1-1993

ROLLER COMPACTED CONCRETE AS A NEW METHOD FOR BUILDING DAMS AND ITS ECONOMIC ADVANTAGES

Sami Tannous
Pittsburg State University

ROLLER COMPACTED CONCRETE AS A NEW METHOD FOR BUILDING DAMS AND ITS ECONOMIC ADVANTAGES

A Thesis Submitted to the Graduate School

in Partial Fulfillment of the Requirements

For the Degree of

Master of Science

by
Sami Tannous

PITTSBURG STATE UNIVERSITY

Pittsburg, Kansas

January, 1993

To my past cousin **"UNCLE TOMMY THOMAS"** for all of the good things he did for me, and all of the support he gave to me throughout all of the years that we spent together. I wish he were alive to see me finishing my thesis, and I would be able to thank him for all the help and support, and for making my dreams come true. May God bless you, and may your soul rest in peace.

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to: my mother Yvon and father Khaddah, my brothers and sisters, and all my family in Lebanon for encouraging and supporting me to make it through school, and for bringing me up to be a good person and student. Thank you Mom and Dad. I thank my wife Marcia for loving me, and being there for me when I needed someone for support, and for encouraging, and helping me throughout my school and social life in the United States. I thank my committee for taking the time to read my thesis, and guiding me through it. Thank you Dr. Slapar and Mr. Fladie for making a special effort and giving time to help me complete my thesis. Dr. William Studyvin, Associate Dean for Graduate Students, I thank for guiding me throughout my thesis. I thank very much Mr. Bill Bradrick for helping, in his own way, to process the thesis. Finally, I thank Pittsburg State University Axe Library, in particular Ms. Cynthia Pfannenstiel, and Mr. Richard Samford in Special Services (Interlibrary Loan), for helping collect data and materials that were used in my thesis.

ROLLER COMPACTED CONCRETE AS A NEW METHOD FOR BUILDING DAMS AND ITS ECONOMIC ADVANTAGES

An Abstract of the Thesis by
Sami Tannous

The 1980s could be considered to be the decade during which roller-compacted concrete dams (RCC) came to age. This economic method of construction has been proven sufficiently that very large dams can now be designed. Techniques have been developed for the design of the mixture proportions of RCC to have sufficient cohesion and tensile strength to withstand the required static and thermal loading on these large dams. The development and applications of roller-compacted concrete (RCC) for water control structures has progressed rapidly in the past decade. The concept of building a concrete activity dam rapidly and economically using earth compaction techniques with a minimum of forms and joints has attracted considerable interest worldwide.

This document includes overviews of the planning and design processes, reviews of construction operations, evaluations of the behavior, and performance of completed dams. Included in this document are examples of roller-compacted concrete dam construction in the U.S., South America, Europe, Asia, and Australia.

This document also provides information on the development of roller compacted concrete (RCC) to support the use of RCC in dam construction. This procedure offers rapid construction with a lower cost, compared with the traditional concrete practice, and challenges the economics of earthfill and rockfill embankment dams.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

CHAPTER I

INTRODUCTION

Introduction to the Problem

The first attempt to use the product which is now being called Roller Compacted Concrete (RCC) for dams was in the early 1960's in the United States. Its development and refinement in dam construction has been slow.

Initially the composition of RCC was somewhat experimental in that the more optimum combination of ingredients was not known, nor was the durability or reliability of the product known. Basically, this early RCC was a dry concrete (the word dry must be emphasized) which was made up of low-cost aggregate. The RCC may have also been produced with a relatively low quantity of water. The objective was to make a lower cost concrete which did not need the elaborate and expensive formwork. This dryness normally eliminated the use of formwork and allowed the contractor to haul or move the mixture in open-topped dump trucks, and to shape and push the RCC, applying it in layers and compacting each layer much as if it were soil.

Statement of The Problem

This study was conducted to determine the feasibility of constructing large dams for water reservoirs through Roller Compacted Concrete (RCC) techniques.

Research Questions Addressed

1) What is the Roller Compacted Concrete (RCC) Technique?
2) Would the use of RCC be accepted in the construction industry?
3) Would the use of RCC in dam construction result in savings in time and money when compared to traditional concrete practice?
4) What are the advantages of RCC for dam construction?
5) What are the disadvantages of RCC for dam construction?
6) What are some outstanding examples of RCC dam construction?
7) What are some of the techniques used in RCC dam construct-ion?
8) What special equipment is needed for RCC dam construction?
9) Does the RCC method replace any other techniques ?

Delimitations

This study was limited to the use of information, and data that could be obtained in Pittsburg State University's AXE Library, Personnel Interviews of Engineers and Contractors, and Computer Searches through AXE Library.

Limitations

This study was limited by the authenticity of the material that has been written in the sources listed in the bibliography.

Assumptions

For this study the writer has assumed that for projects in which dams are constructed to create water reservoirs that the most feasible techniques known are employed to conduct the project. It is also assumed that the RCC Techniques are able to be conducted in the locale where the dams are to be constructed.

<u>Definitions of Terms</u>

Aggregates: Granular materials, such as, gravel, crushed stones used with a cementing medium to form concrete

Autogenous: A natural process of filling and sealing cracks in concrete or in mortar when kept damp.

Batch Plant: An installation for batching of concrete, or mortar.

Batching: Weighing, or volumetrically measuring the ingredients for a batch of either concrete or mortar, and introducing them into the mixer.

Creep: A time-dependent part of strain resulting from stress.

Fillet: A concave junction formed where two surfaces meet. Also called chamfer strip, which is a triangular or curved insert placed in an inside form corner to produce a rounded, or flat chamfer, or to form a dummy joint.

Galleries: Any similar enclosed narrow passageway, as a hall or corridor, used for a specified purpose.

Lift: The concrete placed between two consecutive horizontal construction joints, usually consisting of several layers or courses.

Mortar: A mixture of cement paste and fine aggregates; in fresh concrete, the material occupying the interstices among particles of coarse aggregates.

Overtop: To extend or rise over or beyond the top of: rise above.

Pozzolan: A siliceous, or siliceous and aluminuous material, which in itself poses little or no cementitious value, but will chemically react with calcium hydroxide at ordinary temperatures to form compounds posessing cementitious properties.

Pugmills-Horizontal Shaft: A mixer having a stationary cylindrical mixing compartment, with the axis of the cylinder horizontal, and one or more rotating horizontal shafts to which mixing blades or paddles are attached.

Roller Compacted Concrete(RCC): A RCC is a dry concrete material which has been consolidated through external vibrations from vibratory roller. It differs from conventional concrete principally in its required consistency. For effective consolidation, RCC must be dry enough to support the weight of the vibratory equipment, but wet enough to permit adequate distribution of the paste binder throughout the mass during the mixing and vibration process. The consistency requirements have a direct effect on the mixture proportion requirements.

Significance of the Problem

The research was conducted to obtain information and present paper to inform contractors and engineers about the roller compacted concrete technique.

Using this information, data was presented which shows factors which are either advantages, or disadvantages, in the use of RCC in the construction industry. It was intended to show that factors such as height of dams, the type of rock available to make the RCC, variation in composition, climate at the construction site, comparative costs, and time are all factors that should be included in dam construction. Other factors were also found which affects the application of RCC.

CHAPTER II

HISTORICAL BACKGROUND

History of Roller Compacted Concrete

Of all the dams built throughout the world, excluding China, through 1950, 38 percent of the structures 50 ft (15cm) or higher had been built with concrete. From 1951 to 1977, the number of concrete dams built had dropped to 25 percent of the total. The world-wide percentage decreased further to 16.5 percent during the period from 1978 to 1982 (8).

However, this general and steady decline in the popularity of concrete dams came during a period when the use of concrete arch dams in narrow-valley sites was increasing. Therefore, the greatest decrease was occurring in wide-valley sites, where concrete gravity dams were being replaced by less costly earth and rock embankments. Their cost advantage over concrete dams was derived mainly from the greater efficiency of the equipment and methods used in construction. The increased popularity of concrete dams also coincided with the emergence of soil mechanics technology. This situation led the Engineering News-Record to editorialize in its March 6, 1969, issue:

> The technology of mass concrete construction simply has not kept pace with the art and science of earth moving. It is time for a study into ways of reducing the cost of concrete dams. Dams must be conservatively designed and carefully built. But it does seem that in all the years since Hoover Dam, there should have more changes in the bucket-by-bucket method of moving mass concrete into place. What's needed is a lot more systems analysis and a bit less "grandpa-ism" (8:2).

Concern for the decline of concrete dams led to the organization of two important meetings of the dam-building community in the United States at the Asilomar conference grounds in California (1).

The first conference, in 1970, was called "Rapid Construction of Concrete Dams" at which Professor Jerome M. Raphael presented a paper entitled "The Optimum Gravity Dam" in which he extrapolated from soil-cement applications the concept of placement and compaction of an embankment with cement-enriched granular fill materials ("bank" or "pit run" materials) using earth-moving and compaction equipment. He postulated that an increase in shear strength of the cement-enriched granular fill materials would result in significant reduction of the gravity dam cross section as compared with a typical embankment dam. Use of continuous placement methods similar to those utilized in an embankment dam would accomplish savings in time and money as compared with the construction of the usual gravity concrete dam (1).

The second conference, in 1972, was entitled "Economical Construction of Concrete Dams" at which Robert W. Cannon presented a paper, "Concrete Dam Construction Using Earth Compaction Methods." In this paper Cannon presented results obtained from tests made on concrete transported by trucks, spread by front-end loaders, and compacted by vibratory rollers. The concrete mix was proportioned by extrapolation from typical interior mass mix for dam construction by increasing the coarse aggregate fraction by 1/2 cu.ft. and decreasing the mortar fraction by the same volume (1).

In the meantime, while embankment dams were being reduced in cost relative to concrete dams, they have been more prone to failure. No concrete dam higher than 50 ft. (15m.) has failed in the United States since 1928, when St. Francis dam, a 205 ft. high (62m.) curved gravity dam in California, failed due to defective foundation material. Outside the United States, the most recent concrete dam failure was in 1959 at Malpasset dam in France. The 200 ft. high (61m.) thin concrete arch failed by sliding along a weak seam in the left abutment (1).

By comparison, hundreds of earth embankment of all sizes have failed during the past 60 years. The primary cause of embankment dam failures is overtopping and internal erosion of the fill material (8).

Taking note of the relative vulnerability of fill dams, the experts at Asilomar and elsewhere were searching for a new type of dam that would combine the safety advantages of concrete and the efficiencies of embankment dam construction. By a number of different routes, their searches in the early 1960's and 1970's led to the development of roller-compacted concrete (RCC) dam building (8).

The first roller compacted concrete used for a feature of a dam project appears to be that of a stabilization buttress at the toe of a cliff behind the power house of the Yale hydro-electric project in the State of Washington. The buttress is 500 ft. (152m.) long and has a maximum height of 60 ft. (18m.). The buttress covers a soft tuft formation which occurs at the base of a basalt cliff about 400 ft. (120m.) high. The construction was completed in 1952 (1).

The first use of roller compacted concrete in a dam proper was in 1960-61 for the core of the 210 ft. (65m.) high cofferdam, which was incorporated in the 340 ft. (104m.) high Shihmen Earthfill dam, Taiwan. The fill concrete for the foundation for the powerhouse was transported from the batching plant to the site in small dump trucks and spread with small bulldozers. Compaction was by immersion vibrators.

Similar construction was used for the entire Aple Gera Dam in Italy, completed in 1965. Vertical transverse joints were provided by a joint cutter at this dam (1).

The first use of RCC as a major structural element in embankment dam construction was 1974 at Tarbela Dam in Pakistan. After 11 months of operations, approximately 250 ft. (76m.) of the upstream section of a power and diversion tunnel collapsed as a consequence of cavitation (1). This created the need to rebuild the collapsed portions of the tunnel, to replace the rock, and to restore the surrounding embankment. Because of time constraints dictated by the onset of the rainy season and reservoir filling, RCC offered the only suitable method of repair. A total of 460,000 cu.yd. (352,000 cu.m.) of roller compacted concrete was placed at a maximum placement rate of 24,000 cu.yd. (18,000 cu.m.) per day. From 1977 to 1980, 1,180,000 cu.yd. (920,000 cu.m.) of RCC was used to line the side of the Tarbela Service Spillway Plunge Pool. From 1980 to 1982, 1,230,000 cu.yd. (940,000 cu.m.) of RCC was used to create a similar lining for the sides of the Auxiliary Spillway Plunge Pool at Tarbela Dam Project (7).

The Tennessee Valley Authority was responsible for the first structural placement of RCC in the United States. It was used in 1976 at the Tennessee Valley authority's Bellefonte

Nuclear Plant where 8,000 cu.yd. (6,000 cu.m.) of RCC was used to raise the supporting base under the turbine building (2).

Willow Creek Dam, the first all-RCC dam structure constructed in the United States, was completed in 1982, near Heppner, Oregon. It was the first roller compacted concrete dam fully utilizing earthfill methods of construction. The structure is 169 ft. (52m.) high, 1,780 ft. (543m.) long, and contains 430,000 cu.yd. (329,000 cu.m.) of RCC. It was completed in approximately one-third the estimated time required for an alternate rockfill design and at approximately 50 percent of the cost ($14 million versus $27 million) (7).

The Japanese have successfully incorporated RCC into portions of five major gravity dams. Since 1974, 1.43 million cu.yd. (1.1 million cu.m.) of RCC has been placed in Japan with approximately another 6.2 million cu.yd. (4.7 million cu.m.) being planned in several other dam structures. Dams with heights in excess of 330 ft. (100m.) are being built (7).

In 1980, the Japanese Ministry of Construction completed the 292 ft. (89 m.) high Shimajigawa Dam, the first dam to be constructed by the roller compacted dam concrete (RCD) method (6).

Early Progress

Several projects in the 1960s were designed with the idea of combining the advantages of concrete and embankment dams. These hybrid dams were the brainchildren of both structural and geotechnical engineers. Unfortunately, because of a high degree of specialization in these fields, there was limited communication between the early theorists (8).

The most notable and earliest example was the 564 ft. high (172 m.) "Alpe Gera Dam" in Italy, designed by a structural engineer There Gentile, and completed in 1964. The concept behind "Alpe Gera" was to maintain the traditional cross section of the concrete gravity dam while reducing the unit cost of placing a mass of concrete. Some of the cost reduction was accomplished by reducing the cement content in the concrete mix used for the interior of the dam, where stresses are low and durability requirements are minimal (8).

Another early hybrid was developed by concrete dam designers at Hydro Quebec in Montreal. Their ideas were incorporated in two 60 ft. high (18m.) gravity wing walls at the Manicougan I dam in Quebec in 1965. On this project, lean mass concrete was placed by dozers for the core of the dam and was internally vibrated (4).

A richer mix was used for the upstream face of the wing dams. The facing concrete was slip-formed vertically. Joints with water-stops were spaced at 50 ft. (15 m.) intervals. Precast blocks were used for the downstream face. Hydro Quebec estimated that the system saved 20 percent of the cost and two-thirds of the time that would have been required to build the concrete wing walls using conventional methods (5).

Sly Creek Dam in northern California was designed in 1967 as a 60 ft. high (18m.) solid soil-cement dam. The entire section had to be erosion-resistant because the dam was designed to be overtopped and ultimately inundated during high-flow conditions. The increased shear resistance of soil-cement over earthfill construction allowed both the upstream and downstream slopes of Sly Creek to be steepened 1H : 1V slopes. The project was never built, however, because of a lack of funds (5).

Besides being the only large dam constructed entirely of soil-cement, the "Barney M. Davis" reservoir embankment marked the first recorded use on a dam of vibratory rollers to compact soil-cement. No joints were incorporated in the 351,000 cu.yd. (268,000 cu.m.) of soil-cement used to construct the long, low dike, see Figure 1. Transverse cracks occurred in the soil-cement section as anticipated but, they were not of sufficient width to allow passage of water (5).

CHAPTER III

EVALUATION OF METHODS OF DESIGN OF RCC DAMS

Three Paths Taken in RCC Design

RCC dam design was evolving in three different directions during the 1970s. In the United States, a lean-concrete alternative based on soils technology was being developed by the Army Corps of Engineers and other investigators. British engineers were focusing on the so-called high-past alternative, a hybrid of conventional concrete mix design and earthfill dam construction methods. The Japanese research team, set up to explore rationalized concrete dam construction methods, was developing the third approach concrete method, called roller-compacted dam (RCD). Of the three, RCD is the most cautious departure from traditional concrete gravity dam design and construction practices, (7).

There are three paths that are used in designing RCC dams, and these are as follows:

1. The lean RCC dam
2. The high paste dam
3. RCC in Japan

These will be discussed in detail at this time.

The Lean RCC Dam

The United States Army Corps of Engineers began a concerted effort to develop RCC for use in building concrete dams in the early 1970s. The Corps built field test sections at Jackson, Mississippi, in 1972 and at the site of Lost Creek Dam in Oregon in 1973. The field tests confirmed the basic construction method and provided information on material properties and strength of the bond between successive layers of RCC. In fact, the name " roller compacted concrete" may have been first used by Corps investigators in reporting on the Lost Creek test section.

Based on the data developed in these tests, the Corps in Walla Walla District designed an RCC alternative for Zintal Canyon dam near Kennewick, Washington. The first dam section investigated in the design was an embankment with a 45 degree face (1H : 1V) on the upstream and downstream slopes. It was to be constructed almost entirely of a lean RCC mixture, enriched only in the exposed exterior zones.

Thus, the lean RCC dam evolved from a concept in which a cement-stabilized, controlled-gradation aggregate is placed and completed rapidly from abutment to abutment without forms or joints. In order to make the idea work economically the slopes had to be steepened, creating a need for some method of forming the vertical upstream face. The initial plan at Zintel Canyon was to build an earth berm upstream to buttress and

form the RCC mass. At Willow Creek, that method was first specified as precast "reinforced earth" concrete panels tied back into the RCC.

Lean RCC mix designs, by definition, contain cement, aggregate, and water. In some cases, pozzolans and admixtures may also be included. Typical cement contents are on the order of 80 to 125 lb/cu.yd. (47 to 74 Kg/cu.m.). Pozzolan are usually used only if a high cement content is truly needed and if pozzolan is economically available (6).

The amount of pozzolan that is optimal depends on each project. In some cases, adding silt or rock dust has had the same effect as adding pozzolan. In other cases, replacement of up to 50 percent pozzolan for cement has resulted in essentially the same strength as the cement-only mix. In still other cases, the addition of pozzolan has resulted in a loss of long-term strength below what was achieved with the same cement content and no pozzolan. Each case is evaluated individually.

The High-Paste RCC Dam

After some initial work in the early 1970's by the Tennessee Valley Authority on a concrete mix with a low-portland-cement and high-fly-ash content, the development of this so-called high-paste RCC alternative shifted to the

United Kingdom. The properties of the material were demonstrated in 1976 following field trials in Cornwall, England. The intent of the field trials was to develop a high-paste RCC design for Milton Brook Dam at Devon, England.

The central philosophy of the high-paste-content RCC dam includes the following:

* It should perform as well as a conventionally placed concrete dam, with a design philosophy that the whole structure should be considered to be impermeable.
* The method of construction should be kept as simple as possible. With simplicity will come speed, which is one of the main advantages of the overall method of construction.
* The design of a high-paste content RCC dam must be considered as a whole. This includes the cross section of the structure; the details, such as, spillways and galleries; and the design of the mixture proportions,

The choice of the optimum mixture proportions is only one of the factors to consider within the concept of the design of an RCC dam. For some sites it may be necessary to design a concrete with particular properties, for example, because of an extreme temperature regime at the site. It may then be beneficial to use these properties in order to refine the cross-section of the structure (6).

RCC in Japan

At the same time that considerable progress was being made toward the development of RCC for dams in the United States, Japan was also working independently to develop a rationalized method for building concrete dams that would speed the replacement of concrete and lower the cost of construction. The product of this research through the 1970's is referred to by Japanese engineers as the "roller-compacted dam, concrete method," or RCD.

Most of the dam construction in Japan has occurred in the period after World War II. More than 80 percent of the existing dams in Japan are built of concrete, and most proposed dams are planned as concrete gravity structures because of their inherent safety. Like their American counterparts, Japanese designers saw a need to improve the economics of concrete dam construction and focus on RCC as the preferred alternative (5).

Because of seismic, hydrologic, and topographic problems associated with most dam sites in Japan, designers there have taken a more conservative approach to RCC dam construction. Their aim is for a product with the same quality and appearance as that of conventionally-placed, mass concrete gravity dams.

The potential benefits of the RCD method over conventional concrete dam-building techniques in Japan, as Japanese engineers report, are lower construction costs; faster construction and time saving; greater worker safety because of uncontested level working surfaces, and because of the possibility of developing more sites by using an RCD base mat for a conventional dam; and greater concrete gravity dam design diversity.

The criteria for mixes designed for the RCD method include:

* Cement content should be as low as possible while being consistent with strength requirements. Some fly-ash should be used as an admixture to reduce heat of hydration and mixing water requirements.
* A sand/aggregate ratio higher than conventional mass concrete should be used to reduce segregation and to facilitate compaction by a vibratory roller (6:325-340).

For future projects, Japanese researchers have been studying a method of controlling concrete temperature, and the compaction mechanism of vibratory rollers.

Materials and Mixture Proportioning for RCC

Properly proportioned RCC is workable, free of segregation and easily consolidated using external vibratory compaction. The RCC mix must contain sufficient paste (portland cement, pozzolan, water, and admixtures) to fill voids within the mortar, and must contain sufficient mortar to fill voids within the coarse aggregate, see Table I. The mortar provides cohesion and workability to the mix during placement, and determines the resulting strength, bonding potential, durability and permeability of the hardened RCC. The coarse aggregate provides stability to support placing and compaction equipment. A wide range of materials has been used successfully to produce RCC mixtures.

Cementitious Materials

The quality of cementitious material in an RCC mix is dependent on the water/cement (W/C) ratio selected to meet strength or durability requirments. The durability of saturated non-air-entrained RCC, subject to freezing and thawing (F/T) cycles, is poor regardless of W/C and therefore, F/T durability will not normally affect the selection of W/C ratio. Flyash is normally used in RCC as a partial replacement for cement, to reduce heat generation, improve workability, and cost (1).

Cementitious content used in RCC dams have ranged from 100 lb/cu.yd. (60 Kg/cu.m.) of cement for Urugua-I dam in Argentina to 418 lb/cu.yd. (248 Kg/cu.m.) for the predominant mix at Upper Stillwater Dam. The high-paste mix at Upper Stillwater contained 129 lb/cu.yd. (77 Kg/cu.m.) of cement plus 289 lb/cu.yd. (171 Kg/cu.m.) of class F flyash (2).

In Japan, the cement-plus-pozzolan content is usually about 202 lb/cu.yd. (120 Kg/cu.m.). The pozzolan amounts to 20 to 30 percent by weight of the cementitious material (8).

Portland Cement - For massive RCC dams, engineers consider cements with lower heat-generation properties than normal or ordinary portland cement (Type I). They include moderate-heat cement (Type II), portland-blast furnace slag cement (Type IS).

Strength development for the lower-heat cements is generally slower than Type I, particularly at early ages. Beyond 90 days, however, the lower-heat cements generally produce higher strengths than Type I. The U.S. Army Corps of Engineers and U.S. Bureau of Reclamation usually specify type II cement for dams. Outside the United States, a blended portland-pozzolan cement was used for Brazil's saco de Nova

Olina Dam, while a portland-blast furnace slag cement produced the desired strengths and heat-generation conditions for Les Olivettes Dam in France. The choice of cement types for exposure to aggressive chemicals or aggregate reactivity should follow standard practice for conventionally-placed concrete (7).

Pozzolans - The selection of pozzolans suitable for RCC should be based on conformance with applicable standards (such as ASTM C618), the pozzolan's past performance in concrete, and its cost and availability in the volumes required. ASTM C618 defines a pozzolan as a "siliceous or a siliceous and aluminous material, which in itself possesses little or no cementitious value, but will, in finely divided form in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" (2-E5).

Pozzolans require moisture to react chemically with the calcium hydroxide released during the cement hydroxide process. Therefore, pozzolans perform better in a wetter mixtures than they do in a drier consistency mixers.

Most RCC mixtures that have included a pozzolan to date have used a Class F (low-lime) fly ash. Because adequate air

entrainment is generally not achievable in RCC, limits on the carbon content of the fly ash (as measured by percent lost on ignition) may be raised as long as strength properties are not adversely affected (1).

Several completed projects have used pozzolans other than a class F fly ash. They include a class C (high-lime) fly ash for the RCC in the Stacy Dam spillway. Arabie and Zaaihoek Dams in South Africa used a ground blast-furnace slag as pozzolan in the RCC mix. Calcined clay, a natural pozzolan, was used in the RCC mix for the navigation lock at Tucurui Dam in Brazil.

Aggregates

For RCC, like conventionally-placed concrete, aggregate quality and gradation are important factors influencing the final product. Slight differences have occurred among designers in the selection of maximum size aggregate (MSA), the proportion of sand in the mix, and the percentage of fines passing a No. 200 (0.75 mm.) sieve for RCC mixtures when compared with conventional concrete mixtures.

The segregation of coarse aggregate at the bottom of RCC lifts has led to decisions to reduce the MSA in some cases or increase the proportion of sand in the mix in other cases.

Most soils-approach RCC mixes have a greater percentage of fines than conventional concrete mixes. This is particularly so if the fines are nonplastic, fill voids in the aggregate, and lead to decreased water demand and improved compatibility (1).

Rounded river gravel and crushed aggregates have been used for RCC. At Copperfield Dam, difficulty was encountered maintaining an unformed 0.8H : 1V downstream slope using a mix containing rounded gravel. No problem was encountered in constructing the same slope at Willow Creek and Galesville Dams using crushed aggregate in the RCC mix.

The selection of a suitable aggregate source is an important step in the RCC mix design process since the type and quality of aggregate used will directly effect the quality and economy of the resulting RCC.

The greatest economy to the RCC mix is achieved by the use of the largest possible aggregate size because as aggregate sizes increase, mortar and paste volume requirments decrease. However, aggregate larger than 3-inches increases the tendency for segregation during handling, spreading and compacting, and will not be technically or economically feasible.

Quality - The quality of the aggregate required depends on the desired properties of the RCC, primarily its strength. For high-strength RCC, high-quality aggregate is needed. Standard tests to determine the characteristics and quality of aggregates are listed in Table II.

For RCC that is not highly stressed or not exposed to freeze-thaw conditions while wet, lower-quality aggregates may be used. This applies mainly to the interior concrete. Suitable aggregate for RCC can come from a variety of sources, but the material closest to the dam site should be investigated first. It has been assumed that concrete made using marlstone aggregate would be as strong or durable as concrete made using granite, basalt, or sandstone. Tests done for Middle Fork Dam proved those assumptions wrong (6).

Grading - Grading for both coarse and fine aggregate and the proportions used have an important effect on the properties of RCC. Specifications for grading of aggregates have varied considerably.

The difference in mix design philosophy has produced some differing trends with respect to specifying aggregates for RCC. This is true with respect to maximum size aggregate, percentage of sand and fines desired, and the number of separate sizes processed and then combined to produce the desired grading.

Sand percentages have generally been between 30 to 35 percent of total aggregate. The percentage of fines passing the No. 200 sieve (0.75mm.) has usually been limited to 3 percent of the total weight of aggregates, especially if a high percentage of pozzolan is used in remix (1).

Soils approach mixes specified for many early RCC dams required 3 in. (75mm.) MSA and 30 to 35 percent sand. However, with these drier-consistency mixtures, there is a greater tendency for the larger particles to segregate during transport, deposition, and spreading. Segregation can be minimized by reducing the maximum size aggregate and increasing the percentage of sand. There is a trend toward 2 in. (50mm.) MSA and sand percentages in the 35 to 40 percent range, primarily for mixtures that conform to the soils philosophy (1).

RCC mixes made with excessive amount of clay have shown a higher water demand due to the surface activity of the clay minerals. The increased water content increases shrinkage in the RCC and creates a greater potential for cracking and reduced strength. The general consensus is that fines should be nonplastic and allowed only to the extent that they fill voids to reduce water requirements and improve compatibility.

Water

The only requirement for water in RCC mixes is to be free from excessive amounts of alkalis, acids, or organic matter that might inhibit proper strength gain. Most RCC mixes require 150 to 200 lb. of water per cubic yard (89 to 119 Kg/cu.m.) for MSA greater than 2 in. (59mm.) (8).

Admixtures

With little success, air-entraining, as well as water-reducing and air-retarding admixtures have been tried in RCC mixtures, with proportions based on soils principles. Due primarily to the dry consistency and fines content of these mixes, a proper air-void system has not been established at any application rate using normal batching or proportioning procedures (1).

Air-entraining and water-reducing admixtures are introduced into all Japanese RCD mixtures. A water-reducing, set-retarding admixture was used in the RCC for Elk Creek Dam. A relatively high dosage of 14 to 21 oz. per hundredweight (0.87 to 1.3 kg. per 100 Kg.) of portland cement showed good results. Batch water was reduced by 27.5 lb/cu.yd. (16.3 Kg/cu.m.) and the initial design time was reduced from 20 to 10 seconds. Mix design investigations revealed that the use of

the water reducer retarded compressive development at early ages from 7 to 55 days and enhanced the strength gain after 55 days (1).

Properties of RCC

The properties of RCC in place depend on the quality of materials used, mixture proportions, and the degree of compaction or consolidation. Because a wide range of materials and mixes have been used, there are no typical values for RCC properties that fall within a narrow range. RCC properties that are aggregate dependent, such as elastic and thermal properties, are similar to conventional concrete made from the same aggregate.

Because RCC mixes that conform to the soils approach usually contain more than 2 percent air voids, the degree of compaction plays a greater role introducing strength for these mixtures. Increased compaction tends to decrease these voids, producing a denser RCC with a corresponding increase in strength. Poorly-graded aggregate or those within a high percentage of coarse aggregate may have an aggregate matrix that is fully compacted and yet have a relatively high percentage of voids resulting in lower density and strength. Even though there may be a greater volume of voids in a soil approach mix, all aggregate contacts are cemented together (7).

Strength Properties

The significant material properties of hardened RCC include compressive strength, tensile strength, permeability, durability, erosion, volume change, thermal conductivity, drying shrinkage, creep, controlling temperature, and unit weight. Differences between the hardened properties of RCC and conventional concrete are primarily due to differences in mixture proportions, gradings, and voids content.

The aggregate quality, grading, and physical properties have a major influence on the physical properties of conventional concrete. They can be even more important in RCC. Because some RCC mixtures use marginal or inferior aggregates, the range in properties of RCC goes well beyond the range of normal properties for conventional concrete (1).

Compressive Strength - Compressive strength is relatively easy to determine. Many other properties are directly related to the concrete's unconfined compressive strength at a certain age.

The relationship between unit water content and compressive strength is that the compressive strength increases with a reduction in water content as long as the RCC is fully compacted. The maximum compressive strength for a

certain mix is obtained at the optimum water content consistancy with a specified compactive effort for the material. Water contents less than optimum produce lower compressive strength. This indicates that the presence of voids in the mix has greater negative effects on strength than the positive effects of water reduction (6:89).

For most RCC dams, the designer establishes a relatively fixed water content. The designer for a soils approach RCC mix may decide to specify a water content slightly wet or optimum in order to obtain improved workability. Once a water content and a compactive effort are established, the concrete compressive strength depends on the cement or the cement plus pozzolan content. Compressive strength increases with time and the amount of cementitious materials in the mix, see Figure 2.

Tensile Strength - Tensile strength of RCC dams can either be determined by tests to measure direct tension or splitting (indirect) tension. For conventional concrete dams splitting tension tests of cores show strengths averaging about 10 percent of compressive strengths. Direct tension tests of the same cores show tensile strengths at about 5 percent of compressive strengths or about half of splitting tension.

An analysis of RCC mixes for nine dams, after discarding the high and low values to obtain a more representative average, shows splitting tension to average 13 percent of compressive strength. Because of its steep downstream slope, Upper Stillwater is the only RCC dam constructed to date for which the direct tensile strength of the RCC was primary design criteria (7).

Shear Strength - Construction of a concrete dam using RCC methods produces a structure with lift lines every 1 or 2 ft. (0.3 to 0.6 m.) vertically. The shear strength at the compacted lift lines is more important to the designer than the shear strength of the parent material (1).

The break bond shear strength may also be called the peak strength, and the sliding friction denote the residual shear strengths, see Table V.

Permeability

The total seepage through an RCC dam is the sum of the water passing through the material itself plus that through any cracks or joints in the structure.

Impermeability is the single most important property of the RCC mix, and impermeability of RCC can be directly related to its cementitious content. This fact is especially

applicable to RCC mixtures that conform to the concrete approach where the paste exceeds the voids in the aggregate. Therefore, greater cementitious content produce a more watertight paste, which controls the permeability of the RCC material. For soils approach mixes, greater impermeability can be achieved by a combination of increased cementitious content, greater compaction, and sufficient well-graded fine aggregate, all of which reduce voids in the material (4:13).

Durability

The durability of RCC is especially important if the material is exposed to weather or severe hydraulic forces.

Experiences have shown that RCC made with a substantial amount of clayey fines will check and crack when subjects to alternating wet-dry cycles. RCC made with nonplastic fines or with no fines has shown no deterioration from wetting and drying (1).

Freeze-Thaw Resistance - Because proper air entrainment in RCC is generally not attainable with admixtures, freeze-thaw resistance must come from its strength and impermeability. High-strength RCC mixes with low permeabilities have greater freeze-thaw resistance than lean, low-strength mixes.

Freeze-thaw resistance in a dam is of greatest concern for horizontal surfaces or other surfaces exposed to freeze-thaw cycles while wet. High-strength exposed RCC pavements have shown very good freeze-thaw resistance after being in service in British Columbia, Canada, for more than 10 years.

The freeze-thaw resistance of actual RCC pavements and dams is better than would be predicted by laboratory tests or test sections. Most RCC mixes have shown poor freeze-thaw resistance in the laboratory when subjected to the severe ASTM C566 rapid freezing and thawing test (4).

If RCC mixes are designed for durability using freeze-thaw weight loss test and criteria as develop for soil-cement, acceptable freeze-thaw durability can be expected. The amount of cement to produce a sufficiently durable RCC mix may be greater than that required to achieve other properties such as compressive strength. Little or no pozzolan replacement for cement is advised where horizontal RCC surfaces will be exposed to early freeze-thaw cycles while wet because high early strength is required under these conditions (1).

Erosion or Abrasion Resistance - Resistance of RCC to freezing and thawing has been very good in the fields and has also been acceptable in modified tests simulating natural surface frost.

However, RCC subject to ASTM C 666, Procedure A, typically performs very poorly. Large blocks of the Lost Creek test fill material totally deteriorated when subjected to the combined action of salt water, wet-dry cycles, and freezing and thawing at Treat Island, Maine. It appears that, except for very severe exposure conditions, RCC can adequately resist natural freezing and thawing (5).

The erosion-resistance properties of RCC have been demonstrated in many projects. The most notable are the spillway rehabilitation at Tarbela Dam, the spillway for North Fork of the Toutle River derbies retention dam, and the Kerrville ponding dam (5).

Volume Change

In any massive concrete structure, the understanding of and the design for volume changes is necessary to minimize uncontrolled cracking. The reduction of volume could be due to thermal, or drying shrinkage, or creep.

Thermal Properties - The RCC properties that may be needed in a thermal analysis include specific heat, diffusivity, conductivity, and coefficient of thermal expansion, together with tensile-capacity. Typical thermal propertied are shown in Figure 3. Thermal properties are mainly aggregate dependent, so RCC and conventional concrete made from the same aggregate source have similar values (7).

Drying Shrinkage - Increases in moisture cause concrete to expand and decreases in moisture cause it to shrink. In the cement hydration process, water combines with the cement so the basic process is one of moisture loss or shrinkage.

In any concrete mix, it is only the paste that shrinks. So for a constant cementitious content, the drying shrinkage rate depends primarily on the amount of water in the mix. Because RCC requires less water and cement than conventional concrete, RCC shrinks less in the hydration process.

Creep - When concrete is subject to a load, the deformation caused can be divided into an immediate deformation such as, an elastic strain and a time-dependent compressive deformation called creep. Creep begins immediately and continues at a decreasing rate for as long as the load remains on the concrete.

Creep in RCC is a function of the aggregate and RCC strength. Aggregates that produce low modulus of elasticity concrete will produce a high creep value. For RCC dams, a high creep value or the ability to relieve a sustained stress is usually desirable. Compressive stresses in gravity dams are generally low; however, and creep is not usually a major concern to dam designers (1:16).

Unit Weight

The unit weight of concrete depends primarily on the specific gravity of the aggregate and the amount of voids in the RCC mass. There are few entrained-air voids in RCC, and compaction reduces that number further. This means that there are more solids in a unit of volume of RCC and, therefore, its unit weight is generally greater than conventional concrete made with aggregate of the same specific gravity. Unit weights greater than 150 lb/cu.ft. (2400 Kg/cu.m.) are common for RCC (8).

Controlling Temperature Rise

The maximum internal temperature raise can be limited either by reducing the temperature rise of the RCC mixture or by reducing the placing temperature. Consistent with strength and permeability requirements, the use of low-heat cement, a reduction in total cementitious material, and an increase in pozzolan percentage by winter production or water spray, introducing ice to satisfy mixing water requirements, or placing the RCC at night are methods that have been used to reduce the placing temperature of the RCC mixture. Night placement also aids with minimizing radiant heat effects on the exposed upper surface.

Dam sites that have low annual average temperature, such as high mountain locations, provide a greater potential temperature drop. Designers of RCC dams at such locations may desire to limit concrete placing temperature to as low as 50 degree F. (10 degree C.). This was the case at Upper Stillwater Dam, located at about 8000 ft. (2450 m.) above sea level, where the annual average temperature is only 37 degree F. (3 degree C.). The 50 degree F. (10 degree C.) RCC placing limitation was met almost all the time by using ice as mixing water. With no-slump RCC there is less mixing water than in conventional concrete, so expensive liquid nitrogen had to be introduced into the mixers to cool the RCC (4).

Forms

Large surface areas that are not horizontal can be shaped to most desired slopes and configurations, but special consideration must be given to anchorages, appearance, and technique.

Handling and raising conventional formwork may become the limiting factor in an RCC mass-production situation. Near the top of a dam, where the volume of RCC per lift is low and the the form area for upstream and downstream faces is relatively large, it typically takes more time to set and move the forms than it takes to place the RCC.

These are some examples of types of forms used in constructing dams:

* Middle Fork and Glesville Dams used straight forming.
* Willow Creek Dam used precast panels.
* Elk Creek Dam used upstream face. They had a concern over RCC, and slipform curb needed a good bond. Slipform was not allowed.
* Site-specific conditions allow contractors options on methods to complete the job.
* Extruded forms are good on the downstream face for producing a stepped spillway.

<u>Time Limitations on Operations</u>

There are different types of time limitations on operations for RCC dams and these are:

* Haul time (time periods needed to avoid compacting or stiffening of materials) ; Upper Stillwater Dam specifies 15 minutes; Elk Creek dam specifies 30 minutes.
* Total elapsed time (water in cement to completed rolling); 1.5 hours in Japan (using retarder); 45 minutes at Upper Stillwater Dam.

* Wind velocity, temperature, and humidity affect time. Loss in quality are avoided by controlling time.
* When time frames are not met, the inspector must decide on the disposition of the material reject or continue. Specifications should be simple. Total time elapsed is not broken out by mixing, hauling, or compacting activities.
* Consensus was a 45-minute threshold. Times ranged from 30 to 60 minutes (8:45-63).

CHAPTER IV

DATA AND PERFORMANCE OF COMPLETED ROLLER COMPACTED CONCRETE DAMS

Data on Completed RCC Dams

The economic advantage of RCC combined with the long-term safety record of concrete dams have led to rapid acceptance of RCC dams throughout the world. By the end of 1989, data were available on more than 45 RCC dams greater than 50 ft. (15m.) high or containing more than 13,000 cu.yd. (10,000 cu.m.) of RCC that had been completed in 12 countries. RCC dams have been completed on all six continents: North America has 13; Asia, 13; Africa, 7; Europe, 6; Australia, 4; and South America, 2; see Table VI (8).

In addition, seven major cofferdams have been constructed by using the RCC method and are listed in Table VI. They are listed separately with less design information due to the relatively short design life for these structures. Nevertheless, they are important dams and can contain large volumes of RCC. In fact, the largest volumes of RCC in dams at the planning stage are for the cofferdams for the proposed Three Gorges project in China. If built, the 312 ft. (95 m.) high longitudinal cofferdam requires an estimated 2,220,000

cu.yd. (1,720,000 cu.m.), while the 279 ft. (85 m.) high third-stage transverse cofferdam will contain 1,860,000 cu.yd. (1,420,000 cu.m.) of RCC (8).

Firsts and Records for RCC Dams

The following is a historical review of RCC dams, including a list of the first dams built in each continent and country, the first RCC use for certain aspects of a dam or dam project, first design and construction applications in an RCC dam, first performance test, and miscellaneous records for RCC dams:

First RCC Dams by Location (Year RCC Completed)

1. Asia:
   a. Japan, Shimajigawa (1980)
   b. China, Kenghou (1986)
   c. Turkey, Sir Cofferdam (1987)

2. North America:
   a. United States, Willow Creek (1982)
   b. Mexico, La Manzanialla (1987)

3. Australia:
   a. Copperfield (1984)

4. Europe:
   a. Spain, Castilblanco de los Arroyas (1985)
   b. France, Les Olivettes (1987)
   c. USSR, Tashkumir (1988)

5. Africa:
   a. South Africa, DeMist Kraal Diversion (1986)
   b. Morocco, Ain Al Koreima (1988)

6. South America:
   a. Brazil, Saco de Nova Olinda (1986)
   b. Argentina, Urugaui (1989) (8).

First Specific RCC Application in a Dam Project

1. Gravity retaining wall: Yale Hydroelectric project, United States, 1952.

2. Central core in embankment cofferdam: Shihmen dam, Taiwan, 1960.

3. Foundation build up: Cochiti Dam, United States, 1968.

4. Emergency repairs: Tarbela Dam, Pakistan, 1974.

5. Overflow structure: Chena Dam, United States, 1978.

6. Cap for embankment cofferdam: Revelstoke, Dam Canada, 1979

7. Main portion of cofferdam: Tarbela Dam, Pakistan, 1980.

8. Main portion of gravity dam, RCD method: Shimajigawa, Japan, 1980.

9. Rehabilitate overflow section (timber crip dam): Ocoee No. 2 Dam, United States, 1980.

10. Entire gravity dam, lean RCC dam: Willow Creek Dam, United States, 1984.

11. Spillway in a new earth dam: Dolet Hills Dam, United States, 1984.

12. High-paste RCC dam: Upper Stillwater Dam, United States, 1985 (8).

First Design in an RCC Dam Project

1. Design concept:
   a. Similar to conventionally-placed dam: Shimajigawa Dam, Japan, 1980.
   b. Exposed RCC downstream face and spillway: Willow Creek Dam, United States, 1982.
   c. Design for zero cohesion in shear: Copperfield Dam, Australia, 1984.

2. Upstream face design:
   a. Waterstopped transverse joints in conventional concrete face and transverse joints in RCC: Shimjigawa, Japan, 1980.
   b. RCC placed against fill: Tarbela dam cofferdam, Pakistan, 1980.
   c. Precast concrete forms, no transverse joints in RCC: Willow Creek Dam, United States, 1984.
   d. Crack inducers in conventional concrete face: Middle Fork Dam, United States, 1984.
   e. Plastic-membrane-faced precast concrete panels: Winchester Dam, United States, 1984.
   f. Unformed RCC on sloped face: Bucca Weir, Australia, 1985.
   g. Horizontal slip-formed elements: Upper Stillwater Dam, United States, 1985.
   h. Asphalt mortar behind precast concrete panels: Kengkou, China, 1986.
   i. Expansive cement concrete: Longmentan, China, 1989.
   j. Reinforced concrete and waterstopped joints: Stacy Dam Spillway, United States, 1989.

3. Foundation:
   a. Nonrock foundation: Cedar Falls dam, United States, 1986.
   b. On RCC mat foundation: Lower Chase Creek Dam, United States, 1987.

4. Dam Shape:
   a. Curved in plan (partial): Saco Dam de Nova Olinda, Brazil, 1986.
   b. Curved gravity dam: Knellpoort Dam, South Africa, 1988 (8).

5. Construction methods or features:
   a. Bedding mortar on every lift: Shimajigawa Dam, Japan, 1980.
   b. Inclined railway transport of RCC: Tamagawa Dam, Japan, 1983.
   c. Conveyor transport of RCC and stepped conventional concrete downstream face: Middle Fork Dam, United States, 1984.
   d. Special vibrating device for compacting stepped RCC downstream face: Les Olivettes Dam, France, 1987.

First Performance Test for an RCC Dam

a. Reservoir filled: Shimajigawa, Japan, 1981.

b. Overtopped after construction: Kerrville Ponding Dam, United States, 1985.

c. Overtopped during construction: Craigbourne Dam, Australia, 1986.

Miscellaneous Records for RCC Dams

a. Highest: Tamagawa Dam, Japan, 328ft. (100 m.).

b. Longest: Pirica Dam, Japan, 2986 ft. (910 m.).

c. Largest RCC volume: Upper Stillwater Dam, United States, 1.471 million cu.yd. (1.125 million cu.m.).

d. Greatest RCC volume placed in 24-hour period, dam repairs: Tarbela Dam, Pakistan, 23,500 cu.yd. (18,000 cu.m.), 1975.

e. Greatest RCC volume placed in 24-hour period in gravity dam: Elk Creek Dam, United States, 12,392 cu.yd. (9474 cu.m.) 1987.

f. First RCC dam constructed in one day: Dryden Weir, United States, 1986.

g. Largest-capacity reservoir: Uruguai, Argentina, 950,000 acre-ft. (1175 million cu.m.) (8).

Performance of Completed RCC Dams

It is important for designers to obtain accurate records or reports of performance of dams in service so as to compare actual with predicted performance and to learn from unanticipated or unsatisfactory performance.

The designers of RCC dams should be complimented on the information that they published during their studies of the performance of their dams. While most of the results have been positive, there have been some negatives, especially with respect to seepage, and its related phenomena (4).

Structural Performance

For the dams which have been subjected to full reservoir load, there have been no failures or unanticipated movements or deformations in the RCC structures.

There is no record of an RCC dam having been shaken by a significant earthquake to date, eventhough seven RCC dams have been completed in Japan and others are located in seismically active areas (8:269).

Seepage

To evaluate overall seepage through or around an RCC dam and its foundation properly, information on the designed seepage collection and seepage control system is listed in Table VII for various types of dams.

The measured seepage is an indication of the performance of the designed seepage control system. the total measured seepage can consist of the following items: (1) leakage through joints and cracks; (2) seepage through a conventional

concrete face if used and the RCC materials itself; and (3) seepage through foundation materials. The water passing through the RCC depends upon the void characteristics of the mixture in addition to construction-related voids, such as those produced by segregation of large aggregate at or near the bottom of the lift and possibly inadequate compaction of a lift.

Most measurements of seepage have been from weirs located in the gallery, at the downstream gallery entrance tunnel, or at a point in the waterway downstream of the dam. Some seepage that may proceed through the dam has been measured by weirs at the intersection of the dam with the abutment just prior to the water being deposited into the stilling basin or other waterway (8).

Lessons Learned From Seepage and Seepage-Related Phenomena

Seepage and seepage-related phenomena from early RCC dams have taught designers a number of lessons:

* Initial seepage volumes from early lean RCC dams were in some cases more than anticipated.

* The amount of seepage through the RCC has been reduced considerably with time due to external effects such as siltation into voids and natural internal autogenous healing due to production of additional concrete gel and calcification after contact with seepage water.

* Where measured seepage has increased significantly, it is usually due to leakage passing through a newly formed crack.

* Side effects of seepage such as visual wet spots, leaching, or passing reservoir-induced gases through the dam have generally created more public concern than the total seepage through the dam and foundation.

* As expected, seepage is greater with increased head, with increased wetted surface area, and during cold weather when the RCC mass shrinks, thus creating greater crack widths.

* RCC dams can be designed to have equal seepage to dams constructed of conventionally placed concrete.

* Designs incorporating conventional concrete faces with water-stopped joints and membrane-faced precast concrete panels have proved to provide a high level of watertightness.

* Leakage through cracks can be repaired more efficiently than seepage through the entire RCC mass.

* The permeability of the RCC material can be improved with higher cementitious contents, higher sand contents, and construction methods to minimize voids in the compacted mass concrete.

* Construction control is extremely important in ensuring that the planned design is executed in a manner to minimize seepage. Special attention should be placed on installing waterstops and applying sealants at planned joints or grooves.

* The content of the dam with its base foundation or abutments as with any dam is a prime potential seepage path and care must be taken to ensure this intersection has a high degree of watertightness (8:283).

Cracking

Cracking in any nonreinforced concrete dam can be expected. From a design standpoint, joints or crack inducers may be installed in the dam to help control cracking or the dam can be constructed with no relief. Cracks that extend below the waterline and have sufficient width to pass water are of greatest concern to dam designers. Therefore, leakage and cracking performance are directly related. Cracking in gravity dams are generally vertical and transverse to the dam's axis and pose no threat to the structural stability of the dam (6).

Cracking Case Studies

Information on cracking from the following RCC dams provide considerable insight into the information of cracks and their repair.

Shimigawa - Detailed investigation of the dam which was constructed with full-section contraction joints spaced at 49 ft. (15 m.) revealed no cracking in the upstream face, the downstream faces, or in the gallery which has caused water leakage. The maximum opening of the joints was 0.20 in. (5 mm.), and the mean opening width was 0.11 in. (2.7 mm.) (5).

Willow Creek Dam - Narrow hairline cracks have been noticed in the exposed RCC at the crest and within the gallery. These cracks are closely spaced and not of sufficient width to pass any water to the downstream face. In the gallery roof, however, there is evidence of greater water leakage at the location of the cracks (7)..

Copper Dam, Craigbourne Dam, and Bucca Dam - The experience gained at these three Australian dams provides an insight into the temperature drop required to cause cracking, taking into account tensile capacity of the RCC mixes used. Crack widths were also measured.

At Copperfield, a single transverse uncontrolled crack developed through the spillway as a result of a temperature of 59 degree F. (35 deg. C.). Leakage increased following the formation of this crack and then naturally diminished thereafter (8).

No cracking has been identified after one year at Craigborune Dam. At this location RCC temperature peaked at 68 to 70 degree F. (20 to 21 deg. C.) and were expected to stabilize at 54 to 57 degree F. (12 to 14 deg. C.). Thus the maximum temperature drop of 16 degree F. (9 deg. C.) was not expected to cause thermal cracking (5).

Delays at Bucca Weir pushed construction into the summer months, and RCC temperatures peaked at 113 degree F. (45 deg. C.) or about 18 degree F. (10 deg. C.) more than anticipated in the design. After the peak temperature dropped 22 degree F. (12 deg.C.), three transverse, nearly vertical cracks developed through the section at approximately the mid and third points, and the transverse contraction control joints spaced at 381 ft. (116 m.) opened. The width of the opened joint was about 0.04 to 0.06 in. (1 to 1.5 mm.) through the RCC (5).

Galesville Dam - A delay in the start of RCC placement contributed to formation of seven cracks which are the primary cause of the leakage at Galesville. The uppermost lifts of RCC were placed during the hottest part of the year. The cracking occurred when unusually cold weather hit 60 days later and caused rapid cooling of the concrete. The delay in construction caused the peak temperature to be more than 21 degree F. (12 deg. C.) greater than originally predicted due to the higher temperatures of both the RCC and ambient air. Capping the crest of the dam with conventional concrete on three sides contributed to the heat rise in this area.

The cracking occurred when there was a differential of measured temperature between the downstream face and interior mass of about 28 degree F. (16 deg. C.). The cracks started at the crest and extended vertically down both faces. The first crack noticed was located near the right abutment angled from the vertical so that it intercepted the entrance admit to the gallery, a hole which provided the least resistance to the thermally induced tensile stresses (6).

Cedar Falls Dam - An error in control of cement fed the mixing plant produced an RCC mix containing 320 lb/cu.yd. (190 Kg/cu.m.) of cement plus 155 lb/cu.yd. (92 Kg/cu.m.) of fly ash (5).

Calculations indicated the richer mix would produce a 20 degree F. (11 deg. C.) greater temperature rise than originally anticipated, which was confirmed by sensors within the dam. A maximum temperature of 120 degree F. (49 deg. C.) was actually reached compared to the predicted 100 degree F. (38 deg.C.) for the specified mixture. An inspection of the completed structure indicated the higher internal temperature in the RCC produced no more cracking than originally anticipated in the conventional concrete faces (5).

Upper Stillwater Dam - As the dam being constructed with horizontal slip-formed elements of conventional nonreinforced concrete on both the upstream and downstream faces, narrow vertical cracks spaced 20 to 30 ft. (6 to 9 m.) apart were noticed in the concrete surface within two days after placement. These shrinkage-related cracks were limited to the facing elements and did not extend into the RCC mass.

In the original design, cracking was predicted. However, higher than anticipated peak temperatures near the top of the dam produced cracking deeper into the mass than expected. The spacing between cracks was greater than anticipated, which resulted in fewer but wider cracks in the 2673 ft. (815 m.) structure (8).

While the reservoir was filling, the single major crack was reportedly noticed first at the base of the dam and then propagated upward to the crest. The external temperature restraint condition best explains the formation of this crack, but it appears to have been triggered by a slight downstream movement in the foundation (8).

Elk Creek Dam - Actual peak temperatures during construction of the dam in the spring of 1987 were significantly higher than predicted in the Corps of Engineers computer program. The higher temperature was due to both higher ambient air and RCC

placing temperature than had been put into the program. These factors, plus a belief that finite-element analysis does not accurately predict the effect of radiant solar heat into the RCC surface, produced a peak temperature of 101.6 degree F. (38.7 deg. C.) on the left side of outlet works compared to a computer-projected peak of 75 degree F.(24 deg. C). The difference on the right side of the outlet works was not as pronounced, with an actual 88.3 degree F.(31.3 deg. C.) peak compared to the same maximum computer project temperature at the time of this RCC placement. Six months after placement, the high RCC temperature had caused no noticeable problems. The contraction joints installed in the upstream face at a spacing up to 300 ft. (91 m.) had opened up approximately 0.06 in. (1.5 mm.) (8).

Summary of Cracking Performance

From the performance of the RCC dams in service, the following conclusions, which are mostly considered positive and are self-evident, can be made:

1. There is less potential for cracking in RCC than in conventional concrete due to less contraction of the RCC mass combined with generally lower elastic modules and higher creep rates for RCC. The lesser amount of shrinkage is due to lower water and cementitious contents in the RCC mixtures as compared to conventionally placed concrete.

2. Most cracking in RCC dams can be attributed to thermally induced stresses. Cracking occurs when thermal stress exceeds the tensile capacity of the concrete. Cracks can occur with a temperature drop of as little as 20 degree F (11 deg. C) from the peak RCC temperature for lean weaker mixes to as much as 36 degree F. (20 deg. C.) for stronger mixes. Cracks in conventional concrete faces are also influenced by drying shrinkage stresses.

3. The spacing between cracks apparently depends upon the tensile strength of the RCC, with greater spacing noticed in dams constructed of high-strength RCC such as, Upper Stillwater Dam, than those of lean lower-strength mixes.

4. Full-section transverse contraction joints with upstream water stops, and drain holes are an effective means of controlling cracking through the entire RCC dam. When the spacing between joints is too great, cracking will occur between the joints.

5. Cracks invariably will occur in intentionally planned transverse contraction joints or at a point of reduced dam section where the overall tensile resistance of the section is less. This crack location can be at a reentrant angle in the foundation rock, producing a stress concentration, through a central spillway section, at a transverse entrance admit, or at a planned groove in the conventional concrete faces.

6. Cracks in RCC dams are generally vertical, transverse to the dam axis, and pose no problem to the structure stability of the gravity section. The proceeding conclusions provide an insight into the potential spacing and location of transverse contraction joints through all or a portion of an RCC dam if desired.

7. Initial cracking can usually be attributed to the internal temperature restraint condition where the temperature at the center of the concrete mass is greater than at the exposed faces of the dam. These cracks invariably start at the dam's crest, where the section of the dam is at a minimum and there is a greater exposed surface area to cool. Then the cracks propagate down both upstream and downstream faces.

8. Greater cracking than initially predicted by thermal analysis has occurred due to delays in the construction schedule, forcing placement during warmer weather, thus producing higher peak temperatures in the concrete than anticipated. Also, the thermal analysis being used does not appear to properly account for radiant heat effectiveness exposed RCC surfaces.

9. Cracking in conventional concrete faces can be effectively controlled by either joints or crack inducers formed in the concrete. Horizontal spacing of vertical-face-inducer grooves 1.5 to 3 in. deep (38 to 75 mm.) in a face that averages 1.5 ft. (0.46 m.) thick have ranged from 10 to 16 ft. (3 to 5 m.).

10. Cracks may be sealed or repaired by a variety of materials and methods. Sealants formulated from polyurethane resins and polysulfides have been used to the greatest degree to date. Crack repair with the reservoir lowered is the most efficient situation, but underwater crack-sealing methods have been used, including dumped pelletized bentonite and use of quick-set cement by divers (4).

CHAPTER V

MIXING AND DELIVERY OF ROLLER COMPACTED CONCRETE

Introduction

Mixing methods and delivery of RCC materials are critical to the success of roller compacted concrete (RCC). They include issues ranging from strength, variability, and joint integrity to productablity, efficiency, schedule, and profit. Mixing options include pugmills and rotating drums, both of which may be "batch" or " continuous" mixing plants. Delivery systems include haul vehicles, traveling hoppers, chutes, conveyors, and combinations of these systems.

Design/Construction Relationship

Design and construction are very interrelated in the successful completion of an RCC project. Equipment selection should consider quality, economics, schedule, risk, and practicality. The designer should specify the mixing and delivery requirements necessary for the design to be successful during construction and later during operation of the project. The contractor should understand that this equipment and the construction procedures directly influence the achievable quality of RCC, and that these options may be limited by design requirements.

In order to assure that the job is properly priced and that the equipment will provide the needed quality and speed of construction, the designer should thoroughly evaluate and specify equipment requirements. By doing so, less risk, fewer claims, lower contingencies, and more responsive bids can be expected. This may involve specifying the rate of mixing and delivery that must be achieved during different time periods, when placement must start, the maximum and minimum numbers of lifts to be placed per day, and when the aggregate should be produced. The specifications may require that only certain methods or types of mixing and delivery equipment will be allowed.

Thermal stresses due to hydration are an important design consideration in dams. Conventional concrete dams can cool the mix with ice and use refrigeration pipes to help control thermal stresses. These methods are not very effective in most RCC, but controlling the rate of placement is. The time of year when placing is done and aggregates are produced is important. Sometimes, high internal thermal stresses can be avoided only by placing during very limited time periods and at certain rates of production. However, the required mixing and placing capacity should consider inefficiencies for confined work areas, rain, and obstacles such as galleries.

Contractors should realize that they can not normally extend the placing time later into the year thinking that the temperature at the time of placement is the only controlling factor. The length of time between when peak temperatures are reached and when cooling begins, as well as the rate of cooling, are critical factors.

Another important part of design is lift joint quality, both for structural stability and watertightness. The speed of construction, temperature, and potential for contamination or damage to lift surfaces all effect joint quality. If a joint with good bond, friction, and watertightness is needed, delivery methods that tend to damage the surface, result in unplanned delays, or extend the exposure time of the surfaces should not be permitted.

Evaluation of weather and its effect on quality for various methods and rates of placement is another important factor to the designer. If rain cannot be avoided, using trucks on the lift surfaces could cause enough damage to reduce the joint quality below acceptable levels for the design. For a given design, schedule, and tolerable risk a conveyor system may be the only acceptable delivery method. A different design, location, or foundation may be suited for both conveyor and truck delivery.

Mixture and Strength Variability

Another design concern, which depends on equipment, is variability of the mix. An "overdesign" factor is used to account for variability. The designer must address how much variability is expected and how much overdesign to apply. Because mixing and delivery systems are major factors that contribute to variability, the designer is put in a position of evaluating various options for mixing and delivery, and then requiring equipment consistent with the design criteria.

The mixer is the first major piece of equipment responsible for variability, but it is only a part of the system. Quality and variability at the placement is the issue, not just variability at the mixer. Testing should be done on the material after it has been placed and spread. If the mixer does a good job of blending all the ingredients, drying occurs in trucks at transfer points, on a poorly designed conveyor or while spreading, the end product can have unacceptable variability. On the other hand, if a mixer does a poor job of blending ingredients, but a well designed conveyor with efficient transfers provides additional mixing, the end result may be acceptable (6).

Mixture Equipment

Before mixing methods are selected, consideration should be given to aggregate size, shape, gradation, moisture content, hardness, and a number of size groups; methods of feeding the mixer; available space; erection requirements; other uses of the plant on this and subsequent projects; availability of spare parts; the cement and pozzolan contents; wetness of the mix; and variablity. Equipment capable of handling RCC paving mixes with small aggregates may not be capable of handling larger dam aggregates. Mixers suited for "wet" RCC or conventional concrete do not necessarily provide adequate mixing, productivity, or operate without excessive downtime with drier RCC mixes. Mixers suitable for cement treated base do not necessarily perform adequately with RCC. It is a mistake to assume that expensive drum mixers that have proven themselves on paving and/or mass concrete projects with conventional concrete will be suited to RCC. Another mistake is assuming that pugmills, good for asphalt, will be able to provide similar uniformity and productivity with RCC. A further mistake is assuming the more complicated and expensive a plant is, with more electronic controls, the better it will perform.

At Willow Creek Dam the contractor proposed using a pugmill mixer instead of the specified drum mixer, but without pugmill experience the engineer did not allow it. This provided a valuable learning experience in early RCC. A twin tilting drum paving plant in rebuilt conditions was used.

Middle Fork and Stagecoach Dams used a large drum mixer capable of making good quality conventional concrete. Neither project justified complete mixer tests to establish the degree of uniformality of the fresh RCC. A review of the strength data after the fact indicated that the mixer performed poorly.

Drum mixers at Upper Stillwater Dam, used in combination with pugmill mixers, had low productivity and a problem with build-up that eventually led to lining with plastic.

Trigomil Dam originally followed the same early thinking of Willow Creek Dam believing that conventional batch type drum mixers would be a safe and reliable way to produce RCC. After their initial use, the contractor replaced the batch plant with a continuous mix pugmill.

Saco and Urugua-I Dams used continuous mix pugmills that had a good reputation for asphalt, lime stabilized base, and cement treated base. They did not have proven experience of uniformity, productivity, and dependability with relatively low cement content and dry RCC mixes containing large coarse aggregates.

There are numerous examples of efficient and reliable RCC mix plants where equipment specifically designed to handle RCC was used, see Figure 3. Plants of this type with a proven experience record are economically available, and easy to ship and erect. These plants are primarily batch type pugmills typical in Japan RCD, and continuous mix pugmills such as those developed in Australia. Two of the Australian type pugmills were shipped to Honduras and used on Conception Dams. They were operated with minimal downtime and wear (6).

Weight and Volume Proportions

Both weight and volume proportioning have been used with RCC mixers. Both methods can provide adequate control and good uniformity. The important issue is proper calibration and maintenance of that calibration. Volumetric control with continuous mixing has been used successfully on more RCC projects than any other procedure. After initial reluctance in the U.S.A., this method has been well accepted.

Specific Drum Mixer Comments

This procedure is not recommended for future projects unless there are special circumstances. If it is used, attention should be given to wear of the interior blades or fins, the exact sequence of loading the mixer, build-up within

the mixer, limiting the amount of materials in the drum to quantities that tests show can be adequately mixed, and testing the mix to assure that all ingredients including cement and fines are uniformly distributed (6).

Transit trucks do a poor job of mixing and discharging RCC of all compositions. When there is no other option and some compromise in the mix quality can be tolerated, the mix can first be discharged into a dump truck so that it spreads over the bed in layers. Typically, the first part of the load from the transit truck will be coarse and the last portion will be sand with higher cement contents (7).

Continuous mix drums have been used successfully for high production RCC, see Figure 4. These were permanent mixers designed by a major contractor for large aggregate dry RCC at Tarbela Dam. The purpose of RCC was primarily non-structural, and it was used in very large masses where low stresses allowed less than perfection. Still, the equipment worked well and offered another option.

Specific Pugmill Mixer Comments

Both "batch" and "continuous" mix pugmills have a horizontal box that is the mixing chamber with two parallel horizontal rotating shafts onto which a series of mixing paddles are

attached. The batch type plant fills the chamber with all of the material for given volume, mixes it, and then discharges it out the bottom. The conventional batch mixers have been used in all the placements to date, except Tarbela. Mixers are capable of mixing 3 in. (76 mm.) and 6 in. (152 mm.) maximum aggregates have no problem in mixing the no-slump consistency and larger aggregate volumes associated with RCC, although a longer mixing time may be required than with conventional concrete (6).

Variations in free moisture on the aggregates can be particularly troublesome in initial batches because of the low water requirements of the mix. Most operators make the mistake of overestimating free moisture and provide too little water in the initial mixes. This is particularly undesirable because most initial mixes will be used for covering construction joints and should be on the wet side for adequate bond. It is much better to start with a wet batch and reduce batch water in subsequent batches to achieve the desired consistency (12).

Compaction difficulties of the wet batch can be reduced or eliminated by spreading in a thinner layer. Excess water rises in subsequent layer placements, thereby eliminating any strength concerns for the wet batch.

The continuous type mixer continuously introduces all materials into one end of the chamber at the required propo-

rtions. The paddles then mix the material as they direct it to the discharge end of the chamber. Continuous mixers have not been widely used in the United States, but have been and are being successfully used in Great Britain, and elsewhere. They are particularly adapted to high volume output, such as mechanized placement of continuous pavement slabs. The principal of utilizing RCC as a mechanized placement system for pavement would be similar to placing it in layers or lifts during the construction of a dam. Principal advantages of continuous mixers are the elimination of batching time from the production time cycle and the significantly lower cost of plant in relation to the output capacity. These are important factors when considering the productive requirements of large projects where the use of RCC would permit the placement of large volumes of concrete in short periods of time, such as, in the order of a million cu.yd. (3.4 million cy.m.) in 3 months (7).

Retention time in continuous mix plants may only be 5 to 10 seconds. If additional mixing is needed, some paddles can be reversed to cause the material to throw back against the flow path, the angle of the paddles can be changed, an end baffle can be added so that the volume of the mix chamber is increased, or a longer chamber may be needed.

In general, pugmills perform best when they are operated at or near their capacity. Slowing down the rate of flow decreases the volume of material in the chamber and degree of agitation. The first one or two cubic yards through a continuous mix pugmill should be wasted at the start of production. Every effort should be made to then keep a continuous operation.

The corners of the mixing chamber will fill with RCC and/or aggregates as soon as material starts flowing through a clean mixing chamber. This material will pack into place and stay there. It does not need to be removed and it will not effect the quality of the mix. It acts as a fillet that could have been a part of the chamber design. Water requirements in most RCC mixes are very low. This may require smaller water lines, recirculating piping, or restructures if the mixer was designed to handle larger flows and cannot accurately meter low flows. A common way to introduce water into the mixer is with two longitudinal pipes above the mixing chamber that have small holes for the water to run out. It drops into the material being mixed. If the holes are large and/or the water addition is very small, the water may only run out of one pipe on one side of the chamber. Using smaller holes and turning the pipes so they are transverse to the axis of the mixing chamber has helped this situation.

Cement and pozzolan feeders need special attention for low cement content mixes, or low production rates, and for high cement contents or production rates. High production and cementitious contents use cement at an unusually fast rate. If on-site storage consists of only one silo, trucks must be continually filling it without interruption. The flow of cement from the silo site into the cement feeder should be the same with both a full silo and a nearly empty silo, but the fluid flow of cement may act differently when the silo gets to a certain level.

Most RCC projects now require proven continous pugmills. Batch type drum mixers are typically being disallowed. This trend is expected to continue, with batch type high volume pugmills specifically designed for RCC also being used where they are available. Future projects may find this to be a practical and economical option (4).

Delivery

A variety of delivery methods have been used or attempted with RCC. These include dozing, front end loaders, bottom and end dump trucks, highway and off highway equipment, scrapers, traveling hoppers, chutes, inclined gravity pipes, elephant trunks, various conveyor belt systems, and combinations of these methods.

Dozing

Dozers should not be used as a primary method of delivery. RCC should only be pushed relatively short distances by bulldozer. The practical distance that can be achieved without drying or segregation depends on the properties of the mix, the quality required in place, the skill of the operator, and the speed of production. In general this ranges from 10 to 60 feet (4). Because of damage caused by its tracks, dozers should only operate on RCC that has not been compacted.

Front End Loaders

Front end loaders can be used to deliver small quantities of RCC distances on the order about 20 to 200 ft. This is useful for reaching isolated ares that are not accessible by trucks, or with a fixed conveyor system, but it should not normally be used as a primary method of delivery. An exception

might be a low dam that has a small volume, a short haul distance, an adequate room, and minimal requirements for joint quality.

Disadvantages include low productivity, damage from the tires, contamination due to spillage, and interference with other equipment. Some designers believe that RCC becomes compacted under the tires prior to rolling, and the roller later rides on these compacted ridges without giving enough compactive efforts to materials between the tire paths.

Trucks

Trucks can be highway or off-highway, and bottom or end dumps. They may be used to deliver RCC from the mixer to the dam, and then over the lift surface. They may be used just on the lift surface with a conveyor delivering RCC to them, or they may be used to bring materials to a conveyor that reaches out onto the dam from off the dam.

Damages caused by the truck tires, and contamination from spillage are significant problems that have been blamed as the principal cause of seepage, lift joint separation; and thus reduced stability in a number of completed dams. This method of delivery can be used, but the consequences have often been reduced performance, segregation, claims, increased costs, delays, difficult relations between design and construction personnel, and compromised in-place quality (7).

There are two main ways that hidden costs result from truck deliveries. One is if the designer compensates for expected problems by being more conservative in the design and by modifying the mix to include more cement, pozzolan, water, and possibly retarder. The other hidden cost is in cleaning necessary to properly prepare the surface. Regardless of what is specified, contractors do not appreciate how time consuming and expensive cleaning can be. For example, delays come from waiting to clean surfaces damaged by the trucks.

Segregation occurs when dump trucks are filled and coarse aggregates roll down the sides of the pile. During the drop onto the lift surface, coarse aggregates tend to roll out first, often under the rest of the pile where it is hidden from view and can result in a poor quality joint interface. By dumping the mix onto the uncompacted material of the lift being advanced instead of onto the previously compacted layer, the dozer can provide remixing as it pushes the RCC forward.

Bottom dump trucks have the benefit of some spreading action while dumping. These trucks are not effective, in most dam construction, because they lack maneuverability. They have been useful in long narrow areas including the top of the dams when the truck can drive onto one end and off the other without turning. End dumps have often been used in the upper non-overflow portions of dams that are separated by a spillway, but productions are extremely slow.

Scrapers

Despite their size, scrapers are remarkably maneuverable, and can be backed into tight areas by a skilled operator. They carry large volumes and deposit with a spreading action at about the thickness of a lift. Their tires trend to cause less damage than truck tires, but like trucks, they cause surface damages and contaminations by spillage.

Hoppers

Hoppers or delivery bins traveling on rails from the plant to the lift surface can minimize some of the haul vehicles problems between the mixer and the dam. Depending on the size of the structure, time constraints, terrain and cost, they may be a best choice for a portion of the delivery system.

Chutes and Gravity Pipes

In general, chutes and pipes should only be accepted after a thorough and well evaluated demonstration. Their potential for success increases with increased cement content and cohesiveness of the mix. A large diameter, and very steep CMP pipe was successfully used at Cumberland Lock to deliver RCC to the lock floor.

Elephant Trunks (Tremie)

Elephant trunks (vertically suspended rubber hoses) have been used to drop RCC mixes distances ranging from about 6 to 45 feet (7). These are especially useful at the end of elevated conveyors that deliver the mix to its final point of depositions. If the trunk is operated at low capacity, segregation and loss of coarse aggregate will probably occur at the discharge end. However, if the trunk is kept full enough, the problem can be overcome.

Conveyors

Conveyors have been used on a number of RCC dams to deliver materials onto the dam, with loaders or trucks used for final delivery on the lift surfaces. This approach solves some of the truck delivery problems, but it still leaves the serious issues concerning damages to the lift surfaces, interference among equipment in confined areas, segregation due to loading and dumping, and aging of the mix prior to compaction.

Conveyors should operate at a high speed in order to reduce exposure times and the amount of materials actually on the belt. They should have covers to protect the RCC from rain, wind, and sun. They should have scrapers that thoroughly wipe the return side of the belt so that no paste is lost from

the mix and nothing drops off onto the lift surfaces. Deflector plates or baffles should be provided at the end of each conveyor section to remix the RCC as it drops onto the next belt.

Two basic approaches have been used with all the conveyor systems. First, they each use a series of semi-permanently fixed feed belts from the mixer to the area close to the dam. The other approach uses conveyors that are supported on posts partially embedded in the dam (7).

Conclusions

There are a number of methods for mixing and delivering RCC. The design may control which of these methods is acceptable at a given project. Construction speed, low variability, low maintenance/downtime, and avoiding damage to previously compacted lift surfaces are the key construction factors to be considered.

RCC offers rapid construction with a lower unit cost. In developing countries, the reduction in cement importing and handling costs, and the use of lower grade aggregates are further points that may also be significant. The RCC technique can save both time and capital cost construction, enhancing the cost benefit ratio of many future water related projects, and mass concrete structures.

Roller compaction of concrete for dams is now coming of age. The initial experimentation is coming to an end, and although, the method of construction will continue to develop, there is now sufficient data available on which to base engineering decisions. Large dams are under consideration with several dams up to 600 ft. (185 m.) in height being investigated. With dams of this height, it is necessary to redefine the criteria for RCC (4). The properties will have to be at least as good as that of conventional concrete dams. The shear strength will necessitate relatively high cementitious contents, or full treatments of each lift surface and bedding mix.

In order that RCC can be considered for dams of all reasonable heights, and become a true replacment for the conventional monolith methods of construction, the properties of the interior concrete will have to be improved above the level of the majority of concrete so far placed. If the properties are not improved, RCC may become considered to be a concrete-faced cement-stabilized rockfill dam, albeit with rather steeper slopes.

Roller compaction of concrete for dams is a new method of construction, but it is not a solution for all sites. With a good foundation, an RCC dam will probably be the most cost-

effective solution, but the dam should be built up to the quality of a conventional concrete dam and not down to the price to make it the most economical solution.

CHAPTER VI

COST ESTIMATES FOR RCC DAMS

Introduction

Roller compacted concrete dams have gained world-wide acceptance. Since the completion of Shimajigawa Dam in Japan and Willow Creek Dam in the U.S. in 1982, 19 dams, which are more than 59 ft. (15m.) high, have been completed using this new construction method to build a concrete gravity dam. All of the six major continents now have at least one dam constructed of RCC and many more are in various stages of development (7).

Roller compacted concrete technology has matured to the point where RCC dams are ready to take their rightful place among the major dam types. In the RCC dam concept, the inherent safety, aesthetic, and maintenance advantages of a concrete dam are combined with the low cost and high production rates normally associated with earth or rockfill embankments.

The economic advantage of RCC dams as compared with a fill alternative is not just the smaller volume of the dam. Many other factors lead to potential cost savings.

Site Selection

When considering an RCC alternative to a fill dam, it is sometimes economic to investigate sites other than that originally proposed for the fill structure. For example, the foundation conditions found for the Upper Stillwater Dam were rather different from that expected.

Material Selection

Although low-lime flyash has been the most commonly-used pozzolan, both ground-granulated blast-furnace slag and natural pozzolan have been used within the cementitious contents of RCC. Natural pozzolan, for example, was used in the roller compacted concrete in the navigation lock at Tucurui Dam in Brazil.

Spillway

Any form of spillway that is possible for a conventional concrete gravity dam could be created with a RCC dam. However, an old type of spillway has been found to be ideally suited to the RCC dam method of construction the stepped spillway. Upper Stillwater and Monksville Dams use a stepped spillway, for example.

Intake and Outlet Towers

If the structure to be designed contains an intake or other tower, with an RCC dam it can usually be constructed

alongside or as a part of the upstream face of the dam. With a fill dam, the tower will usually have to be free-standing and some distance from the dam. In addition, as the dam cross-section of the RCC alternative is very much thinner than that of a fill dam, the transmission pipework and associated galleries will be very much shorter. All these factors can lead to significant savings.

Speed of Construction

The speed of construction of an RCC dam is probably the greatest advantage, when compared with a fill dam. In order to utilize the advantage, it is suggested that the method of construction should be kept as simple as possible.

If the smaller volume of RCC required for a concrete gravity dam section can be constructed with production rates approaching that for an embankment dam, an RCC dam can be completed in less time. One or two years earlier completion is quite common. The reduced time for completion of the RCC dam offers many benefits, one being considerable savings in interim construction financing.

Project benefits and less on-site costs for maintaining an engineering and quality control staff due to shorter construction time are other financial savings that can occur to the owner. It should be noted that rapid construction can

only be accomplished with careful design and construction planning, large volumes of materials on-site, and an adequate cash flow (7).

The best example of rapid completion of a RCC dam project is Copperfield Dam in Australia. The 131 ft. (40 m.) high dam requiring 183,000 cu.yd. (140,000 cu.m.) of RCC took only ten months from conception to reservoir filling. This included the time required for planning, design, contracts, permits, and construction of the dam. Daily RCC placement rates in the U.S. have been impressive. At both Upper Stillwater and Elk Creek Dams, there were a number of days where more than 10,000 cu.yd. (7,650 cu m) were placed in either two eight, or two ten-hour shifts (8).

Estimating Costs

RCC prices as submitted by the low bidder for 14 dam projects in the U.S. are listed in Table III. The table provides the cost of aggregates and all other construction operations related to processing as a single item separate from the cost of cement and flyash. The total cost per unit volume is then the sum of the aggregates and processing cost plus the cost of the cementitious materials.

The cost per unit volume is a function of the volume required, with lower costs associated with larger volumes. The cost of RCC per cubic yard as shown in Figure 5 represents the cost of aggregates, mixing, transporting, spreading. compacting, and curing a RCC mixture containing 150 lb/cu.yd. (89 Kg/cu.m.) of cement and 50 lb/cu.yd. (30 Kg/cu.m.) of flyash, or 175 lb/cu.yd. (104 Kg/cu m) of cement if no flyash is planned for the project. All of the prices were escalated to 1989 cost levels using the U.S. Bureau of Reclamation construction cost trend factors (8).

Cost of Upstream Face

Table IV represents the prices submitted by the low bidder for various upstream face designs. The costs as presented in the table are calculated as either an added cost per cubic yard of RCC, or as an added cost per square foot of face

It can be seen from table 10.6 that for dams requiring more than 100,000 cu.yd. (76,500 cu.m.) of RCC, the added cost of facing per cubic yard of RCC generally ranges from $4 to $6. For dams with less than 100,000 cu.yd. (76,500 cu.m.) of RCC, the cost of the upstream face can be considered more expensive when expressed as an added cost per cubic yard of RCC (8).

Mobilization Cost

Mobilization costs submitted on 10 dams in the United States have ranged from an unbalanced low of 0.03 percent to a high of 10.43 percent of the total low bid. Mobilization costs, neglecting these extremes, have been within a relatively narrow range from 4.70 to 7.97 percent with an average of 5.83 percent of the total bid. In some cases, the cost of mobilization is specified in the bid documents, (8). If there is no mobilizatin bid item listed in a unit price contract, it may be expected that the unit cost of RCC and other items requiring plant or special equipment to construct must be increased accordingly.

Economic Aspects of RCC Utilization in Dam Construction

The use of RCC in dam construction placed by conventional earthwork techniques results in a much lower unit cost per cubic yard of concrete placed compared to gravity dams constructed by conventional mass concrete placement techniques. Economy in RCC gravity dams may be realized if a dam is greater than a certain height and/or if earthfill, or rockfill materials are not readily available.

At a given height, the RCC gravity dam contains a much smaller volume of construction material. This, together with the speed of the RCC construction method, results in a much

shorter construction time than that required for embankment dams. Therefore, RCC construction has considerable appeal in areas where the construction season is short, and in general, has an economic advantage in the time factor of cost.

Also, appurtenant location/elimination and construction alternatives provided by RCC offer additional economic advantages. Specifically, spillway, energy dissipator, and intake structure requirements can have an adverse impact on overall embankment dam construction economics. With an RCC gravity dam, floodwater can be spilled directly over the dam crest by way of an overflow spillway, thus eliminating the need for a conventional separate side channel spillway. Such a structure can typically constitute a significant line item in the construction budget.

Another appurtenant structure to consider is the water intake tower. If a multi-port intake structure, extending to or near the full height of the reservoir for water quality blending, is required, it can easily be anchored to the vertical upstream face of an RCC gravity dam. In the case of an embankment dam, this type of tower is normally freestanding in the reservoir, or built up a reservoir side slope. A freestanding tower is considerably more expensive in both structural design and construction than an intake tower anchored to the vertical upstream face of a gravity dam.

RCC Gravity Dam Construction-Cost Comparisons

General cost comparisons between RCC gravity dam structures and conventionally constructed mass concrete dams indicates the use of RCC in conjunction with conventional earthwork placement techniques resulting in lower completed costs per unit of concrete, see Figure 6. For placement of approximately 2 million cu.yd. (1.5 million cu.m.) or less, a minimum per cubic yard cost advantage of about 1:2 is realized with RCC versus conventionally constructed mass concrete gravity dams (4).

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The RCC technique is a new type of dam construction that combines the safety advantages of concrete dams and the efficiencies of embankment dam construction. It is a relatively dry concrete material which has been consolidated through external vibrations from a vibratory roller. It differs from conventional concrete principally in its required consistency which has a direct effect on the mixture proportion requirements. The RCC is a new method used to improve the economy of concrete dam construction. RCC dams cost advantage over concrete dams was derived mainly from the greater efficiency of the handling equipment and methods used in construction. The economic advantage of RCC dams as compared with a fill alternative is not just the smaller volume of dams. Many other factors, such as site and material selection, spillway construction, intake and outlet towers, and speed of construction, lead to potential cost and time saving operations. For example, time periods needed to avoid compacting, or stiffening of materials was 15 minutes for the Upper Stillwater Dam and 30 minutes for the Elk Creek Dam.

The potential benefits of the RCC methods over conventional concrete dam building techniques are lower construction costs; faster construction and time savings; and greater worker safety because of uncontested level working surfaces. The technique promotes the possibility of developing more sites by using a RCC base mat for a conventional dam and greater concrete gravity dam design diversity.

Roller compaction of concrete for dams is now coming of age. The initial experimentation is coming to an end. Although, the method of construction will continue to develop, RCC dams have gained a world-wide acceptance. All of the six major continents, for example, have at least one dam constructed of RCC, and many more are in various stages of development. In the United States, 19 dams have been completed since 1982, using this new method of construction. Some of these dams are Willow Creek, Cochiti, Chena, Middle Fork, Stacy, and Upper Stillwater. Others world-wide are Shimajigawa, Japan; Copperfield, Australia; Les Olivetts, France; Aim Al Koreima, Morocco; and Urugaui, Argentina;

Erosion is one of the disadvantages of RCC dam construction. For example, when RCC is subjected to ASTM C666, Procedure A, typically it performs very poorly. Large blocks of the Lost Creek testfill material totally deteriorated when subjected to the combined action of salt water, wet dry cycles, and freezing-thawing at Treat Island, Maine.

Controlling temperature rise is another RCC disadvantage. For instance, with no-slump RCC there is less mixing water than in conventional concrete, so expensive liquid nitrogen had to be introduced into the mixers to cool the RCC.

RCC dam designers have tested the performance of completed RCC dams. While most of the results have been positive, there have been some negatives, i.e., seepage, and seepage related phenomena, and that is another RCC disadvantage.

The properties of RCC in place depend on the quality of cementitious materials used, which depends on the water/cement ratio selected to meet strength and durability requirements, mixture proportions, and the degree of compaction, or consolidation. Because a wide range of materials and mixes have been used, there are no typical values for RCC properties that fall within a narrow range. RCC properties that are aggregate dependent, such as elastic and thermal properties, are similar to conventional concrete made from the same aggregate.

Design and construction (mixing and delivery) are very critical to the success and completion of a RCC project. Before mixing methods are selected, consideration should be given to :

* aggregate size
* shape

* gradation
* moisture content
* hardness
* method of feeding the mixer
* available space
* erection requirements the length of time between when peak temperatures are reached and when cooling begins
* the rate of cooling evaluation of weather and its effect on quality for various methods and rates of placement
* the cement and pozzlan contents
* wetness of the mix, and variability.

Equipment selection should consider quality, economics, schedule, risk, and practicality. Mixing options include pugmills and rotating drums; both of which may be "batch" or "continuous" mixing plant. Delivery systems include haul vehicles, traveling hoppers, chutes, conveyors, and combinations of these systems.

Between early 1950's and mid 1970's, the number of concrete dams built had dropped 25 percent of the total. This decline in the popularity of concrete dams came during a period when the use of concrete arch dams in narrow-valley sites was increasing. Concern for the decline of concrete dams

led to the organization of important meetings of the dam-building community in the United States. The experts were searching for a new type of dams that would combine the safety and efficiency of embankment dam construction. Their searches in the early 1970's finally led to the development of RCC which has, to a certain degree, been traditional replacing concrete, and embankment dams.

Conclusions

The history of RCC goes back primarily through the last two decades, or even further depending on its definition; however, until the recent completion of Willow Creek Dam in 1982, it had not been used as a principal material from which a permanent dam was built in its entirety. Just two years after completion of Willow Creek Dam, RCC dams have passed beyond the infancy planning stage and become relatively common in design, planning, and construction. Design and construction concepts were established to assure a low rate of seepage, to provide a smooth and durable exposed surface for the full height of the upstream face and spillway, and to increase the rate of placement of the roller compacted concrete.

At the beginning of 1980s, no roller-compacted concrete (RCC) dams had been finished, as a whole unit, worldwide. By the middle of the decade (1985), only seven large dams had

been completed, but by the end of the 1980s, 59 dams had been constructed. The method of construction has become accepted in a very short time, and very large RCC dams are now being designed and constructed. The study has shown that all of the six major continents now have at least one dam constructed of RCC, and many more are in various stages of development.

Within the next few years, it is expected that a number of RCC dams with heights over 150 m. will be completed. The RCC Technology has matured to the point where RCC as a newly developed method for building dams, has grown and been accepted worldwide, and is ready to take a rightful place among the major dam types.

The study has also shown that for dams which have been subjected to full reservoir load, there have been no failures, or unanticipated movements, or deformations in the RCC structures. There is also, to date, no record of an RCC dam having been shaken by a significant earthquake, even-though, seven RCC dams have been completed in Japan, and others are located in seismically active areas. All of this indicates that RCC dams are strong enough, compared to any other dam types, to accept the construction industry's trust, and are rapidly gaining popularity in Brazil, Venezuela, France, Australia, South Africa as well as North America and Japan.

Differences between the hardened properties of RCC and conventional concrete are primarily due to differences in mixture proportions, grading, aggregates, and voids.

There are several methods discussed in this document for mixing and delivering RCC. The design may control which of these methods is acceptable at a project. Construction speed low variability, low maintenance/downtime, and avoiding damage to previously compacted lift surfaces are the key construction factors to be considered.

The economic advantage of RCC combined with the long-term safety record of concrete dams have led to rapid acceptance of RCC dams throughout the world. By the end of 1989, data were available on more than 45 RCC Dams containing more than 13,000 cu. yd. of RCC that had been completed in twelve countries.

In developing countries, the reduction in cement importing and handling costs, and the use of lower grade aggregates are further points that may also be significant. Project benefits and less on-site costs for maintaining an engineering and quality control staff due to shorter construction time are other financial savings that can occur to the owner.

RCC was developed as a result of efforts to design more economical concrete dams that could be constructed rapidly. General cost comparisons between RCC gravity dam structures,

and conventionally constructed mass concrete dams indicates a minimum per cubic yard cost advantage of about 1:2 ratio. For example, Willow Creek Dam, in Oregon, was completed in approximately one-third the estimated time required, and at approximately 50% of the cost ($14 million versus $ 27 million) for an alternate coventional concrete dam.

The RCC technique offers greater reliability, more saving in both time and capital cost construction, compared to conventional concrete dams. With all of these economic advantages and the rapid refinement of roller compacted concrete technology, RCC gravity dams have become the primary alternative for potential dam sites with suitable rock foundations and adequate aggregate sources.

Recommendations

The following recommendations are given:

1. Further studies on this subject area should be conducted, such as, a method of controlling the concrete temperature and the compaction mechanism of vibratory rollers.
2. Engineers and Contractors should become more familiar with Roller Compacted Concrete.

3. Researcher Organizations, such as TVA, should conduct, and provide more workshops which may be investigated for possible use of other products (i.e. pavement).

4. More RCC conferences should be conducted so contractors and owners would become aware of the procedure, and the use the product to their advantage due to its cost effectiveness and decreased time consumption for the construction industry.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. American Concrete Institute (ACI), Committee 207, "Roller Compacted Concrete." Manual of Concrete Practice, ACI 207.5R - 89, 1991.

2. Corps of Engineers, "Roller Compacted Concrete." Engineer Manual No. 1110-2-2006, U.S. Corps of Engineers, Washington, D.C., 1990.

3. Dunstan, M.R.H., "Design and Construction Consideration for Roller Compacted Concrete Dams." XVIth ICOLD Congress, Q.26-R.25, V.III, San Francisco, 1988.

4. Hansen, K.D., "Roller Compacted Concrete," The American Society of Civil Engineers. N.Y., N.Y. 1985.

5. Hansen, K.D., "Roller Compacted Dams Worldwide," Water Power and Dam Construction Handbook, Reed Business Publishing, Limited Survey, United Kingdom, 1987.

6. Hansen, K.D., and Francis, G. Mclean, "Roller Compacted Concrete III," The American Society of Civil Engineers, N.Y., N.Y., 1992.

7. Hansen, K.D., and Leslie, K. Guice, " Roller Compacted Concrete II," The American Society of Engineers, N.Y., N.Y., 1988.

8. Hansen, K. D., and William, G. Reinhardt, "Roller Compacted Concrete Dams," McGraw-Hill, Inc., N.Y., N.Y., 1991.

9. Logie, C. V., "Economic Considerations in Selection of a Roller-Compacted Concrete Dam," Roller Compacted Concrete ASCE, N.Y., N.Y., 1985.

10. McKcon, T.J., and Gross, L., "Roller Compacted Concrete," The Construction Specifier, Construct Specification Institute Inc., Washington D.C., 1986.

11. Prendergast, John, "Roller Compacted Concrete at 10," Civil Engineering Magazine, October 1992, P 44-47.

12. Reeves, G. N., and Yates, L. B., "Simplified Design and Construction Control for Roller Compacted Concrete," Roller Compacted Concrete, American Society of Civil Engineers, N.Y., 1985.

13. Shrader, E. K., "Permeability and Seepage Control in Roller Compacted Concrete Dams," Roller Compacted Concrete, American Society of Civil engineers, N.Y. 1985.

14. Shrader, E. K., "Design for Strength Variability: Testing and Effects on Cracking in RCC and Conventional Concrete," ACI publication SP 104, Detroit, MI, 1987.

15. U.S. Department of the Army, "Roller Compacted Concrete,"Engineering and Design, U.S. Army Corps of Engineers, Washington D. C., 1985.

16. U.S. Department of the Interior, Bureau of Reclamation, "Roller Compacted Concrete Interagency Forum," Interior Bureau of Reclamation, Lakewood, Colorado, 1985.

17. William, Morris, "The American Heritage Dictionary of the English Language," Houghton Mifflin Company, Boston MA., 1978.

APPENDIX A

Table I. RCC mixture proportions for dams. (Hansen & Reinhardt (1991))

Dam	Mix designation	Vebe or VC time, s	Cement* lb/yd³ (kg/m³)	Pozzolan† lb/yd³ (kg/m³)	Water, lb/yd³ (kg/m³)	Admixture, lb/yd³	W/(C + P)	P/(C + P)‡	MSA, in (mm)	Sand§ lb/yd³ (kg/m³)	CA lb/yd³ (kg/m³)	% sand§ (by wt.)
AFRICA												
South Africa												
1. De Mist Kraal Diversion		—	98 (58)	98 (58)	177 (105)	2.0 oz air (78 cm³)	0.91	0.50	3 (75)	1241 (736)	2918 (1731)	29.8
2. Arabie (now Mokgama Matlala)		—	61 (36)	125 S (74)	190 ± (113)	0	1.02	0.67	3 (75)	1473 (874)	2210 (1311)	40.0
3. Zaaihoek			61 (36)	142 S (84)	179 (106)	2.02 oz air (84 cm³)	0.89	0.70	3 (75)	1019 (640)	2933 (1740)	26.9
4. Knellpoort (gravity arch)			103 (61)	239 (142)	172 (102)	0	0.50	0.70	2.0 (50)	1175 (697)	2820 (1673)	29.4
5. Wolwedans (gravity arch)			98 (58)	229 (136)	140 (83)	0	0.43	0.70	2.1 (53)	1145 (679)	2569 (1524)	30.8
Morocco												
1. Ain Al Koreima	upstream		337 (200)	0	202 (120)	0	0.60	0	2.5			40.0
	downstream		169 (100)	0	202 (120)	0	1.20	0	(63)			
2. Rwedat			169 (100)	0	202 (120)	0	1.20	0	2 (50)			38.0
SOUTH AMERICA												
Brazil												
1. Saco de Nova Olinda	(lower)	—	127 II P (75)	—	284 (168)	0	2.24	approx. 0.20	3 (75)	694 (410)	2935 (1735)	19.1

Table I. RCC mixture proportions for dams. (Hansen & Reinhardt (1991))

Dam	Mix designation	Vebe or VC time, s	Cement* lb/yd³ (kg/m³)	Pozzolan† lb/yd³ (kg/m³)	Water, lb/yd³ (kg/m³)	Admixture, lb/yd³	W/(C + P)	P/(C + P) ‡	MSA, in (mm)	Sand§ lb/yd³ (kg/m³)	CA lb/yd³ (kg/m³)	% sand§ (by wt.)
ASIA												
Japan												
1. Shimajigawa	B-1 (lower)	15	153 (91)	66 (39)	177 (105)	0.55 WRA (0.325) + air	0.81	0.30	3.1 (80)	1262 (749)	2488 (1476)	33.7
	B-2 (upper)	20	142 (84)	61 (36)	177 (105)	0.51 WRA (0.30) + air	0.88	0.30	3.1 (80)	1268 (752)	2498 (1482)	33.7
2. Tamagawa		20	153 (91)	66 (39)	160 (95)	0.55 WRA (0.325) + air	0.73	0.30	6 (150)	1107 (657)	2602 (1544)	29.8
3. Mano		20	162 (96)	40 (24)	174 (103)	0.51 WRA (0.30) + air	0.88	0.20	3.1 (80)	1239 (735)	2562 (1520)	32.6
4. Pirika		20	142 (84)	61 (36)	152 (90)	0.55 WRA (0.325) + air	0.75	0.30	3.1 (80)	1126 (668)	2677 (1588)	30.0
5. Shiromizugawa		20	162 (96)	40 (24)	172 (102)	0.42 WRA (0.25) + air	0.85	0.20	3.1 (80)	1134 (673)	2574 (1527)	30.6
6. Asahi Ogawa		20	162 (96)	40 (24)	155 (92)	0.51 WRA (0.30) + air	0.77	0.20	3.1 (80)	1187 (704)	2589 (1536)	31.9
7. Nunome		20	142 (84.5)	77 (45.5)	165 (98)	0.42 WRA (0.26) + air	0.75	0.35	6 (150)	1032 (612)	2820 (1673)	26.8
China												
1. Kengkou		15	101 (60)	135 (80)	165 (98)	0.47 WRA (0.28)	0.70	0.57	3.1 (80)	1345 (798)	2309 (1370)	36.6
2. Tianshengqiao #2			93 (55)	143 (85)		0		0.61				
3. Longmentan			91 (54)	145 (86)				0.61				

Table I. RCC mixture proportions for dams. (Hansen & Reinhardt (1991))

NORTH AMERICA												
United States												
1. Willow Creek	A (interior mass)	—	80 II (47)	32 (19)	180 (107)	0	1.61	0.29	3 (75)	total 3956 (1 size) (2347)		—
	B (upstream)	—	175 II (104)	0 —	185 (110)	0	1.06	0	3 (75)	total 3902 (1 size) (2315)		—
	C (downstream)	—	175 II (104)	80 (47)	185 (110)	0	0.73	0.31	3 (75)	total 3826 (1 size) (2270)		—
2. Winchester (now Carroll E. Ecton)		—	175 (104)	0 —	175 (104)	0	1.00	0	3 (75)	total 3790 (1 size) (2248)		—
3. Middle Fork		—	112 II (66)	0	160 (95)	0	1.43	0	3 (75)	1152 (683)	2138 (1268)	35.0
4. Galesville	A (interior)	—	89 (53)	86 (51)	190 (113)	0	1.09	0.49	3 (75)	1310 (777)	2560 (1519)	33.9
	B (downstream)	—	115 (68)	110 (65)	190 (113)	0	0.84	0.49	3 (75)	1290 (765)	2520 (1495)	33.9
5. Grindstone Canyon	(upper portion)	—	130 (77)	0 —	200 (119)	0	1.54	0	3.5 (89)	1361 (781)	2500 (1531)	33.8
6. Monksville			105 (62)	0 —	230 (119)	0	2.15	0	3 (75)	1500 (890)	2313 (1372	39.3
7. Lower Chase Creek		20 (64)	108 V (40)	67 (107)	180	0	1.03	0.38 (63)	2.5 (714)	1203 (1451)	2445	33.0
8. Upper Stillwater	A (interior)	19	134 II (79)	290 (172)	171	17 oz. WRA (658 cm³)	0.40	0.68	2 (50)	1148 (681)	2213 (1313)	34.1
	B (upstream)	15	155 II (92)	343 (203)	169 (100)	21 oz. WRA (812 cm³)	0.34	0.69	2 (50)	1162 (689)	2128 (1262)	35.3
9. Elk Creek	Spring 1987	10 17–21	118 II (70)	56 (33)	174 (103)	41 oz. WRA + set retarding (1586 cm³)	1.00	0.32	3.0 (75)	1227 (728)	2422 (1439)	33.6

Table I. RCC mixture proportions for dams. (Hansen & Reinhardt (1991))

Dam	Mix designation	Vebe or VC time, s	Cement* lb/yd³ (kg/m³)	Pozzolan† lb/yd³ (kg/m³)	Water, lb/yd³ (kg/m³)	Admixture, lb/yd³	W / C + P	P / C + P ‡	MSA, in (mm)	Sand§ lb/yd³ (kg/m³)	CA lb/yd³ (kg/m³)	% sand§ (by wt.)
NORTH AMERICA												
United States												
10. Stagecoach		—	120 (II-V) (71)	130 (77)	233 (138)	0	0.93	0.52	2.0 (50)	1156 (686)	2459 (1459)	32.0
11. Stacy Spillway (now S.W. Freese)		—	210 (125)	105C (62)	259 (154)	0	0.82	0.33	1.5 (38)	total 3500 (1 size) (2076)		—
12. Marmot-Replacement		10	120 (71)	180 (107)	175 (104)	41 oz. WRA + set retarding (1586 cm³)	0.58	0.60	3 (75)	1270 (753)	2060 (1222)	38.1
Mexico												
1. La Manzanilla		—			6% by wt.				3 (75)			
AUSTRALIA												
1. Copperfield	A (exterior)	—	185 II (110)	0 —	219 (130)	0	1.18	0	2 (50)	total 3573 (1 size) (2120)		40.0
	B (interior)	—	135 II (80)	51 (30)	219 (130)	0	1.18	0.27	2 (50)	total 3573 (1 size) (2120)		40.0
2. Craigbourne		—	118 II (70)	101 (60)	197 (117)	0	0.90	0.46	2 (53)	total 3835 (1 size) (2275)		36.0
3. Bucca Weir		—	152 II (90)	152 (90)	185 (110)	0	0.61	0.50	1.6 (40)	total 3523 (2090)		38.0

Table I. RCC mixture proportions for dams. (Hansen & Reinhardt(1991))

AUSTRALIA												
4. Wright's Basin		—	244 (145)	122 (72.5)	266 (158)	0	1.00	0.33	1.6 (40)	total 3329 (1 size) (1975)		—
EUROPE												
Spain												
1. Castilblanco de los Arroyos	(upper) (lower)	38 46	147 II P (87) 172 II P (102)	158 (94) 144 (85.5)	185 (101) 172 (102)	0 0	0.56 0.54	0.61 0.57	1.6 (40) 1.6 (40)	1126 (668) 1334 (672.5)	2427 (1440) 2447 (1452)	31.7 31.6
2. Erizana - dike		—	152 IP (90)	152 (90)	193 (115)	0	0.64	0.60	4 (100)	930 (552)	2798 (1660)	24.9
3. Los Morales	(upper) (middle)		116 (69) 121 (72)	258 (153) 214 (127)	170 (101) 165 (98)	0 0	0.45 0.49	0.69 0.64	1.6 (40) 3.1 (80)	1104 (655) 944 (560)	2394 (1420) 2562 (1520)	31.6 26.9
4. Santa Eugenia	HC-1 HC-2	27 31	185 IP (110) 152 IP (90)	34 (20) 59 (35)	169 (100) 152 (90)	0 0	0.77 0.72	0.31 0.42	2.75 (70) 4 (100)	930 (552) 725 430)	2756 (1635) 3085 (1830)	25.2 19.0
France												
1. Les Olivettes			148 R (88)	79 (47)	211 (125)	0	0.93	0.35	2.5 (63)	total 3756 (1 size) (2250)		—
USSR												
1. Tashkumy	(lower) (upper)	20–30 20—30	202 IP(N) (120) 169 IP(N) (100)	— —	177 (105)	0.51 WRA (0.30) OAZWRA (0.25)	0.875	0.25 0.25	2 (50) 2 (50)	total 3708 (2200) total 3708 (2200)		30.4

Table II. Characteristics and tests for aggregates for RCC dams. (Hansen & Reinhardt (1991))

Characteristic	Significance	Test designation (U.S.)	Test name
Grading	Consistency, compactability economy	ASTM C136	Sieve Analysis of Fine and Coarse Aggregate
		ASTM C117	Materials Finer than 75 μm (No. 200) in Mineral Aggregates by Washing
Resistance to abrasion	Aggregate quality, wear resistance of surface	ASTM C131	Resistance to Degradation of Small Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
		ASTM C535	Resistance to Degradation of large Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
		ASTM C295	Petrographic Examination of Aggregates for Concrete
Specific gravity—absorption	Mix design calculations	ASTM C127	Specific Gravity and Absorption of Coarse Aggregate
		ASTM C128	Specific Gravity and Absorption of Fine Aggregate
Bulk unit weight or density	Mix design calculations	ASTM C29	Unit Weight and Voids in Aggregate
Sulfate resistance	Soundness against weathering and chemical attack	ASTM C88	Soundness of Aggregates by Sodium Sulfate or Magnesium Sulfate
Organic impurities	Strength gain	ASTM C40	Organic Impurities in Fine Aggregate for Concrete

Table III. RCC prices by low bidder. (Hansen & Reinhardt (1991))

Prospect	Bid date	RCC construction date	As bid, yd^3	Aggregate and process	Cost per yd^3 (U.S. $) Cement	Fly ash	Total
1. Willow Creek Dam, Oregon	10-23-81	1982	401,000 Average of four mixes	11.56	6.23 (117# average @ 106.20/ton)	1.21 (39# @ 61.60/ton)	19.00
2. Austin Detention Dams, Texas	6-28-83	1984	20,670	18.00	7.00 (200# @ 70.00/ton)	1.20 (80# @ 30.00/ton)	26.20
3. Upper Stillwater Dam, Utah	10-17-83	1983-87	1,357,000 Average of two mixes	10.78 1.07[*]	5.37 (132# @ 81.50/ton)	6.59 (293# @ 45.00/ton)	23.81
4. Winchester Dam, Kentucky	12-13-83	1984	32,000		Bid at lump sum item (175#)	—	32.50
5. Dolet Hills Plant Spillway, Louisiana	12-20-83	1984	26,123 Average of two mixes	27.00	5.60 (160# @ 70.00/ton)	0.91 (64# @ 28.50/ton)	33.51
6. Galesville Dam, Oregon	3-14-84	1983	210,500 Average of two mixes	15.56[†]	3.95 (91# average @ 87.00/ton)	1.91 (87# average @ 44.00/ton)	21.42
7. Monksville Dam, New Jersey	4-10-84	1986	289,000 Average of two mixes	13.72	3.70 (108# average @ 68.58/ton)	—	17.42[‡]
8. Middle Fork Dam, Colorado	3-21-84	1984	35,000			—	less than 25.00
9. Grindstone Canyon Dam, New Mexico	6-20-85	1986	114,500	20.20	4.38 (125# @ 70.00)[§]	1.00 (50# @ 40.00)§	25.58
10. Elk Creek Dam, Oregon	1-16-86	1987-88	999,000 + 41,860	14.00	4.13 (118# @ 70.00/ton)	1.14 (56# @ 2.90/ft^3) + 0.29 admix (70#)	19.56
11. Lower Chase Creek Dam, Arizona	2-3-87	1987	26,830		Bid as lump sum contract (105#)		33.80
12. Stacy Dam Spillway, Texas	3-5-87	1988-89	103,800	18.05	4.62 (200# @ 46.17/ton)	1.20 (100# @ 23.83/ton)	23.87[‖]
13. Stagecoach Dam, Colorado	3-5-87	1988	43,500	23.00	4.80 (120# @ 80.00/ton)	1.54 (88# @ 35.00/ton)	29.34
14. Cuchillo Negro Dam, New Mexico	9-19-89	1990	103,700	15.00	5.20 (130# @ 80/ton)	2.00 (100# @ 40/ton) + 0.68 Admix	22.88

NOTE: 1 yd^3 = 0.765 m^3; 1 lb/yd^3 = 0.593 kg/m^3.
[*]Cost of government-furnished sand for RCC mix.
[†]6-in. (−) aggregate furnished from previous road contract—cost $6.75/$yd^3$ (not included in bid).
[‡]Includes 5.5 percent increase from actual bid due to one-year delay in award.
[§]Actual mix contained an average of 135 lb of cement and no fly ash.
[‖]Average of three lowest bidders—low bidder at $19.41/$yd^3$.

Table IV. Upstream face designs and costs. (Tarbox & Hansen (1988))

Dam	Location	Height, ft (m)	RCC volume as bid, yd^3 (kg/m^3)	Type of face	Added cost per yd^3 RCC	Facing concrete cost per yd^3*	Added cost per ft^2 face
1. Winchester	Kentucky	74 (23)	32,000 (24,500)	Precast concrete panels with 65-mil PVC membrane plus 18-in concrete backing	$ 10.04 +2.34	— $ 60.00	$ 8.50 +1.98
2. Galesville	Oregon	162.5 (50)	210,500 (160,800)	Average 18-in-thick concrete plus sprayed on membrane	5.88	117.85†	6.54 +1.50
3. Grindstone Canyon	New Mexico	139 (42)	114,500 (87,500)	Average 24-in-thick concrete	5.46	107.81†	7.99
4. Monksville	New Jersey	157 (48)	289,000 (221,000)	Average 24-in-thick concrete	5.38	95.69†	7.09
5. Upper Stillwater	Utah	294 (91)	1,357,000 (1,037,500)	Horizontal slip-formed elements—24-average	3.88‡ (both faces)	58.47†	4.03‡
6. Elk Creek	Oregon	249 (76)	999,000 (763,800)	Average 36-in-thick concrete plus waterstopped joints	4.91 +0.58 jts.	71.64†	7.96
7. Stacy spillway	Texas	103 (31)	103,800 (79,400)	18-in concrete-reinforced plus waterstopped joints	4.23	110.29†	8.04

*Includes cement and pozzolan (if used).
†Includes cost of forming the face.
‡Not considered as water barrier—added cost of high-paste RCC must be considered in cost evaluation.

NOTE: Costs presented were submitted by the low bidder and have not been escalated to 1987 or later cost levels. See Fig. 10.4 for bid date.

Table V. Summary of RCC shear strength data and comparison with conventional concrete. (McLean & Pierce (1981))

			Range of values				Statistical Evaluation			
			Break-bond		Sliding friction					
Subset	No. of projects	No. of tests	φ, deg.	c, lb/in²	φ, deg.	c, lb/in²	Mean φ, deg.	Std. dev. φ deg.	Mean c, lb/in²	Std. dev. c, lb/in²
Parent Material										
Conventional	2	18	40–76	269–573	—	—	58	14	364	134
RCC	3	40	33–76	74–641	—	—	49	16	437	179
Bonded Joints										
Conventional	6	62	25–78	205–527	—	—	55	13	350	98
RCC	8	142	24–73	9–622	—	—	48	9	280	172
Lean	6	76	24–67	9–441	—	—	47	10	189	106
Rich	2	55	35–73	165–622	—	—	49	9	384	175
Unbonded Joints*†										
Conventional	10	146	—	—	35–51	18–216	47	3	86	50
RCC	4	163	—	—	34–52	14–83	43	4	35	18
Lean	2	58	—	—	34–47	14–83	40	4	46	24
Rich	2	105	—	—	38–52	16–48	45	4	30	8
Conventional Concrete Reference Value‡										
Triaxial	4	226	40–48	605–1360	—	—	44	2	1075	217
Tension-compression	2	95	52–69	300–615	—	—	59	3	480	90

*Apparent cohesion (c_a).

†Includes sliding friction results of break-bond tests.

‡Harboe, E.M. "Properties of Mass Concrete in Bureau of Reclamation Dams" Bureau of Reclamation Report No. C-1009, December 1961.

Table VI. Completed roller compacted concrete dams. (Hansen & Reinhardt (1991))

Dam/river	RCC completed	State or province	Owner/Designer	Ht, ft (m)	Length, ft (m)	RCC volume, yd³ (m³)	Total volume, yd³ (m³)	Face of dam: Upstream Slope	Upstream Type	Downstream Slope	Downstream Type	Spillway Slope	Spillway Type
ASIA													
Japan													
Shimajigawa/ Shimaji	1980	Yamaguchi	Japan Ministry of Construction (JMC)	292 (89)	787 (240)	216,000 (165,000)	415,000 (317,000)	V/ 0.30	(1)	0.80	(1)	0.80	(1)
Tamagawa/Tama	1986	Akita	JMC	328 (100)	1448 (441.5)	944,000 (757,000)	1,509,000 (1,154,000)	V/ 0.60	(1)	0.81	(1)	0.81	(1)
Mano/Mano	1987	Fukushima	Fukushima Prefecture	226 (69)	784 (239)	135,000 (103,000)	286,000 (219,000)	V	(1)	0.80	(1)	0.80	(1)
Pirika/ Shiribeshitoshibetsu	1987	Hokkaido	JMC+ Hokkaido Development Bureau	131 (40)	2986 (910)	212,000 (162,000)	471,000 (360,000)	V/ 0.80	(1)	0.80	(1)	0.80	(1)
Shiromizugawa/ Shiromizu	1988	Yamagata	Yamagata Prefecture	179 (54.5)	1204 (367)	186,000 (142,000)	412,000 (315,000)	V	(1)	0.80	(1)	0.80	(1)
Asahiogawa/O	1988	Toyama	Toyama Prefecture	276 (84)	853 (260)	217,000 (160,000)	472,000 (361,000)	V/ 0.80	(1)	0.80	(1)	0.80	(1)
Nunome/Nunome	1989	Nara	Water Resources Development Corp.	236 (72)	1056 (322)	144,000 (110,000)	492,000 (370,000)	V/ 0.40	(1)	0.76	(1)	0.76	(1)
China													
Kengkou/Pingshan	1986	Fujian	Fujian Provincial Dept. of Water Conservancy & Hydropower/Fujian Water Conservancy & Hydropower Investigation & Design Institute	186 (57)	402 (123)	56,000 (43,000)	78,500 (60,000)	V	(6)	0.75	(9)	0.75	(1)
Tianshengqiao 2/ Nanpan	1988	Guizhou & Guangxi	Guizhou & Guangxi Provinces/Guiyang Hydroelectric Power Investigation & Design Institute	193 (59)	1542 (470)	171,000 (131,000)	421,000 (322,000)	V	(1)	0.75	(9)	0.75	(1)
Mahui/ Jialing	1989	Sichuan	Sichuan Province/Sichuan Water Conservancy & Hydropower Investigation & Design Institute	75 (23)	463 (141)	196,000 (150,000)	327,000 (250,000)	V	(1)	—		1.18	(1)

Table VI. Completed roller compacted concrete.

Longmentan/Luxi	1989	Fujian	Dehua County, Fujian Province/Fujian Water Conservancy & Hydropower Investigation & Design Institute	189 (58)	515 (157)	95,000 (73,000)	132,000 (101,000)	V/ 0.30	(8)	0.75	(9)	0.75 (1)
Tongjiezi'/Dadu	1989	Sichuan	Sichuan Province/Chendu Hydroelectric Power Investigation & Design Institute	285 (87)	3310 (1009)	589,000 (450,000)	3,544,000 (2,710,000)	V	(1)	0.75	(9)	0.75 (1)
Pajiakou/Luanhe	1989	Hebei	Bureau of Panjiakou Control Works/Tianjin Prospecting & Design Institute	80 (24.5)	801 (244)	27,000 (21,000)	39,000 (30,000)	V	(1)	0.60	(9)	—
					NORTH AMERICA							
					United States							
Willow Creek/Willow Creek	1982	Oregon	U.S. Army Corps of Engineers—Walla Walla, Washington District	169 (52)	1780 (543)	433,000 (331,000)	433,000 (331,000)	V	(2)	0.80	(4)	0.80 (4)
Winchester (now Carroll E. Ecton)/ Upper Howards Creek	1984	Kentucky	Winchester Municipal Utilities/Palmer Engineering & Parrett, Ely. & Hurt	74 (23)	1192 (363)	32,000 (24,500)	35,000 (27,000)	V	(3)	1.00	(4)	1.00 (1)
Middle Fork/Middle Fork of Parachute Creek	1984	Colorado	Exxon Co. U.S.A./ Morrison-Knudsen Engineers	124 (38)	410 (125)	55,000 (42,000	60,000 (45,000)	V	(1)	0.80 Stepped	(1)	Conduit
Galesville/Cow Creek	1985	Oregon	Douglas County/ Morrison-Knudsen Engineers	162.5 (50)	950 (290)	210,000 (161,000)	223,000 (170,000)	V	(1)	0.80	(4)	0.80 (1)
Grindstone Canyon/ Grindstone Creek	1986	New Mexico	Village of Ruidoso/ Boyle Engineering	139 (42)	1416 (432)	115,000 (88,000)	126,000 (96,000)	V	(1)	0.75 Stepped	(1)	0.75 (1)
Monksville/Wanaque	1986	New Jersey	No. Jersey Dist. Water Supply Comm. & Hackensack Water Co./ O'Brien & Gere	157 (48)	2200 (670)	287,000 (219,000)	304,000 (232,000)	V	(1)	0.78	(4)	0.78 (1) Stepped
Lower Chase Creek/ Lower Chase Creek	1987	Arizona	Phelps Dodge Morenci, Inc. + Sumitomo Metal Mining Arizona/Dames & Moore	64 (20)	400 (122)	18,000 (13,800)	29,000 (22,200)	V	(1)	0.70 Stepped	(1)	0.70 (1) Stepped

Table VI. Completed roller compacted concrete dams.

Dam/river	RCC com-pleted	State or province	Owner/Designer	Ht, ft (m)	Length, ft (m)	RCC volume, yd³ (m³)	Total volume, yd³ (m³)	Face of dam: Upstream Slope	Upstream Type	Downstream Slope	Downstream Type	Spillway Slope	Spillway Type
Upper Stillwater/Rock Creek	1987	Utah	U.S. Bureau of Reclamation	294 (90)	2673 (815)	1,471,000 (1,125,000)	1,675,000 (1,281,000)	V	(7)	0.32/ 0.60	(7)	0.32/ 0.60 Stepped	(7)
Elk Creek/ Elk Creek	1988	Oregon	U.S. Army Corps of Engineers (as halted) Portland District (as planned)	83 (25) 249 (76)	1197 (365) 2580 (786)	348,000 (266,000) 1,041,000 (796,000)	455,000 (348,000) 1,100,100 (841,000)	V	(1)	0.80	(7)	0.80	(1)
Stagecoach/Yampa	1988	Colorado	Upper Yampa Water Conservancy District/ Woodward Clyde Consultants	150 (46)	380 (115)	44,000 (34,000)	50,500 (38,500)	V	(1)	0.80 Stepped	(1)	0.80 Stepped	(1)
Stacy (now S.W. Freese) Spillway/Colorado	1989	Texas	Colorado River Municipal Water District/Freese & Nichols	103 (31)	568 (173)	117,000 (89,000)	209,000 (160,000)	V	(1)	0.831	(1)	0.831	(1)
Marmot (replacement)/ Sandy	1989	Oregon	Portland General Electric/ Ebasco Services	50 (15)	194 (59)	10,300 (8,000)	13,000 (10,000)	V	(1)	0.80	(1)	0.80	(1)
Mexico													
La Manzanilla/Ibarilla	1987	Leon	Secretaria de Agricultura y Recursos Hidraulicos (SARH)	118 (36)	492 (150)		65,400 (50,000)	V/ 0.24	(1)	0.80	(1)	0.80	(1)
AUSTRALIA													
Copperfield/ Copperfield	1984	Queensland	Kidston Gold Mine, Ltd./ Gutteridge, Haskins & Davey	131 (40)	1115 (340)	183,000 (140,000)	205,000 (157,000)	V	(1) & (5)	0.90/ 0.80	(4)	0.80	(1)
Craigbourne/Coal	1986	Tasmania	Tasmanian Rivers & Water Commission/ Gutteridge, Haskins, & Davey	82 (25)	810 (247)	29,000 (22,500)	29,000 (22,500)	V	(2)	1.00	(4)	Separate	

Table VI. Completed roller compacted concrete dams.

Bucca Weir/Kolan	1987	Queensland	Queensland Water Resources Commission/ Gutteridge, Haskins, & Davey	39 (12)	420 (124)	31,400 (24,000)	39,300 (30,000)	1.00	(4)	Spillway		0.50 Stepped	(1)
Wright's Basin/Point Hut Creek	1989	Australian Capital Territory	Australian Capitol Territory Government/ Willing & Partners	59 (18)	282 (86)	11,900 (9,100)	11,900 (9,100)	V	(2)	1.0	(4)	Conduit	
EUROPE													
Spain													
Castilblanco de los Arroyos/Rivera de Cala	1985	Seville	Junta de Andalucia/Hydro-graphic de Guadalqvirir	82 (25)	404 (123)	-18,000 (14,000)	26,000 (20,000)	V	(1)	0.75	(1)	0.75	(1)
Erizana (dike)	1987	Galicia	Confederación Hidraulica del Norte de Espana	50• (15)	361• (110)	15,700 (12,000)	85,000 (65,000)	—					
Los Moralès/Morales	1967	New Castile	Confederación Hidro-grafica del Tajo/OCISA	92 (28)	656 (200)	29,000 (22,000)		V	(1)	0.75 Stepped	(5)	0.75	(1)
Santa Eugenia/Xallas	1988	La Coruña	Sociedad Española de Carburos Metálicos S.A./ INARSA	281 (85.5)	935 (285)	286,000 (219,000)	306,000 (234,000)	0.05	(5)	0.75 Stepped	(5)	0.75	(1)
France													
Les Olivettes/ Tributary of Herault	1987	Bas Rhone	Conseil General del'Herault/ Compagnie Nationale du Bas Rhone et du Langueduc (CNARBRL)	118 (36)	837 (255)	105,000 (80,000)	111,000 (85,000)	V	(1)	0.75	(10)	0.75 Stepped	(1)
USSR													
Tashkumir/Narin	1988	Kirgizia	Gidroproject	246 (75)	1050 (320)	111,000 (85,000)	—	V	(1)	0.75	(1)	0.75	(1)
AFRICA													
South Africa													
De Mist Kraal Diversion/Little Fish	1966	Cape	Department of Water Affairs	98 (30	984 (300)	46,000 (35,000)	85,000 (65,000)	V	(1)	0.60 Stepped	(1)	0.60 Stepped	(1)
Arabie (now Mokgoma Matlala/ Oliphants	1986	Lebowa	Department of Coopera-tive Development/Theron, Prinsloo, & Van Tonder	118 (36)	1493 (455)	132,000 (101,000)	185,000 (141,500)	V	(1)	0.75/ 0.50 Stepped	(1)	0.75	(1)

Table VI. Completed roller compacted concrete dams. (Hansen & Reinhardt (1991))

Dam/river	RCC completed	State or province	Owner/Designer	Ht, ft (m)	Length, ft (m)	RCC volume, yd³ (m³)	Total volume, yd³ (m³)	Face of dam: Upstream Slope	Upstream Type	Downstream Slope	Downstream Type	Spillway Slope	Spillway Type
AFRICA *(Continued)*													
South Africa *(Continued)*													
Zaaihoek/Slang	1987	Natal	Department of Water Affairs	154 (47)	1729 (527)	127,000 (97,000)	175,000 (134,000)	V	(1)	0.62 Stepped	(1)	0.62 Stepped	(1)
Knellpoort (gravity arch)/Rietspruit	1988	South Eastern	Department of Water Affairs	164 (50)	656 (200)	59,000 (45,000)	77,000 (59,000)	V	(1)	0.60 Stepped	(1)	0.60 Stepped	(1)
Wolwedans (gravity arch)/Great Brak	1989	Cape	Department of Water Affairs	230 (70)	879 (268)	(196,000) (150,000)	(221,000) (169,000)	V	(1)	0.50 Stepped	(1)	0.50 Stepped	(1)
Morocco													
Ain Al Koreima/ Akruech	1988	Rabat	Direction des Aménagements Hydrauliques	85 (26)	407 (124)	34,700 (26,500)	39,000 (30,000)	0.20	(1)	0.60/ 0.75	(2) (5)	0.75 Stepped	(1)
Rwedat/-	1988	Rabat	Direction des Aménagements Hydrauliques	76 (23)	410 (125)	33,000 (25,000)	(35,000) (27,000)	0.40 Stepped	(11)	0.40 Stepped	(11)	0.40 Stepped	(11)
SOUTH AMERICA													
Brazil													
Saco de Nova Olinda/ Gravata	1986	Paraiba	State of Paraiba/Icoplan	184 (56)	755 (230)	173,000 (132,000)	187,000 (143,000)	V	(1)	0.80	(4)	Separate	
Argentina													
Urugua/Urugua-í	1989	Misiones	Electricidad de Misiones Sociedad Anonima/ Inconas	249 (76)	2254 (687)	772,000 (590,000)	819,000 (626,000)	V	(3)	0.80	(4)	0.80	(1)

NOTE: Type of face for dam: (1) conventional concrete; (2) precast concrete panels; (3) precast concrete panels with membrane plus conventional concrete; (4) unformed RCC; (5) RCC against forms; (6) precast concrete panels plus asphalt mortar; (7) conventional concrete slip-formed or extruded elements; (8) Conventional concrete—expansive cement; (9) precast concrete blocks; (10) mechnically compacted unformed RCC; (11) RCC with wire netting.
*Main gravity dam is 148 ft (45 m) high and 591 ft (186 m) long.
†Left nonoverflow section and lower portion of overflow section.

Table VII. Seepage collection and seepage reduction for various RCC dams. (Hansne & Reinhardt (1991))

Dam	Purpose	Max. hydraulic head, ft (m)	Max. wetted area, ft^2 (m^2)	Seepage control system	Seepage collection system
Shimajigawa	Flood and river control Municipal water storage	246 (75)	89,300 (8290)	Upstream facing concrete, 10 ft (3m) thick Double waterstop in contraction joints through entire section at 49 ft (15 m) on center Bedding concrete entire lift RCC interior Foundation grout curtain	Drain pipes downstream of water stops in contraction joints Drainage gallery Foundation drainage curtain
Willow Creek	Flood control	141 (43)	149,000 (13,900)	Zoned RCC Bedding concrete 1 ft (0.3 m) wide upper portion of dam	Drainage gallery Foundation drainage curtain
Copperfield	Industrial water storage	95 (29)	62,100 (5,770)	Thin wedge of conventional concrete (not full height of lift) Zoned RCC Three PVC waterstopped joints at key locations Foundation grout curtain	Drainage gallery Geofabric drain tubes Internal and foundation drainage curtain Geofabric strip drain every fourth lift near downstream face connected to voids produced by form jacking pipes
Middle Fork	Flood control	94 (29)	16,800 (1560)	Upstream facing concrete ±1.5-ft-thick (0.46 m) Partially caulked crack-inducer grooves 12 ft (3.7 m) on center Bedding concrete 6 ft. (1.8 m) wide RCC Foundation grout curtain	Drainage gallery/tunnel Internal and foundation drainage curtain Geofabric drain tubes near downstream face below gallery elevation Porous concrete zone hear downstream face
Winchester (now Carroll E. Ecton)	Municipal water storage	61 (19)	29,600 (2750)	PVC lined (65-mil = 1.65-mm) precast concrete upstream facing panels Conventional concrete ±1.5-ft-thick (0.46 m) downstream of panels RCC Foundation grout curtain	Geofabric/crushed rock toe drain

Table VII. Seepage collection and seepage reduction for various RCC dams. (Hansen & Reinhardt (1991))

Galesville	Multipurpose storage Hydroelectric	146 (45)	87,900 (8160)	40-mil (1-mm) thick elastomeric rubber membrane sprayed on upstream faces in two coats Facing concrete ±2 ft (0.6 m) thick Bedding concrete 6 ft (1.8 m) wide Zoned RCC Foundation grout curtain	Drainage gallery Internal andfoundation drainage curtain
Grindstone Canyon	Municipal water storage	128 (39)	90,400 (8400)	Upstream facing concrete ±2 ft (0.6 m) Partially caulked crack-inducer grooves 16 ft (4.9 m) on center Bedding concrete RCC Foundation grout curtain	Drainage gallery Internal and foundation drainage curtain
Monksville	Municipal water storage	141 (43)	131,000 (12,100)	Upstream facing concrete ±1.8 ft (0.55 m) thick PVC waterstops in crack inducers at 20-ft (6.1-m) and 40-ft (12.2-m) spacing Contraction joints through dam at 120-ft (3.7-m) spacing upper 40 ft (12.2 m) Bedding concrete 8 ft (2.4 m) wide plus hydrophytic rubber strip at end RCC Foundation grout curtain	Partial drainage gallery Internal and foundation drainage curtain
Arabie (now Mokgoma Matlala)	Agricultural and municipal water strage	98 (30)		Upstream facing concrete ±2.5 ft (0.76 m) thick PVC waterstops in crack inducers at 3.9 ft (12 m) on center Bedding concrete H/4 wide RCC Foundation grout curtain	Drainage gallery Internal and foundation drainage curtain
Upper Stillwater	Municipal, agricultural and Industrial storage	288 (88)	528,000 (49,000)	Slip-formed upstream concrete elements 2 ft (0.6 m) average thickness Zoned high-paste RCC Foundation group curtain	Drainage gallery/tunnel Foundation drainage tunnel

APPENDIX B

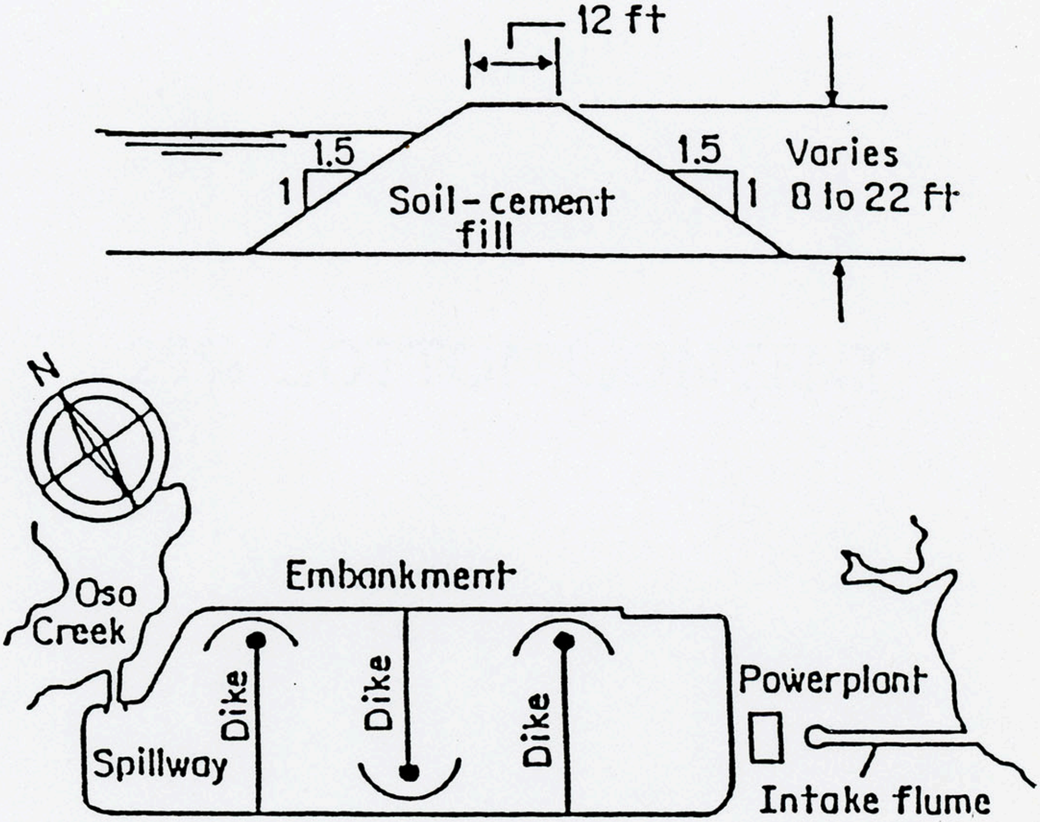

Figure 1. Barney M. Davis Powerplant.
(a) Typical embankment section;
(b) Plan of the cooling lake.
(Hansen & Reinhardt (1991))

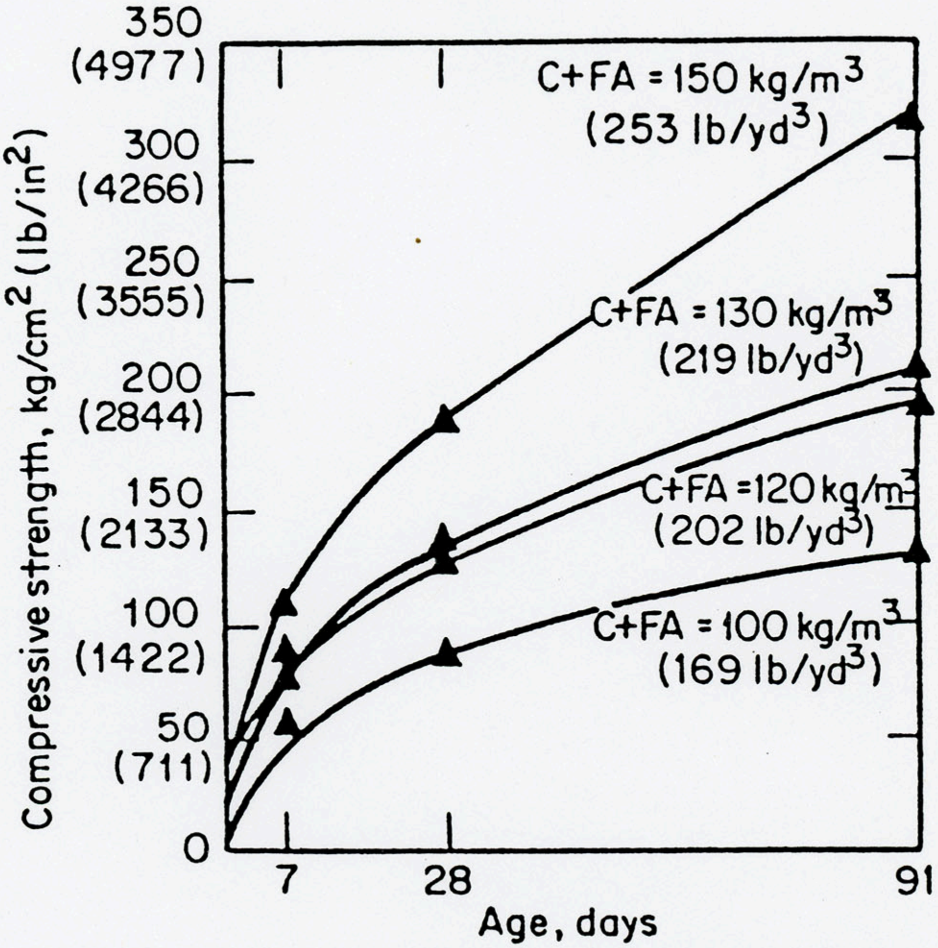

Figure 2. Relationship between cemntitious content & compressive strength with age.

(Hansen & Reinhardt (1991))

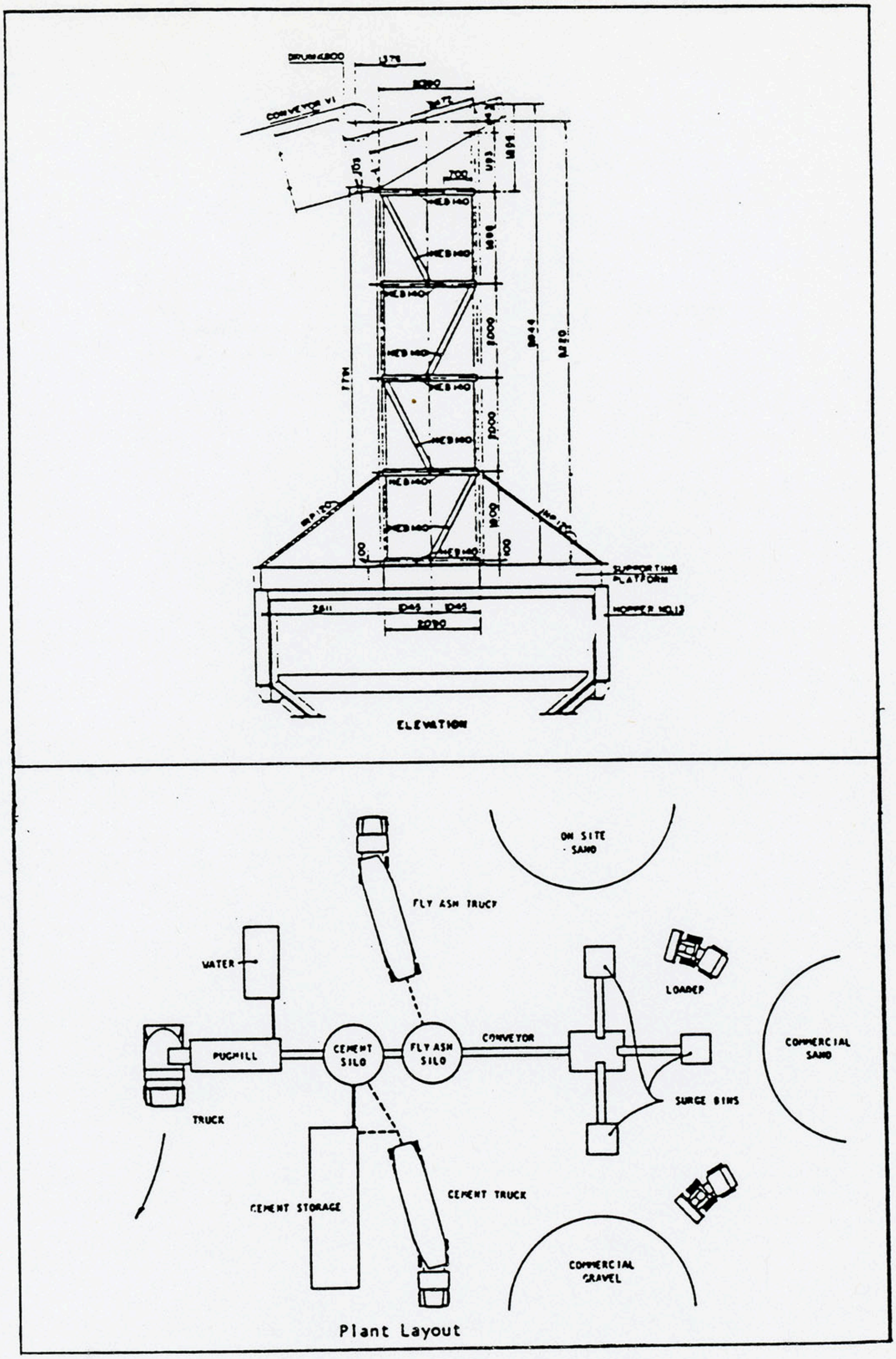

Figure 3. Mixing tower plan & elevation.
(Concrete International (1984))

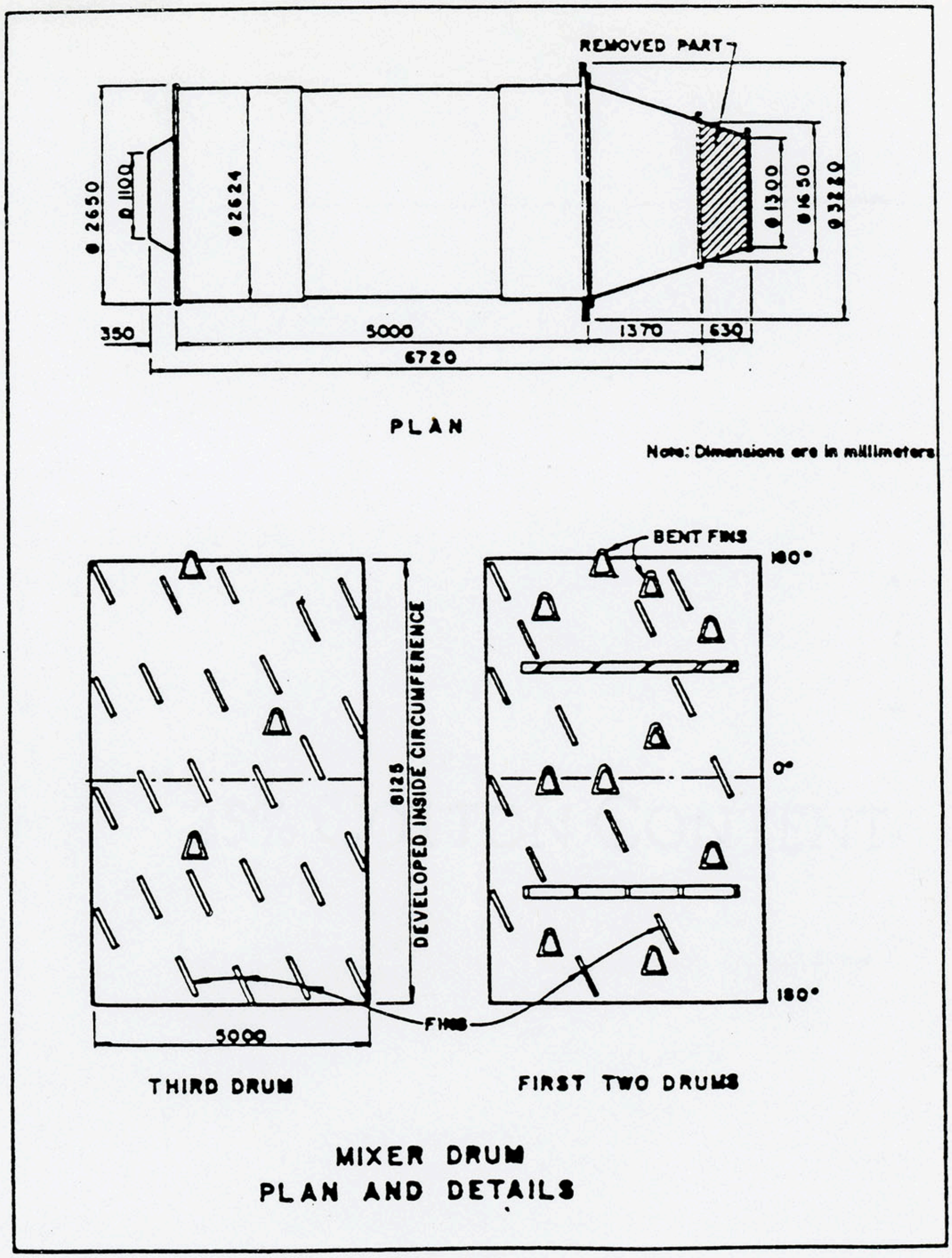

Figure 4. Mixer drum plan and section.

(Concrete International (1984))

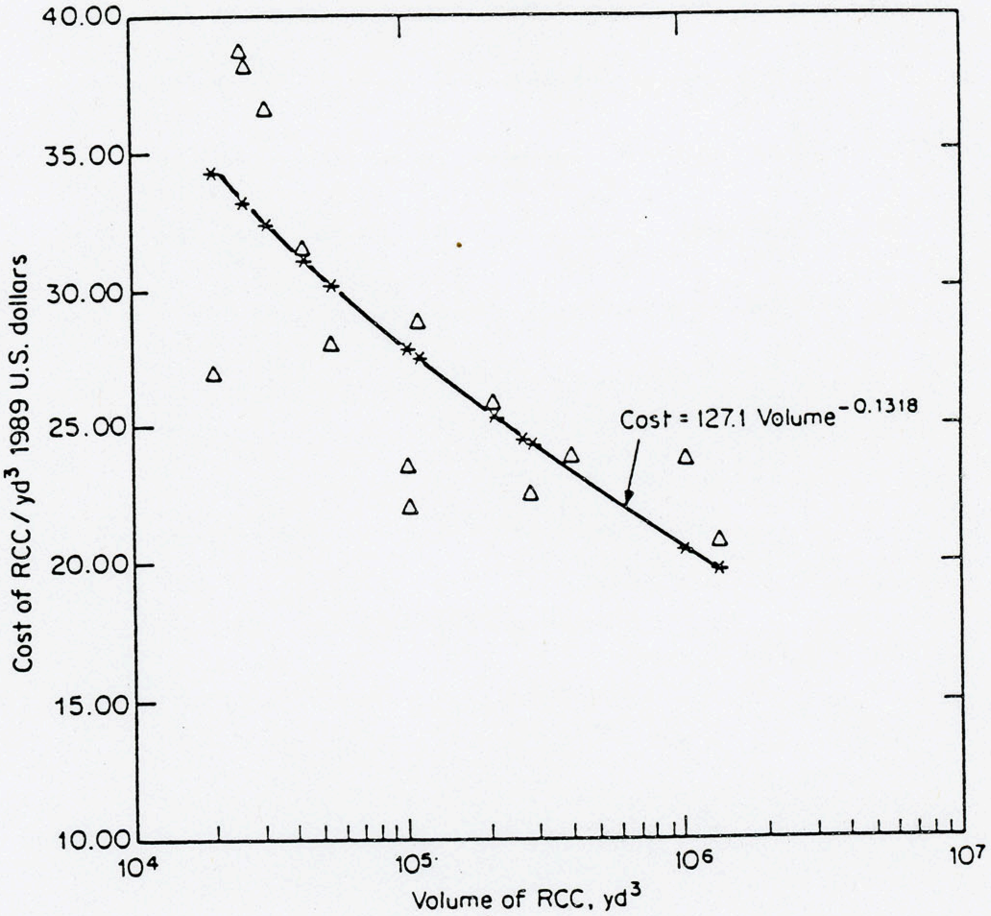

Figure 5. Costs of RCC per cubic yard.
(Note: 1cu.yd.=0.76cu.m.)
(Hansen & Reinhardt (1991))

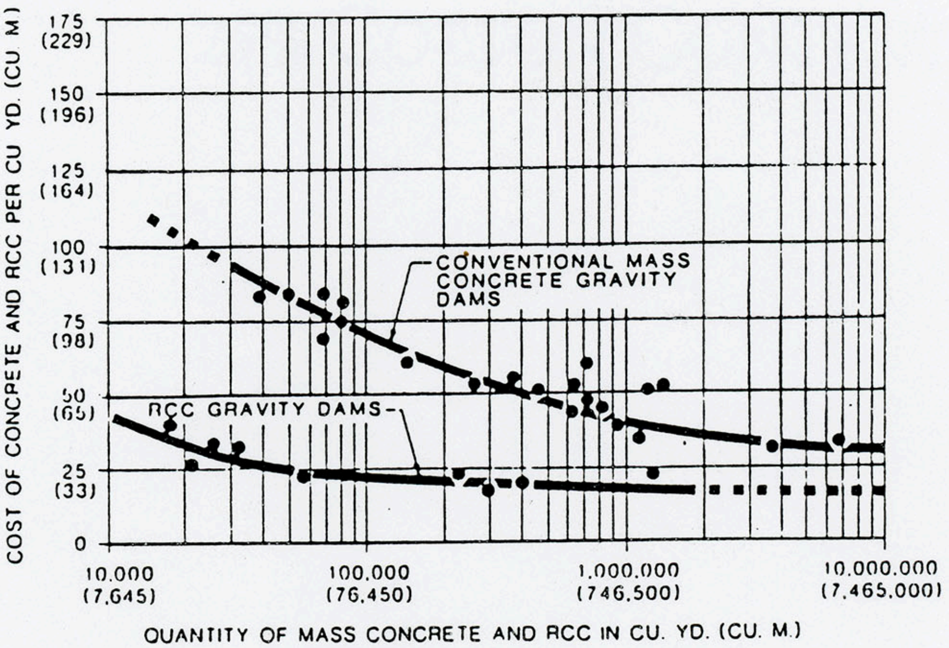

Figure 6. Comparison of RCC and mass concrete costs. (Hansen (1985))