DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
CECW-ED Washington, DC 20314-1000 ETL 1110-2-343

Technical Letter
No. 1110-2-343 31 May 1993

Engineering and Design
STRUCTURAL DESIGN USING THE ROLLER-COMPACTED
CONCRETE (RCC) CONSTRUCTION PROCESS

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1. Purpose

This engineer technical letter (ETL) provides guidance for design engineers considering roller-compacted concrete (RCC) as a cost-saving alternative for civil works structures.

2. Applicability

This ETL applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and separate field operating activities having civil works responsibilities for the design of civil works projects.

3. References

a. EM 1110-2-2000, Standard Practice for Concrete.

b. EM 1110-2-2006, Roller Compacted Concrete.

c. Draft EM 1110-2-2200, Gravity Dam Design.

d. ETL 1110-2-324, Special Design Provisions for Massive Concrete Structures.

e. ACI Committee 207, Roller Compacted Concrete, 207.5R, ACI Materials Journal, September - October 1988.

f. ACI Committee 210, Erosion of Concrete in Hydraulic Structures, ACI 210R-87, ACI Materials Journal, March - April 1987.

g. Heaton, B. S. 1968 (Oct). Strength, Durability and Shrinkage of Incompletely Compacted Concrete, pp 846-850.

4. Purpose

RCC has developed over the past 20 years in response to the need to provide more economical mass concrete structures that can be constructed rapidly. RCC is replacing conventional mass concrete as the primary construction material for gravity dams and has become a viable alternative material for structures other than dams. The enclosed guidance (Enclosure 1) also provides design engineers with material considerations for RCC to assure that the completed structure meets strength and serviceability requirements. The enclosure includes:

a. Structural design guidance for RCC structures.

b. Examples of past usage and the types of structures suited to RCC construction.

c. Similarities and differences with respect to conventionally placed mass concrete.

d. The structural engineer's role in the testing and construction processes.

e. Construction processes and features unique to RCC construction.

f. Material properties that affect strength, serviceability, durability, impermeability, and density.

g. Processes and procedures necessary to establish accurate strength parameters for design.

5. Recommendations and Requirements

a. Once strength and serviceability requirements for the RCC have been established by the structural designers, in accordance with EM 1110-2-2006, the structural design engineer should work with material engineers and the material testing laboratory to establish suitable mix designs, a comprehensive laboratory and field testing program, and a quality assurance program to assure that the in-place RCC meets the design requirements.

b. Hydraulic structures require concrete that is durable and watertight, with moderate to high bond strength. To assure that the RCC will have these properties, the mix design should have:

(1) Adequate paste and mortar to fill all aggregate voids.

(2) High slump mortar bedding on all lift joint surfaces.

(3) Aggregates meeting the standards for quality and grading as required for conventionally placed concrete.

Conventional concrete should be provided for regions where the RCC would be exposed to flowing water with velocities exceeding 25 fps and/or when flows are of significant duration and frequency to cause erosion and maintenance problems. Air-entrained conventional concrete should also be provided in all regions where the surface of the structure would be exposed to freeze-thaw cycles while critically saturated.

c. When RCC is used for massive concrete structures, the design objectives of ETL 1110-2-324, "Special Design Provisions for Massive Concrete Structures" should be considered and a nonlinear structural analysis performed where required to meet design objectives.

d. Test placements during the mixture design phase and during the initial phase of construction are needed to verify adequacy of the mixture ingredients, mixture proportions, and construction techniques.

e. Consultation with and approval by CECW-E is required when selecting consultants outside the Corps of Engineers for recommendations on RCC design and construction practices.

f. The special uplift and sliding stability requirements of Section 9 of the enclosure shall be followed when designing RCC gravity dams.

g. A Post-Construction Structural Report should be submitted as outlined in Section 9d of the enclosure.

FOR THE DIRECTOR:

Paul D Barber

1 Encl

PAUL D. BARBER, P.E.
Chief, Engineering Division
Directorate of Civil Works

STRUCTURAL DESIGN USING THE ROLLER-COMPACTED CONCRETE (RCC) CONSTRUCTION PROCESS

1. Introduction

Roller-compacted concrete (RCC) construction was first considered as a low-cost, rapid construction alternative to earth and rockfill dams and is now considered a viable alternative to any conventional mass concrete that can be placed at sites providing sufficient space to accommodate spreading and compaction equipment.

This Engineer Technical Letter (ETL) discusses the special problem areas and concerns related to RCC construction in order to assure that the concrete properties required are ultimately realized in the completed structure. A quality RCC product requires a coordinated effort between the structural designer, the materials engineer, the materials laboratory, and those responsible for field quality control and quality assurance.

Additional detailed RCC materials information can be found in the American Concrete Institute (ACI) Committee 207 report 207.5R, "Roller Compacted Concrete" (Reference 12a), and in Engineer Manual (EM) 1110-2-2006, "Roller Compacted Concrete" (Reference 12c).

2. Elements of RCC Mixture Design and Construction Important to Structural Safety and Serviceability

a. General design considerations. 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 concrete is high, and 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., earthquake conditions) some tensile stress is permitted. Tensile stresses can also develop due to short-term temperature gradients as the RCC hydrates and long-term temperature changes. It is therefore necessary to conduct temperature studies to identify potential cracking zones and thus control cracking. In addition to strength requirements, hydraulic structures must be designed to minimize seepage, to control uplift pressures, and to assure long-term durability. Figure 1-1 shows a gravity dam constructed of roller-compacted concrete. Features include an unformed RCC downstream face and spillway. The spillway is inset and the spillway training walls are constructed using precast concrete panels. The spillway crest was constructed using conventionally placed reinforced concrete.

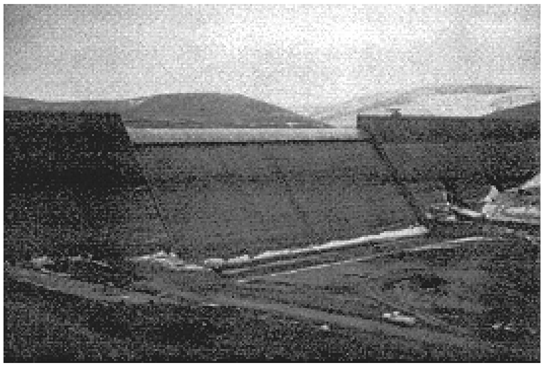


Figure 1-1. RCC gravity dam

b. RCC strength. The RCC construction process results in horizontal lift joints at 6- to 24-in. intervals. The strength at lift joint surfaces is generally lower than that of the parent concrete. Therefore, mixture designs, placement procedures, and quality control measures to assure maximum bond and strength at the lift joint surfaces are important. Test data from constructed projects indicate that RCC joint strengths are sensitive to:

(1) The time interval between the placement of successive lifts.

(2) The water and cementitious material content (cement plus pozzolan) of the mixture, and total paste volume.

(3) The joint surface condition and treatment used. In general, the application of joint treatment (bedding mortar) and rapid placement of successive lifts will produce higher joint strengths. The design

values for joint cohesion and tensile strength must be based on a laboratory test program that includes evaluation of joint strength using core samples from test placements constructed under anticipated field conditions. A comprehensive laboratory test program will assure a greater degree of certainty and, in some cases, may eliminate overly conservative or redundant design assumptions.

c. RCC permeability. The permeability or watertightness of concrete may be of more concern than the strength, especially with respect to hydraulic structures. The ease with which water migrates through the concrete mass may ultimately affect the performance of the concrete over time. The factors affecting the permeability of RCC are essentially the same as those that affect the permeability of conventional concrete. Historically, high permeability in RCC structures has been the result of segregation and lack of consolidation at lift joint surfaces.

d. RCC durability. Air-entraining admixtures are available and have been used to successfully entrain air in RCC mixes in the laboratory. However, most RCC placed to date has not been air-entrained and as a result, has performed poorly when subjected to repeated cycles of freezing and thawing in a critically saturated state. When not critically saturated, RCC has been found to have adequate resistance to freeze-thaw damage. Currently, research is in progress to determine the most effective type of air-entraining admixtures and type of air void systems that may be achieved with RCC.

3. Conventional Mass Concrete versus RCC

RCC is designed to meet the material strength and durability requirements established by the structural engineer. The factors that affect the properties of conventional mass concrete such as water-cement ratio, quality of mixing ingredients, and degree of consolidation and curing, also affect the material properties of RCC. The principal difference in the two is the mixture consistency and the method of consolidation. Internal consolidation using immersion-type vibrators is used for conventional concrete, while external consolidation with spreading equipment and vibratory rollers is used for RCC. The controls placed on mixture ingredient selection for conventional mass concrete will apply to RCC. RCC mixture proportioning procedures are similar to conventional concrete; however, RCC mixtures will normally contain less water and paste and more sand to limit segregation.

4. Structures Suited to RCC Construction

RCC has gained worldwide acceptance as an alternative to conventional concrete in dams as well as other types of structures. It may be used for any application that allows access of placing, spreading, and compacting equipment and can be considered for use in new construction as well as rehabilitation work. 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, 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 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, it may prove that the use of RCC will allow a more economical layout of project features such as an over-the-crest spillway as opposed to a side channel spillway (Reference 12c). Figures 1-2 and 1-3 show a portable pugmill continuous mixing plant, which is often used in RCC construction.

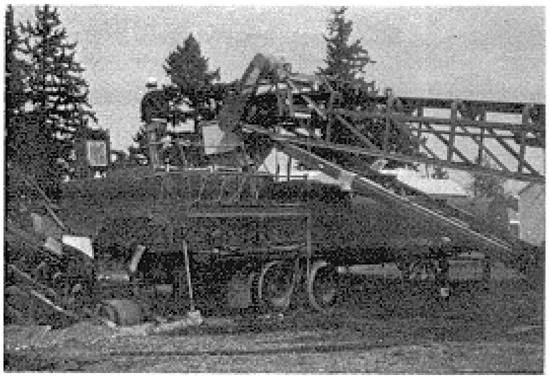


Figure 1-2. Portable pugmill continuous mixing plant. Pugmill mixers are often used in RCC construction for maximum efficiency and production

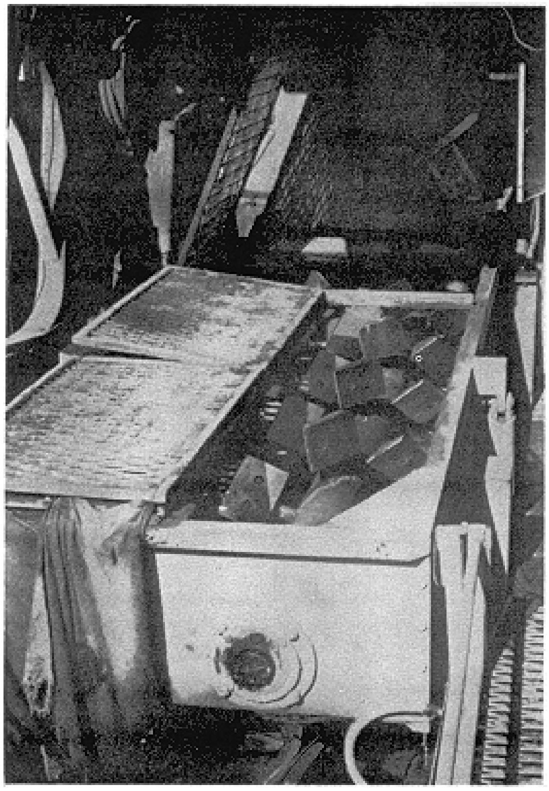


Figure 1-3. Pugmill mixing chamber. Paddles are mounted on horizontal shafts in the pugmill mixing chamber. The paddles can be adjusted or replaced as required to maintain mixing efficiency

The Corps has used RCC for the construction of gravity dams, a lock floor at New Cumberland Lock and Dam, in place of riprap for erosion protection downstream of a floodwater sill on the Chena Project, as erosion protection for the Toutle Sediment Retention Structure, at the Bonneville Project to protect weak foundation rock from weathering, and as navigation lock guide/wing walls. RCC has also been used for emergency repairs of a check dam and as a spillway through an earthen sediment retention dam on the Toutle River. RCC can and has been used for stilling basins, plunge pools, spillway repair and replacement, foundation mats, diversion walls and open channel lining.

5. Mixture Proportions and RCC structural Properties

a. Paste and mortar content. RCC mixtures must be workable, free of segregation, and easily compacted using external vibratory rollers. The RCC must also be sufficiently stiff to support hauling, spreading, and compaction equipment; and must contain adequate paste at the appropriate consistency to become distributed throughout the concrete mass during mixing, placing and compaction. RCC must contain sufficient mortar to prevent segregation and fill large voids between coarse aggregate particles. The paste is the binder that ties the coarse and fine aggregates together. In a plastic state, the paste provides cohesion and workability to the RCC. In a hardened state, the paste content and quality will dictate the concrete strength, bonding potential, permeability, and durability. The paste volume is proportioned to fill the void system of the fine aggregate. Typically, fine aggregate has a void content ranging from approximately 35 to 40 percent. The minimum paste-to-mortar volume ratio (Vp/Vm) specified in EM 1110-2-2006 ensures that voids in the mortar fraction are completely filled. Guidance for typical RCC mortar contents are also given in EM 1110-2-2006 (Reference 12c).

b. Water-cement ratio. The compressive strength of RCC depends primarily on the water-cement ratio and degree of compaction. For RCC that is fully consolidated, the compressive strength will increase as the water-cement ratio decreases. Water-cement ratio guidance for conventional concrete is given in EM 1110-2-2000, "Standard Practice for Concrete" (Reference 12b). In this guidance, the maximum permissible water-cement ratio is provided for various anticipated exposure conditions of the structures. Water-cement ratios should be selected during the laboratory mixture design phase to meet all strength and durability requirements.

c. Aggregate quality and gradation. Aggregates for RCC should meet the same high standards for quality and grading as required for conventional concrete. Only where extraordinary circumstances exist, such as construction during an emergency situation in which use of a poorer quality does not prevent meeting design quality requirements of the concrete, could aggregates of a lesser quality be justified. Coarse aggregates for RCC are graded to standards identical to those for conventional mass concrete; however, the fine aggregate used for RCC will normally contain a greater proportion of material passing the No. 200 sieve in order to fulfill paste and workability requirements. RCC containing minimally processed pit run aggregate may require a greater water content, be less durable, have a lower strength, and less bond between lifts than RCC containing properly processed aggregates.

d. Fly ash (Pozzolan). Fly ash is used in RCC construction to serve three purposes; (1) as a partial replacement for cement to reduce heat generation, (2) to reduce cost, and (3) as a mineral addition to the mixture to provide fines to improve workability (Reference 12a). The use of higher fly ash contents may be helpful in obtaining adequate paste content in situations where natural fines are not available, while at the same time keeping the total Portland cement content at relatively low levels. However, fly ash slows strength gain, and the use of high fly ash contents in combination with high water-cement ratios can produce very low strengths at early ages. Because of this, RCC strength requirements are generally specified based on compressive strength at 1 year rather than at 28 days, as is the practice for conventional concrete.

e. Strength and density. Work performed by M. F. Kaplan (Reference 12f) demonstrated that 5-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. 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 of the mix, thereby reducing air voids. This effect has also been observed with difficult-to-consolidate conventional concrete mixtures. The chance of obtaining the desired bond and tensile 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 and mortar volumes. Bonding and permeability at the lift joints will be improved with a mortar bedding; however, the permeability of the drier consistency mixtures may still be unacceptably high. The bond and tensile strength at the lift joints for properly proportioned, well-consolidated RCC will approach that achieved at the lift joints of conventionally placed mass concrete.

f. Permeability. Permeability along lift joint surfaces is generally higher than the permeability of the parent concrete. Joints between layers of RCC must be well bonded to provide low permeability, and reduce potential damage caused by water seeping along lift joint surfaces. The permeability of both conventional and RCC concrete is dependent on the pore structure and air void system within the parent concrete and along lift joint surfaces. Concrete with low permeability generally has a low water-cement 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. RCC structures are generally constructed with concrete having much higher water-cement ratios than used for conventional concrete structures. The effect that these high water-cement ratios have on pore pressures within the body of hydraulic structures and on long-term durability is unknown.

g. Thermal cracking.

(1) The extent of thermal cracking in an RCC structure will be affected by the type and degree of temperature control used. Temperature is controlled in RCC by selecting cementitious materials that generate the least heat of hydration, by cooling various components of the RCC mixture prior to mixing and placing, and by restricting RCC placements to cool weather seasons.

(2) The selection of cement and fly ash proportions will significantly affect the heat of hydration and subsequent thermal cracking. To reduce temperature rise, low-heat-of-hydration cement and the maximum pozzolan replacement of cement, consistent with strength requirements, are generally specified. The potential for thermal cracking in massive RCC structures should be determined by a thermal analysis that includes a temperature study to identify temperature gradients, and a stress analysis to identify the critical tensile stresses that can develop within the structure due to temperature gradients. Critical temperature differentials are best determined using computer models that have lift-by-lift construction sequencing capabilities. Variables important to the temperature studies include placement temperature, placement rate, diffusivity, heat of hydration, and external temperature cycles. Variables important to stress analyses include joint spacing, restraint conditions, modulus of elasticity, creep effects, and tensile strength. Many of the variables described should be verified through laboratory testing and RCC test placements.

h. Anisotropic effects. Tests on RCC cores indicate the direction of drilling may affect test results. Strength tests on several RCC projects indicate that in some cases, cores drilled vertically yield higher strengths than companion horizontally drilled cores (similar to conventional concrete), whereas in other cases the opposite result has been observed. For conventional concrete, the anisotropic behavior is usually attributed to accumulation of bleed water. For RCC, the observed anisotropic behavior may be due to the distribution and orientation of aggregate particles resulting from spreading and compacting the individual RCC layers. The degrees of consolidation and segregation will also have an effect. 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.

6. Construction Methods and Features

a. General. RCC is usually transported by truck or conveyor belt and deposited in piles or windrows at the placement site. The RCC is then spread in layers with dozers and consolidated with vibratory rollers. Due to the stiff no-slump consistency of the RCC, all or most of the form work and associated labor required for conventional mass concrete can be eliminated. There is little or no accumulation of surface water by bleeding; consequently, the removal of laitance at lift surfaces is not required as with conventional concrete. Therefore, the RCC construction method offers potential cost advantages over conventionally placed concrete due to:

(1) Higher production rate.

(2) Reduced lift surface cleanup and preparation.

(3) Reduced labor for conventional formwork.

(4) More efficient equipment utilization for placement and consolidation.

Adequate bond and watertightness at the lift joints between successive RCC layers is critical for structural integrity. Good quality aggregates, good workability and compaction effort, and the use of bedding mortar are required to obtain adequate bond strength at the joint. In general, the disadvantages of RCC construction are that:

(1) In-place properties are highly dependent on field quality control.

(2) The layered construction method can result in poor bond, low tensile strengths, and high permeability as a result of incomplete consolidation, contamination and/or drying of the lift joint surfaces.

b. RCC placement procedures. Segregation and improper construction techniques may result in poor bonding at the lift joints, increased water seepage, decreased strength, and lower overall density of the in-place RCC. The procedures used during spreading of the RCC layers are critical for achieving a uniform and non-segregated RCC placement. One method that has been used to successfully place the RCC begins by constructing a working pad of RCC large enough for subsequent RCC to be dumped and worked by the dozer. Figure 1-4 shows RCC being transported to a placement site.

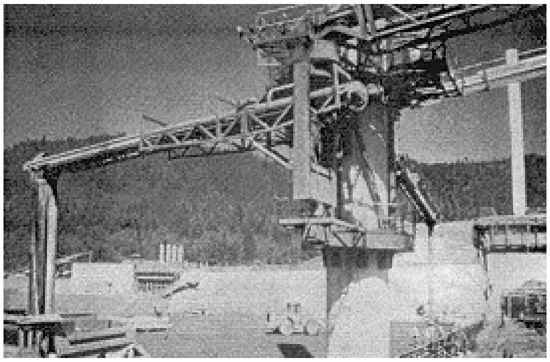


Figure 1-4. Transporting RCC

RCC can be transported to the placement site by belt conveyer, by conventional batch haul methods, or by a combination of both. Conventional haul methods include end dump trucks, scrapers and bottom dumps. Care must be taken to assure that transportation vehicles do not track dirt or mud onto the RCC placement, and that segregation does not occur prior to final compaction of the RCC.

RCC is then placed on the working pad, leveled, and spread into place by the dozer at the leading edge of the pad in approximately 6-in.-thick tapered layers. The dozers work continuously spreading the RCC so that all surfaces of the RCC layers receive at least two passes of the dozer. In this manner, the RCC will be nearly completely consolidated by the action of the dozers. Areas of segregation are removed and remixed with fresh RCC and respread by the dozers. Additional layers of RCC are spread until the final lift thickness is achieved and final compaction rolling begins. Final compaction is accomplished using self-propelled single-or double-drum vibratory roller-compactors, rolled with sufficient passes until optimum compaction is achieved. The interval between mixing and final compaction should be kept to a minimum, generally less than 45 min (Reference 12c). Figure 1-5 shows RCC being compacted by vibratory roller. Most of the compactive effort is initially provided by dozer action. Final compaction is accomplished by vibratory rollers. Density requirements will normally be established during test fill placements, and at the initial start of RCC placement, and will be based on the evaluation of density test results and visual observations. After final rolling, the compacted RCC surface must be kept clean and continuously moist until placement of the next lift. Figure 1-6 shows an RCC placement operation. RCC is deposited on the previous lift that has been covered with a thin layer of high slump mortar bedding or conventional concrete. The mortar bedding assures that there is adequate paste at the lift surface boundary to provide bond and to reduce lift surface materials, and partially compact the RCC prior to final compaction by the vibratory roller. Care must be taken by the dozer operator, as well as other equipment operators, so as not to damage the surface of the previous RCC lift and to prevent unnecessary segregation.

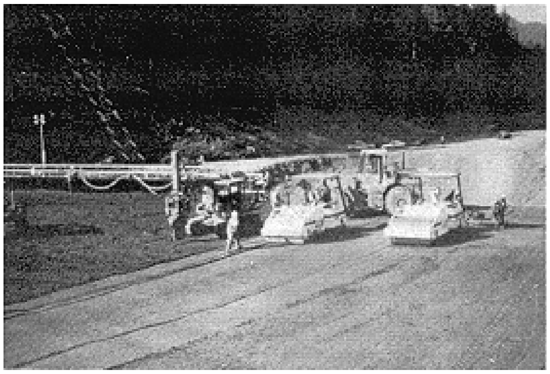


Figure 1-5. Compaction by vibratory roller

c. Lift joints (Horizontal Construction Joints). RCC lifts may range in thickness from 6 to 24 in., depending on the placement size, production capacity of the concrete batch plant, mixture proportions, and compaction equipment. Lift joints or horizontal construction joints are formed at the interface between successive RCC lifts. The total number of lift joints in an RCC structure is determined by the thickness of each RCC lift and the overall height of the structure. Tensile and shear strength at lift joints are less than in the parent RCC. Segregation of the RCC and lack of bond at the lift joints can result in increased seepage and potentially high uplift pressures at joints exposed to hydrostatic pressure. Final structural design and stability analysis for RCC structures should be based on joint strength determined from laboratory tests made on cast specimens and cores from test placement sections.

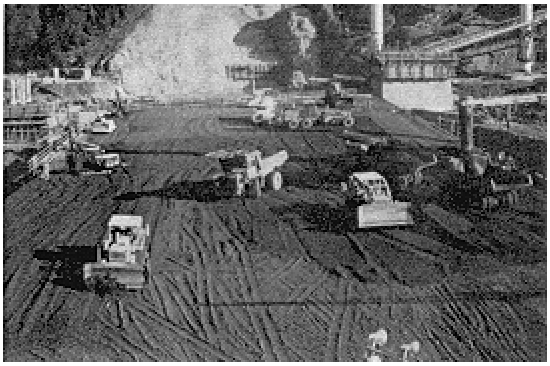


Figure 1-6. RCC placement operation

d. Horizontal lift joint treatment.

(1) The type and degree of lift joint surface treatment used is dependent on the required bond and watertightness needed for the structure. Standard lift joint treatments consist of simple continuous moist curing, cleaning contaminated areas by washing and vacuuming, and application of a bedding mortar or bedding concrete immediately prior to placing the next RCC lift. For RCC lifts where bonding and watertightness are not critical, lift joint treatment may consist of simple continuous moist curing only. However, the elimination of bedding mortar will require the submittal of supporting backup data and the approval of CECW-E. For RCC hydraulic structures where bonding and watertightness are important, a bedding mix shall be applied to all lift joint surfaces. Insulation and temperature monitoring may be required in cold weather to ensure that exposed surfaces are not

allowed to freeze. Provisions for windbreaks, shading, fog spraying, pounding, or other methods may be needed to prevent excessive moisture loss or excessive heat generation in hot weather.

(2) Specifications should require sufficient plant capacity to meet the high production rates common for RCC placements and to assure that horizontal lift joint surfaces are left exposed for a minimum amount of time. Laboratory studies indicate that the loss of bonding capacity at the joints begins almost immediately after placing and that the bond strength of lift joints is therefore improved when joints remain exposed for a minimum amount of time.

e. Cold joints and treatment.

(1) An RCC cold joint may occur at any horizontal lift surface that is allowed to dry, set, or become contaminated prior to receiving the next lift. These surfaces can result in reduced bond strength with the successive lift, even under moist cure conditions, unless special measures are taken to assure bonding of the two lifts. Cold joints can develop at a lift surface if the RCC surface remains uncovered by the next lift long enough for the surface to attain its initial set, or approximately 1 to 3 hr after placing. Environmental conditions such as heat, humidity, and wind, which contribute to drying of the RCC surface, are also significant factors in reducing the strength of the RCC joints. If the RCC surface is allowed to dry, the strength development of the mortar and paste at the surface stops, due to lack of moisture for cement hydration. Although the hydration process continues if additional moisture is added, the bond strength capacity at the joint is significantly reduced. Specifications should establish the criteria used to determine if a lift surface is a cold joint. This is usually done by stating the combinations of time and weather conditions that require that RCC surfaces be treated as a cold joint. Generally, joints that are 2000 Fahrenheit degree-hours or more old, or that have been allowed to dry, should be treated as cold joints.

(2) Vertical cold joints occur when placement of the RCC is stopped or interrupted before an entire lift is complete. The leading edge of the RCC at a vertical cold joint should be tapered to form an interlocking feathered edge with the underlying lift.

(3) RCC cold joints require special treatment in order to assure adequate bonding with the successive lift. Typical cold joint treatments include high pressure washing or wet sandblasting to remove mortar coatings, or other contaminants, followed by a high volume, low pressure washing and vacuuming to remove all excess water and debris. The surface is then maintained in a damp condition and covered with a thin layer of mortar or concrete bedding mix immediately before placing the next lift of RCC.

f. Contraction joints.

(1) Vertical joints may be formed in mass RCC sections to control cracking by inserting steel or plastic sheets, or any other bond breaker material, into the full thickness of the uncompacted RCC lift. The plates or sheets are placed adjacent to each other end to end from the upstream to downstream face to form a bond breaker that serves as a contraction joint. The sheets are usually 1/8-in. thick by 3-ft long and are installed using a vibrating plate installed on a backhoe. The width of the plates should be somewhat less than the lift thickness (1 to 2 in. less) to make sure the edge of the plate will not protrude above the lift surface where it could be damaged by placing and compacting equipment. The contraction joint plates should be installed in every lift of RCC so that 100 percent of the vertical section at the contraction joint has the bond breaker plates. The practice of only installing plates in every other lift can result in the formation of cracks in undesired locations, which could compromise strength and stability.

(2) The number and placement of the contraction joints should be determined by the structural engineer based on thermal studies and by examination of the foundation profile parallel to the axis of the structure. Abrupt changes in the foundation profile may cause stress concentrations and require additional contraction joints. Normally, contraction joint spacing will range from 60 to 80 ft. Figure 1-7 shows a contraction joint being installed. Steel or plastic sheeting is placed in the RCC to form contraction joints. A vibrating blade mounted on a backhoe may be used to install the sheeting. Contraction joints placed in this manner help to control random cracking due to volume change effects.

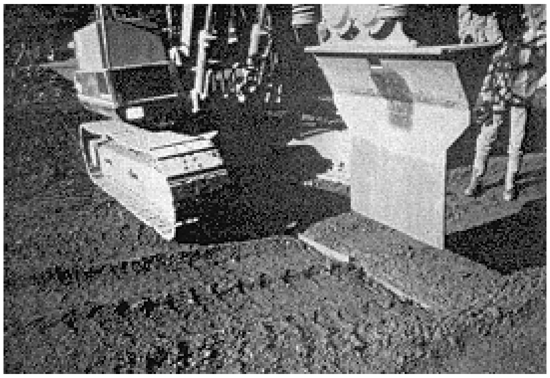


Figure 1-7. Contraction joint installation

Figure 1-8. Application of mortar bedding

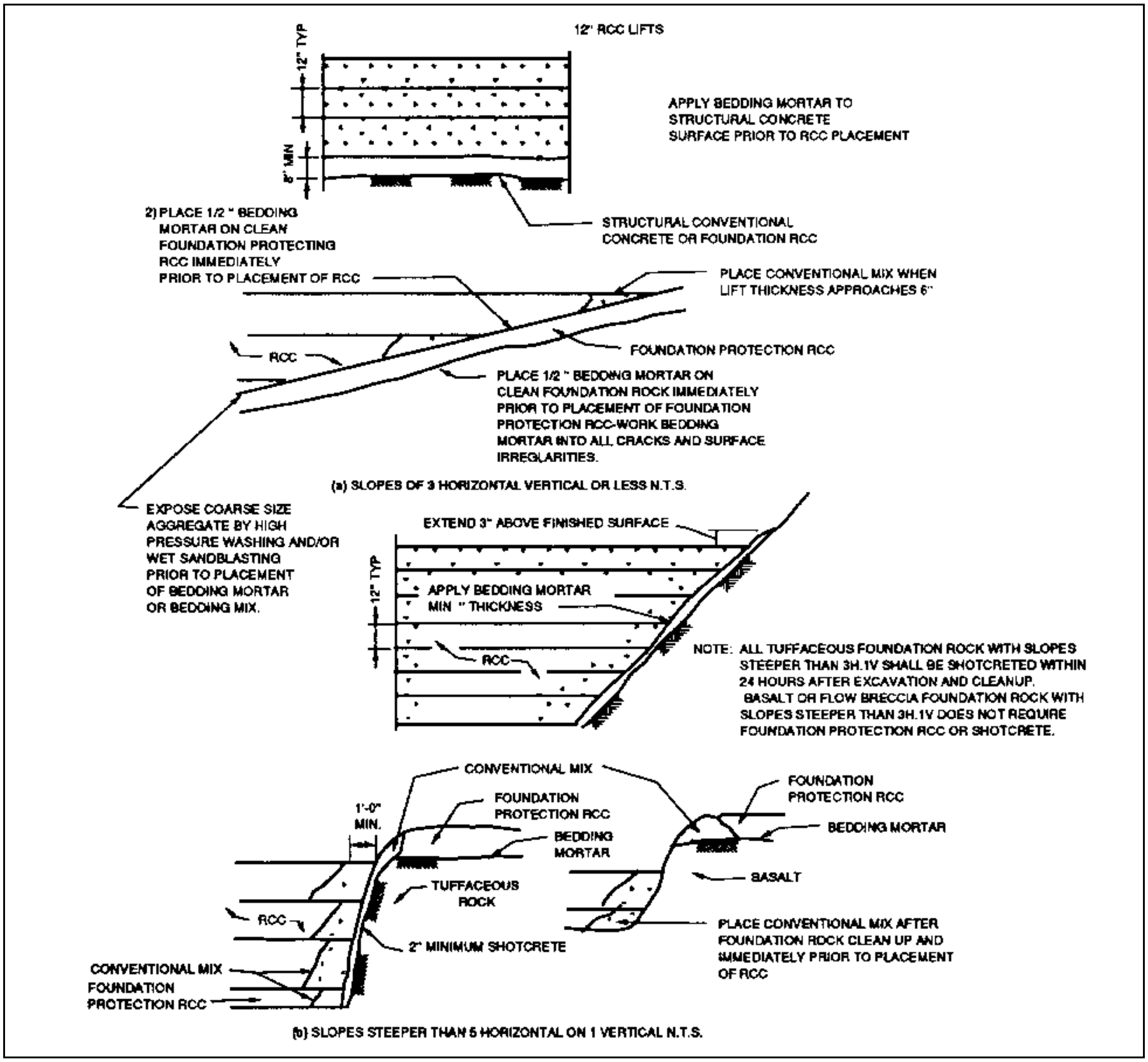
g. Bedding. Mortar or concrete bedding is required on all RCC cold joints and is required for use on all lift joint surface areas of hydraulic structures in order to maximize bond and water tightness. Bedding mixes are designed for maximum workability with 7- to 9 in. slump and a design strength that at minimum exceeds the strength of the parent RCC. Bedding concrete is designed with 3/4-in. or less nominal maximum-size aggregate (NMSA) and bedding mortar with 3/8-in. NMSA or less. Normally, bedding mortar is spread in a 1/4- to 1/2-in. thick layer and bedding concrete in a 1/2- to 1-in. thick layer on the RCC surface. Bedding is placed immediately prior to the next RCC lift on the underlying RCC surface. Figure 1-8 shows mortar bedding being applied and Figure 1-9 shows foundation treatment details. Bond and watertightness are improved by spreading a thin layer of high-slump mortar or concrete as a bedding on previously compacted RCC surfaces and on foundation rock surfaces to receive RCC placements. The extent and type of foundation treatment used will vary considerably depending on job conditions. Typical foundation treatment details are shown for (a) foundation slopes of 3 horizontal to 1 vertical or less, and (b) slopes steeper than 3 horizontal to 1 vertical.

h. Facing systems.

(1) A facing system may be used to cover the exposed vertical or sloping edges of an RCC structure in order to protect the RCC from the effects of freezing and thawing, to help minimize seepage through the RCC, or simply to enhance the appearance of the exposed RCC. Facing system details are shown in Figure 1-10. A facing system may be used to protect the RCC from environment exposure or to enhance the appearance of the structure.

(2) At Elk Creek Dam, the upstream facing system consisted of a 3- to 4-ft-wide zone of air-entrained conventional concrete placed concurrently with the RCC lifts. The conventional concrete was consolidated with internal vibrators and tied to the RCC with reinforcing steel at the lift joints. This system required formwork at the upstream face of the dam to contain the conventional concrete, but resulted in superior protection of the RCC as well as a conventional concrete appearance to the structure. Figures 1-11, 1-12, and 1-13 show the stages in the placement of a conventional concrete facing. Conventional concrete is placed against the form, followed by RCC. The conventional concrete and conventional concrete RCC interface is consolidated with immersion-type vibrators. Final consolidation of the RCC at the conventional concrete RCC interface is accomplished with the vibratory roller.

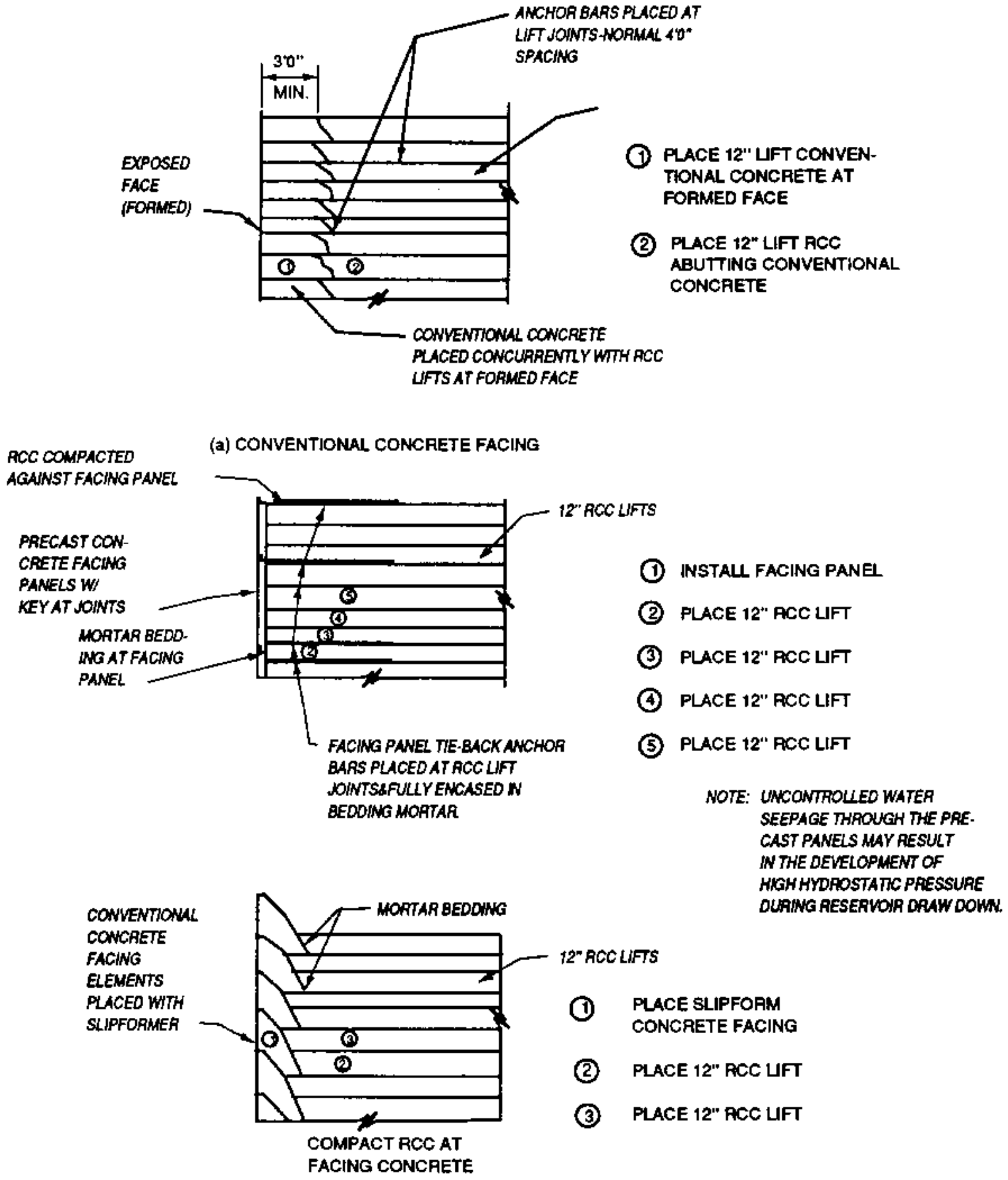
(3) Precast concrete panels were used at the upstream face of the Willow Creek Dam. The panels were fitted with tie-back straps, that, when embedded in the RCC at the lift joint, would hold the panels in position during consolidation of the RCC and provide the vertical formwork required at the upstream face. The panels provided a pleasing architectural appearance to the dam at the upstream face, but did not limit water seepage through the RCC. It is important to note that uncontrolled water seepage through the precast concrete panel facing system may allow very high hydrostatic pressures to develop during rapid drawdown of a reservoir, resulting in possible failure of the facing



(a) SLOPES OF 3 HORIZONTAL VERTICAL OR LESS N.T.S.

(b) SLOPES STEEPER THAN 5 HORIZONTAL ON 1 VERTICAL N.T.S.

Figure 1-9. Foundation treatment details



(a) CONVENTIONAL CONCRETE FACING

(C) SLIPFORM CONCRETE FACING

Figure 1-10. Facing system details

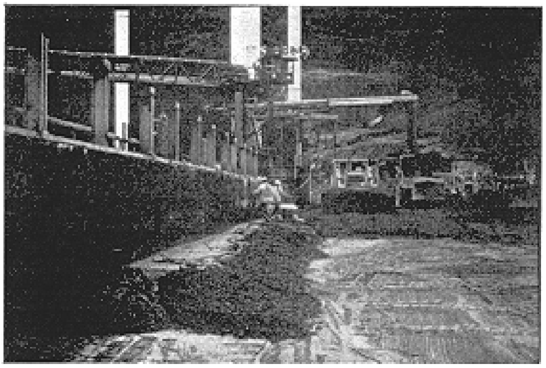


Figure 1-11. Placement of conventional concrete facing

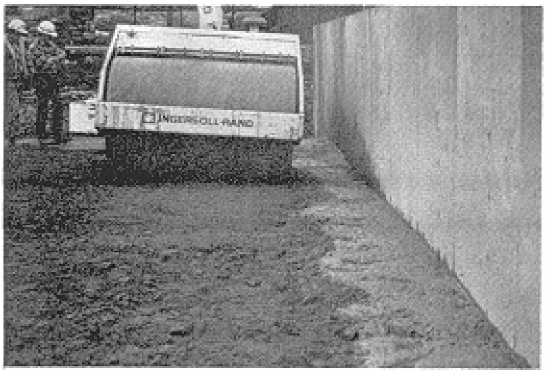


Figure 1-12. Final consolidation accomplished with vibratory roller

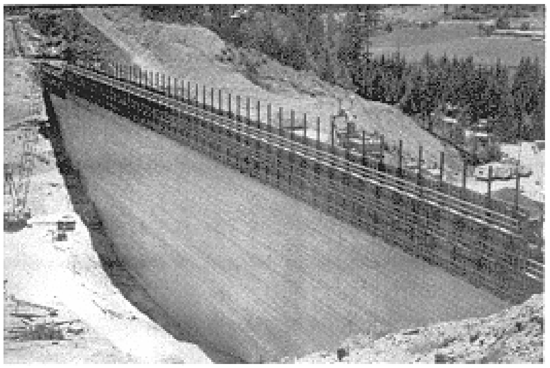


Figure 1-13. The conventional concrete facing gives a conventional concrete appearance to the RCC structure

system. Several dams have been successfully constructed using a high-density polyethylene liner backing in conjunction with the precast panels to limit water seepage. Joint sealants have also been used with precast panels and other formed joints to effectively limit water seepage. Precast concrete panels are shown in Figure 1-14. Precast stay-in-place concrete panels give a conventional concrete appearance to the RCC structure. These forms are anchored to the RCC by straps or rods and are quickly and easily erected during construction. Concrete at the upstream and downstream faces of Upper Stillwater Dam was a conventional curb-type facing concrete placed using a slipformer. The conventional concrete was placed in approximately 2-ft-high sections at the upstream and downstream edges. After curing for 4 hr, the conventional concrete provided the form boundaries between which the RCC was placed and consolidated. At the upstream face, the slipformed sections were placed one on top of another, producing a vertical wall. At the downstream face, the slipformed sections were stair-stepped at the spillway section to dissipate hydraulic energy and to reduce cavitation problems associated with high-velocity flow.

(4) Other facing systems such as steel sheetpiling, or a combination of conventional and precast concrete panels, may also be used. An example of an unformed (D/S) surface finish is shown in Figure 1-15. The RCC shown was allowed to assume a natural angle of repose on the downstream face of the gravity dam. The angle of repose ranges between approximately 45 and 55 deg. The outer portion of the RCC at an unformed surface is not fully consolidated and therefore is of little structural value. The ragged and uneven appearance of an unformed face may be improved by trimming the loose RCC.

i. Special surface treatments for erosion protection.

(1) *General.* 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.

(2) *Cavitation erosion.* Cavitation from surface imperfections has been known to cause surface

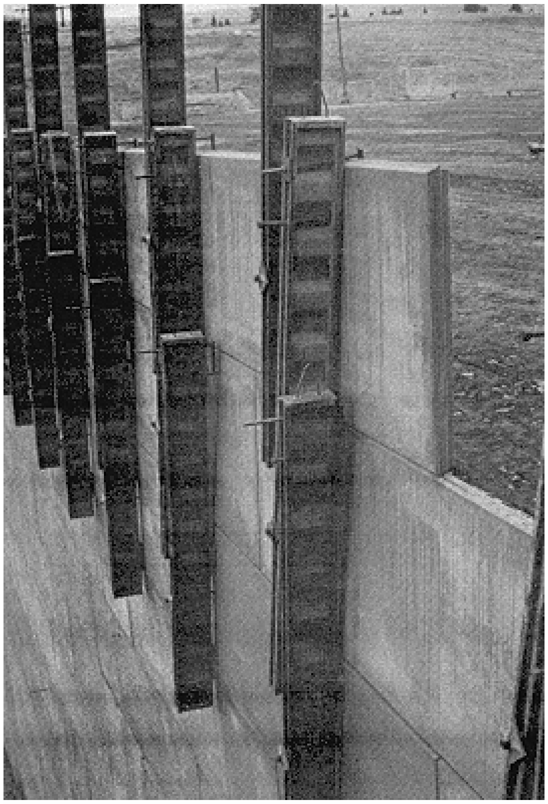


Figure 1-14. Precast concrete panels

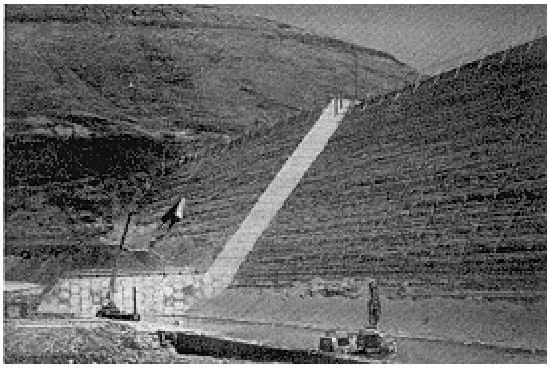


Figure 1-15. Unformed (D/S) surface finish

damage at flow velocities as low as 40 fps (Reference 12c). 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 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.

(3) *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.

(4) *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 25 fps. The surface tolerance control obtained with RCC construction is not suitable when flow velocities exceed 25 fps. RCC construction may be considered for spillways, stilling basins, and other flow channelization projects, where velocities exceed 25 fps; however, a conventionally placed surface concrete screeded and floated to meet specified tolerance requirements must be used. Conventional concrete overlay details are shown in Figure 1-16. Typical conventional concrete applications in RCC dams include spillways, spillway caps, spillway bucket and stilling basins.

j. Galleries, joints, waterstops, and other special features. Galleries, joints, waterstops, and other special features that are easily incorporated into conventional concrete placements are much more difficult when RCC construction methods are used. Designers must carefully consider the construction details for such features when RCC is specified, to minimize the impact of these features on the RCC placement process and to assure that these features will perform as intended. Galleries in dams must be located to provide adequate space for

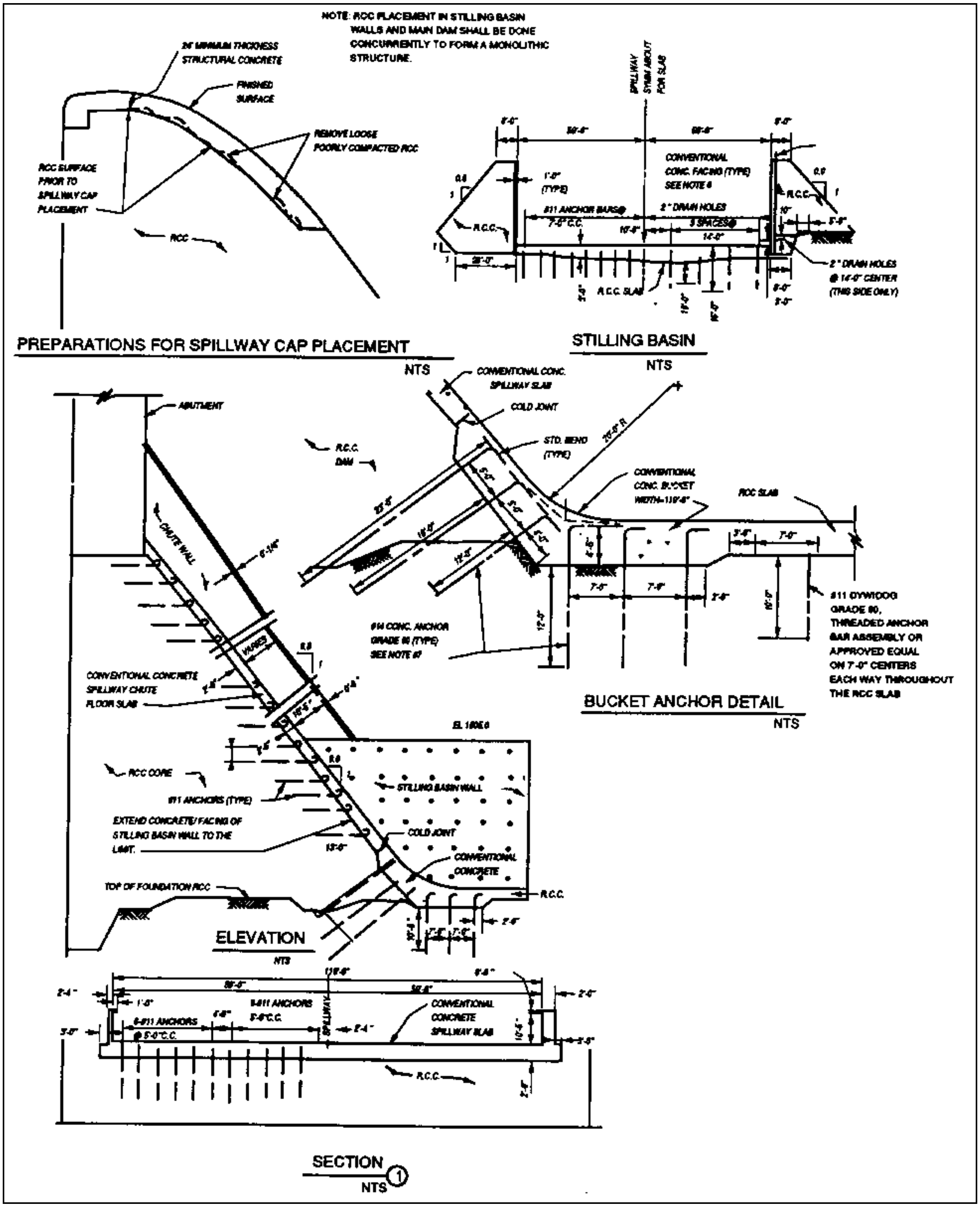


Figure 1-16. Conventional concrete overlays may be required to resist erosion

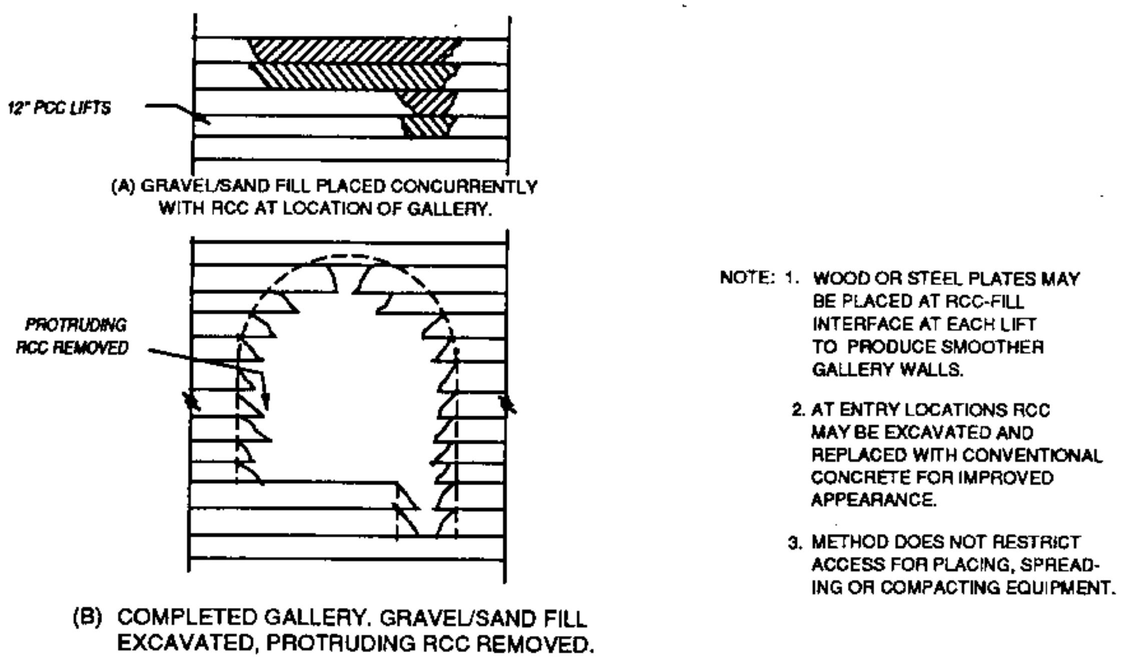
RCC placing and compaction equipment in all areas adjacent to the gallery. Since any interruption or opening in the RCC lifts will reduce placement rates, the location and method of gallery construction should be selected to minimize the extent to which RCC production is affected. The opening or void created by the gallery may also contribute to stress concentrations and cracking and should be considered in the design. Gallery construction details are shown in Figure 1-17 and gallery construction is shown in Figures 1-18 to 1-20. Typical gallery construction details are shown using (a) gravel/sand fill replacement, and (b) cast-in-place concrete methods. Gravel/sand is placed concurrently with RCC at the desired location of the gallery. After placement of the RCC the gravel/sand fill is excavated to form the completed gallery. The advantage of this method is that access for placing, spreading, and compacting equipment is not restricted. Waterstops must be encased in a region of conventionally placed slump concrete in order to achieve the desired seepage control. Similarly, joints that require load transfer through dowel action shear friction must be detailed so the dowels are encapsulated in conventional concrete. Waterstop details are shown in Figure 1-21 and Figure 1-22 shows installation of a waterstop at a contraction joint. The waterstop is placed in a zone of conventional concrete facing at the upstream face of a gravity dam at the location of the designed contraction joint.

k. Test placements. A preliminary test placement section should be completed during project design to confirm RCC mixture design characteristics and to allow observation of placement and compaction procedures. This will provide a means of evaluating mixture proportions, aggregate characteristics, time intervals between lift placements, lift thickness, placement and compaction techniques, RCC temperature gain characteristics, and lift joint treatment. For smaller projects it may be more practical to construct such a test section early in the life of the contract. 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. The "project" test section will provide an opportunity for a contractor to develop and confirm techniques and equipment for efficient placement of the RCC. A project test section should also be used to demonstrate the contractor's capability to produce the quality and quantity of RCC required by contract specifications. Project test sections should be constructed outside the footprint of all project features. Any test section placed during the design phase should be constructed by an experienced contractor hired especially to construct the test section. Construction should be closely controlled by the designers and the materials engineer, and extensive testing should be performed. Tests on the unhardened, freshly mixed RCC should include: (1) vebe consistency using the modified vebe apparatus shown in EM 1110-2-2006 (Reference 12c), (2) determination of inplace density using a nuclear density meter, (3) moisture content, (4) air content, and (5) fabrication of strength test specimens. Tests on the in situ samples retrieved from the hardened RCC may include permeability and compressive, tensile, shear, and flexural strength tests on samples with and without lift joints. Each test section should be sufficiently large to permit use of full-size production equipment (similar to the type anticipated for use on the project) and to permit "shake-down" and subsequent steady operations to be attained. Funds expended on the test section are nearly always returned many times over in increased quality of production construction. All operations to be used in the RCC placement process should be included in the test fill construction in order to identify any potential problem areas. This includes operations such as: forming for conventional concrete to be placed upstream and/or downstream; bedding mortar placement; compaction of downstream unformed faces; and the use of any unusual equipment to deliver, spread or compact the RCC.

l. Reinforcement in RCC placements.

(1) Anchorage reinforcement. It becomes necessary at times to embed reinforcing steel in the RCC for the purpose of anchoring various structural features and appendages. These structural features could be intakes for outlet work, training walls for spillways, parapets, etc. The anchorage of these features to the RCC structure can either be accomplished by installing the rebar during RCC placement, or by drilling and grouting the rebar 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 rebar so that it meets location

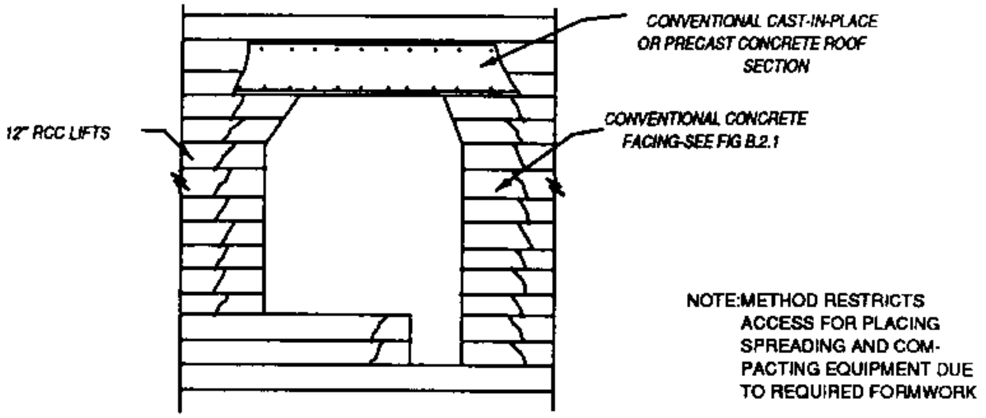


NOTE: 1. WOOD OR STEEL PLATES MAY BE PLACED AT RCC-FILL INTERFACE AT EACH LIFT TO PRODUCE SMOOTHER GALLERY WALLS.

2. AT ENTRY LOCATIONS RCC MAY BE EXCAVATED AND REPLACED WITH CONVENTIONAL CONCRETE FOR IMPROVED APPEARANCE.

3. METHOD DOES NOT RESTRICT ACCESS FOR PLACING, SPREADING OR COMPACTING EQUIPMENT.

(a) GRAVEL&SAND FILL REPLACEMENT METHOD



NOTE: METHOD RESTRICTS ACCESS FOR PLACING SPREADING AND COMPACTING EQUIPMENT DUE TO REQUIRED FORMWORK

(b) FORMED CAST-IN-PLACE CONCRETE METHOD

Figure 1-17. Galleries and other special features in RCC structures must be compatible with RCC construction

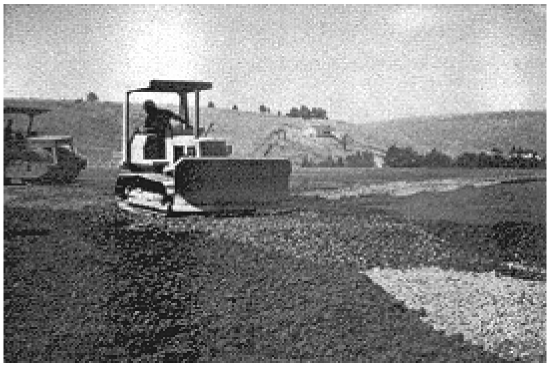


Figure 1-18. Gallery construction

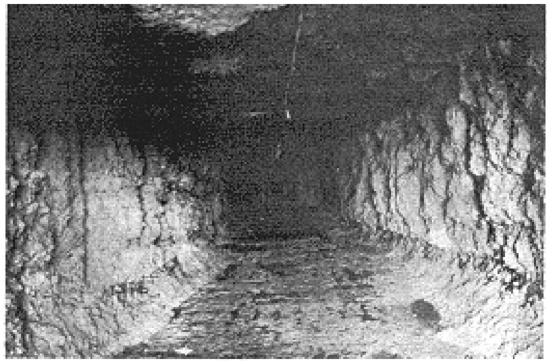


Figure 1-19. After excavation of the gravel/sand fill, protruding or loose RCC is removed. However, gallery walls are irregular and rough

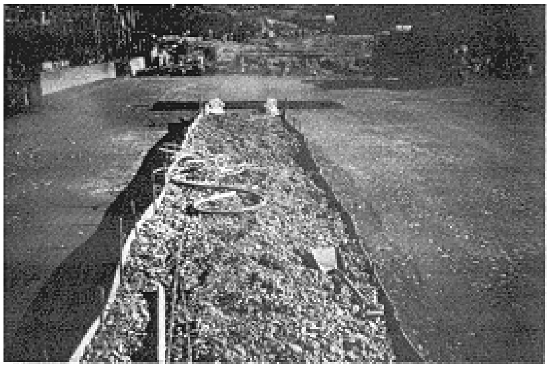


Figure 1-20. Gallery construction using the gravel/sand replacement method with wood plank forms to separate the RCC and gravel/sand fill to produce smoother, more uniform walls in the completed gallery

requirements with respect to the appended structural feature. Second, it is difficult to support the rebar during RCC placement such that it will not displace; and often it is difficult to devise a rebar 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 rebar can be placed at an RCC lift surface where mortar bedding will be provided to ensure complete rebar encapsulation. Rebar 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 assure full bond strength development. As an alternative, anchorage reinforcement can be installed after RCC placement by drilling and grouting. This procedure is much more costly but does allow for more accurate positioning of rebar and does ensure bar encapsulation and bond development.

(2) Structural reinforcement. RCC can and has been placed with 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: 1) prevent the formation of wide cracks that might make the RCC susceptible to deep abrasion erosion from ash-laden flood flows, 2) provide bending resistance to limit cracking due to differential settlement, and 3) 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. Another means of improving RCC bending resistance might be to place conventional reinforced concrete at the extremities of an RCC placement where it is needed to resist tensile bending stresses. This method offers promise, but has not been used to date. Reinforced RCC is shown in Figure 1-23.

7. Sampling and Testing Materials

a. General. A comprehensive laboratory testing program is required to obtain the design mixture proportions for RCC strength and workability, to

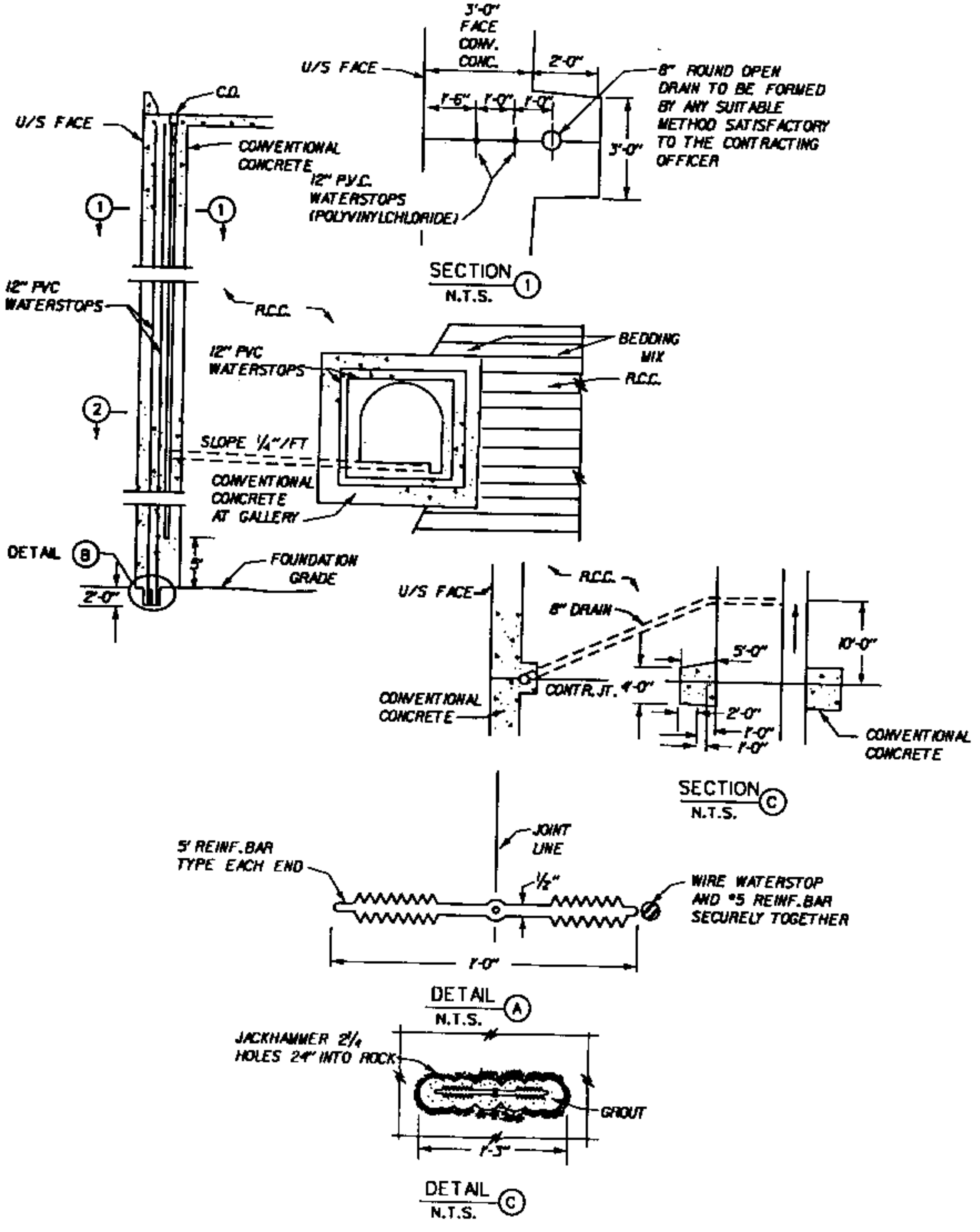


Figure 1-21. Waterstop details

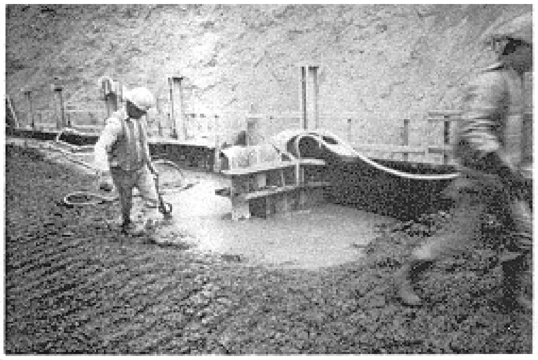


Figure 1-22. Installation of a waterstop at a contraction joint

Figure 1-23. Reinforced RCC. Heavy welded wire mats can be placed in RCC to resist cracking and increase resistance to tensile stresses

obtain the material properties important to structural analysis and thermal studies, and to validate in-place concrete strengths of both the parent concrete and RCC lift joints. Information is provided in the following paragraphs on sampling, tests, and testing procedures used for RCC concrete. The structural engineer and the laboratory materials engineers should work closely together to establish a laboratory testing program that meets structural needs. The structural engineer should become familiar with the testing program and understand how testing procedures and specimen size can affect results.

b. Fabrication of laboratory and field RCC specimens. Fabrication of RCC strength specimens requires some special equipment for compacting and consolidating the "stiffer" RCC mixtures into specimen molds or forms. Specimens may be consolidated by either tamping (for drier mixes) or more commonly, by vibration. The vibration method requires the use of a vibrating table, miscellaneous surcharge tools, and molds meeting standard American Society for Testing Materials (ASTM) requirements. Standard plastic, paper, or tin molds may be used for either method of consolidation but will require some type of exterior confinement, such as a close-fitting steel sleeve to withstand the heavy impact loads if consolidated by tamping. Currently, research is continuing for developing standard procedures for preparing and testing RCC specimens.

c. Retrieval of in situ samples. RCC may be cored or sawn in the same manner as conventional concrete. In order to reduce damage or failure at lift joints, core barrels should be of the inner tube or split-sleeve type that support the RCC core during drilling. It may be several months before the strength gain in mass RCC is sufficient to obtain intact samples by coring or sawing. The success of retrieval will be primarily dependent on the type and condition of the drilling equipment, and the experience of the drill crews. Field cores extracted from in-place RCC are shown in Figure 1-24. Evidence of "good" and "poor" consolidation is visually apparent. Cores are often tested to confirm compressive strength of the parent RCC and shear, bond, and tensile strength of the lift joint surfaces.

d. Specimen size and curing. 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 specimens should be moisture conditioned the same as conventional concrete specimens.

e. Compressive strength. Compressive strength tests are normally made on laboratory cast 6- by 12-in. cylinders or on drilled cores following standard ASTM testing procedures. Test results from laboratory cast specimens are analyzed, and mixture proportions are adjusted, to obtain the desired strength and workability. During construction, RCC is sampled and compressive strength cylinders are cast at a frequency and at test ages defined by EM 1110-2-2000 (Reference 12b).

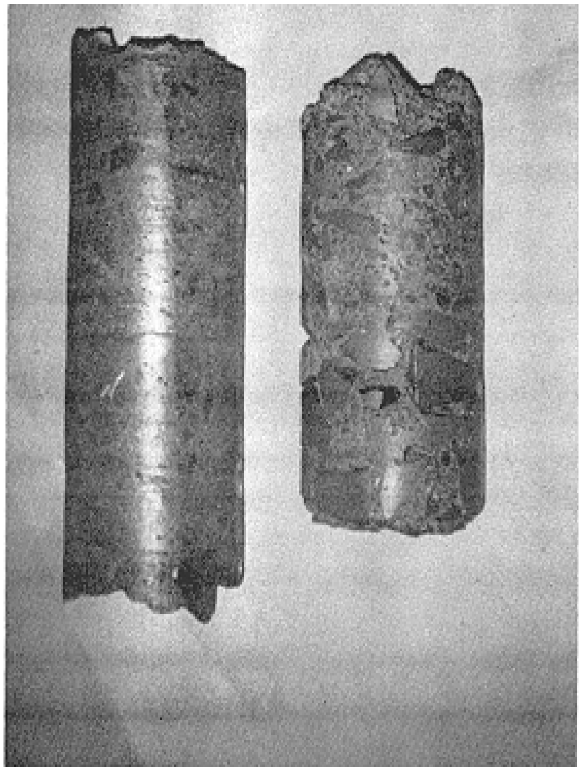


Figure 1-24. Field core extracted from in-place RCC

Cylinders are cured and capped using the same procedures as for conventionally placed concrete.

f. Tensile strength. Direct tensile strength tests are made on cylinders, cores, or blocks using procedures outlined in ASTM D2936, "Direct Tensile Strength of Intact Rock Core Specimens." Specimens are cemented to steel end plates using high-strength epoxy and moisture conditioned prior to testing. Specimens with lift joints are tested with the lift joint centered within the middle third of the tensile strength specimens. After testing, specimens are examined for type and location of failure, degree of bonded mortar, and aggregate failure. Since tensile strength is normally only between 5 and 10 percent of the concrete compressive strength, it is important that sufficient tests be made to ensure representative results. Other more indirect tests may also be made to determine or correlate with tensile strength. These include: the tensile splitting strength test (ASTM C496), the point load tensile strength test (proposed method depicted in Proceedings of the International Construction Industry Research and Information Association Conference dated 10 June 1981), and flexural strength (ASTM C78).

g. Direct shear strength, bond, angle of internal friction. Shear strength of RCC or RCC lift joints may be determined using laboratory-cast cylinders, laboratory-cast blocks or panels, or sawn blocks and drilled cores removed from the RCC structure. The tests are made following procedures described in the U.S. Army Corps of Engineers Rock Testing Handbook (RTH), Method RTH 203-80, "Direct Shear Strength of Rock Core Specimens." Tests are normally performed using various confining pressures, and typical test programs will include the determination of cohesion (shear strength at zero confining load) and the angle of internal friction. With the use of appropriate dial gages, residual sliding shear strength may also be determined.

h. Post-construction evaluation. A post-construction drilling and testing program should be conducted on all major hydraulic structures to confirm that the as-built properties of the RCC are in conformance with the design requirements. Drilling of the completed structure should be scheduled a sufficient time after RCC placement as required to assure adequate core recovery, but should be conducted within 1 year of completion.

Drilling should penetrate the full height of the structure at a sufficient number of locations to ensure a statistically adequate sampling of the structure. Testing should be conducted on the recovered cores to confirm that: (a) lift joints meet structural requirements for shear and tensile strength, (b) the RCC has the required compressive strength, and (c) full uniform compaction has been achieved without segregation. If an upstream zone of conventional concrete has been used, a majority of the core samples should be taken far enough downstream to avoid intersecting the contact between RCC and the conventional concrete. The results of the drilling and testing should be reported in the Post-Construction Structural Report required by Section 9.d.

8. Preliminary Structural Analysis Strength, Elastic and Thermal Properties

a. General. Properties important to preliminary structural investigations include compressive strength, tensile strength, shear strength, modulus of elasticity, Poisson’s ratio, adiabatic heat rise and coefficient of thermal expansion. The range of values for each of these RCC properties is presented in the following paragraphs. It should be noted that the rapid construction time of RCC structures, and the general practice of specifying the required RCC strength at 1 year, can lead to the structure being loaded prior to the RCC attaining the required design strength. It is therefore important that the structural engineer be involved in the mix design process in order to assure that the required strength gain characteristics of the mix are attained. All values assumed in the preliminary design must be verified through testing as outlined in Section 7.

b. Compressive strength. RCC with high quality aggregates will produce compressive strength equal to conventional concrete. The strength will depend primarily on the water-cement ratio. The relationship between water-cement ratio and strength for RCC is similar to that for conventional concrete. Normally, for durability reasons, the RCC mixture will have a minimum compressive strength of 2,000 psi at 1 year. However, higher compressive strengths may be required to produce RCC with the desired tensile and shear strengths.

c. Tensile strength. The tensile strength of RCC is dependent on the method of test used (split cylinder, flexural, direct tension). The tensile strength of RCC can be expressed as a function of the compressive strength and, in general, is lower than for conventional concrete. The in-place tensile strength of RCC is sensitive to the maximum size of aggregates, the workability of the mixture, and the condition of the lift joint surface. With the use of a mortar bedding on lift surfaces, direct tensile strengths in the range of 3 to 9 percent of the compressive strength can be expected. A direct tensile strength equal to 5 percent of the compressive strength is recommended for preliminary design investigations. This value can be increased by 50 percent for seismic load conditions that involve high strain rates.

d. Shear strength. The total shear strength along horizontal lift surfaces of RCC is a combination of cohesion (bond) and frictional resistance. 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. Cohesion varies a great deal from lift surface to lift surface, while the angle of internal friction is usually quite consistent. The factors that affect tensile strength at lift joint surfaces also affect shear strength. Cohesion can vary from 0 to 10 percent of the compressive strength. A preliminary design value of 5 percent of the compressive strength is recommended for lift joint surfaces that are to receive a mortar bedding; 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.

e. Modulus of elasticity. Properly proportioned and consolidated RCC should provide a modulus of elasticity equal to or greater than that of a conventional concrete of equal compressive strength. The same modulus-strength relationships used for conventional concrete may be used for RCC. For rapid strain rate loading, such as occurs during earthquakes, the modulus of elasticity may be 15 percent higher than that predicted by the usual strength modulus formula. For thermal analyses, where creep effects are considered, the effective modulus may be 33 percent less. Preliminary design studies should assume the modulus of elasticity to be equal to 57,000 $(f'c)^{1/2}$ psi (increased by 15 percent for seismic load conditions and reduced by one third for long-time load conditions where creep effects are important).

f. Poisson's ratio. The normal range for Poisson's ratio is between 0.17 and 0.22. A value of 0.20 should be used for preliminary design studies.

g. Coefficient of thermal expansion. The thermal movements in concrete are primarily dependent on the aggregate type and content. The coefficient of thermal expansion, or the thermal movement per unit temperature rise, is usually smaller for RCC (because of higher aggregate content) than for conventional concrete. The coefficient of thermal expansion for conventional concrete varies between 4 and 8 x 10^{-6} inches per inch per degree F. A value of 5 x 10^{-6} inches per inch per degree F should be used for preliminary RCC design studies.

9. 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 roller-compacted concrete gravity dams. However, there are differences in the requirements for uplift within the body of the dam, and additional testing requirements to assure adequate factors of safety against sliding.

b. Uplift within the body of an RCC dam. Uplift within the body of an RCC dam constructed without mortar bedding on all lift joint surfaces 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. When mortar bedding is used, uplift within the body of the dam can be assumed in accordance with the requirements for conventional concrete gravity dams.

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. Preliminary cohesion strengths can be assumed in accordance with Section 8.d herein, however, assumed values must be verified by tests performed on samples prepared during mix design in the lab and on cores taken from test fills. In addition, the Post Construction Structural Report required in Section 9.d must demonstrate that the shear resistance of a typical lift joint meets or exceeds the design requirements. The shear resistance of a typical joint will be the sum of the frictional resistance plus the average cohesion strength of the bonded portion of the joint. Only the percentage of the joint which is bonded, as indicated by the coring and testing of the completed structure, should be used in the calculation of cohesion strength.

d. Post construction structural report. The drilling and testing required by Section 7.h and the final structural stability and stress analysis, using the values obtained during the drilling, should be included in a Post-Construction Structural Report. In addition, a summary of the findings of the final Concrete Report should be included. The purpose of the Structural Report is to evaluate the ability of the completed RCC structure to perform as assumed during the design process. Items of particular interest are:

(1) A final stability analysis using the shear strength values determined from the drilling and testing program.

(2) A final stress analysis using actual temperature gradients and RCC strengths obtained from instrumentation built into the structure and the drilling and testing program.

(3) The percentage of the lift surfaces estimated to be bonded, as indicated by the drilling program.

(4) A comparison of the strength indicated from the post-construction drilling and testing program with that indicated by testing performed on RCC cylinders taken during construction.

This comparison, as well as an evaluation of the other testing performed during construction, should be used to confirm that the required RCC strengths were obtained in the field.

10. The Design Team

a. Once the structural designer determines the strength and serviceability requirements for a proposed RCC structure, he should work with the materials engineer to develop mixture designs 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 much dependent on field control of mixing and placing operations as mixture ingredients or mixture proportions. Therefore, the structural and materials engineers must jointly develop requirements for test fill placements, in situ testing, and actual construction placements. The in situ testing program should address: (1) The type and numbers of tests required to assure 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 occur at lift joints.

b. Serviceability of an RCC structure is a function of durability, seepage control, and crack control. These are dependent on mixture ingredients, mixture proportioning, and field control. Again, the structural engineer should work with the materials engineer to develop a testing program that will assure that properties important to serviceability can be achieved throughout the RCC placement. In massive RCC structures, the cement content, placement temperatures, construction sequencing, and thermal gradients will affect the spacing, location, and widths of cracks. Special design provisions for massive concrete structures as described in ETL 1110-2-324 (Reference 12e), should be considered in the design of massive RCC structures. Options which can be used to minimize thermal stresses include: (1) cement replacement with pozzolan, (2) limiting placement to cool weather times of the year, (3) lowering the placement temperature, and, (4) jointing. Because of the rapid rate of RCC construction, it is extremely important that any conditions that can lead to poor consolidation and poor joint bonding are recognized and corrected immediately. The structural designer should work closely with the materials engineer and quality control personnel to identify poor consolidation and construction practices and to implement changes to correct any deficiencies. This is best accomplished with a test section placed as part of the construction contract. The design team should be present during placement of the test section and during the initial placements for the RCC structure to assure that strength and serviceability requirements will be met.

11. RCC Costs

Unit costs of RCC range from 25 to 50 percent of the cost of conventionally placed concrete, depending on the quantity of RCC being placed and on the complexity of placement. More detailed information regarding RCC cost is provided in EM 1110-2-2006, "Roller Compacted Concrete" (Reference 12c).

12. References

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b. EM 1110-2-2000. "Standard Practice for Concrete."

c. EM 1110-2-2006. "Roller Compacted Concrete."

d. EM 1110-2-2200. "Gravity Dam Design."

e. ETL 1110-2-324. "Special Design Provisions for Massive Concrete Structures."

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