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.