiled aggregate into a tunnel under the stockpile and then conveying the aggregate to the batch bin.

c. Mass batch systems. Mass batching of aggregates involves transferring aggregates from the feed bin to the mass hopper. One or more aggregates are individually discharged into the hopper at prescribed accumulated target masses. Once all the aggregates are batched, they are discharged into the mixer. While mixing progresses, the mass hopper is then recharged with aggregate to continue the process. Many systems of this type have been successfully used in the production of RCC. These batch systems must be coupled to a batch-mixer. The other mixture constituents, cement, fly ash, water, and admixtures, are accumulated in individual mass hoppers or volumetric containers to be transferred with the aggregate to the mixer.

d. Continuous feed systems. Continuous feed systems are used to provide a continuous, uninterrupted flow of material and RCC. The system usually includes an initial feed bin or bins that are maintained at a certain capacity. Material is discharged from these bins through an adjustable gate opening onto a variable-speed conveyor belt. The gate opening and belt speed are varied to achieve a specific rate of aggregate feed. Belt scales, which measure the mass of a section of belt, are often an integral part of the control system where variable-speed belts are utilized. Individual aggregates are often layered onto a single belt feeding the continuous mixer. The feed rate of the other constituents is adjusted in proportion to the rate of aggregate feed. Continuous feed systems are most suited for continuous mixers, but there are a few examples of continuous-feed aggregate systems that supply a batch mixer.

e. Batch- mixers. Batch-mixers are available in several variations. The traditional mixer is a rotating drum mixer. These mixers may be stationary or mounted on a truck frame (transit mixer) and have the capacity to tilt to discharge (tilting-drum mixer). Horizontal shaft mixers, often referred to as compulsory mixers, are composed of a mixing chamber containing two horizontal rotating shafts fitted with paddles. Both mixer types have successfully mixed RCC. The drum mixer is a simpler piece of equipment. Care must be exercised not to overcharge the drum, as buildup of material on drum surfaces is a common problem. Mixing times must be carefully evaluated to ensure complete mixing of the constituents. The horizontal shaft mixers provide complete mixing in much shorter time periods; however, they are more complex equipment. The use of transit mixers should be avoided for most RCC applications. RCC is much less workable than conventional concrete and, consequently, is difficult to mix and discharge from the transit mixer. Transit mixers should only be considered for projects where the RCC volume is small, low production is tolerable, and mixtures can be properly formulated.

f. Continuous mixers. The twin-horizontal shaft mixer is the predominant continuous mixer used for production of RCC. Sometimes referred to as a pugmill, this mixer is capable of handling aggregates up to 100-mm (4-in.) NMSA; however, 35- to 75-mm (1.5- to 3-in.) NMSA is the recommended aggregate size for most applications. Continuous drum mixers, capable of mixing aggregate over 150-mm (6-in.) NMSA, are not often used for RCC construction in the United States. Continuous mixers operate best when production is uninterrupted for long periods of time. These systems are less efficient when operations require frequent stopping of the mixing process. This type of mixer is well suited for most RCC placements since continuous high production rates are desired. Control of mixtures in a continuous feed, continuous mixing process is different from batch systems. Mixture proportions are based on the feed rate of the material rather than mass per volume.

Orientation of quality assurance personnel should be required to prevent the confusion and frustration created by the differences in continuous systems compared with batch systems.

g. Mixer uniformity. Uniformity of the mixing operation is critical to good-quality RCC. Mixer uniformity testing is the primary means to establish whether consistent mixing of materials is occurring. Mixer uniformity for conventional concrete production is determined in accordance with CRD-C 55. A modified implementation of CRD-C 55 is necessary for RCC operations and for continuous mixing operations. A determination of the uniformity of cementitious materials distribution throughout the mixture is the critical component in this evaluation. Strength development is the commonly used indicator of cement content since direct cement content testing by titration methods is difficult and time consuming. Unfortunately, early age strengths of RCC are so low that using compressive strength as a uniformity indicator is not always conclusive. The probable range of production rates to be used on a project should be considered when evaluating mixer uniformity. Many continuous mixers may provide uniform mixtures at higher production rates and perform poorly at very low production rates.

6-3. RCC Transportation Systems

a. General issues. The selection of a transportation system for RCC is an integral part of the design package. The quality of the lift surface is affected by the process used to transport material to the placement area. In general, high-quality lift surfaces, particularly those requiring high lift strength, are better constructed using a transportation system that uses conveyors for transportation on the dam. Vehicle placement systems are more appropriate for placements where lift surface quality and consequent lift strength are not as critical. The apparent high relative cost of the conveyor system compared with vehicle haul systems may be tempered when consideration is given to haul road logistics, placement areas, and damage control measures. Transportation systems that combine conveyor and vehicle methods have been effective on many projects.

b. Conveyor systems. Conveyor systems have proven to be an efficient and safe way to transport RCC and conventional concrete from the mixer to the placement area. Conveyor systems can be configured in several ways. Simple installations convey RCC from the plant to the placement site with just a few fixed conveyors. A rotating, retractable conveyor then deposits the RCC on the lift surface via a drop chute. This configuration is ideal for small placements in tight quarters where the plant is located very near the placement area. The number and length of fixed conveyors increases if the plant is located some distance from the site. Some larger projects have utilized a continuous conveyor on the upstream face of the dam that side discharges RCC to a self-propelled conveyor or moveable conveyor capable of positioning a drop chute at any desired location. Segregation is minimized if the drop chute is maintained just above the top of the pile of RCC and if RCC pile heights are limited to 600 mm (24 in.). If segregation is a significant problem, RCC should be discharged onto uncompacted RCC so that it can be spread by the dozer onto the hardened lift surface. There are several basic requirements for the belt conveyors. They should be of ample width and capable of operation at speeds that meet the production requirements without mixture segregation. Depending on the speed of the belts and exposure conditions, it may be necessary to protect the RCC on the belts from excessive drying and from wetting by rain. The mechanism for cleaning the belts is a key component in conveyor operations. Many conveyors are fitted with a wiper or brush system that removes most of the mortar from the belt. Adjustment and replacement of wipers or brushes may be a frequent operation. In case of a breakdown, critical system components should be accessible for machine removal of RCC before it hardens. Drop chutes (elephant trunks) should be provided at belt discharge points to prevent segregation of material coming off the end of the belt. Also, the drop chutes must be of sufficient length and diameter to prevent plugging and at the same time prevent flaring of material that can result in unacceptable segregation.

c. Mobile conveyors. Many conveyor systems have used a system of fixed belts that feed a rotating and retracting conveyor to place RCC. These systems require the addition of more rotating/retracting units to cover large placement areas. More recent implementations have replaced the rotating/retracting unit with a mobile conveyor. One method is for the RCC supply belt to be installed over the full length of the dam. At desired locations, the RCC is diverted from the belt to a secondary belt feeding a track-mounted rotating/retracting conveyor. This mobile unit is capable of positioning a drop chute at any location on the lift surface (Figures 6-1 and 6-2). This system practically eliminates the need for vehicles to transport RCC on the dam surface.

d. Vehicle transportation systems. RCC can be hauled from the mixer or from the distribution point in end-dump trucks. Front-end loaders have been used in situations where the haul distance is short. Bottom-dump trucks and scrapers normally place RCC in full-thickness lifts and in longitudinal lanes. The distance that RCC can be hauled is dependent on road conditions, weather, traffic, and site topography. If vehicles are used for transporting from the mixer or from a

Figure 6-1. Conveyor system with self-propelled crawler-placer

Figure 6-2. Conveyor system with mobile side discharge belt

distribution point not on the dam itself, care must be taken to prevent their tracking dirt and other foreign material onto the placing site and the damage from vehicles turning on the lift surfaces.

(1) End-dump trucks. Hauling and dumping of RCC with end-dump trucks, combined with remixing and spreading of RCC by dozers, has proven to be an economical and effective method of placing RCC. While all RCC mixtures will segregate when end dumped, the tendency to segregate is more apparent for RCC mixtures with 38-mm (1.5-in.) and larger NMSA. In all cases, dozer spreading and remixing procedures should be specified and enforced to reduce or eliminate the segregation that occurs when RCC is dumped. Large front-end loaders have been used for hauling and dumping RCC to supplement dump trucks in tightly restricted areas. Modifications to the truck bed or loader bucket may be necessary to reduce segregation during dumping. Dumping RCC onto uncompacted RCC is a key method to deal with the problem of segregation. This prevents segregated coarse aggregate from accumulating on the lift surface and allows the dozer to remix the material during spreading.

(2) Scrapers and bottom-dump trucks. Scrapers and bottom-dump trucks place RCC while moving in parallel lanes. Segregation is minimal except at the margin of spread lanes where RCC is susceptible to segregation, especially with large NMSA placed in thick lifts. Also, this same area cannot be compacted until after placement of adjacent spread lanes; therefore, the time interval between placement of adjacent spread lanes will be excessive unless carefully controlled. Such delay will result in RCC that is not satisfactorily compacted and is subject to seepage. In general, RCC should never be placed in a lane pattern. A lift on a dam should be placed as an advancing face where the full upstream to downstream face advances in a uniform manner. This requirement precludes the use of scrapers and bottom-dump trucks for most dam placements.

e. Combination systems. Many projects have used a combination system where RCC is transported to the site using a conveyor and transferred on the dam by a haul vehicle. This system allows the use of inexpensive conveyors off the dam and available equipment on the dam. This practice eliminates many contamination problems; however, surface damage to the RCC by the vehicles will continue. Other configurations transport RCC from the plant with vehicles that transfer the RCC to a conveyor system for transportation onto the dam. In all cases, these systems must include a hopper between the conveyor and the vehicle. The hopper allows continuous operation of the conveyor when vehicles are not in position for loading. The hopper also prevents scattering of RCC onto the lift surface under the conveyor, which can be a major source of segregation and surface contamination.

6-4. Placement Procedures

RCC has been successfully placed in lift thicknesses ranging from a minimum of 150 mm (6 in.) (compacted thickness) to well over 1 m (3 ft), although RCC lift placements in the United States have rarely exceeded 0.6 m (2 ft). Lift thickness can vary depending on mixture proportions, plant and transport capability, placement rates, spreading and compacting procedures, whether or not a bedding layer is used, and size of placement area. For most applications, an initial lift thickness of 300 mm (12 in.) is suggested, with subsequent adjustments based on results of specified preconstruction investigations. The lift thickness should be determined by the designer and specified in the project specifications.

a. Spreading RCC. When lift thickness is limited to 300 mm (12 in.), small dozers have been successfully used to spread and level RCC. Dozer sizes range from a Cat D3 for placement rates up to 150 m^3/hr (200 yd^3/hr) to a Cat D5 size for placements up to 375 m^3/hr (500 yd^3/hr). Combinations of various sized dozers have been used to efficiently place RCC at varying placing rates. RCC should be advanced across the length of the dam for the full upstream-downstream dimension. Placing RCC in lanes must be avoided. RCC should be spread to provide a uniform surface capable of uniform compaction. Ruts, bellies, and humps in RCC surfaces should not be excessive since they prevent uniform compaction. Dozers should never operate on compacted RCC surfaces. When traversing RCC surfaces, protective sheets, such as waste conveyor belts, should be used to prevent damage to the young RCC by the dozer treads. Where lift joint quality is not critical, a single straight track of the dozer across the dam may be allowable. Most RCC contractors utilize a rotating beam laser to control the grade of the RCC lift. These units are ideal for consistent grade control whether the lift surface is level or sloping. Receivers can be mounted on dozer blades for exacting control of RCC spreading. Under production conditions it is more important to spread the RCC to a uniform surface in as short a time as possible than to spend extra time to perfect the final grade. The design of dams with lift thicknesses greater than 300 mm (12 in.) has been based on the realization that the constant spreading of the RCC with dozers not only remixes and redistributes the RCC in such a way as to eliminate (or overcome) segregation but also provides most of the required compaction. This approach also results in thoroughly distributing the paste and mortar in the mass. These procedures have been established and proven in construction and testing of large-scale, well-controlled test sections and in full-scale production of RCC for dams. Dozers spread the RCC in thin sloping layers until three to six layers create a lift with a uniform thickness of 600 mm (24 in.). After completion of spreading, vibratory steel-wheel rollers are used to compact and seal the top surface of each 600-mm (24-in.) lift. The success of this process is largely a result of the compaction resulting from the continuous tracking and natural vibration of the heavy dozers. A sloping layer method (Jiang et al. 1999; Forbes et al. 1999) has been used recently to construct lifts of multiple layes. RCC is placed in layers approximately 200 to 300 mm (8 to 12 in.) thick for a total thickness of 3 to 4 m (10 to 13 ft). With the sloping layer method, each layer is placed at an inclination of approximately 1:10 to 1:20 instead of the typical horizontal orientation. The length of the slope depends on the plant capacity and production rate with typical slope lengths of 20 to 40 m (65 to 130 ft). The sloping layer is placed for the full width of the placement and progresses the full length of the placement. The primary goal of this method is to minimize the exposure of fresh RCC until it is covered with the next sloping layer. Bedding mortar is placed on the mature RCC surface prior to placing the next lift.

b. Compaction. Each lift is compacted with a vibrating steel-wheel roller. It has been determined from various test sections and actual construction projects that RCC can be adequately compacted using a variety of vibratory compactors. These compactors range from relatively small and light asphalt rollers, used extensively for compaction of RCC in Japan, to heavy single-drum units designed to compact rock fills. However, for most applications it is recommended that a double-drum, self-propelled, midsize asphalt roller be used. Rollers of this type should have a high frequency, low amplitude, and dynamic force of 65 to 100 N/mm (350 to 550 lbf/in.) of drum width. Compaction in tight spaces inaccessible to large vibratory rollers requires the use of smaller equipment. Walk-behind rollers can be effective provided they also produce a dynamic force of at least 40 N/mm (215 lbf/in.) of drum width. Manual compaction equipment such as tampers (also known as jumping jacks) and heavy plate compactors have been effective in compacting RCC when lift thicknesses are reduced or workability levels increased. However, many other types of plate compactors and walk-behind vibratory rollers have been ineffective in compacting RCC. Performance must be verified during test section construction. Typically, four to six roller passes (a round trip with a double-drum roller across the same area constitutes two passes) are adequate to achieve desired densities for RCC lifts of 150- to 300-mm (6- to 12-in.) thickness. This result assumes compaction is done in a timely manner with appropriate equipment. It should be noted that excessive rolling can actually decrease density of some mixtures. Compaction in thick lifts after spreading in thin layers is effective provided proper dozer equipment and technique are used and the mixture is proportioned for a workability in the 10- to 30-sec range. In addition to the desired compaction, a vibratory roller provides a tight, smooth lift surface which facilitates cleanup, prevents excess water penetration in wet weather, and reduces drying of RCC in hot and arid conditions. Compaction should be accomplished as soon as possible after the RCC is spread, especially in hot weather. Typically, it is specified that compaction is to be completed within 15 min after spreading and within 45 min from the time of initial mixing for mixture temperatures between 10 and 27 °C (50 and 80 °F). Tests have shown substantial reduction in strength values if RCC is compacted later than these times or when excessive mixture temperatures occur. Cooler temperatures may allow extended time limits. While recompaction of areas damaged by traffic is possible up to the time of initial setting, this practice should be avoided because it masks areas that require lift cleanup prior to placement of the next lift.

6-5. Lift Surfaces

a. Surface moisture conditions. Following completion of rolling, lift surfaces should be moistened and kept damp at all times until the next lift is placed or until the end of the required curing period. This requirement has been one of the hardest to achieve since the tendency of the contractors has been to use water trucks or fire hoses with coarse sprays to wet the surface of the lift. Such procedures should not be permitted since good fog spray nozzles that provide an extremely fine spray are readily available. If coarse sprays are used, paste and fine aggregates sometimes erode away from the surface. Also, the operators of water trucks often make tight turns and repeated passes over the same areas in attempts to cover all parts of the surface. This procedure should not be permitted because tire action mechanically damages the surface. Even though a properly proportioned RCC mixture will not develop laitance, improper use of a water truck can produce a surface scum much like laitance because of overwetting, erosion, and tire action. Consideration should be given to requiring the use of piping and hand-operated hoses with fogging nozzles. Better yet, the RCC should be placed fast enough so that each lift surface is covered before it dries out, or it should be placed during cool and humid periods so that little additional wetting is required. However, seldom will either of these procedures completely eliminate the need for fogging the surface. Shear testing of lift joints subject to various moisture treatments indicates that some drying of the lift surface improves the bonding at the surface. Allowing an exposed surface to dry to a moisture content just below saturated-surface dry conditions is beneficial. However, further drying will decrease the bonding at the surface. Conversely, extra wet surfaces exhibit lower joint strengths than slightly dry surfaces. Such testing reinforces the use of fog nozzles to maintain moisture conditions and allows some latitude in the application of moisture during RCC operations. It may be prudent to reduce or suspend water applications 30 min to 1 hr in advance of RCC placement during hot weather. Field determinations are necessary to establish these constraints.

b. Lift surface preparation. The lift surface preparation required prior to placement of the overlying lift of RCC depends to some extent on the construction procedures and sequence being used. In all cases, the surface of the underlying RCC lift surface must be maintained in a moist condition commencing immediately following completion of rolling, and the lift surface should be cleaned, as necessary, prior to placement of the next lift. The cleanup should include the removal of all loose material, laitance, debris, standing or running water, snow, ice, oil, and grease. Dirt and debris, as well as construction traffic, should be kept off the joint surface at all times possible.

(1) Air nozzle cleanup. Under ideal conditions, cleanup is best accomplished by simply blowing the surface of the lift with an air nozzle when the RCC is less than 24 hr old.

(2) Aggressive cleanup. Surfaces that are several days old or have excessive damage, debris, or contamination may require more aggressive treatment. This can be accomplished with a combination of water hoses, brooms, shovels, buckets, and the use of vacuum trucks. A vacuum truck is a necessary piece of equipment for conditions where waste material and water cannot be easily removed from the surface.

(3) Air/water jet cleanup. If a thick laitance-like scum exists, it may be necessary to use an air/water jet for removal. Specifications should require that the contractor have this equipment onsite. High-pressure water jet cleaning will be required only in extreme cases. This procedure is usually limited to preparation of existing contaminated concrete surfaces or rock surfaces. A paragraph describing the high-pressure water jet is in the "Guide Specification for Civil Works Construction, Mass Concrete," CEGS-03700.

c. Application of bedding mortar. A bedding mortar is a high-slump, high-cement content material that is used to increase bond between RCC lifts and to improve watertightness by filling any voids that may occur at the bottom of an RCC lift during placement and compaction. The bedding mortar must be placed in sufficient thickness to fill such voids without affecting workability of the RCC. Retarders should always be used to extend the time of setting of the bedding mortar. A typical bedding mortar contains 4.75-mm (No. 4 sieve) NMSA, is highly retarded, has a slump of 180 to 230 mm (7 to 9 in.), and contains a high quantity of cementitious materials (approximately 1000 to 1500 kg/m^3 (1685 to 2530 lb/ft^3) of portland cement and fly ash). Bedding mortar should be placed in a zone approximately 10 to 20 m (33 to 66 ft) wide in front of the area where the RCC is being spread. Application of the bedding mortar should precede placement of the RCC, usually by 10 to 15 min. The interval between spreading of the bedding mortar and placement of the RCC should be shortened during hot weather and may be extended during cool weather. Bedding mortar is usually delivered to the placement area by transit mixer for projects where vehicle access onto the lift surface is convenient, or more commonly by crane and bucket. The bedding mortar is distributed from the chutes of ready-mix trucks or from the bucket onto the lift surface and then manually spread with serrated rakes common to asphalt concrete placement. Large projects have used small four-wheel tractors with front-mounted rubber squeegees to spread bedding mortar over large areas. Bedding mortar has also been pumped onto the lift surface and applied as wet-mix shotcrete. This method is excellent for controlling the extent of bedding application and the thickness of the bedding layer.

d. Alternate bedding mixture application. Concrete has been used as a bedding mixture to provide watertightness at the upstream face of some dams. Bedding concrete is a concrete mixture having up to 19.0-mm (3/4-in.) NMSA proportioned to have a slump of 130 to 180 mm (5 to 7 in.). Bedding concrete is spread, usually by manual labor, to a thickness of 25 to 50 mm (1 to 2 in.) in a zone along the upstream face of the dam. The width of application ranges from several feet to approximately one-third of the width of the dam.

e. Adverse weather conditions. Precipitation can be a frequent occurrence during RCC construction. Generally, RCC placement and compaction at a consistent rate greater than 100 m^3/hr (130 yd^3/hr)can continue uninterrupted at precipation rates less than 5 mm/hr (0.2 in./hr). This volume of water is not usually detrimental to RCC performance. However, runoff that accumulates on the lift surface must be avoided. If the rate of precipitation increases above 5 mm/hr (0.2 in./hr), RCC operations should be suspended. The compacted RCC surface should adequately withstand effects of precipitation. Excessive rainfall may require a surface washing prior to restarting RCC placement. In general, RCC placements should be suspended when ambient temperatures drop below 0 °C (32 °F). Massive placements in protected areas may be placed at temperatures a few degrees lower so long as freezing of the surface RCC is prevented. Limits on hot weather placements depend on the temperature limits established from a thermal study and on the ability to maintain surface moisture conditions.

6-6. Placing RCC on the Foundation

Foundation treatments and dental concrete placements should be completed prior to initiating RCC placements. All large cavities, voids, surface irregularities, and areas where RCC cannot be placed and compacted should be filled with dental concrete and properly consolidated and finished. A conventional concrete foundation bedding should be used at the contact between RCC and rock at the abutments and at the dam foundation. This conventional concrete should be proportioned with an NMSA of 19 mm (3/4 in.) to provide a slump of 70 to 140 mm (2-3/4 to 5-1/2 in.) and a 28-day compressive strength in excess of the 1-year compressive strength of the RCC. The conventional concrete and the RCC should be intermixed at the abutments as described for upstream facing concrete. The thickness of the foundation bedding on the abutments should be sufficient to allow for this intermingling. The thickness of the bedding on the foundation will be governed by the roughness of the foundation but should be no thicker than is necessary to fill the voids at the RCC-foundation interface. RCC should be rolled into the concrete bedding, when possible, to ensure intimate foundation contact. Care should be taken to avoid overextending the placement of bedding concrete beyond the area to be covered with RCC. Grout-enriched RCC has also been used successfully at interfaces between RCC and rock foundations (Forbes 1999). After spreading a lift of RCC, fluid grout is poured onto the RCC surface in the vicinity of the abutment. The RCC in this zone is then consolidated with internal vibrators. The RCC adjacent to and overlapping the grout-enriched RCC is then compacted with a vibratory roller.

6-7. Facing Systems for RCC

a. Precast concrete panels. Precast concrete panels are commonly used to form vertical faces of RCC structures. Typical panels are approximately 1 by 5 m (3 by 15 ft) and 100 mm (4 in.) thick.

(1) Construction. Panels can be constructed in an offsite precast concrete facility and transported to the site, or they can be constructed onsite. Onsite construction may include a casting bed where up to 20 panels are cast at one time. This daily casting is repeated until the required number of panels have been constructed. Stack casting is a popular onsite precasting method. This method uses a casting bed where a number of panels are initially cast. A new layer of panels is then formed and cast on top of the previous panels with a bond breaker between. Membranes integrally cast with panels are easily incorporated during precasting.

(2) Placement. Placement of panels requires that a footing be constructed to level and align the first row of panels. For most applications, simple footings are all that is required. For applications where a membrane is tied to the foundation, more elaborate forming is necessary, and extensive placements must be laid up each abutment. Panels may be placed in a row fashion or a checkerboard fashion. Row placement of panels requires that panels be placed in a single row resulting in a continuous horizontal joint line. This placement method usually requires that the panels be supported by external bracing. Such bracing is secured to lower anchored panels through embedded inserts. Checkerboard placing of panels means that a row of panels is placed omitting every other panel. The next row is one-half a panel height higher than the previous row. This method allows for new rows of panels to be supported by the previous row of panels. External bracing can be eliminated using this method; however, more latitude in panel misalignment and bulging must be allowed. In all cases, panels are anchored to the RCC mass by anchor rods or straps secured to the panel by embedded inserts.

b. Simultaneous placement of RCC and conventional concrete facing or abutment coating. When cast-in-place conventional concrete is placed on the upstream face of a dam constructed of RCC, or when conventional concrete is placed against rock abutments, care must be taken to ensure that the interface between conventional concrete and RCC is thoroughly consolidated and intermixed. Consolidation should take place in a sequence such that the entire interface area is intermixed and becomes monolithic without segregation or voids in either material or at the interface itself. The recommended construction sequence is to place the conventional concrete against the rigid forms or abutment rock, then place the RCC in thin layers against the conventional concrete. Each layer of RCC should be vigorously tracked into the conventional concrete by the dozer until the full lift thickness is achieved. The two concrete types should be extended across the dam at as nearly the same placing time as can be accomplished with the equipment available. It is essential that the interface between the two mixtures be consolidated with heavy-duty internal concrete vibrators inserted at close intervals along the interface before time of initial setting occurs in either concrete mixture. Heavy-duty vibrators that are gang-mounted on a tractor, backhoe, or similar equipment should be required rather than expecting workmen with hand-operated vibrators to properly accomplish the work. Using a retarder in each type of concrete to extend the working time is beneficial in attaining a good joint between the two materials. Consolidation of this interface has at times been a difficult quality control problem. Successful consolidation requires intensive use of closely spaced heavy vibrators and care in removing segregated coarse aggregate particles.

c. Curb-forming systems. Placement of vertical, stepped, or inclined facing elements can be accomplished with a curb-forming system. This slipformed concrete placement technique is well suited for projects where the work area is large, the length of the dam is long, and the rise of the structure is limited to less than one lift per 24-hr period. Concrete is generally supplied to the slipform machine by transit mixer; however, a concrete pump with extended boom could be used where access onto the lift surface is difficult. This method can result in good-quality facing elements constructed with minimal interference to ongoing RCC operations. This method requires that elements gain sufficient strength to support RCC placement within 24 hr. The resulting high-strength mixtures may result in extensive cracking within the elements if proper controls are not implemented.

d. Forming systems. Many projects have used traditional forming systems to form the vertical, stepped, and sloped faces of RCC. These systems are used as forms for a conventional concrete facing or for RCC placement directly against the forms. Standard formwork for constructing vertical faces is common. External bracing is used to support forms that are "jumped" to the next level as the dam rises. Stepped form systems are often supported by internal and external bracing secured to the top surface of the previous step. Specifications must include a requirement to ensure that the top surface of stepped forms are at the required elevation. Sloped face forms are similar to forms for vertical faces. Some variations use embedded wire anchors secured to the previous lift surface. Anchors are often short lengths of reinforcing steel driven into the RCC surface. In any case, the formwork must be capable of withstanding the forces created by significant internal vibration of conventional concrete or surface compaction of RCC. The impacts of forming operations on RCC placement increase as the width of the dam section narrows and the length of the dam increases.

6-8. Installing Joints, Waterstops, and Drains

a. Transverse contraction joints. Placing vertical transverse contraction joints in dams constructed with RCC and installing waterstops in these joints near the upstream face should be considered for crack control. This technique and its many variations have been successfully used in many dams. Not all transverse joints require the installation of waterstops and joint drains. One common and effective construction procedure involves forcing galvanized sheet metal panels into the uncompacted RCC lift surface with a backhoe-mounted vibratory blade (Figure 6-3) to form a line of sheet metal in the lift extending from upstream to downstream. Since the metal panels are aligned with those in each lower lift, they form a vertical separation plane from top to bottom. The number and placement of these contraction joints should be determined by a thermal study, construction considerations, and examination of the foundation profile parallel to the dam axis. Another construction procedure involves placement of a sheet panel wrapped with PVC sheeting at the intended joint location. After RCC is carefully placed on each side, the steel panel is removed, leaving the PVC sheeting at the desired joint location. The RCC is then compacted. Generally, this method is effective only when using a crawler-placer, and even then requires great care by workers for proper installation (Figure 6-4).

b. Waterstops and joint drains. The installation of waterstops and downstream joint drains typically requires the placement of conventional concrete. This is usually done in conjunction with placement of a conventional concrete upstream facing. A common method is to fabricate an assembly that includes a steel plate, to form a portion of the joint, coupled to a vertical pipe that forms the round joint drain, and a framework to support the waterstop. In the area of the waterstop and joint drain installation, the facing concrete extends downstream to encapsulate the entire unit (Figure 6-5). Grout-enriched RCC appears to be an effective alternative to conventional concrete for encapsulating waterstops and joint drains (Forbes 1999). Waterstops and joint drains are not usually included in structures with an impermeable membrane at the upstream face or in structures that do not impound a permanent reservoir.

c. Face drains. Many projects incorporate a form of face drain in the design of the structure. As in conventional concrete structures, face drains in RCC structures intercept water seeping along lift joints, random cracks, and construction joints and transfer that water via a drainage system to some downstream discharge point. Several methods have been used to provide these drains. A popular method is to drill a pattern of vertical or angled holes from the top of the dam down to intercept the gallery or drainage manifold. Another method is to install horizontal drains on the lift surfaces. These drains can be permeable pipes along lifts or rock drains within lifts.

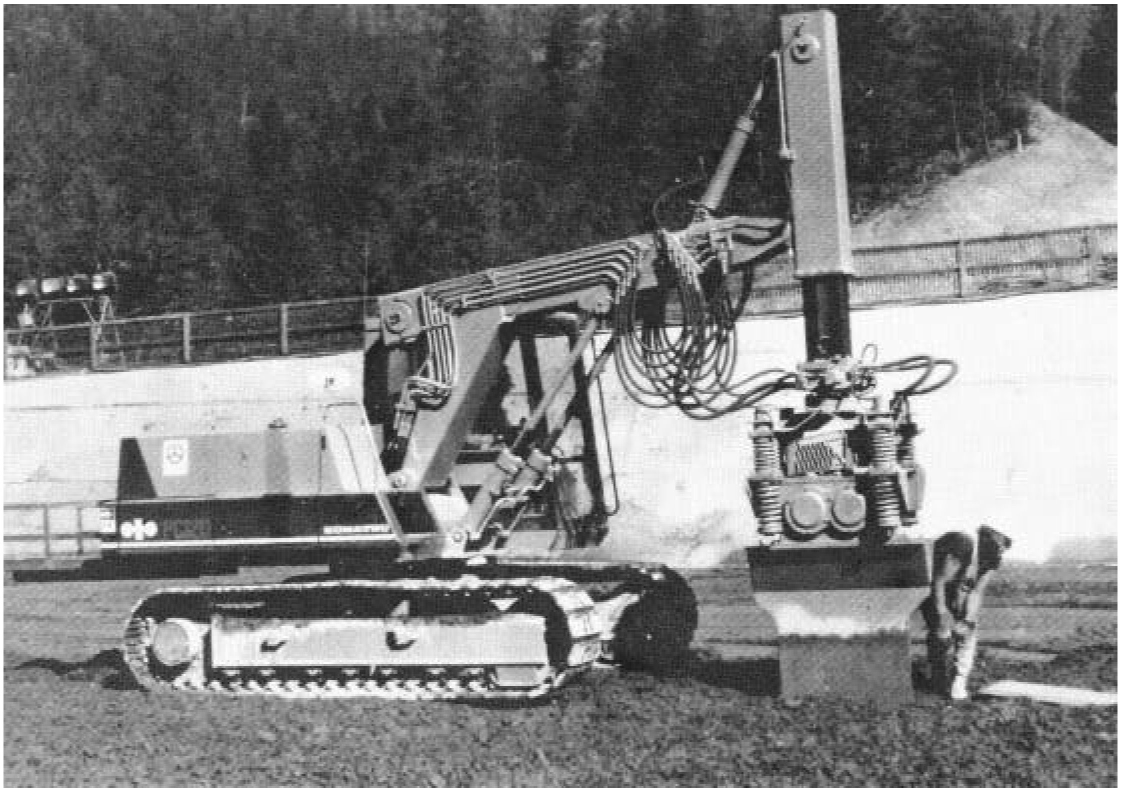

Figure 6-3. Installation of sheet metal joints with vibrating blade

Figure 6-4. Transverse contraction joint construction with plastic-wrapped joint form

Figure 6-5. Installation of waterstop, joint drain, and crack initiator

Chapter 7
Quality Control and Quality Assurance in RCC Construction

7-1. Quality RCC

a. General. Construction quality management policy and guidance are provided in ER 1180-1-6, "Construction Quality Management," and identify the requirements and procedures for Contractor Quality Control (CQC) and Government Quality Assurance (GQA). The contractor is responsible for the management, control, and documentation of activities that are necessary for compliance with all contract requirements. The government program is responsible for ensuring that contract documents establish performance periods and quality control requirements and for ensuring that the CQC program is functioning as required. Contracting Officers are responsible for ensuring that RCC material quality and workmanship quality are clearly defined, that the construction contractors meet the operational requirements, and that the final RCC structure meets the design requirements. The common goal of obtaining quality construction for RCC should be developed between the construction contractor and the government. Clear objectives shall be established within this working relationship that accomplish the end product quality required by the contract documents.

b. GQA program. Government Quality Assurance is the system by which the government fulfills its responsibility to ascertain that the CQC is functioning and the specified end product is realized. During the construction stage, the Contracting Officer, through his authorized representatives, which include the resident engineer and his staff, is responsible for acceptance testing and quality verification to enforce all specification requirements and for monitoring the Contractor's quality control operations. These functions include, but are not limited to, verification of all operations for compliance with specifications and reviewing and, when required, approving contractor submittals, including certificates of compliance and contractor-developed mixture proportions. If acceptance testing of cement, pozzolan, slag, admixtures, or curing compounds is required, the resident engineer is responsible for making the necessary arrangements for such tests. Government surveillance and acceptance inspection and testing are necessary, starting during aggregate production and continuing through the mixing, placing, and curing of RCC. For the surveillance to be effective, surveillance and inspection personnel must be trained prior to the initiation of construction. This can be achieved by seeking instruction from other Corps personnel who have had experience with RCC and by the use of available training aids in the form of slides and videotapes. In addition, there are periodic seminars and conferences on RCC design and construction sponsored by the Portland Cement Association, American Society of Civil Engineers (ASCE), and ACI. The GQA responsibility is not to be imposed on the construction contractor. If personnel shortages preclude the use of government personnel to accomplish GQA, it should be accomplished by a commercial testing organization under contract to the Government.

(1) GQA representative. This individual may be a government employee or may be an employee of a private engineering firm under contract to the Government and not affiliated with the construction contractor. The GQA representative is the key figure in the operations attendant to concrete quality assurance. The effectiveness of the quality verification operation in ensuring uniformity of the concrete and in obtaining compliance with specification requirements depends to a large degree on the thoroughness with which the quality assurance representative is instructed and trained in the performance of the required duties. Instructions to the GQA representative should be accomplished through training conferences and written guides and instructions prepared by the government materials engineer. Previous experience on similar work is highly desirable. Previous experience cannot entirely compensate, however, for proper instruction and training of quality assurance representatives in the duties unique to a particular project. Preferably, they should be trained for duty on a particular project as the concrete plant is being erected so they may become thoroughly familiar with the plant and particularly those aspects of the equipment bearing on the quality verification procedures. For example, on a large project, the mixing plant quality assurance representative should become familiar with the mixing plant and all of its operating features. All persons assigned as quality assurance representatives should be certified by ACI or have equivalent training. EP 415-1-261, "Quality Assurance Representative's Guide," provides detailed responsibilities and a checklist for the GQA representative.

(2) Engineering and construction guidance. For critical projects such as water-retention dams, it is beneficial for a materials engineer from the district or division office who is knowledgeable of the investigations and design of the RCC project to be detailed to the resident engineer. A qualified materials engineer is necessary to provide critical instructions and oversight for engineering and construction coordination. This individual should be able to provide guidance concerning

adjustment of mixture proportions and to evaluate marginal or substandard material constituents used in the mixture. The materials engineer should not be assigned as part of the inspection team required to ensure that compliance with project specifications is enforced. He should be assigned to provide guidance to the resident engineer and his staff on items which include (a) assessment of lift-surface cleanup compared with that assumed in design, (b) guidance on the reduction of segregation, (c) assessment of mixture proportions for adequacy and consistency, and (d) interpretation of Vebe, nuclear density, and other test results. Generally, he is to provide guidance as to which details of the contract specifications that come into question are the most critical in fulfilling design requirements. The materials engineer should also be responsible for the collection of testing data, evaluation, and writing the final concrete report.

c. CQC program. Contractor Quality Control is the system used by the construction contractors to manage, control, and document their activities and those of their suppliers and their subcontractors to comply with contract requirements. For RCC production there are several areas of concern dealing with the CQC program. One area of concern is maintaining a well-managed and trained CQC staff. This is in part due to the geographical market area from which quality CQC personnel can be drawn. In many areas, qualified personnel with experience and training are not available. Training through ACI and government-sponsored courses will help; however, this is not a substitute for training gained through on-the-job experience. The GQA staff should be aware of this and provide appropriate guidance and training to CQC personnel, especially early in construction.

(1) Three-phase program. The CQC program is specified in the Guide Specifications to consist of a three-part program. Participation in the three-phase control process is necessary to ensure that the contractor is adequately conducting the required control processes. Preparatory and initial-phase meetings are necessary to identify and monitor details of each phase of the construction progress while further identifying certain elements of the contract requirements and determining the acceptability of such. The contractor should prepare minutes of each preparatory and initial meeting involving the CQC/GQA activities in order to properly identify and document the mutual agreements concerning adherence to contract specifications. The final inspection and review should ensure that an acceptable end product quality is achieved.

(2) Personnel requirements. Personnel should have experience or sufficient training in order to perform the various testing and inspections required by the project contract. Adequate communication must be developed between the testing, mixing plant, and placement operations personnel. Generally, the CQC testing requirements alone will dictate the staffing needs for a project. At a minimum, two qualified full-time employees should be available for materials testing in the project lab and at the placement for in-place nuclear density testing. Testing personnel will be required prior to beginning daily mixing operations, throughout production placement, and for follow-up testing after compaction and placement operations have ceased for the day. Testing performed by the contracting officer representative does not relieve the contractor from performing all the testing required by the contract specifications. All work performed by technicians must be in strict accordance with applicable standards to ensure the validity and acceptance of test results.

(3) Project laboratory requirements. A project laboratory facility should be available for use by CQC testing personnel, the contracting officer representative, and any GQA testing personnel. A facility with sufficient floor space to allow for sieving, oven drying, weighing, sample processing, and testing and office space is required. The water and electrical needs for the various test equipment should be met.

d. Quality monitoring and control. Another concern is that CQC organizations often do not respond to or modify, in a timely manner, operations that do not meet specifications. Certain activities such as making aggregate free of moisture or grading adjustments must be addressed immediately to prevent permanent deficiencies. A project GQA program should emphasize monitoring and correcting those features that must be responded to immediately. There are also parts of the specifications that the contractor might not view to be as significant as does the government. As an example, a contractor may try to make the case that an aggregate grading slightly out of specification will not alter the product quality and surely does not warrant stopping RCC production. For such issues, it is best to develop a clear understanding at a high level (government resident engineer and contractor project engineer) of what appropriate actions should be taken to prevent problems from occurring and, when they do occur, how to prevent a similar event in the future. In the example given, it is possible that most of the aggregate has already been produced and there is no practical way to bring the aggregate back into grading. It may be more prudent to analyze the consequences of using the aggregate as is or adjusting the mixture proportions to a new grading curve. Quality control problems associated with specific monitoring or testing can be well defined and are, therefore, usually easier to control.

e. Quality control concerns for RCC. There are many construction procedures used in RCC production that are not defined precisely but, nevertheless, significantly impact RCC production quality. The CQC requirements, intended to ensure that RCC production procedures are accomplished correctly, are not rigidly defined. The following are brief discussions with quality control concerns in these areas:

(1) Lift-surface treatment, protection, and cleanup. Contract specifications usually stipulate when and how a lift surface is to be cleaned prior to the next placement; however, there can be several approaches as to which type of treatment to use and how much treatment will be necessary. The amount of treatment will depend on variables such as weather conditions, whether or not a bedding mortar is used, the condition of the previous lift surface, the interval between placements, etc. Judgment is required by both the government inspector and the contractor in providing the appropriate lift-surface treatment for any particular placement condition. Requiring the contractor to meet “the letter of the law” may, under some circumstances, result in unnecessary delays or cause more problems than solutions.

(2) Actions necessary in preventing segregation. Actions to control or prevent segregation within the RCC can be generally defined; however, due to changing site conditions, procedures may have to be adjusted. An increase in segregation as the RCC comes off the conveyor or out of end-dump trucks will require considerably more dozer action to distribute the segregated materials (rock pockets) and rework them into the surrounding RCC. When RCC becomes dryer, more effort is required by the dozer and vibratory-roller operators to achieve a uniformly compacted material that is free of voids. Segregation is also more likely to occur during RCC start-up operations at the beginning of a shift or when placing RCC and conventional concrete against an abutment (or other hard surface such as pipes, forms, instrumentation blockouts, etc.). The government inspector, placement foreman, dozer operator, vibratory-roller operator, and concrete finishers all must be aware of these and other problem areas and be ready to take necessary action to prevent permanent voids from occurring.

(3) Curing. As with conventional concrete, RCC must be kept continuously moist for the prescribed curing period. However, because of large lift-surface areas and the variable intervals between lift placements, the procedures to achieve the necessary curing will vary throughout the job. Because RCC is dryer than conventional concrete, surfaces tend to dry more rapidly during warm weather. During such conditions, considerable effort will be required to maintain a uniformly moist surface. Contract specifications should address the significance of proper curing of RCC along with minimum equipment and procedures that will be required for curing the RCC. During cool weather or when the interval between lift placement is short, no overt curing action may be called for. Judgment and cooperation between the government inspector and the contractor in developing and agreeing on procedures to be taken ahead of time for various changing conditions will result in the most economical and highest quality product.

(4) Consolidation at interface between RCC and conventional concrete. Consolidation at the interface of RCC and conventional concrete is a critical area of concrete construction that, if not executed properly, can and likely will result in voids. Such voids, because of their location and distribution, may allow leakage through a structure. It is a procedure that is straightforward and will result in a high-quality, void-free product if RCC and conventional concrete are fresh, are of proper consistency, and are consolidated with immersion vibrators on a proper spacing. On a day-in, day-out basis, however, this has been difficult to achieve. This is a construction procedure in which attempts to compensate for a developing problem may actually compound the problem. For example, while extra efforts are being made to consolidate concrete that has begun to set or stiffen in one area, concrete materials in another area are becoming progressively older and thus harder to consolidate. Eventually, a condition develops in which the contractor has lost control and no amount of effort will prevent permanent voids from occurring. The contractor and GQA personnel should be aware of the criticality of necessary rapid adjustments that may be required to prevent this situation. Such adjustments may include immediate addition of extra crews and termination of RCC placement until consolidation of the conventional concrete/RCC interface is again on schedule. Judgment and cooperation should be used in establishing criteria for when and under what conditions these extra procedures are to be initiated.

7-2. Activities Prior to RCC Placement

a. Engineering considerations and instructions for field personnel (ECIFP). Prior to award of a contract for construction which involves concrete features, a report should be prepared by the designer outlining all special engineering considerations and design assumptions and providing instructions to aid the contracting officer’s field personnel in the supervision and quality verification of the construction contract. The information provided will, for the most part, summarize the data contained in the Design Memorandums and include all required formal discussions on why specific aggregate sources, plant locations, structural designs, etc. were selected so that the construction personnel in the field will be provided the necessary insight and background needed to perform reviews of the Contractor's various submittal proposals and to resolve construction conflicts without compromising the intent of the design. This information must not conflict with the project specifications and must not contain any request to change these requirements. In all cases, the contract specification will govern. The designated materials engineer should be intimately familiar with the design and construction of the RCC structure and should develop the ECIFP report with the designer. A typical outline for the concrete construction part of such a report is provided as an aid in EM 1110-2-2000, "Standard Practice for Concrete for Civil Works Structures."

b. Construction coordination. As part of preparation and training prior to the initiation of construction, pre-construction meetings with the field staff in review of contract specification requirements should be held with participation by the designated materials engineer experienced in design and construction of RCC dams. A review of allowable construction techniques, testing, inspections, and investigations required by the contract specifications should familiarize field personnel with potential problems that could be encountered, improper construction techniques, and critical design requirements of the RCC dam. This review should be accomplished prior to scheduling any preconstruction meeting with the contractor. RCC design and construction principles should be understood prior to review and acceptance of contract submittals. The preconstruction meeting between the resident engineer and contract personnel should review materials processing, RCC mixing, transporting, placement, and compaction processes, equipment to be used, required testing, and inspections to be performed in relation to meeting contract specification requirements.

c. Plant calibration. Continuous or batch mixing plants require calibration in order to prove the capability of producing a uniform and homogeneous mixture of RCC. Calibrations are the responsibility of the contractor. Accuracy of batching or proportioning equipment shall be checked and documented for each type of material constituent. The methods for verifying accuracy shall follow recognized standards. Mass or volume checks shall be performed using certified scales, reference masses, or measures. The ability to meet prescribed tolerances of the individual material constituents should be verified and documented for the batch or continuous-mixing operation. All of this should be documented and provided to the Contracting Officer prior to beginning the test section.

d. Test strip. As part of the required continuous or batch mixing calibration process, the contractor should develop a test strip prior to scheduling a test section. The recommended test strip would allow for preliminary evaluation of the RCC mixture proportions produced from the mixing operations and would facilitate calibration adjustments to the plant. Further, it would provide for staging the mixing, transporting, spreading, and compaction equipment in order to evaluate the ability to meet the contract requirements.

e. Test section. As a further aid in training both government personnel and contractor personnel, construction of a project test section by the contractor after award of the contract and prior to start of production operations is essential in almost every case where RCC is an option or requirement. This is discussed in section 5-5. The experience gained on a test section will provide a common basis of knowledge between government and contractor personnel and allows for the contractor to try new and innovative construction techniques in work not affecting the safety or function of the project. The test section also provides an opportunity to adjust the RCC mixture proportions. The test section should be designed to demonstrate the contractor's capability to produce the quality and quantity of RCC required by contract specifications. A project test section should be constructed sufficiently early in the contract to allow the contractor time to increase the size of the batching, mixing, or transporting system, if necessary, to modify placing, spreading, and compaction techniques, or modify any other operation that is considered essential to the success of the job. The test section should not be part of the permanent structure. In many instances, test sections have been constructed in a rapid and uncontrolled manner where it is difficult to assess the results. Appropriate planning, equipment, and personnel should be in place in order to accomplish all tasks and testing necessary. The following is a list of tasks that should be performed and significant features that should be evaluated within a test section:

(1) Evaluate mixture performance

(2) Fabricate a density block for calibration of density gauges

(3) RCC transport and movement activities

(4) RCC placement activities

(5) Avoiding segregation

(6) RCC compaction

(7) RCC curing

(8) Evaluate equipment performance

(9) Evaluate plant production and operation

(10) Personnel training

(11) Installation techniques for panels or other structures

(12) Formwork

(13) Hand work and compaction of RCC

(14) Use of bedding mortar

(15) Lift joint preparation

(16) Evaluate fresh and cold joints

(17) Determine a target density

(18) Performance density testing

(19) Other sampling and testing

7-3. Activities During RCC Placement

a. Placement inspection. The inspector on the placement operations should watch all details related to the overall success of RCC placement operations. The following list indicates some of the items to be checked:

(1) Lift surfaces have been adequately cleaned prior to placement of bedding mortars or RCC. RCC contact surfaces shall be free from ponded water, loose debris, mud or silt accumulations, laitance, coatings or other detrimental material, and loose, unkeyed, or deteriorated rock.

(2) Bedding mortar is placed at the required thickness and correct consistency and is adequately spread.

(3) RCC is deposited, spread, and compacted only on fresh bedding mortar that has not begun to dry or set.

(4) RCC is deposited on lift surfaces in the proper location and spread in the required layer thickness, and the action of the dozers is controlled in a manner to eliminate voids and ensure proper compaction.

(5) RCC as it is deposited and spread is of the required workability as determined by the Vebe tests and by observing spreading and compaction operations.

(6) Compaction of the RCC occurs while RCC is still fresh and has not begun to lose workability.

(7) Lift surfaces are maintained in a moist state at all times.

(8) Internal vibration at interfaces between RCC and conventional concrete is in the right location and done correctly with the right number of immersion vibrators of adequate size and for sufficient duration.

(9) Conventional concrete is deposited and consolidated in those areas where it is required, such as around waterstops and drains, against abutments, and other locations as shown on the plans.

(10) The proper and completed installation of facing panels, embedded items, and facing formwork prior to placement of conventional concrete, mortar, or RCC where applicable.

(11) Installation of contraction joints, if required, is completed prior to compaction by rollers and before RCC has begun to lose workability.

(12) The required passes, determined by concurrent nuclear density testing for the vibratory roller on each lift of RCC, are obtained.

(13) All tests, including Vebe tests, nuclear density tests, aggregate moisture tests, and grading tests, are performed, monitored, and evaluated.

b. Monitoring consistency and workability of RCC. To a very large extent, the stability and watertightness of an RCC structure depend on the mixture proportions used and the resulting consistency and workability of the RCC. The inspector on an RCC placement is responsible for ensuring that RCC consistency and workability are adequate for complete compaction. Two testing procedures should be used at frequent intervals to determine if the RCC being produced is of the correct consistency for compaction. The modified Vebe test is used to determine consistency, and the nuclear density gauge is used to determine if compaction is adequate. The modified Vebe test generally provides a good tool for controlling RCC consistency as an indicator of RCC workability and the ease with which RCC can be compacted. Some projects, however, have encountered difficulty in using the Vebe test to monitor consistency and workability. In these cases, visual observation of the RCC mixing and placement operations becomes the primary tool in monitoring for a quality product. In most instances, the Vebe test can provide the best measure for experienced inspectors by developing their visual observation ability.

c. Monitoring density of RCC. Density measurements are typically performed following RCC compaction efforts using a nuclear density gauge in accordance with CRD-C 64 (ASTM C 1040). A single-probe or double-probe nuclear gauge provides reliable information when large numbers of readings are taken. However, the two-probe gauge provides the capability of monitoring RCC densities at all depths within the limit of fresh RCC and provides a better measure of density at lower depth in a lift.

d. Other tests. Other tests are used for monitoring the consistency of material constituents, for evaluating mixing performance, and for controlling the field placement. Following are descriptions of various test methods used for evaluating RCC:

(1) Grading of fine and coarse aggregates, CRD-C 103 (ASTM C 136). Sieve analyses are performed to monitor aggregate grading as delivered to the mixer. This test procedure allows for tracking consistency while providing control over the potential use of non-uniformly graded materials. Tests are performed at least daily on all aggregates as they are sampled from the stockpiles or mixing plant feed belts. Care should be taken when sampling coarse aggregates from stockpiles by using approved and standardized sampling procedures. Many problems have been encountered from improperly sampled aggregates. Sampling for combined aggregates is generally done at the plant discharge belt. If a discharge belt for combined aggregates is inaccessible or if wide variations occur in those samples, a sample of RCC from the mixing discharge belt can be obtained. The RCC mass of the sample should be determined and it should then be washed over a 75-µm (No. 200) sieve, and a representative moisture content should be determined. The plus 75-µm (No. 200) combined aggregate can then be dried and shaken to determine the grading.

(2) Percent finer than the 75-µm (No. 200) sieve, CRD-C 105 (ASTM C 117). This test is performed in order to monitor the minus 75-µm (No. 200) fines content of coarse and fine aggregates used within the mixture. Variability in minus 75-µm (No. 200) content will lead to mixture proportioning deviations and, at times, affects mixture uniformity, water demand, workability, or strength.

(3) Moisture content determination, CRD-C 113 (ASTM C 566). The moisture content of aggregates and RCC are generally performed using a conventional oven, hot plate, or microwave oven as described in ASTM C 566.

(a) Aggregate moisture. The moisture content of aggregates should be determined at least daily for proper RCC moisture control. Test results allow for initial mixing plant adjustments as well as verification of any changes in moisture condition throughout the day, lending to moisture control at the plant. When admixtures are used, increased testing will be necessary to ensure that aggregates remain wet to avoid losing the effectiveness of the admixture.

(b) RCC moisture content. RCC moisture determination allows for monitoring the mixture as it is discharged from the mixing operation, transported, or placed or immediately prior to compaction.

(4) Vebe testing. The modified Vebe apparatus is described in CRD-C 53. Vebe times are used as an indicator of RCC consistency. Samples of RCC are usually taken from the discharge belt or from the placement prior to compaction. The Vebe time used during construction is determined initially during the mixture proportioning studies. The time is then adjusted as necessary during the preconstruction engineering and design phase of the project when a test strip is constructed. It is later further adjusted when the project test section is built after award of contract. Still further adjustments may be made, as necessary, to the Vebe time during construction. Once a Vebe time is established, the normal procedure is to maintain a consistent Vebe time for the RCC being produced by making batch water adjustments to compensate for changes in aggregate moisture and changes in humidity, wind, and temperature. The batch water adjustments should be made if two consecutive Vebe readings vary from a target Vebe time by 10 sec or more. Changes to the established Vebe time should be made only to improve compactibility and the resulting density. Changes should be made only after consultation with the designated onsite materials engineer who is familiar with proportioning mixtures. Densities can also be determined and monitored in conjunction with the Vebe testing.

(5) Determination of mortar content. Mortar contents of RCC can be determined to verify correct mixture proportions and are normally determined in conjunction with mixer uniformity tests. The test is performed on an RCC sample by washing over a 4.75-mm (No. 4) sieve, determining mass, and comparing with initial moisture and mass of the sample.

(6) Determining target density. To obtain percent compaction, the target density should be developed. It should be determined by one of the following methods;

(a) Upon completion of the mixture proportioning, the optimal wet density is selected. During the test section placement, the target density can be verified or determined from the field prototype test results.

(b) The average maximum density (AMD) is determined from the test section placement and verified periodically with the use of control sections that will be part of the production placement. The control sections should be at least 25 - 30 m (80 - 100 ft) long and 4.5 - 6.0 m (15 - 20 ft) wide. As the control section is compacted, in-place wet density tests shall be made after each pass of the vibratory roller until the maximum density of the lift is achieved. The AMD of the control section should be determined from the average of at least six sites selected by the contracting officer's representative. The AMD should not be accepted until the test section has proven that the mixing, placing, spreading, and compacting operations are satisfactory and that the mixture used produces other acceptable test results.

(c) The soil modified compaction test procedure can be utilized to determine a target density. However, compaction testing is limited by the nominal maximum size aggregate selected for the RCC mixture. Excess quantities of plus 19-mm (3/4-in.) NMSA result in increased aggregate breakage or particle bridging, lending to inconsistent and erroneous densities. The compaction procedure involves the use of a 155-mm- (6-in.-) diam mold, a 4.5-kg (10-lb) sliding sleeve rammer with a 457-mm (18-in.) drop height, and 55 blows per each of 5 layers. The wet density is computed from the measured mass and mold volume of the compacted specimen. For RCC with smaller NMSA mixtures, this method can be another useful tool for monitoring mixture consistency.

(7) Monitoring wet density of RCC. Wet density is monitored in order to control compaction of RCC lifts. Testing for wet density is generally done using a nuclear density gauge with a 305-mm (12-in.) probe. One-minute gauge readings are commonly performed in the direct transmission mode. Data from the nuclear gauge readings can be used during the compaction process to confirm that the mixture proportions are correct for achieving the required densities and for determining if densities are uniform throughout the lift. Field nuclear gauge readings should be compared on a continuous basis with RCC densities measured in the project laboratory.

(a) Gauge calibration. To ensure the accuracy of the nuclear gauges being used, a test block should be made during the early stages of the project and kept available. The nuclear gauges must be calibrated upon initiating the test section and also checked daily against a source of known density. This is accomplished by fabricating a test block or calibration block of RCC to a predetermined density. The calibration block should be at least 457 by 457 mm (18 by 18 in.) by the maximum thickness of one lift plus 25.4 mm (1 in.). The block should be compacted to between 98 and 100 percent of the target density. Once fabricated, the mass of block shall be determined and the block measured to verify actual density, or density may be determined by measuring and determining the mass of cores taken from the block. The block should then be used daily before RCC production begins to calibrate the full-depth readings of the nuclear density gauges. Larger calibration blocks, about 0.76 m^3 (1 yd^3) in size, are commonly produced. This provides a significantly greater mass of RCC while, at times, minimizing nuclear density gauge reading and measurement errors.

(b) Percent compaction. Percent compaction is computed from nuclear density and target density results. Control and acceptance should be determined for compaction requirements based upon design criteria, mixture proportioning design, and test section results.

(8) Temperature, CRD-C 3 (ASTM C 1064). Temperature monitoring should be performed at least daily. When daily ambient air temperatures rise significantly above or below the allowable range of temperature for the RCC, more frequent readings should be documented for both RCC and ambient air.

(9) Air content, CRD-C 41 (ASTM C 231). Air content testing is generally not performed on RCC due to the difficulty in maintaining consistent levels of air content in no-slump concrete. When testing is prescribed, the Type B air meters are most commonly used. RCC is screened over the 37.5-mm (1.5-in.) sieve, placed into the air meter in three equal-volume layers, and consolidated by externally applied vibration such as that provided by a Vebe table or pneumatic hammer. The air meter can also be used to determine the density prior to testing for air content.

(10) Fabricating strength specimens. Strength determination testing of RCC from fabricated specimens is customarily performed during construction. Compressive strength specimens can provide an additional tool for monitoring RCC mixture proportioning performance. Consistency of the RCC mixture significantly affects the ability to produce acceptable RCC specimens that can be correlated to in-place RCC. Specimens are generally consolidated or fabricated by externally applied vibration. Typically, overvibration is not a problem because of the very low entrainment of air within RCC mixtures. Overvibration has been known to produce dense specimens that can misrepresent the strength related to that of the actual in-place density. Alternatively, undervibration of stiff mixtures will produce undesirable voids within the specimens and subsequently result in lower and inconsistent strengths. Two types of molds have been used when producing strength specimens. Most commonly, test specimens are molded in cylindrical split molds made of a hard metal or steel. Conventional single-use plastic cylinder molds, placed within a hard metal cylindrical sleeve or split mold for rigidity under consolidation, have also been successfully used. Methods of consolidation for strength specimens have followed two different approaches:

(a) Making RCC in cylinder molds using a vibrating table, CRD-C-160 (ASTM C 1176). This method produces cylindrical test specimens by applying a surcharge weight and table vibration to each of three equal-volume layers of fresh RCC. Each layer is fully vibrated and consolidated when, by observation, mortar forms a ring around the total perimeter of the surcharge within the annular space between the outer edge of the surcharge and the inside mold wall.

(b) Specimens have also been fabricated using pneumatic pole tampers or electric impact hammers with circular rigid metal tamping plates. Three equal-volume layers of fresh RCC are consolidated in a similar manner as that used with the vibratory table.

e. Recommended frequency of testing. Table 7-1 includes the recommended frequency of testing for a typical RCC dam.

Table 7-1
Frequency of Testing for an RCC Dam

Type of Test	Procedure	Frequency Range volume per test	Comments
Grading of fine and coarse aggregates	CRD-C 103/ASTM C 136	Daily or every 2300 m^3 (3000 yd^3) placed	Monitor as-delivered or blended materials
Percent finer than 75-µm (No. 200) sieve	CRD-C 105/ASTM C 117	Daily or every 2300 m^3 (3000 yd^3) placed	Monitor as-delivered or blended materials
Aggregate moisture content	CRD-C 113/ ASTM C 566	once/shift	Rapid drying methods are also used (hot plate)
RCC moisture content	CRD-C 113/ ASTM C 566	twice/shift	Rapid drying methods are also used (hot plate)
Vebe testing	CRD-C 53	twice/shift	ASTM method utilizes a larger surcharge mass
Mortar content	--	--	Verify proportions
Nuclear gauge calibration	--	daily	Checked against calibration block
Monitoring wet density	CRD-C 64/ ASTM C 1040	10 tests/shift	Tracking performance
Temperature	CRD-C 3/ ASTM C 1064	twice/shift	RCC and ambient air
Air content	CRD-C 41/ ASTM C 231	once/shift	When required
Fabricating strength specimens	CRD-C 160/ ASTM C 1176	once/shift	28-, 90-, and 365-day tests

f. Monitoring test results with control charts. The charting of test results is applied to track material quality, mixing operations, and field placement uniformity. Control charts are used to plot daily test results in relation to specified limits, to determine acceptable ranges, and to identify when problems occur or when trends develop. Upper and lower limits for test results are generally prescribed for production and placement control. Individual test data, averages, moving averages for grouped data, and standard deviations can be further developed from control charts. ACI 207.5R, “Roller Compacted Mass Concrete,” provides a good example of control charting for individual test data, standard deviation, average, and moving average for 50 tests. The following tests allow for monitoring consistency of test results through the use of control charts:

(1) Fine and coarse aggregate moisture contents. Absorption can be determined as the lower limit. Moisture contents greater than 1-2 percent above absorption are desired, especially when admixtures are included in the RCC mixture.

(2) RCC moisture content. Several tests daily are recommended. The optimal moisture content is determined from the mixture proportioning study and verified or adjusted during the test section placement. Moisture content is generally expressed as the percent mass of water over the total mass of material. The moisture content should be controlled to within ± 0.2 percent of the optimum.

(3) Grading - minus 4.75 mm (No. 4), minus 75 µm (No. 200). Percentage passing the 4.77-mm (No. 4) and 75-µm (No. 200) sieves can be monitored through control charts for the coarse and fine aggregates. Limits are provided with contract specifications or from recommended size grading requirements such as those provided in Tables 3-1 and 3-2.

(4) Fineness modulus for fine aggregate. The fineness modulus is useful for tracking consistency of the fine aggregate as delivered and used within the RCC mixture. Limits of 2.10 and 2.75 are typically applied, as shown in Table 3-2.

(5) Vebe times for RCC. Vebe testing monitors the consistency of the mixture and allows for performance tracking of the mixing operations. Vebe times of 15 to 20 sec are desirable.

(6) Wet density of the RCC. Nuclear density gauge results are monitored throughout production placement. Some comparisons between control charts for RCC moisture content and wet density reveal where problems occur in the RCC placement. Trend lines falling below the minimum allowable compaction limit may require a review of the mixing operations or a mixture adjustment. The designated materials engineer should review all test results in order to eliminate any other possibilities prior to making mixture adjustments.

(7) Temperature monitoring of the RCC and ambient air. Charting temperature will document the highs and lows and can aid in identifying potential problems on or during particular days within production placement. RCC with temperatures exceeding the specified upper limits may require action to cool the mixture. Tracking ambient temperature will help enforce decisions concerning mixing and placing modifications.

g. Visual observation as an inspection tool. An inspector should be present at all times that RCC is being placed to observe the details listed. To determine if RCC, as delivered, spread, and compacted, is of the correct workability, some visual features should be observed. Visual inspection of the RCC mixture should verify adequate surface coating of the aggregate with paste or mortar. Usually, if the RCC is too dry for proper compaction, obvious signs are: (1) increased segregation of the mixture, (2) aggregate particles on the surface which are cracked by the roller, and (3) little or no reworking of the RCC adjacent to the dozer as the RCC is spread. Cracking of aggregate particles creates a visible scattering of rock flour around the aggregate particles. In addition, concrete which is too dry will not show the development of paste at the surface after three or four roller passes as it should, and individual larger-sized aggregate particles will begin to dry within 10 - 15 min after spreading during warm weather. If closely spaced surface cracking is observed as the roller moves over the surface, the mixture is probably slightly dry. The RCC is likely too wet if heavy equipment produces deep rutting or if surface bleeding of water is observed. The mixture proportions, therefore, may have to be adjusted. An increase in segregation of large aggregate particles from the mixture may be caused by too much or too little water. This condition should be reported by the inspector and corrected as soon as it is observed.

7-4. Postconstruction Activity

a. Drilling program. Samples of RCC can be obtained from coring in order to determine the in situ properties. This provides the best evidence of concrete performance by providing samples for strength and density determination, for viewing the density matrix from top to bottom of the lifts, and for identifying lift joint bond or lack of bond. The primary purpose for obtaining intact lift joints is to determine the performance of shear and tensile strength properties in relation to those used for design. Generally, coring is performed upon completion of the RCC structure. It can also be performed during planned cold joints such as during the planned gallery construction. Skid-mounted or truck-mounted hydraulic coring rigs have successfully obtained intact RCC and foundation cores. Conventional core barrels with a split inner barrel, about 1.5 m (5 ft) in length and 155 mm (6 in.) in diameter, are commonly used for RCC core sampling. Some core breakage occurs where weak lift joints shear during coring. Experienced and careful drillers typically have greater core recovery with intact lift joints. The use of a polymer drilling fluid has also improved recovery of lift joints.

b. Instrumentation. Structural behavior instrumentation programs used in RCC dams are similar to those used in conventional concrete dams. Instrumentation is generally used to monitor temperature, stress, strain, and/or hydrostatic pressure. The extent of instrumentation should result from an evaluation determining the number, type, and location within the structure. The instrumentation program should be designed to avoid interference with rapid placement of RCC and to minimize construction associated with installation. Details and guidance on the planning of instrumentation programs, types of instruments, and the preparation, installation, and collection of data are provided in EM 1110-2-4300, "Instrumentation for Concrete Structures."

c. Documentation. A concrete report will be completed at the conclusion of construction on any major concrete structure such as a concrete dam. The specific requirements for a concrete report are outlined in ER 1110-1-1901, "Project Geotechnical and Concrete Materials Completion Report for Major USACE Projects." The concrete report will serve the dual purpose of meeting the requirements of ER 1110-2-100, "Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures," for engineering data retained at the project site and of advancing the state of the art of constructing large concrete structures by providing personnel working on subsequent projects with a discussion of problems encountered and solutions devised. Construction performance summaries, within the concrete report, should include any developed control charts from test data and should include a discussion of any data trends. Inspection review should include a summary of problems encountered with material storage, mixing, transporting, placing, spreading, compacting, and curing. Any solutions to problems or decisions made concerning modification to the design specifications of the RCC should also be provided in a summary. The postconstruction report should also include an evaluation of the results of strength tests on cores extracted from the structure.

(1) Author. Personnel who are familiar with the project should complete the concrete report, preferably the materials engineer assigned to the project. Personnel from the engineering division should contribute to the report in any areas where they have special knowledge.

(2) Timing. The report should be written as the project progresses so that important information is not lost as personnel changes occur. The report should be completed within 120 days of substantial completion of concrete placing.

Chapter 8
Performance

8-1. General

This chapter discusses the performance of RCC dams and similar RCC structures with respect to watertightness and seepage control measures, joints and cracking, resistance to abrasion-erosion and freezing and thawing, and other effects such as sulfate attack or alkali-aggregate reaction. Strength and other properties of completed RCC structures are addressed in Chapter 4, Properties, and are not discussed in this chapter. Additional information on performance is contained in ACI 207.1R and ACI 207.5R. Since the construction of Willow Creek Dam in Oregon in 1982, over 26 RCC dams had been constructed in the United States, and over 161 RCC dams had been constructed worldwide, by 1994. In spite of the large number of RCC dams constructed worldwide, over 90 percent have been constructed since 1986. Hence, information on long-term performance has yet to be documented. Although this is a relatively short performance record, there are some performance lessons from the structures currently in service. The overall performance to date for RCC dams has been equivalent to conventional concrete dams in all respects.

8-2. Watertightness and Seepage Control Measures

RCC dams have had an overall good performance record for watertightness. Several cases have received a significant amount of attention (notably Willow Creek Dam (Schrader 1988)) for the seepage observed on the downstream face upon first filling. This section covers the reported seepage performance of RCC dams, including the effects of the RCC mixture on seepage, special treatments to reduce seepage, the use of geomembranes, and the use of waterstops and drains. Seepage is generally measured in dams by weirs at key points, or it is measured from collection pipes. Although seepage has been observed on a number of RCC dams, foundation seepage (such as from foundation drains) and seepage through the dam body (generally from joint and other interior dam drains) are often mixed and have not been measured or reported separately. When measurements have isolated foundation and dam seepage, the quantity of seepage penetrating the dam body has often been much smaller than the seepage from the foundation. Moler and Moore (1988) reported that of 15 CMC dams surveyed, only 3 had negligible seepage less than 1 ℓ/sec (10 gal/min). Seepage ranged from 1.2 L/sec to 38 L/sec (20 to 600 gal/min), including foundation seepage. No pattern was found, but seepage decreased with time. Hansen and Reinhardt (1991) and others have shown plots of unit seepage (seepage flow normalized by dividing by the average upstream dam face wetted area and by the average depth to the centroid of the wetted face) versus time for several RCC dams. The most significant feature of these plots is the steady reduction of seepage at all RCC dams with time. This consistent trend for both CMC and RCC dams is the result of healing of seepage routes by calcification, continued cement hydration, and perhaps by some siltation effects. More recent information indicates that RCC dams with minimal seepage have been constructed using a variety of upstream facing and lift joint treatment methods. These RCC dams have generally included some combination of seepage control elements, such as conventional concrete facing, partial lift bedding, and/or membranes embedded in precast panels. A consistent element in RCC dams with minimal seepage is the care applied in constructing the elements that prevent and control seepage in the dam. Geringer (1995) reported minimal seepage through several medium-height South African dams that used conventional concrete in the upstream face, partial bedding of the lift surfaces near the upstream face, workable RCC mixtures, and no membranes. Hansen and Reinhardt (1991) described the seepage performance of several RCC dams, including these conclusions: (1) “Initial seepage volumes from early lean RCC (low workability RCC) dams were in some cases more than anticipated.” (2) “Where measured seepage has increased significantly, it is usually due to leakage passing through a newly formed crack.” (3) “…Seepage is greater with increased head, with increased wetted surface area, and during cold weather when the RCC mass shrinks, thus creating greater crack widths.” (4) “Designs incorporating conventional concrete faces with water-stopped joints ... [or] membrane-faced precast panels have proved to provide a high level of watertightness.” The dam-foundation contact “is a prime potential seepage path and care must be taken to ensure [the contact] has a high degree of watertightness.” Dam seepage is ordinarily reported exiting the dam from such areas as the downstream face, from galleries, and from joints and cracks. Reports on a very few dams suggest foundation seepage entering the dam body through the foundation contact. The edge of RCC lifts tends to be less well compacted compared with the lift interior and tends to absorb more moisture from rain. This effect may result in the lift edges appearing damp, suggesting lift joint seepage instead of simple absorption of rainfall. The performance of some of the significant measures incorporated into RCC dams to control seepage are discussed below.

a. RCC mixture effects on seepage. The workability of the RCC mixture has played a significant role in seepage control, where more workable mixtures (Vebe times < 30 sec) have generally produced improved lift joint bond and watertightness. Some RCC dams constructed with less workable mixtures (Vebe times > 30 sec) (so-called lean RCC) have experienced seepage at the lift joints where segregation and/or incomplete compaction resulted in voids at the lift joint. Workable RCC mixtures can reduce compaction effort and improve compaction consistency, reducing overall permeability of the parent RCC. More significantly, workable mixtures have reduced segregation at the lift joint and have improved lift joint bond, resulting in lower permeability of the lift joint area and reduced seepage. The characteristics of workable RCC mixtures are discussed in Chapter 3, Mixture Proportioning, including Vebe time, sand content, NMSA, and cementitious materials type and content. At Monksville Dam, Hansen and Reinhardt (1991) reported that lower NMSA (from 75 to 50 mm (3 to 2 in.)) and increased sand content (40 percent) resulted in reduced segregation potential and reduced voids. Hansen and Reinhardt (1991) also reported at Arabie Dam that increased sand content (40 percent) assisted in reducing permeability of the RCC.

b. Special treatments and seepage.

(1) Conventional concrete facing. Most RCC dams with conventional concrete facing have had partial lift joint bedding as well. The seepage performance of these dams has been good, although somewhat variable, depending on the care taken during construction, and is likely the result of the lift joint bedding rather than the conventional concrete facing. Conventional concrete facing tends to crack at more frequent intervals than the RCC, due to drying and thermal shrinkage. Cracking of conventional concrete facing may occur as frequently as every 4.6 m (15 ft) and has occasionally initiated crack propagation into the body of the RCC, providing potential seepage paths into the RCC. Cracking of conventional concrete facing has been controlled successfully with contraction joints.

(2) Partial-width lift bedding mortar. This treatment for seepage control has been used on a number of RCC dams. Insufficient data have been reported to indicate how successful this has been, but many of these dams appear to have reasonably low unit seepage.

(3) Full-width lift bedding mortar. This has been used on only a few dams, with little reported seepage performance information available as yet because some of these dams are flood control structures with no permanent pool. Based on laboratory and test section studies, when used with workable RCC mixes, this treatment is expected to result in low rates of seepage.

c. Geomembranes. Upstream face membranes for RCC dams have generally consisted of PVC membranes integrally cast with precast concrete facing panels, with seams heat welded with PVC strips. Some reports of seepage penetrating these membranes suggest that welding of the seams was not completely successful. Urugua-I Dam (Lorenzo and Calivari 1992) experienced significant leakage through a face membrane system, and internal drains behind the membrane became a conduit for relatively substantial flow past the membrane. In addition, the connection of the membrane at the foundation interface has reportedly also led to significant seepage penetrating the membrane. More flexible formulations of PVC membranes have been used recently on at least one RCC dam. These membranes may offer some advantages over more rigid material formulations, depending on the environmental conditions the membrane is subjected to. At Galesville Dam (Hansen and Reinhardt 1991), a coal-tar-based elastomeric membrane was sprayed on the upstream face after cracking developed in the dam. The two 0.5-mm- (20-mil-) thick layers may have contributed to a reduction in overall seepage but could not bridge the existing cracks that penetrated the dam and did not stop leakage at those cracks.

d. Waterstops and drains.

(1) Waterstops. Waterstops have been relatively effective in controlling most leakage through contraction and construction joints, provided they were properly installed (in conventional concrete) and design details did not allow any means for leakage to bypass the waterstops. Where leakage has bypassed waterstops, it has often been due to either poor consolidation of the RCC/conventional concrete interface or cracking that developed around the waterstop. External waterstops placed over joints on the upstream face have been used, but were found to be expensive and subject to leakage when porous areas of concrete exist adjacent to the joint.

(2) Drains. Drains behind waterstops, or between double waterstops, have been successfully installed using cast-in-place techniques and by drilling after concrete construction using percussion drills. The drains have been generally terminated in a

gallery for seepage collection. Both vertical and angled drains through the dam body have been installed in some dams to assist in intercepting and draining any seepage paths through lift joints or cracks. No performance data are yet available to determine if such drainage systems are cost effective.

(3) Sealants. The use of joint sealant in dummy joints on the upstream face of dams has not been generally successful, possibly due to the use of improper sealants, improper application, and weathering of the sealant material. Sealants in general have a limited life, which would require maintenance and replacement at regular intervals during the life of the structure. This method of sealing joints should not be used for dams with permanent pools or where access for sealant replacement is limited.

e. Galleries. Galleries have helped perform several essential roles concerning seepage in all concrete dams, including the collection and measurement of seepage, instrumentation access, and internal observation of the dam structure. The methods of gallery construction in RCC dams have varied widely, resulting in gallery surfaces that range from very rough RCC to smooth cast-in-place or precast conventional concrete. In spite of the wide disparity in appearance, these galleries have performed their essential roles well. In galleries with very rough surfaces (that tend to diminish light), adequate lighting has sometimes been a problem. Where gutters have been omitted from galleries, control of seepage on gallery floors has caused safety and maintenance concerns.

8-3. Joints and Cracking

Cracking of mass concrete may occur in any dam, including RCC dams. Joints, material properties, and other design features are used to minimize or control volume change and consequent potential for cracking. Cracking in RCC dams has been generally similar to that seen in CMC dams. RCC dams have experienced more transverse cracking than CMC dams due to the use of very wide spacing between transverse joints or even the absence of transverse joints. CMC dams have closely spaced transverse construction joints that provide a fair degree of crack control. Longitudinal cracking has been a concern for large RCC and CMC dams, but this cracking has been controlled by reducing thermal contraction of the RCC by a variety of measures. Most cracking in CMC and RCC dams is due to thermal strains, induced as the concrete is cooling from the peak temperature rise, as discussed in Chapter 4, Properties. Cracking in conventional concrete facing for RCC is also affected by drying shrinkage. The spacing of cracks in RCC depends on a number of factors, including the coefficient of thermal expansion and the tensile strain capacity of the concrete. Widely spaced cracks may tend to have wider widths, while closer spaced cracks may have narrow widths. Wider cracks may have more potential for leakage. Cracking has also been caused partly by foundation or design conditions that result in locations of reduced dam section (such as transverse adits or spillway sections), abrupt foundation topographical changes, changes in foundation strength, abrupt dam section changes, or stress concentrations.

a. Transverse contraction joints. Most of the “lean” RCC dams constructed to date have had no transverse contraction joints. Many of these dams have had little significant cracking due to low thermal strain and, possibly, the high creep properties of RCC. Some of these dams have had seepage problems due to causes other than thermal cracking. Transverse contraction joints with upstream waterstops and joint drains have been effective in controlling cracking and leakage of CMC and RCC dams when the joint spacing has been small enough to preclude cracking between joints. Some leakage around waterstops has been reported when the waterstops in conventional concrete were not properly installed. When the spacing of transverse joints was too great, intermediate cracking and leakage have occurred. When installed in RCC dams, contraction joint spacing has varied from 15 to 40 m (50 to 130 ft) and, in some instances, over 90 m (300 ft). Typical joint openings reported have generally varied from 1 to 3 mm (0.04 to 0.12 in.). One instance of cracking due to misaligned transverse joints has been reported (Geringer 1995).

b. Thermal cracking. Thermal volume change has been the primary cause of significant cracking in RCC dams, as is the case with CMC dams. However, the construction joints typically used in CMC to facilitate placement are generally missing from RCC dams due to the abutment-to-abutment method of placement. Contraction joints have been one of the principal means of controlling thermal cracking in RCC dams, but designers have often used widely spaced joints to avoid potential interruption of RCC production and to reduce cost. In many RCC dams, these joints have been spaced too wide for actual construction conditions, and thermal cracking between the joints has developed. Actual placing temperatures have often been higher than considered in thermal studies, due primarily to construction delays pushing placement into warmer weather conditions than anticipated, but also due occasionally to unusual weather or materials problems. Often, thermal cracking has occurred months after construction and first filling of the reservoir, sometimes generating unusual spikes in seepage recordings. Like all concrete dams, the joints and cracks in RCC dams will tend to open with cooler weather and close with warmer weather. Where joints or cracks are widely spaced, these may open to a greater degree than conventional concrete dams with closer joint spacing. This has led to increased leakage in the winter months for some dams. At a number of RCC dams, little to no significant cracking has developed, particularly where relatively closely spaced joints were constructed. Where wider-spaced joints were used, cracks often formed at 30- to 35-m (100- to 120-ft) intervals, with a maximum interval of about 50 m (160 ft). Many of the “lean” RCC dams constructed have had little to no significant cracking, although some of these have had other problems with lift joint seepage. Cracking due to thermal shock has been experienced in RCC dams as in CMC dams. This has occurred when RCC placements were made during periods of moderate to high ambient temperatures followed by relatively sudden drops in temperature of 17 °C (30 °F) or more, rapidly cooling the surficial concrete and initiating surface cracking. These temperature changes have generally occurred unexpectedly, when insulation blankets or other protective measures were not available. A few significant cases of cracking have been described in the literature:

(1) Copperfield Dam (Hansen and Reinhardt 1991) - A transverse crack through the spillway section of the dam occurred 7 months after initial filling.

(2) Upper Stillwater (Hansen and Reinhardt 1991, Richardson 1992) - Transverse thermal cracking was expected in this long structure, and a number of cracks developed, several of which were significant and required treatment due to heavy leakage.

(3) Galesville Dam (Hansen and Reinhardt 1991) - Seven significant transverse thermal cracks occurred through the dam, requiring treatment to reduce seepage.

c. Foundation-related cracking. Foundation terrain or displacements can initiate or affect cracking in any concrete structure or dam. A few RCC dams have had small foundation downstream or vertical displacements upon first filling of the reservoir, some of which may have contributed to cracking in the dam. RCC dams with widely spaced transverse contraction joints may be slightly more prone to foundation-related cracking, lacking more closely spaced joints that can provide strain relief. Foundation terrain, particularly where significant changes in slope exist, have caused designers to locate joints at locations of potential stress/strain concentration. These joints appear to have been mostly effective. A few RCC dams have cracked at changes in dam section such as at gallery locations or where the foundation slope changed. At Upper Stillwater Dam, 10 mm (0.4 in.) of downstream foundation movement was measured after filling, with no movement in the dam detected (Richardson 1992, Hansen and Reinhardt 1991). No further movement has been reported. This may have initiated a significant transverse crack that required later treatment for leakage.

8-4. Durability

The primary durability concerns for RCC dams are resistance to abrasion-erosion of flowing water and freezing and thawing.

a. Abrasion-erosion. The abrasion-erosion resistance parameters for RCC are similar to those for CMC. Concrete surfaces subjected to flow velocity over 12 m/sec (40 ft/sec) should be protected as required in EM 1110-2-2000. Due to the still relatively short performance history of RCC dams, comparatively few have sustained major flows. None have yet been reported as being subjected to high-velocity flows. Some large-scale high-velocity flow tests have been run on RCC at the Detroit Dam Test Flume (Schrader and Stefanakos 1995) at velocities reported ranging from 22 to 32 m/sec (72 to 105 ft/sec) for variable exposure durations. Much of the abrasion-erosion performance of RCC structures is observational in nature (Hansen and Reinhardt 1991, Schrader and Stefanakos 1995). A wide variety of RCC dams and overtopping protection structures have been overtopped with low to moderate velocity flows and have performed well. Some of these have been overtopped during construction, sustaining little damage. Few of these events have flow velocities reported. A number of RCC dams have exposed RCC spillways where relatively high velocity flows are expected, but only for rare events. A few cases of interest are described in the literature:

(1) Tarbella Dam (Lowe 1988) - RCC protection in several applications at the outlet works and downstream performed well under moderate velocity flows.

(2) Kerrville Ponding Dam (McDonald and Curtis 1997) - RCC performed well with minor loss of surface at about 4-m/sec (14-ft/sec) sustained flow velocity, with subsequent overtoppings also causing minimal damage.

(3) Toutle River (McDonald and Curtis 1997) - An RCC spillway for a volcanic debris retaining dam was subjected to sustained severe debris overflows at estimated velocities up to 6.1 m/sec (20 ft/sec), resulting in moderate abrasion-erosion damage. The volcanic sediments ranged up to 0.6 m (2 ft) in size.

b. Freezing and thawing. Although several RCC dams have been constructed in freezing and thawing areas, the RCC has generally been protected by conventional air-entrained concrete surfaces. A few dams have had sacrificial sections of RCC constructed to protect the interior RCC. Little information is yet available concerning the performance of RCC in freezing and thawing areas. Hansen (Hansen and Reinhardt 1991, Liu and Tatro 1995) reported that both Willow Creek and Galesville Dams have exposed RCC sections in moderate freezing and thawing regions and that minimal freezing and thawing damage had occurred to date. Hopman (1992) reported some shallow freezing and thawing damage on the crest of the unfinished Elk Creek Dam where rainwater had ponded and saturated the surface. Dam crests that are adequately sloped or crowned to avoid ponding of water on the surface have been less subject to freezing and thawing damage. Recent RCC dams that have included some air entrainment in the RCC have not had enough exposure time to evaluate the effectiveness of the air entrainment. A significant number of RCC pavements (RCCP) have been constructed in freezing and thawing areas, particularly in Canada and the United States. Entraining air in the very unworkable RCC mixtures used in RCCP has not been possible, so none of these pavements have entrained air for freezing and thawing protection. In spite of this, the majority of these pavements are in good condition after several years of often frequent cycles of freezing and thawing. This appears to be due at least partly to the relatively high strength of most RCCP. The freeze thaw damage usually found in these pavements is spalling and raveling at the cold vertical construction joints and some minor loss of surface. On some dams where the downstream face of RCC has been left exposed, either in steps or on a simple slope, the loose debris remaining from RCC placement at the face has been removed by air blast or other means. Removal of this debris encourages surface runoff and discourages plant growth, allowing observation of any deterioration, reducing safety concerns, and reducing damage due to freezing and thawing.

8-5. Chemical Effects

a. Calcium carbonate. Calcium carbonate precipitation is a common and, generally, minor problem with all concrete dams. The effects of this precipitate have often been beneficial in terms of long-term seepage reduction. Calcium hydroxide is released from the cement hydration and is carried by seepage to a surface where it reacts with the carbon dioxide in air and forms a precipitate, described in the formula:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The formation of this white precipitate or similar reactions is commonly called efflorescence or calcification. Other minerals may alter the color of this precipitate. Calcification tends to heal areas of seepage with time by filling the areas with calcium carbonate, but this may also clog foundation or dam drains and create slippery conditions in galleries and undesirable changes in downstream water pH levels. The clogging of drains often necessitates the cleaning or reaming of drains on a recurring basis. The amount of calcium hydroxide available for reaction diminishes with time, although precipitation in some dams may continue for many years. This is due to the fact that there is a fixed amount of soluble lime free for precipitation in concrete and diminishing seepage will tend to transport diminishing amounts of calcium hydroxide. RCC structures may be slightly less susceptible to calcium carbonate precipitation, due to the slightly lower cementitious materials content of RCC compared with CMC and to the common use in RCC of significant amounts of pozzolan. All pozzolans will react with and tie up significant amounts of the soluble calcium components from cement hydration. This will vary with the cement used, the pozzolan used, and the mixture proportions. For relatively dry RCC mixtures, significant unhydrated cement may produce more calcification than expected. Some reports have indicated calcium-carbonate-laden dam seepage changing the pH in the water downstream of the dam (Hansen and Reinhardt 1991). In one case, the dam seepage was collected and pumped back into the reservoir to reduce the effect downstream. In another, the cracks and joints were repaired to reduce seepage and correspondingly the pH effect in downstream waters. Hansen and Reinhardt (1991) reported higher pH of seepage through slower flowing cracks compared with more rapidly flowing cracks at Copperfield Dam, suggesting that water passing more quickly through concrete may have less opportunity to dissolve available calcium hydroxide than water slowly seeping through the concrete. Higher porosity in portions of a concrete mass may also result in greater calcium carbonate deposition due to the ready availability of a larger concrete surface area to seepage.

b. Hydrogen sulfide. Hydrogen sulfide generation can be a problem in both CMC and RCC structures, depending on water and temperature conditions. Under certain anaerobic water conditions, hydrogen sulfide gas may be generated in reservoirs and dam outlet works, producing a dilute sulfuric acid. This dilute acid can attack and slowly deteriorate the surface of concrete. The effect is often a softened paste appearance on the concrete surface and a slow loss of surface concrete. Hansen and Reinhardt (1991) described this effect at Willow Creek Dam.

c. Other chemical effects. Very aggressive reservoir water that contains unusual chemical constituents can produce acid attack on concrete or unusual precipitates upon contact with concrete. Mineral-free waters (ACI 201.2R) can produce leaching of concrete components. These effects have been observed at least two RCC dams, and in one case the seepage stained the concrete black within days of first appearing on the downstream face. Concerns regarding aggressive water at Willow Creek Dam in the 1980s resulted in a comprehensive investigation that concluded that no deterioration due to aggressive water had occurred to date (Liu and Tatro 1995). There have been no reports to date of any alkali-aggregate reactivity or sulfate attack in any RCC structures.

Appendix A
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A-1. Required Publications

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ER 1110-2-100
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Standard Practice for Concrete for Civil Works Structures

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EM 1110-2-4300
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EP 415-1-261
Quality Assurance Representative's Guide (Vols 1-5)

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