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ROLLER COMPACTED CONCRETE AND ITS APPLICATIONS

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SYNOPSIS

Roller compacted concrete, as the name suggests, is a special type of concrete placed by earth-fill methods and compacted by Rollers instead of conventional immersion, form, or surface vibrators. This is basically a low cement concrete, generally with a pozzolan added as paste increasing component to contribute to the strength and moderation of heat of hydration. Roller compacted concrete is a versatile material with multiple uses, and can safely replace the conventional plain cement concrete in many locations with the advantages of low cost, quick and easier placement and having better scope for Thermal cracking control. This material in one of its forms was introduced and heavily used at Tarbela Dam from 1975 to 1986 and till this day Tarbela remains the greatest single user of the material. But somehow the material could not be afforded its rightful place in our concrete based gravity structures. It deserves a high and urgent consideration in a developing country like ours for various types of structures.

This paper presents an introduction to Roller Compacted Concrete as a material, its applications, design and construction techniques.

INTRODUCTION :

Roller compacted concrete is basically a low cement, no-slump concrete placed by earthfill methods. The concrete is brought to site in dump trucks instead of buckets and compacted by earth compacting rollers instead of immersion, surface or form vibrators. The rate of placement is thus much faster, (Maximum placement rate at Tarbela was 24,000 cyds/day, averaging 10,950 cyds/day which remains unsurpassed till this day) and cost much less than conventional concrete. In some cases the cost may be one half or even less than that of conventional concrete.

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Roller compacted concrete is designated by three different abbreviations viz "Rollcrete", "RCC" & "RCD" in accordance with the different approaches.

(i) "Rollcrete" is the term used in line with the soil Engineers approach.

(ii) "RCC" is the term used in accordance with concrete Engineers approach, and

(iii) The term "RCD" (Roller compacted Dam Concrete) is used while pursuing the approach of Japanese Dam Engineers.

The second and third types of Roller Compacted Concrete are similar in that vibration is essential for its densification and in that every effort is made for the material to duplicate conventional concrete, i.e. a "C" shape gradation is used for aggregates and the intent is to have the paste fill the voids in the aggregate as completely as practicable. A wetter mix than for the first type i.e, rollcrete, is thus formed. Such roller compacted concrete is generally placed in 12 inch layers with the expectation that bond will develop between lifts. Upper still-water dam is an example of this type. At Elk Creek Dam the material was spread in six inch layers and compacted in two feet lifts. Cannon (3) suggests that RCC be used as the designation for this type of roller compacted concrete.

The development of Roller compacted concrete (RCC) followed the idea derived by some field researchers from the behaviour of soil cement pavements and stabilised embankment slopes. The earliest use of "RCC" as Rollcrete is traced to "Yale" Dam in Washington (U.S.A) for a gravity wall in 1952 when 32,000 cyds of the material were laid. Another very small quantity of 20,000 cyds was used in the core of Shihmen Coffer-dam in Taiwan in 1961.

W.H.Price provided the real impetus towards use of R.C.C. in U.S.A. with special reference to Dam Construction about two decades ago, when he wrote to the Concrete Committee of U.S.Committee on large Dams pointing out that "Less than ten percent of the dams built in the U.S. during the previous three years, were constructed of concrete. The implications for the future of concrete dams are clear; build them more rapidly and economically or risk their extinction".

The first major pioneering use of "R.C.C." as rollcrete was started in our country at Tarbela Dam for rehabilitation works in 1975 and by 1986, the total consumption mounted to 3.5 million cyds (refer Table-1).

RCC has become one of the most interesting subjects in the concrete industry. A great diversity of practice exists in this relatively new technology. This diversity of RCC applications was recognized by ICOLD (International Committee on Large Dams) at their 1985 meeting in Lausanne, Switzerland.

B. AGREGATES SELECTION

Aggregates are evaluated for quality and grading depending on environmental exposure and strength requirements of the RCC. Variability in aggregates grading significantly affects cement and water requirements which, in turn, affect strength. Recent experience has shown that aggregates produced for uses other than for conventional concrete may be successfully used as aggregates for RCC. This is especially true for roll-crete applications. It is desirable to limit the MSA (maximum size aggregate) to 2 inches because smaller MSA is less susceptile to segregation during placement and creates fewer bonding problems at the lift joint surfaces. Fineness and grading of fine aggregate affect minimum paste requirements. Good quality RCC requires good quality aggregates.

CEMENTITIOUS MATERIALS AND ADMIXTURES SELECTION

Cementitious material requirements for RCC are similar to those for conventional mass concrete. Cementitious materials consist of portland cement and a suitable pozzolan generally 'Fly-ash'. The cementitious material content must be adequate to develop the required stgrength and at the same time, minimize the heat of hydration. Pozzolans are especially beneficial for RCC for their cementitious and low heat of hydration properties as well as a mineral filler. Use of type II portland cement with pozzolan or blended hydraulic cement may be required to control heat of hydration in mass concrete.

TEMPERATURE CONTROL

Temperature control is effected in RCC in several ways including : replacing a large percentage of cement with pozzolan, by placing the RCC only during the cooler part of the day and/or year, and by cooling the RCC mix with ice or liquid nitrogen. Cooling aggregates naturally during the winter may be beneficial if they are used in the spring and a reclaim system is used to extract cool aggregates, leaving the pile exterior undisturbed.

CONSTRUCTION METHODS AND EQUIPMENT

Adequate construction equipment is paramount to any RCC construction job. It is customary to construct a test section of RCC prior to actual job construction. It is essential to verify the capability of equipment and techniques proposed to be used by the contractor. The batching and mixing plant must be efficient, dependable and have a large production capacity to meet required placement rate, and round the clock working. Numerous delays resulting in cold joints in RCC placement are undesirable. Mixing plants using pug mills are also equally suitable for RCC production. Maintaining cleanliness on lift surfaces is also an important requirement. A conveyer system which delivers the concrete right at the placement site is highly desirable because it allows hauling units to remain on the job, thereby eliminating the dirt tracking problem. Heavy-vibrating, smooth, dual-drum rollers of about 10 tons are generally suitable for compaction. Lighter hand-compaction equipment is used near forms and along foundation contacts. For leaner "Rollcrete" 50 to 100 tons non-vibrating pneumatic typed rollers are more effective.

RCC PRODUCTION AND PLACING

Mixing :

RCC has been successfully mixed in both drum and pug mill batch-type mixers. Charging the mixer properly results in the best mixer efficiency. A dry mix is prone to segregation and is very difficult to compact at the bottom of the lift. A wet mix will not be compactible to a higher maximum density; however, the more critical consideration, bonding, will be improved.

Transporting

Equipments for transporting RCC should be capable of transporting the material quickly, without increasing segregation, reducing workability, or contaminating the lift surface. RCC transportation to the placement should be complete within 15 minuts of mixing. Experience has shown that covered belt conveyors running directly from the concrete plant to the lift surface can meet the preceding requirements. Use of holding hoppers should be minimized or eliminated when possible as these tend to promote segregation, increase transporting time, and may present problems like plugging. On small jobs, less than 40,000 yd^3 a conveyor feeding directly onto the lift surface has worked successfully. On larger jobs, the conveyor can dump directly into waiting trucks to maintain a continuous operation. Vehicles, such as trucks or scrapers, are not recommended for hauling concrete from the plant to lift surface, due to continual contamination problems, damage to the lift at the entrance point, longer cycle times, inefficient energy use, and the need to continually construct and maintain haul roads to the lift surface. Economics may favour truck hauls to smaller jobs.

Placing and Spreading

Constraints of time and segregation control favour minimal handling of RCC during placement, and placing directly from a moveable conveyor appears to be an ideal but costly method.

A more realistic placing operation involves end dump trucks equipped with a spreader allowing dumping and spreading at the same time. End dumping in piles and spreading with a dozer is not recommended as the prime placing method. However, this may be necessary in restricted areas or permitted in case the MSA is restricted to 2 inches. Placing and spreading should be completed within 30 minutes of mixing.

Placement in cool weather and during nights in warm weather can provide the maximum handling time. Such measures reduce internal heat build up resulting in lower potential for thermal cracking.

Compaction

Vibratory steel drum rollers are the primary equipment used to compact the RCC. The size and configuration of rollers used varies. Rollers with a vibrating frequency of 2,200 vpm (vibrations per minute) and higher work well with wetter, more plastic mixes (Vebe times between 15 to 30 s), Lower frequency rollers (1,700 vpm) with higher amplitudes (soil type rollers) are more effective on stiffer RCC mixes (Vebe times greater than 45 s). RCC should be compacted as soon as practicable after the material is spread, but at least within 15 minutes of spreading or 45 minutes of mixing. Lane edges should be rolled if an adjacent lane is not placed within 15 minutes. Vibrating tampers/plate compactors are effective in very restricted areas, such as against kerbs/abutments.

Observation of the concrete during compaction gives a useful indication of workability. When RCC approaches full compaction, the concrete should exhibit slight plasticity as indicated by observable movement of material ahead of the roller. Heavy foot pressure by a person standing on the RCC surface immediately after the last required roller pass should produce a surface yielding, indicating mortar filling all voids between aggregate. A stiff unyielding surface requires additional compaction. If, after additional roller passes the surface remains stiff and unyielding to the roller, inadequate mortar is present to fill all the aggregate voids and rock-to-rock coarse aggregate contact will effectively prevent further compaction. Crushing of aggregate on the lift surface also indicates a stiff mix and lack of needed workability.

RCC MATERIALS

Aggregates

Properties of both freshly mixed and hardened RCC are significantly affected by aggregate characteristics. Aggregates affect the potential for segregation and workability of the mix which determines the scope for compaction of the mixture, and properties of the hardened concrete. Aggregates constitute approximately 85 percent of a concrete mixture and thus significantly affect hardened concrete characteristics such as: strength (compressive, tensile and shear), elastic properties, thermal properties (conductivity, diffusivity, thermal expansion and specific heat), and durability. Aggregate properties such as volume of voids and particle shape affect the paste requirement of concrete.

Aggregates for RCC are evaluated by standard physical tests. Proper selection of suitable aggregates leads to greater economy in design and greater long-term serviceability of RCC Structures.

MSA (Maximum Size Aggregate)

The MSA can affect many of the properties of RCC. As with conventional concrete, increasing the MSA reduces the void content of the aggregate and thus contributes to lowering the paste content. This can lead to greater economy by reducing processing costs, lowering cementitious materials costs, and reducing the potential for thermal cracking. The disadvantages of increasing the MSA are primarily associated with problems in mixing and handling RCC, including segregation and bond.

GAP GRADED AGGREGATE

The use of gap graded aggregate in RCC was recommended by Hilf (13) in 1987 stating that potential problems of seepage along lift lines, temperature and drying shrinkage cracking, and segregation of aggregates may be minimized or eliminated by the use of gap-graded aggregate concrete. This type of concrete consists of a skeleton of single-size coarse aggregate, the voids of which are filled with a graded fine aggregate, cement and water paste. The maximum size of fine aggregate is one-eighth of the minimum size of coarse aggregte and very fine sand is eliminated to reduce the specific surface of the aggregates, thereby minimizing the water and cement requirements. The resulting material is a minimum slump, very dense concrete with low cement content. The proportioning method for the concrete mix is straight forward, depending only on the compaction characteristics of the aggregates, the specific gravities of the materials, and the water-cement ratio needed for design strength. Use of Gap Graded Aggregates has the following benefits : -

(i) The seepage problem is mitigated by fine aggregate in paste reaching the bottom of the compacted lift, coarse grains fraction causing the bond inadequacy absent.

(ii) Temperature shrinkage is reduced on account of low cement content and reduction of heat of hydration. Joint cutting is not required.

(iii) Drying shrinkage is virtually eliminated by coarse grains touching each other and forming non shrink skeleton on compaction, like prepacked concrete.

(iv) Segregation is also precluded as the coarse aggregate consists essentially a single size.

Aggregate Grading

The most significant difference in RCC mix design from conventional concrete concerns the allowable grading limits of aggregates. The aggregate gradings for RCC have ranged from that specified for high quality conventional concrete with normal size separations to the use of pit-run materials with no size separation whatsoever.

Changes in consistency and workability of RCC are affected by changes in aggregate grading. Increases and decreases in fine aggregates proportions are reflected by increases or decreases in water demand and workability. A generally used grading envelope is exhibited in Fig. G.

Fines Content of Aggregate

Non-plastic to low plasticity fines (minus 75-μm No. 200 sieve size) have been successfully used in RCC. Fines having a PI (plasticity index) of 4 or less should pose no problems during construction. Fines having a PI of 5 to 7 may be used only after extensive laboratory tests have proved that the increased plasticity will not result in formation of clay balls or lessen the workability of the material. Fines having a PI greater than 7 are not recommended for use in RCC. The presence of 10 percent or more clay balls, on a wet mass basis, is indicative of potential problems during construction.

Cementitious Materials

Cementitious materials include cement, pozzolan, or blended cements. The strength of RCC (having consistent quality aggregates) is dependent essentially on the proportions of cement, pozzolan, and water. The type of cement has a notable effect on the rate of hydration and the rate of strength development and, therefore, significantly affects strengths at early ages.

Where the volume of RCC involved, requires consideration of the temperature rise, use of low heat cement or partial cement replacement with a pozzolan is required. Total heat generation within the mass is governed by the total cementitious materials content of the mix and replacement percentage of pozzolan. Because no cooling is used in RCC construction, consideration of heat generation is essential. Structures with low strength requirements and correspondingly low cementitious materials content should not experience significant thermal cracking problems under normal conditions. Mixes with higher strength requirements utilizing high cementitious materials contents generally require higher replacement levels of pozzolans to minimize heat generation. Upto 75 percent fly ash by volume of cementitious materials has been used successfully in RCC mixes having strengths exceeding 5,000 lb/in^2 at 1 year and 7,000 lb/in^2 at 5 years. The selection of cement types should be based in part upon design strength requirements and the age at which this strength is required. For massive RCC structures, use of low heat cements such as Type-II, or blended cements are recommended. In RCC construction, use of pozzolans has been successful in reducing heat generation without loss of strength, increasing ultimate strength beyond 180 days, and increasing the paste volume of the mix. Fly ash (due to its spherical shape) is particularly effective in RCC mixes which use standard graded concrete sand as a means of providing fines to aid in compaction. In proportioning mixes for minimum paste volumes, one principal function of a pozzolan or added fines is to occupy void space which would otherwise be occupied by cement or water. Tests show a continuing pozzolanic activity at extended age. Thus, the pozzolans not only occupy space but contribute to strength development as well. Their contribution to heat generation varies inversely with the ratio of pozzolan to cement such that for a given strength requirement, the mix with the lowest cement content (meeting the required strength) will have the least temperature rise.

The reduction in early strength levels of concrete containing pozzolans is well known and the optimum percentage of pozzolan may be governed by early strength requirements. However, for many massive RCC applications with long-term strength requirements, liberal replacement levels are possible.

The quality of a pozzolan determines its effectiveness as a cementitious material and its replacement level with cement for a given strength is affected by the reactivity of the pozzolan.

Admixtures

Chemical admixtures have been specified in many RCC applications to reduce water requirements (ASM: C 494, type A) and to retard setting time (ASTM: C-494, type B and D). Type A's have been used with RCC mixes using clean sands and aggregates. Their ability to lower water requirements or provide added workability with high minus No. 200 fines content is questionable. Types B and D admixtures have been used successfully to delay the setting time of RCC. This may have benefit in keeping an RCC joint "alive" and providing a better bond. Figure-A shows the adiabatic temperature rise of two RCC mixes using both a type A and D admixture. RCC mixes with high fly ash contents have had significant delays in setting when the admixture dosage was based on total cementitious materials content. Therefore, dosage of a chemical admixture has to be based on cement content only.

Most conventional methods of adding AEA's have been marginally successful in entraining air in RCC. If air could be entrained into RCC, it would provide substantial benefits in providing freeze-thaw durability and enhance workability.

RCC MIX DESIGNS

General

Mix design methods for RCC structures can be grouped into three principal categories :

1. Mixes designed similar to conventional mass concrete using consistency measurements,
2. Lean RCC mix designs,
3. Mixes designed by soil compaction methods.

RCC mixes designed and proportioned similar to conventional mass concrete vary in cementitious materials, water and aggregates to achieve a desired level of workability and strength. This method is recommended where joint bonding characteristics are critical, where specific strengths (usually more than 1,500 lb/in^2) must be maintained, and where heat generation characteristics must be considered.

Lean "Rollcrete" mixes are designed using a relatively fixed grading of aggregates, low cementitious materials content, and with the water content varied for "optimum consistency" by visual examination during construction. The main concern with lean RCC mix designs has arisen from poor bond strength along hardened lift joints and seepage between lifts due to the minimum paste volume of the mix. To overcome this problem, the RCC must be placed at a rapid rate to minimize the time interval between lifts or by providing supplemental joint treatment.

Some RCC mixes are designed using soil-cement compaction technology. Soils are blended with a percentage of cement or cementitious materials based on dry weight of soil aggregate. Five laboratory compaction tests are performed on RCC mixes prepared at different moisture contents. The optimum moisture content and calculated laboratory maximum dry unit weight are the basis for specifying mix proportions. The advantage is a simplified design concept, which can readily be applied to many smaller structures without significant cost. The disadvantage is that the moisture content varies significantly depending on type of soil used, the compactive effort applied to test specimens, the method of determining moisture content, and the variation in w/(c+p) ratio. As the moisture contents cannot be accurately determined by oven drying because of cement hydration, only calculatd moisture contents can be used.

Consistency Tests

Proportioning for optimum workability for compaction at specific design strengths was used at the Japanese RCD Shimajigawa, Tamagawa, and Pirica Dams, the Bureau of Reclamation's Upper Stillwater dam, and the COE's Elk Creek Dam. The Modified Vebe Compactibility Test served as the basis for determining workability and optimizing aggregate proportions. The Vebe apparatus consists of a vibrating table of fixed frequency and amplitude with a 0.33-ft^3 container attached to it. A loose RCC sample is placed in the container under a surcharge of either 20 to 50 pounds and the sample is vibrated until fully consolidated. Optimum Vebe time is influenced by mix proportions, particularly water contents, MSA, sand content, and minus No. 200 fines content. Mixes with clean concrete sands and fixed aggregate proportions with 1.5-inch MSA generally require a Vebe time of 15 to 30 seconds to compact. TGests at Elk Creek Dam using 3-inch (75-mm) MSA with higher minus No. 200 fines contents required Vebe times of approximately 20 seconds to compact with a 20 pound surcharge. Two vibration tests similar to the Vebe test are used by Japanese to evaluatge workability; one for 1,5-inch MSA mixes and one for 6-inch MSA mixes. The Vibration compaction time is called tghe VC Value. Figure-B shows the variation in VC Value with water content for fixed cementitious materials content. Lower the VC value the higher unit water content. However, too low a VC value results in bleeding after vibration. Reduction in water content beyond a certain value will not induce any further increase in strength with decrease in the w/(c+p) ratio. This is because aggregate woids will not longer be filled with paste. Figure-C shows the variation in strength with watger content for a fixed cementitious materials content.

Details of some RCC mixed using consistency tests are contained in Table-II.

Proportioning Fine Aggregate for Minimum Paste Requirements.

The void content of fine aggregate, as determined in dry-robbed unit weight measurements, normally ranges from 30 to 42 percent. The actual void content may be somewhat smaller due to the inaccuracy of measurement, but it makes little difference because the minimum cement, pozzolan air, and water contents required to achieve a solid valume must fill all the fine aggregate voids and coat all the aggregate particles.

Proportioning Coarse Aggregate for Minimum Mortar Requirements.

The proportioning of coarse aggregates depends upon the combined effects of aggregate voids, surface area, and particle shape. Dry-rodded densities and combined grading control are dependent upon proportioning and number of separated sizes and the variation of gradings within the individual sizes. Provided grading control is satisfactory, the dry-rodded density increases with the MSA. Since void content decreases with increased dry-rodded unit weight, the void content of aggregates with the same specific gravity in each size fraction decreases with increased aggregates size. Compactibility increases with rounded and cubical shapes and decreases with flattened shapes.

For any grading or MSA, the minimum aggregate volume producing no slump consistency can be established by proportioning the mortar fraction to yield the approximate strength required, and by adjusting the proportions of coarse aggregate and mortar to achieve a zero slump. The proportions of fine aggregate, cementitious material, and water should remain in a fixed relationship during these adjustments. The upper limit of mortar volume corresponds to the quantity just producing zero slump conditions. Vibration time required to fully consolidate this mixture will generally correspond to the minimum stiffness necessary to support the vibratory equipment and is generally about 5 seconds with the Vebe apparatus. Keeping the make up of the mortar consistant, increase the coarse aggregate volume and decrease the mortar volume in equal increments and check the vibration time for full consolidation as shown in Figure-D. The outer limit of mortar volume for consistency will be recognized when the incremental increase in coarse aggregate proportions results in substantial decrease in density for a given compactive effort as illustrated on Figure-E. A coarse aggregate volume approximately halfway between these limits will minimize control problems during placement. An estimate of coarse aggregate volumes for different MSA's is given in Table-III, below : -

Table - III

Absolute Volume of Coarse Aggregate per Unit Volume of RCC

Maximum size aggregate, inches.	Absolute volume, percent of unit concrete volume
6	63 - 64
4.5	61 - 63
3	57 -61
1.5	52 -56
0.75	46 - 52
0.375	42 - 48

Selecting Proportions Using a Maximum Wet Density Approach :

Selecting mix proportions for maximum wet density involves use of some means of extended vibration of mortar and concrete to determine the maximum density and compare with air-free density of the RCC Tables No. IV (Water : (C+F), V- (C : F), VI (Mortar Ratios) and VII. (C : F for different ages of concrete) are quite handy in helping proportion the mixes.

Table - IV

Water to Cement plus Fly ash ratio by Weight and Volume

W/ (c+fa) by weight	w/(c+fa) by volume				
fly ash: (%)	0	25	40	50	75
0.40	1.26	1.16	1.11	1.0-7	0.997
0.50	1.58	1.45	1.38	1.34	1.25
0.75	2.37	2.18	2.07	2.01	1.87
1.00	3.16	2.90	2.77	2.68	2.49

Assuming : Water = 62.3 lb/ft^3 (1000 kg/m^3)
Cement = 197 lb/ft^3 (3156 kg/m^3)
Fly ash = 145 lb/ft^3 (2323 kg/m^3)

Table - V

Percent fly ash by weight and volume

Fly ash percent by weight	Fly ash percent by volume
25	31
40	48
50	58
75	80

Assuming : Fly ash = 145 lb/ft^3 (2323 kg/m^3)
Cement = 197 lb/ft^3 (3156 kg/m^3)

Steps in proportioning are as follows :

1. Determine the minimnum paste volume as discussed in section IV-C. In lieu of these tests, ratios of air-free volume of paste to air-free volume of mortar "pv" of 0.38 for interior mass mixes and 0.46 for bedding mixes have generally been found suitable, or refer to table VI.

2. Select f/c and w/(c+f) ratios from figure F for the trial design strength. An estimate of suggested cement to fly ash ratios for different design strength ages is given in table VII.

3. Determine the volume of coarse aggregate "Vca" either by selection from table-II or by trial.

4. Calculate the volume of air-free mortar per cubic yard "Vm" assuming 1.5 percent entrapped air, from :

$$Vm = Cv\,(0.985) - Vca$$

Where Cv = the unit volume of concrete in cubic yards.

5. Calculate the air-free paste volume "Vp" using the selected volume ratio of step 1. as "pv" from :

$$Vp = Vm\,(pv)$$

6. Determine the fine aggregate volume "Vfa" from :

$$Vfa = Vm\,(1-pv)$$

7. Determine the trial water volume "Vw" from

$$Vw = Vp[w/(c+f)]/[1+w/(c+f)].$$

Where w/(c+f) = water/cementitious materials ratio by volume (Fig. F and table-IV).

8. Determine cement volume "Vc" from :

$$Vc = Vw/[w/(c+f)]\,(1+f/c)$$

Where f/c = ratio of volume of fly ash/volume of cement.

9. Determine the fly ash or pozzolan volume "Vf" from :

$$Vf = Vc\,(f/c)$$

10. Establish the various weights of materials by multiplying the individual volumes by their respective unit weights.

11. Check the consistency of the mix to determine the minimum extent of external vibration in seconds needed to achieve maximum compacted density.

12. With the finalized coarse aggregate volumes, run two additional mixes, one with higher and one with lower w/(c+f) ratios. Plot strength versus w/(c+f) ratio or final mix selection.

Table - VI

Range of paste/mortar ratios (pv) for different joint conditions

pv	Joint / bond condition
0.30 - 0.35	Minimum / no bond.
0.35 - 0.38	12-hour exposed joint
0.40 - 0.43	24-hour exposed joint
0.43 - 0.46	> 24-hour exposed joint or high bond requirement
0.46 - 0.50	Bedding mix

Note : The pv (paste/mortar) ratio is equal to the ratio of the volume of air-free paste of cement, fly ash or pozzolan, and water) to the volume of mortar (paste and fine aggregate). The minimum pv ratio for RCC would be equal to the volume of voids in a given fine aggregate. Thus for an aggregate with a voids content of 34 percent (voids ratio = 0.34), the minimum pv would be 0.34. One cubic foot of mortar at this pv would have 0.34 ft^3 of paste and 0.66 ft^3 of fine aggregate.

Table - VII

Suggested ratio of cement to fly ash for the specified design strength age.

Age 1/ (Days)	Cement : Fly ash ratio (by weight)
28	75 : 25
90	60 : 40
180	50 : 50
365	25 : 75

1/ Age at which specified design strength must be achieved.

Proportioning Lean RCC Mixes

Concrete mixes for a number of RCC structures have been proportioned using a relatively fixed grading of aggregates while varying cementitious materials and water content to meet required strength and optimum compactibility. A significant difference between these mixes and standard concrete mixes has been the use of a significant volume of nonplastic minus No.200 fines to reduce aggregate voids. The paste content of lean mixes is much closer to the minimum paste required to fill the voids in the aggregates. As suggested grading envelope for aggregates for lean mixes (Rollcrete) appears as Figure-'G'.

RCC TESTING AND QUALITY CONTROL

A. Testing

1. General

Testing mixes for major RCC structures follow the same testing requirements as for conventional concrete structures. Strength, elastic properties, thermal properties, and durability are as important for RCC as for other concretes. Because RCC construction methods differ from conventional placing methods (i.e, layered construction and rapid placement), greater emphasis should be placed on tests for bond between lifts and heat generation. Use of greater percentages of pozzolan in RCC mix designs requires greater emphasis on long-term test results, rather than the standard 28-days. If more than 25 percent fly ash is incorporated into the mix design, 90-days strength tests should be considered. Tests at 180 days or even 1 year should be considered if fly ash content exceeds 50 percent. Tests performed for Upper Stillwater Dam revealed an 80-percent increase in compressive strength between 90 days and 1 year for mixes with 70 percent fly ash.

2. Compressive strength and elastic properties.

Tests are performed to confirm compressive strength of the various mixes employed throughout the job. Fabrication of test specimens is difficult for RCC because it is too stiff to consolidte by rodding or internal vibrators. A standard test method for fabricating RCC test specimens by Vebe apparatus has been successful for almost all types of RCC mixes and has been used to consolidate 9-inch-diameter by 18-inch-high specimens with 3-inch MSA. Specimens should be consolidated to their maximum density, provided the same density is achievable in the field.

Testing for creep parameters of RCC provides important information for large structures which will experience an increased loading almost immediately after placing due to rapid construction. The average placing rate at Galesville Dam exceeded 20 feet in height per week.

3. Density.

There are a number of methods available for density testing of both freshly mixed and hardened RCC.

The density of fresh concrete can be determined from a vibrated sample such as the Vebe test sample. It can also be obtained from compacted test cylinders. However, the smaller sample size produces greater variability. In the field, the wet density of RCC is usually determined by a nuclear density gauge. It is necessary to recognize that test results are affected by gauge geometry and calibration errors. A single probe gauge averages the density of the RCC from a source at the bottom of the probe to the detector in the gauge housing. The density obtained is heavily weighted to the upper two-thirds of the lift of RCC, where full compaction is easily achieved. Low density RCC at the bottom of a lift is not easily detected, even though it is the most critical area. A double probe nuclear gauge has recently been used for RCC. This gauge is capable of measuring the density between two probes driven to any given depth of the lift and may prove more useful in evaluating the density at the bottom of a lift along the joint interface.

A nuclear density gauge should not be used for moisture determination because it only measures the moisture at the RCC surface (for a single probe gauge) or along a 4" x 6" area adjacent to the probe (for a double probe gauge). the moisture content reading is also affected by the presence of hydrogen in any form, such as from admixtures.

Use of sand cone apparatus for density test of fresh RCC is not recommended, as this shows very poor results.

4. Lift Joint Bond.

Bond strength may be affected by age of the joint and exposure, strength of the RCC, paste volume of the mix, degree of compaction of the RCC on the lift, and lift preparation methods. Two primary methods of evaluating bond strength are direct tension and direct shear tests. It is particularly important to simulate joint age, exposure, and surface preparation methods used, if any. Time and cost of constructing a testing section must be weighed against the importance of varifying critical design assumptions.

When interpreting shear test results, it is important to differentiate between actual cohesion 'c' of a chemically bonded joint and shear resistance or coefficient of internal friction (tan ϕ) of an unbonded joint. Cohesion is determined from breaking unbroken specimens in direct shear. Tan ϕ is determined by sliding broken joints in direct shear.

5. Thermal Properties.

Because of rapid construction and lack of embedded cooling pipes in RCC structures, it is often necessary to investigate thermal properties of the mix. The adiabatic temperature rise test simulates the expected temperature rise potential of the RCC mix. The adiabatic temperature rise is dependent upon the cement plus pozzolan (usually fly ash) content of the mix. Because pozzolan generates approximately one-half the heat of cement on a pound-for-pound replacement basis, the total temperature rise may be reduced by liberal use of a suitable pozzolan. It is important to use the same cement plus pozzolan contents which will be used in the structure and to use an initial RCC temperature which is representative of the placing temperature expected at the job site. Examples of temperature rise curves for different mixes tested by the USBR appear in Figures H,J & K.

Other thermal properties include specific heat, diffusivity, conductivity, and coefficient of thermal expansion. These properties are dependent upon the quantity of and properties of the RCC materials; aggregates, cementitious materials, and water.

6. Durability.

RCC is not considered durable under freeze-thaw conditions unless some protection against saturation or use of air entrainment is provided. As it is difficult to entrain air in RCC, other means of protection like "sacrificial" RCC in exposed surfaces, a conventional air-entrained concrete facing, or some means of membrane protection have to be considered.

Permeability testing of RCC shows the RCC mass to be comparable to conventional concrete of similar composition. The major concern for permeability of RCC structures has been seepage between lifts of RCC and not the RCC itself.

7. Workability and Consistency.

The primary means of evaluating workability and batch to batch consistency of

RCC is with the Vebe (or VC) vibration test. This test gives an indication of the batch to batch consistency of mixes and a working range where RCC should readily compact under a vibratory roler. For mixes designed similar to conventional mass concrete, this test has proved effective. For drier mixes with lower paste contents, this test has a greater variability. Mixes with a Vebe time in the range of 15 to 30 seconds have been found to compact readily in four to eight passes with a vibratory roller. The Vebe apparatus can also be used for fresh concrete density tests and for test specimen casting.

QUALITY CONTROL.

Quality control programme for RCC structures should be planned prior to construction, monitored during construction, and confirmed after construction. Because of the wide variation in RCC designs and material requirements, the designer should plan a quality control programme for each structure. RCC mixes have shown greater variation in quality than most conventional concrete mixes. This should be compensated for by sufficient over design factors for strength requirements.

Routine testing should be performed throughout construction and extra testing whenever job conditions warrant. Tests should be performed on all materials being used in the RCC mix followed by tests of freshly mixed and hardened concrete. Some test results may be obtained from suppliers of materials such as cement and fly ash.

Aggregate properties should be monitored closely during construction because they have a great influence on the compactibility of the concrete. The percentages of sand and the properties of minus No.200 fines content of the mix are very important factors.

It is essential to have readily available the information on the actual batch proportions of RCC as they are mixed.For effective evaluation of compaction it must be possible to determine the maximum air-free density of the RCC for comparison with nuclear gauge density test results.

There are two reasons to evaluate density. The first is to confirm design assumptions for unit weight of the structure used in stability calculations. The second is an indirect assessment of the compaction of the lift and, particularly, compaction at the joint interface. Failure to properly compact the lower portion of the lift of RCC, results in a low or no-bond situation which may result in significant seepage of water through the structure. An effective means of evaluating in-place density of RCC is with a nuclear gauge. It must be emphasized,however, this method of testing is only an indirect means of evaluating compaction. Achieving the highest value for density may not necessarily result in achieving the greatest bond potential between lifts of RCC. Cores obtained from Upper Stillwater Dam have shown that mixes wet of optimum had improved bond due to reduced segregation and greater compaction.

Nuclear gauge density testing should begin as soon after compaction as possible, to be an effective quality control tool. Sections which do not pass the tests can be rerolled prior to hydration.

The moisture content of RCC mixes is critical for achieving compaction. Tests for moisture content include oven drying, nuclear density gauge, and chemical analysis. The most accurate means of controlling the moisture content is at the batch plant by recording the weights of materials as they enter the mixer.

Consistency test should be performed on a regular basis as a means of evaluating the workability and relative compactibility of the RCC. It is best to sample and test the RCC at the batch plant. The Vebe (or VC) time to compact the sample should be correlated to the compactibility of the mix with a vibratory roller through nuclear gauge density tests and confirmed with cores if possible.

Placement temperature of RCC is extremely important for massive structures. If the RCC temperature is too high, the heat generation which follows could lead to thermal cracking in the structure.

A test section constructed with equipment to be used for the job can facilitate checks on contractors capability to handle the material without segregation, compaction equipment for adequacy, final adjustment of the RCC mix design, and to familiarize contractor's personnel and inspecting Engineers with the procedure and end product expected. Test sections have been very beneficial for projects constructed to date.

The test section should closely simulate actual job placing operation including mixing, transporting, and placing procedures. The placement rate should correspond to the time interval between lifts expected for actual construction. The test section should be readily accessible for coring, saw cutting, or destructive testing for at least 28 days after construction. The primary means of evaluation can be visual observation of cores for segregation, compaction and bond development, unless further testing is needed to confirm design assumptions.

Applications of Roller Compacted Concrete.

Roller compacted concrete on account of its characteristics and advantages, has gained a rapid recognition as a replacement material for conventional cement concrete in several types of gravity structures as enumerated below:

(1) Dams
(2) Pavements
(3) Airfield Aprons
(4) Parking lots
(5) Stocking areas
(6) Streets and
(7) Unreinforced floors, linings etc. and is steadily gaining further ground.

(1) Dams

As mentioned in an earlier paragraph, Tarbela Dam was the first structure where a major quantity of RCC (3.5 Mcyd) was used in place of conventional concrete starting from 1975 till 1986. The first dam constructed with RCC (Shimajigawa) in Japan was completed in 1982. Since its completion 18 more dams over 50 feet high had been completed by March, 1988, (Table-VIII) spread over all the continents of the world and quite a few others were under construction and design work (Table-IX). RCC is also being utilized for rehabilitating, strengthening and repairs to existing concrete or earthfill dams. At Stacy Dam, the earth and rockfill embankment has been provided with an RCC spillway.

Design.

Roller compacted concrete gravity dams are designed for the same considerations of stability against overturning and sliding as a conventional concrete dam. The ACI 207 Committee Report on RCC (1) states: "No concrete gravity Dam has failed under sustained loading or flood conditions as a result of initial failure in the concrete section above base rock. Historically, the failure in the concrete dams has been by sliding or shear failure of the foundation rock". The lift joints in roller compacted concrete are more numerous than the lift joints in conventional concrete. Bonding across lift joints is doubtful not only for the Rollcrete type of roller compacted concrete, but also for the RCC and RCD types. Even with conventional concrete where green cutting of lift joints is done, bond is not always assured on every part of every lift joint. Many conventional concrete gravity dams show dampness at some lift joints on the downstream face of the dam, indicating lack of perfect bonding. Lift joints are therefore critical in the analysis of the concrete section.

For the width of the dam to be kept to a minimum, uplift on the base and on lift joints should be reduced by drainage to say one-third of the reservoir head at about the quarter point downstream of the upstream face, Figure-L.

On this basis the base width of the dam should be equal to about 0.7 of the height of the dam. Downstream slopes of 0.8:1.0 or 0.7:1 have been frequently used since it is about the steepest slope for roller compacted concrete without downstream forming or facing.

To assure that uplift forces are kept under control, a curtain of drain holes should be installed at about the upstream quarter point and an impervious membrane should be incorporated at the upstream face. The drain holes should empty into a low level gallery.

SLIDING STABILITY.

The shear resistance against sliding on lift joints can be expressed by the Mohr-Coulomb failure law as below:

s = c + P tan ϕ, where
s = shear resistance (lb/sq in)
c = Cohesion (shear resistance at zero normal stress)
p = intergranular normal stress on lift joint (lb/sq in)
ϕ = angle of fabrication for the lift joint.

A factor of safety of 1.4 to 1.5 is satisfactory. If bond across lift joints is never developed or is broken due to tensile forces created by earthquake loading or due to hydraulic fracturing, at the location of such loss of bond, the cohesion will become zero. By having the lift joints slope several degrees upward from upstream to downstream, the factor of safety based upon friction alone can be increased to 1.5.

THERMAL CRACKING.

Although low cement contents are used for roller compacted concrete, a temperature rise to 90 degrees Fahrenheit is not unusual. Efforts can be made to reduce the temperature rise by using cold aggregates.

It is desirable to provide roller compacted concrete dam with an impervious upstream membrane of reinforced concrete with water-stopped contraction joints. The contraction joints in the facing will act as the starting point for shrinkage cracks in the roller compacted concrete. Water will be prevented from entering these cracks by the waterstop in the contraction joint of facing concrete.

BONDING OF LIFTS IN R.C.C. DAMS.

Bonding of successive lifts to each other is one of the critical problems of RCC. Inadequacy/absence of bond results in loss of cohesion and seepage through dams. The following 4 methods for achieving bond between successive concrete layers are being used at the present.

1. Time-temperature (maturity) restrictions.
2. Bedding concrete on treated or untreated surface.
3. Mortar layer on treated surface.
4. High paste concrete on treated or untreated surface.

The first method is unrestricted placement of RCC within specified time-temperature (maturity) guidelines for the joint as determined by degree-hours, i.e., the average hourly temperature multiplied by the number of hours the lift is exposed. For instance, if a lift of RCC is exposed at 70^0 F for 10 hours; the lift has a maturity of 700^0 F-hr. Following the expiration of a specified maturity limit, the lift must be treated in some way prior to placing the next lift. The maturity limit has varied from 400^0 F-hr to $1{,}600^0$ F-hr. This concept was used at Willow Creek Dam ($1{,}600^0$ F-hr) and Galesville Dam(500^0 F-hr). This method does not appear to have resulted in effective bonding under all conditions. However, when used with ambient temperatures of approximately 60^0 F (15.6^0 C), the lower maturity appears reasonable.

The second method placing a layer of high slump "bedding concrete" on the lift just ahead of the RCC placement. The surface is either untreated or scarified by brooming, sand blasting, or water jetting prior to placing the bedding concrete. The mix is usually an over sanded 3/4-inch MSA mix with a high cement content and a slump of upto 6 inch laid with a thickness of 1 inch. The bedding mix may be tied into the upstream dam facing to act as an additinal seepage barrier. Relationship between RCC bonding and paste/mortar ratio appears in Figure-M.

The third method is placing a mortar layer on a prepared surface similar to the treatment previously used on horizontal construction joints in conventional mass concrete dams. The joint is sand blasted or waterjetted prior to placing a fluid sand-cement mortar immediately ahead of RCC. The thickness of the mortar has ranged from 1/2 inch at the Corps of Engineers' Elk Creek Dam to 2 inches at typical Japanese RCD constructions. Figure-N exhibits the placing sequence of mortar and R.C.C.

A fourth method, high paste volume RCC, was developed to provide sufficient extra paste in the mix to provide bonding without the additin of bedding concrete or mortar. The mix typically has a high volume of pozzolan to reduce thermal/heat generation due to the high cementitious materials content, and uses admixtures to increase setting time. The mix typically has an MSA of 2 inches or less. Lift treatment prior to placing has included vacuming with sweeping, and waerjetting or sand blasting after delays or precipitation. This concept was used at the Bureau of Reclamation's Upper Stillwater Dam Refer-Table-IX (a).

SEEPAGE THROUGH R.C.C. DAMS

Like dams constructed with conventional concrete, the R.C.C. Dams also experience leakage through the dam body rather more so due to some additinal factors peculiar to the RCC Dams. Generally all Dams are prone to seepage and so are the RCC Dams. The seepage if excessive can result in damages some times leading to failure.

BASIS OF DESIGN

The design of seepage control systems for RCC dams should be based on the same rationale as for conventional concrete and embankment dams.

The primary concern with seepage in all dams, is the effect on the safety of the structure. Therefore, it is generally a design priority to control uplift pressure resulting from seepage by providing drainage.

The second aspect of seepage related to design is the impact on project economics. The amount of money expended on seepage reduction is normally determined by the economic need to retain water.

FACTORS AFFECTING SEEPAGE

Seepage through the RCC dams can generally be divided into four categories :

Foundation

Foundation seepage is not different for an RCC dam than for a conventional concrete gravity dam and can be controlled by Drainage, grouting, and u/s blankets.

Lift Joints

Most seepage through RCC dams has been attributed to seepage along horizontal joints between lifts of RCC. This is caused primarily due to segregation of coarse aggregate at the lift boundaries, dirt tracking and cold joints.

RCC Permeability

The permeability of the RCC itself is controlled by a combination of factors involving aggregate gradation, content of cementitious materials, and density. Laboratory tests on RCC cores from several projects have shown the permeability of the RCC to range from 1.0×10^{-8} to 1.0×10^{-10} feet per second. Packer tests in boreholes, however, have shown the overall permeability of the RCC mass, including lift joints, to range from 1.0×10^{-4} to 1.0×10^{-8} feet per second (Schrader 1985; Schrader, 1984).

Cracking

Uncontrolled transverse vertical cracks contribute significantly to seepage, although it is impossible to determine exactly what percentage of seepage flow is transmitted through the cracks. The cracks are the result of tensile stresses within the dam caused by shrinkage associated with cooling of the RCC and stress concentrations at abrupt changes in the foundation, and are extended by the thermal shock caused by cold water penetrating the cracks.

METHODS OF COLLECTING SEEPAGE

With one exception (Winchester), all RCC dams impounding reservoirs, have had some form of internal seepage collection system. Most of the measures employed to date, either alone or in combination, are shown in Figure-P and fall into the following general categories :

1. Drainage Gallery
2. Internal Drain Holes
3. Foundation Drain Holes
4. Foundation Drain Manifold

5. Drain/Grout Tubes
6. Wick Drains
7. Sand/Porous Concrete Chimney Drain.

Drainage Gallery

This consists of a longitudinal opening through the dam at the lowest possible elevation. The gallery can be extended up the abutments parallel to the foundation or extended into the abutments as a drainage tunnel. The objective is to provide a conduit for seepage collected by the internal and foundation drainage curtains, and provide a means of visual observation and measurement of seepage flow through the dam and foundation. A typical Cross-section for Drainage Gallery appears as Fig. P-1.

Drainage Curtain

A drainage curtain consists of a system of internal drainage to intercept seepage in the interior of the RCC dam and transmit it in a controlled manner to downstream toe to control internal uplift and hydrostatic pressures.

The most popular form of constructing drainage curtains to date has been to drill lines of drain holes from the dam crest or construction joints through the RCC into the drainage gallery. The hole diameter is generally 3 inches with the holes spaced at 10 feet. The holes below the gallery can be extended to pass through the RCC into the rock and relieve uplift pressure from within the foundation. The drain holes above the gallery usually extend to the normal reservoir impounding level.

Several alternative drainage curtain methods are employed. One involves the installation of geofabric tubes or wick drains horizontally or vertically between RCC lifts, just downstream of the upstream face. These tubes can discharge into the drainage gallery or at the downstream tow of the dam. An advantage of drain tubes is that they can be used to introduce chemical grout into the RCC if seepage is considered excessive although this has not been tried to date. When watertight upstream facing panels are anchored into the RCC, a continuous sand or porous concrete chimney drain can be constructed between the panels and the RCC mass.

These methods help control internal uplift pressure, and relieve hydrostatic pressure acting against the conventional concrete and prevent seepage from showing up at the downstream face of the dam.

METHODS OF REDUCING SEEPAGE

Filling the reservoir formed by the first few RCC dams has shown that undesirable leakage can occur due to concentrated seepage along lift joints and cracks. The following are the methods that have been or may be used to reduce seepage in RCC dams. Figure-R illustrates these alternatives.

1- RCC
2- Cast-in-place concrete
3- Bedding Concrete
4- Elastomeric Liners
5- Water Stops
6- Precast Panels
7- PVC Liners

RCC MIX.

RCC mixes can be tailored for each individual site for reducing permeability by decreasing the maximum size aggregate, increasing the paste/mortar ratio, or optimizing the mix for economic reasons and then resorting to alternate methods to reduce seepage.

RCC Placement.

The placement of RCC is very important to the permeability of the mass. The single biggest problem in RCC placement causing seepage is segregation at the lift joints. Segregation can be reduced somewhat during the mixing, delivering, and spreading activities by attention to details.

Bedding Concrete.

The effect of permeability due to segregation at the lift boundaries can be mitigated by placing a highly plastic bedding concrete layer between RCC lifts. The bedding concrete tends to absorb the loose pieces of large aggregate into its matrix and thus forms an integrated transition between lifts. Bedding concrete has the additional advantage of adding to the bond between lifts, thus increasing the shear and tensile strength of the joint.

Upstream Reduction.

Upstream reduction is characterized by systems designed to decrease seepage, and systems intended to cut off seepage altogether. The following describes the principal methods utilized to date, the relative effectiveness of each, and suggests some methods that might be used in the future.

Precast Panels.

Precast panels of conventional concrete have been used as a means of forming the upstream face at several dams. The membrane-backed precast panels are generally considered the most reliable method of reducing seepage in RCC dams. The main drawback to the impervious precast panel systems is the cost.

Cast-in Place Concrete Facing.

The most common method of reducing seepage through the upstream face is placement of conventional concrete against adjacent form work at the upstream face and then spreading and rolling the RCC into the facing concrete (Shimajigwa, Middle Fork, Galesville, Arabie).

An idea to provide positive seepage cut off utilizing a cast-in-place upstream facing concrete is to slip-form the upstream face of the dam after the RCC placement has been completed. The facing has to be anchored to the RCC mass and vertical joints between panels have to be sealed by conventional waterstops (upper Still water).

Post-Construction Seepage Reduction.

The most effective methods of post construction seepage reduction are caulking and grouting. Conventional neat cement grouting of open lift joints in the RCC mass has been successful in reducing seepage by upto 95 percent (Willow Creek) (USCOLD, 1985).

All RCC dams do not necessarily exhibit more seepage than conventional concrete dams and have been able to satisfactorily fulfill project functions.

The rate of seepage in all RCC dams that leak, reduces exponentially with time due primarily to siltation and calcification. This is borne out by Figure-S based on seepage monitoring data for impounding dams.

As experience is gained with RCC mixes and placement techniques, the ability of RCC mass itself to resist seepage will increase. Till then however, designers will probably rely on upstream face reduction measures to limit seepage.

R.C.C. PAVEMENTS

As mentioned earlier, RCC has been put to wide spread use in industrial and transportation pavements in America, Tasmania, Newzealand and Spain. Employing known materials and techniques, Roller Compacted Concrete Pavements provide the advantages and durability close to rigid concrete pavements and a cost lower than even the traditional flexible asphaltic pavements.

DESIGN

Design methods for RCC pavements are similar to those for conventional concrete pavements.

Most rigid pavement design methods are generally based on the AASHTO Road Tests (American Association of State Highway and Transportation Officials 1986), the Portland Cement Association's approach (Packard 1973), or the Corps of Engineers' approach (Department of the Army 1987). The Corps of Engineers' approach is oriented towards air-field design and it is particularly suited to designing for heavy loads. It also can account for the lack of load transfer at the joint and contraction cracks in Roller Compacted Concrete. More detailed discussion of the basis of this design approach and comparison with other design approaches can be found elsewhere (Rollings 1985, Rollings 1987a).

The Corps of Engineers rigid pavement design method is essentially a fatigue analysis based on stresses calculated from the Westergaard free edge load analytical model (Westergaard 1948). Figure-T shows the results for fatigue tests on beams sawn from roller compacted concrete from Tayabji and Okamoto (1987) plotted with some typical beam fatigue relationships reported by the American Concrete Institute (1981). Beam fatigue tests are often highly variable as can be seen by the probability of failure lines in Figure-T. Also the actual fatigue relationship is a function of the ratio of minimum and maximum stresses. In general the results of Tayabji and Okamoto (1987) show general agreement between the roller compacted beams tested at minimum to maximum stress ratio of 0.10 compared with other conventional concrete beam fatigue relationships. Consequently fatigue relationships for conventional concrete appear appropriate for roller compacted concrete made of conventional materials.

The Corps of Engineers uses a concrete fatigue relationship based on full-scale, accelerated traffic tests of pavements. As discussed in more detail by Rollings (1987a), this field fatigue relationship includes, to some extent, some of the real pavement factors such as nonuniform subgrade support, fluctuating minimum to maximum stress ratios due to temperature variations, rest periods, etc. Since the laboratory beams fatigue tests or roller compacted concrete pavements appear similar to those of conventional concrete beams, the Corps of Engineers fatigue equation based on accelerated traffic tests of conventional concrete would also be appropriate for roller compacted concrete. The current Corps of Engineers fatigue equation for concrete pavement design using the Westergaard free edge model is :

$$DF = 0.50 + 0.25 \operatorname{Log}(C)$$

Where

DF = Design Factor

= Concrete flexural strength + Westergaard calculated stress

C = Coverages of Traffic

= Maximum number of stress repetitions at any point in the pavement.

Based on the design factor so calculated, the pavement thickness can be calculated for given loads. In case, the thickness requires laying of pavement in more than one lift (over 10 inches), the thickness of each layer has to be calculated using the equation for partially bonded overlay below :

$$h_t^{1.4} = h_o^{1.4} \quad h_b^{1.4}$$

Where h_t = Required thickness of the top lift.

h_o = The original monolithic thickness of the pavement.

h_b = Thickness of the bottom lift (Actual or adopted)

Another method for design of Industrial pavements is explained in a publication of Portland Cement Association, 1987, titled, "Structural Design of Roller Compacted Concrete for Industrial Pavement". (29)

MIX DESIGN

The mix proportions for the RCC pavement are also determined in a manner similar to conventional concrete. The strength requirements are established from the design loads and pavement thickness.

Cementitious materials are required to be portland cement and pozzolan. Cement is type I or type II and is required to be low alkali if reactive aggregates are used. Pozzolan is required to be fly ash, either class F or C, and is to be used as 25 to 40 percent of the total cementitious material. Although a very few projects have successfully used a natural pozzolan or straight portland cement, it is generally felt that the fly ash aids by adding lubrication to the mix. Total cementitious content of the mixes is essentially the same as for conventional paving concrete.

GRADING OF AGGREGATES

Aggregate quality is essentially required to conform to ASTM C33, upgraded slightly. Nominal maximum aggregate size is 3/4 inch. On the first Fort Hood (17) Project, 1-1/2 inch aggregate was used for most of the job and was found to be difficult to finish and to cause excessive segregation. On early jobs in the Northwest, a single aggregate graded from 5/8 inch down to fine aggregate was used because it was thought to finish well. but it had the disadvantage that, being one-sized, no change in gradation could be made by adjusting proportions. Additionally, later experience showed that 3/4 inch aggregate mixes finished equally well. The aggregate is now required to be furnished in two size groups, split on the No. 4 sieve. The size groups must be graded such that they can be combined to meet the gradation as shown in Table-X.

Table - X

U.S. Corps of Engineers Gradation
Requirement for RCC Pavement Aggregates

Sieve Size	Cumulative Percent passing by Wt.
1 inch	100
3/4 inch	83 - 100
1/2 inch	72 - 93
3/8 inch	66 - 85
No. 4	51 - 69
No. 8	38 - 56
No. 16	28 - 46
No. 30	18 - 36
No. 50	11 - 27

No. 100	8 - 20
No. 200	2 - 8

MANUFACTURING OF R.C.C.

The R.C.C. is manufactured in a central pug mill which combines stone aggregate with cement and water in a continuous mix process. Fly ash is used to supplement the cement, reduce heat of hydration and effect greater economy of material. The aggregates typically used are crushed stone, similar to the aggregates used for either hot mix or conventional concrete. The amount of cement and fly ash used is much less than that used in concrete pavement produced in conventional way.

PLACEMENT

Roller compacted concrete pavement material is transported from the central mixing plant in ordinary dump trucks, in the same way as the hot mix asphaltic concrete is transported for paving operations. The paver or laydown machine is similar to a hot mix paver and the dump trucks discharge directly into a hopper on the front of the device. The pavers can place the material in four inch to ten inch thick lifts. A tamping bar and vibrating screed at the rear of the machine produces nearly complete compaction as it is placed. Campaction is finished off to 98% of Modified Proctor density or better by heavy vibrating flat wheel rollers and pneumatic tire rollers.

The material is placed on major paving projects by at least two pavers working in tandem, which can place lane widths of twelve to twenty-four feet at speeds of six to twelve feet per minute. This translates to as much as 15,000 square yards per machine per eight-hour day, although such placement rates are not always realized in practice because of restricted work area or obstacles. Such production rates would be possible, for example, on a highway project of considerable size.

QUALITY CONTROL

Quality control of the product is essential. The continuous feed batch plant requires careful attention to batching ratios and requires constant monitoring, much as a hot mix asphaltic plant does. In addition, the water content and densities at the time of placement are critical and require constant monitoring in the field, typically using nucler density meter. Attention must also be given to maintaining constant quality of the aggregates utilized.

CRACKING

The only problem in RCC Pavement is strong possibility of shrinkage cracks that appear at random locations and some times look unsightly, although structurally these may not matter much.

COST

The life cycle cost of the RCC Pavement as indicated in table below is about 68 percent of that for conventional concrete and 53 percent of the cost of asphaltic concrete.

Table - XI
Life Cycle Costs for Paving Alternatives

	(UNIT COST IN $ /SQ. YD)		
Alternatives	Estimated Capital Cost	Estimated Annual Maint. Cost	Estimated Life Cycle Cost
a) 12" Thick HMAC	15.00	1.65	33.93
b) 9" Conventional Reinforced Concrete	25.00	0.125	26.43
c) 12" Roller Compacted Concrete	16.00	0.16	17.84
d) 12" Soil Cement	8.00	1.75	28.07

a. replacement of top 6-inches after five years, plus patching.

b. minor repairs required, estimated useful life is about 40 years.

c. minor repairs required, estimated useful life is about 20 years.

d. replacement of entire thickness after five years, plus patching.

e. at an assumed interest rate of 6% and inflation rate of 5%, design life of 20 years.

Another Table XII compares the cost of R.C.C.P. with P.C.C.P. for six projects executed by Corps of Engineers and indicates a saving of 8 to 44 percent with the use of R.C.C.

The main features that contribute to lower cost are :

1. Somewhat Lower priced Aggregates.
2. Minimal use of cement and maximum use of fly ash.
3. No requirement of forms.
4. Manual finishing is not required.
5. Expansion or control joints are not provided.
6. No reinforcing steel is used.
7. High placement speed and the need of small labour crew.

GENERAL

Roller compacted concrete offers an economical construction method for certain types of pavements. As long as conventional concrete materials are used in the roller compacted concrete, it has essentially the same engineering characteristics as conventionally constructed concrete. This will not necessarily be true if substandard or marginal materials are used. The construction methods used for roller compacted concrete must be considered in design. A sound base must be provided so that adequate compaction can be achieved. If the concrete is to be exposed to freezing and thawing, an effective drainage layer must be provided below the concrete and de-icing salts should not be used. The lack of load transfer at the joints in roller compacted concrete must be recognized and accounted for in the design. If the thickness of the pavement requires it to be placed in two lifts, either bonding between lifts must be assured, or the top lift should be designed as a partially bonded overlay. Some of the roller compacted concrete placed in the past has shown high variability in strength results. The likely variations in strength must be considered when proportioning the concrete mixture to ensure that the strength used in design is consistently equalled or exceeded.

CONCLUSIONS

1. The use of R.C.C. can affect appreciable savings in cost and time of construction of large concrete structures such as gravity dams and other features. It has the same benefit for use in pavements both for industry and Transportation.

2. R.C.C. can also be used in overflow structures like spillways in locations where velocities are low or operating requirement infrequent. At this stage of development of R.C.C. it appears expedient to design gravity dams on the basis of net compression over the entire width of lift joints. This criterion would

require a minimum base width of 0.7 of the dam height.

3. All R.C.C. dams do not necessarily exhibit more seepage than conventional concrete dams and have been successful in satisfactorily achieving the project functions. The rate of seepage in all R.C.C. dams that leak, reduces exponentially with time to acceptable limits due primarily to siltation and calcification.

   As experience is gained with R.C.C. mixes and placement techniques, the ability of the materials to resist seepage will increase. Till then, however, the designers will probably have to rely on Upstream face reduction measures to limit seepage.

4. Provision of high paste conventional concrete in the U/S face and between successive lifts of R.C.C. in the U/S zone is a good method of seepage control.

5. Cores obtained from completed dams indicate satisfactory texture of R.C.C. and acceptable strength test results.

6. R.C.C. has now been established as a cost effective and time saving alternative for pavements in almost all continents of the world. The use of R.C.C. for pavements has till now been mostly limited to heavy-duty pavements. R.C.C. has the potential for making significant advances in the speed, quality and economics of all concrete paving. With the eventual standardization of test methods, and improvements in surface smoothness and joint performance the number and variety of R.C.C. pavement applications wil rapidly increase.

7. Further research is necessary to determine as to how-much recoverable compression strain can develop in well compacted, well graded rollcrete with rise in temperature occurring in the initial stages of cement hydration.

8. Further research is also needed on R.C.C. mix designs and proportioning techniques, preparation of test specimens and bonding of lift joints.

RECOMMENDATIONS

1. The Roller Compacted Concrete deserves more attention and consideration on account of its usefulness and saving in cost and construction time.

2. The Roller Compacted Concrete technology has now come of age and medium and high dams are being built with this material.

There are so many examples like Shimajigawa, Tamagawa in Japan and Upper Still Water dam in U.S.A. (All the three are around 300 feet high). From 1980 to 1988 ten dams of over 120 feet height had also been built with R.C.C.

In view of above, it is high time that we also give a chance to this versatile material atleast on small dams which do not require much of research and advanced technology. With experience, we can switch over to high dams in future.

3. R.C.C. has now been established as a cost effective and time saving alternative for pavements in almost all continents of the world, and we should also give it a chance on atleast unimportant transportation links, industrial aprons, and the like, as Canal lining in bed or on the level.

4. It is really perturbing that a material, usefulness of which was established on our works (Tarbela Dam) is not finding any place in our concrete gravity structures.

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* * * * *

Table - XII

Roller Compacted Pavement - Comparison Data - C.O.E.

LOCATION	DISTRICT	PROJECT	BID DATE	QUANTITY	RCCP UNIT PRICE	PCCP UNIT PRICE	THICKNESS INCHES	SAVINGS USING RCCP
PORT BENNING GA.	SAVANNAH	EXPAND MAINT. FACILITY	JULY 86	23,630/SY 4,900 CY	14.71/SY 71/CY	21.78/SY 104/CY	7.5	32.5%
FT. CAMPBELL KY.	LOUISVILLE	TACTICAL EQUIPMENT SHOP	MARCH 86	62,250 SY 11,700 CY	13.84/SY 71/CY	20.50/SY 105.17/CY	7.0	32.4%
FT. BLISS TEXAS	FT. WORTH	MARD ST. & MOTOR MARKS	JULY 86	87,900 SY 19,535 CY	15.43/SY 69.43/CY	18/SY 81.10/CY	8.0	14.3%
FT. HOOD TEXAS	FT. WORTH	TACTICAL EQUIPMENT SHOP	SEPT. 86	63,900 SY 14,200 CY	11.55/SY 51.96/CY	20.67/SY 93.02/CY	8.0	44.1%
ABERDEEN PROVING MD	BALTIMORE	APPLIED INSTRUCTION FACILITY	DEC. 84	21,160 SY 5,000 CY	25.67/SY 108.O/SY	27.86/SY 117/CY	8.5	7.9%
FT. LEWIS, WASH.	SEATTLE	TACTICAL EQUIPMENT SHOP	MAY 85	15,700 SY 3,700 CY	13.69/S 58/CY	23.53/SY 100/CY	8.5	41.8%

Table - I

Volume of Roller Compacted Concrete, Repair & Extension Works of Yale, Shihmen and Tarbela Dam Project

Date completed	Project Name	Location	Feature	Volume Roller compacted Concrete (cu yd)
1952	Yale	Washington USA	Gravity Wall	32,000
1961	Shihmen	Taiwan	Core of Cofferdam	20,000
1975	Tarbela	Pakistan	Abutment restoration at Tunnel # 2	460,000
1980	Tarbela	Pakistan	Lining of Service Spillway Plunge Pool	1,180,000
1980	Tarbela	Pakistan	Cofferdam for Auxiliary spillway Plunge Pool Construction	50,000
1981	Tarbela	Pakistan	Lining of Auxiliary Spillway Plunge Pool	1,230,000
1982	Tarbela	Pakistan	Backfill of stilling Basin of Tunnel # 4	110,000
1983	Tarbela	Pakistan	Lining of Tunnel # 4 Plunge Pool	95,000
1983	Tarbela	Pakistan	Gravity Wall of Power house Area	175,000
1986	Tarbela	Pakistan	Extension of Gravity Wall for Power House area	200,000
			Total of All Tarbela Features upto - 1986.	3,500,000

Table - II

Proportion of RCC mixes designed by consistency measurements

Dam	Completed	Volume yd^3	MSA inches	$\frac{w}{c + fa}$	$\frac{fa}{c + fa}$	Quantities lb/yd^3					Vebe (VC) Seconds
						Water	Cement	Flyash	Sand	Coarse Aggregate	
Shimajigawa	1980										
B - I		120,325	3.1	0.81	30	177	153.4	65.7	1262	2488	(15)
B - 2		95,500	3.1	0.88	30	177	141.6	60.7	1267	2498	(20)
Tamagawa	Under Construction	980,900	6.0	0.73	30	160	153.4	65.7	1107	2602	(20)
Pirika	Under Construction	157,000	3.1	0.75	30	152	141.6	60.7	1126	2626	(20)
Upper Stillwater	Under construction										
A		1,200,000	2.0	0.40	68	170	134	289	1140	2330	17
B		157,000	2.0	0.33	69	168	156	346	1190	2170	15
Elk Creek	Under construction	1,000,000	3.0	1.12	32	195	118	56	1275	2610	20

*Note: All mixes contain a water-reducing admixture; Elk Creek Dam used a water-reducing, retarding admixture.

Table - VIII

Roller Compacted Concrete Gravity Dams - Higher than 50 feet - Completed upto 1987

Date completed	Project Name	Location	Maximum Height (ft)	Cement and Fly Ash (lb/cu yd)	Downstream Face slope H:V	Volume Roller compacted Concrete (cu yd)
1980	Shimajigawa	Yamaguchi Japan	292	(153 + 66)	0.8 : 1.0	222,000
1982	Willom Creek	Oregon USA	169	(118 + 39) av	0.8 : 1.0	433,000
1984	Winchester	Kentucky USA	70	(175 + 0)	1.0 : 1.0	32,000
1984	Middle Fork	Colorado USA	124	(112 + 0)	0.8 : 1.0	55,000
1984	Kidston Copperfield River	Queensland Australia	131	(150 + 25) av	0.8 to 0.9 : 1.0	183,000
1985	Galesvile	Oregon USA	167	(91 + 87(av	0.8 : 1.0	210,3000
1986	Monksville	New Jersy USA	150	(108 + 0)	0.78 : 1.0	286,700
1986	Craigbourne	Tasmania Australia	82	(118 + 101)	1.1 : 1.0	29,400
1986	De Mist Kraal Weir	Cape S. Africa	98	(99 + 99)	0.60 : 1.0	78,500
1986	Arablie	Lebowa S. Africa	115	(61 + 124)		140,000
1986	Daten	Frijan China	184			65,000
1986	Grindstone Canyon	New Mexico USA	139	(125 + 50)	0.75 : 1.0	114,000
1986	Zaailoek	Natal S. Africa	164	(53 + 124)	0,.62 : 1.0	157,000
1986	Saco de Nova Olinda	Paraiba Brazil	187	(121 + O)av*	0.8 : 1.0	173,000
1987	Tamagawa	Akita Japan	338	(153 + 66)	0.81 : 1.0	981,000
1987	Upper Stillwater	Utah USA	285	(129 + 289)	0.60 : 1.0	1,441,000
1987	Les Olivettes	Bas Rhone France	118	(148 + 79)	0.75 : 1.0	111,000
1987	Lower Chase creek	Arizona USA	59	(108 + 67)	0.7 : 1.0	18,000
1986	Erizana (dike)	Spain	50	(152 + 152)		15,700

* Portland - Pozzolan Cement

Table - VIII (a)

Gross costs of RCC Dams

	Dam	Volume-cu. yds (m^3) RCC		Upstream face Concrete		Total		Total cost of RCC and Upstream Face Concrete		Project Bid Price	Cost of Concrete/ Project Bid Price
1.	Willow Creek Oregan	403,100 (308,200)	+	2,100 (1,600)	=	405,200 (309,800)	$	9,040,000	$	14,95,000	64%
2.	Upper Stillwater Utah	1,357,000 (1,037,500)	+	35,200 (26,900)	=	1,392,200 (1,064,400)	$	34,788,000	$	60,604,000	57%
3.	Monksvile New Jersy	289,000 (221,000)	+	19,500 (14,900)	=	308,500 (235,900)	$	6,504,000	$	14,678,000	44%
4.	Galesville Oregan	210,500 (160,800)	+	10,500 (8,000)	=	221,000 (168,800)	$	5,819,000	$	12,759,000	46%
5.	Grindstone Canyon New Mexico	114,500 (87,500)	+	5,800 (4,400)	=	120,300 (91,900)	$	4,237,000	$	7,477,000	57%
6.	Eik Creek Dam Oregon	1,040,800 (770,700)	+	69,500 (53,200)	=	1,110,300 (848,900)	$	25,366,000	$	62,783,000	40%

* Includes bedding concrete where applicable

Table - IX

Roller compacted Concrete Dams Planned, Designed & under construction/repairs.

S.No	Name of Project	Location	Country	Height in feet	Storage (A.F.)	D/s face slope (H.V)	R.C.C. Volume (cyd)	Remarks.
1.	Stacy Dam	Colorado River (San-Angelo) T.X	U.S.A.	148	554,340	0.83 : 1	194,000	Under construction.
2.	Gibralter	Santa Barbara C.A.	U.S.A.	194	--	--	--	Strengthening
3.	Ceder Falls	Seattle W.A.	U.S.A.	30	--	0.8 : 1	5500	Rehabilitation
4.	Pamo Dam	Ramona C.A.	U.S.A.	269	130,000	0.7 : 1	556,000	Uunder Construction
5.	Elk-creek Dam	Elk-creek Oregon	U.S.A.	249	--	0.7 : 1	1,110,000	-do-
6.	Urugua-I Dam	Puerto Iguazu	Argentina	253	952,000	0.8 : 1	786,000	-do-

Table - IX (a)

Summary of Properties of Cores Extracted From Various RCC Structures

Property	Unit	Lean RCC	RCD	High Paste R.C.C.
Permeability	m/s (ft/s)	10^{-4} to 10^{-8} (10^{-4} to 10^{-8})	10^{-7} to 10^{-10} (10^{-7} to 10^{-10})	10^{-10} to 10^{13} (10^{-10} to 10^{-13})
Direct tensile strength	MPA (psi)	0.50 ± (75 ±)	--	1.40 to 2.10 (200 to 300)
(At joints)		0.25 ± (35 ±)	--	1.40 to 1.70 (200 to 25)
Indirect Tensile Strength	MPA (psi)	1.00 to 1.35 (150 to 195	1.4 to 1.7 (200 to 245)	200 + (300 +)
(At joints)		--	0.40 to 0.70 (60 to 100)	0.85 + (125 +)
Shear strength cohesion	MPA (psi)	0.50 to 1.00 *75 to 150)	2.50 to 3.00 (350 to 450)	2.20 + (320 +)
Compressive strength	MPA (psi)	8.00 to 10.00 (1150 to 1450)	12.00 to 16.00 1750 to 2300)	20.0 to 40.0 (2900 to 5800)

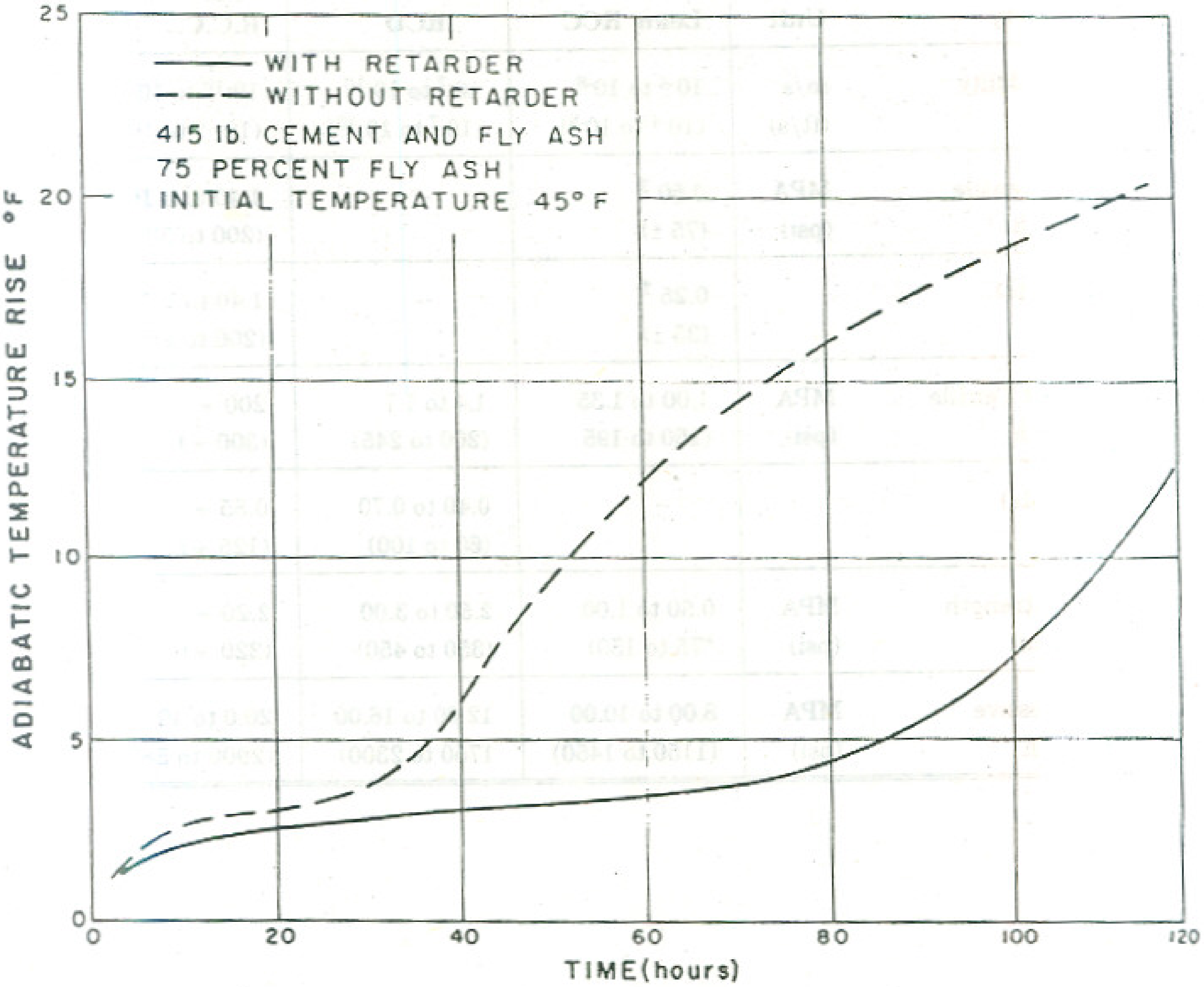


Figure-A. - Adiabatic temperature rise of RCC laboratory mix design L-3 with and without set-retardation chemical admixture. [ ]

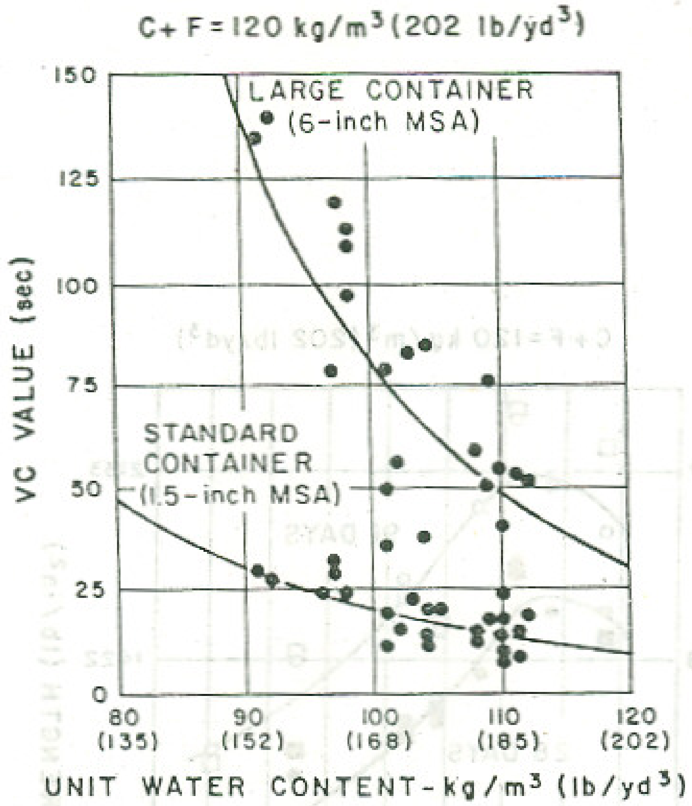


Figure-B. - Relation between unit water content and VC (vibration compaction time) value in cases of using large- and standard-sized consistency meters. [ ]

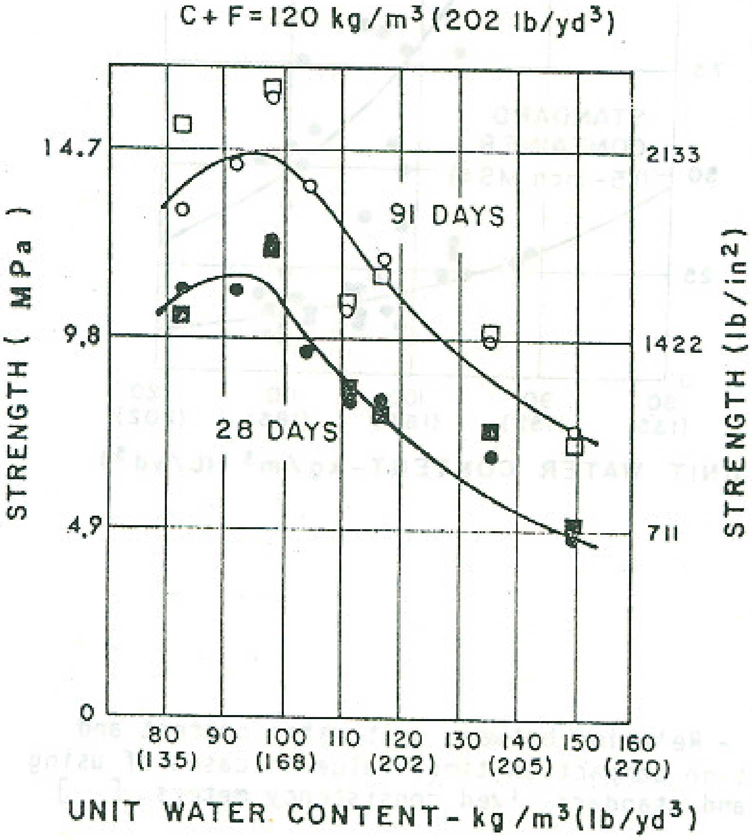


Figure-C. - Relation between unit water content and compressive strength of dam concrete. [ ]

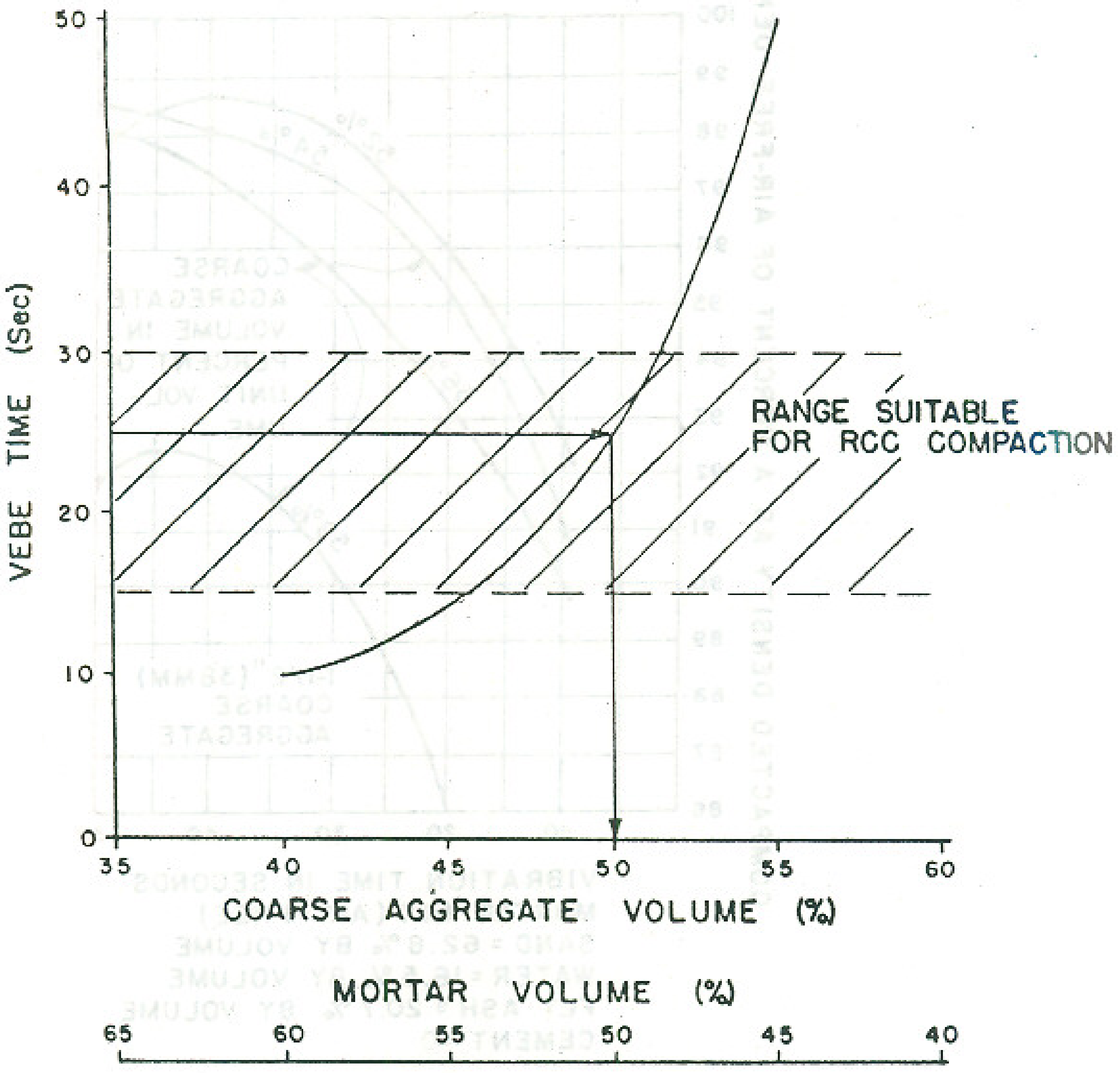


Figure-D. - Effect of mortar volume on Vebe compaction time for roller-compacted concrete.
(Reference - Upper Stillwater Dam mix design studies)

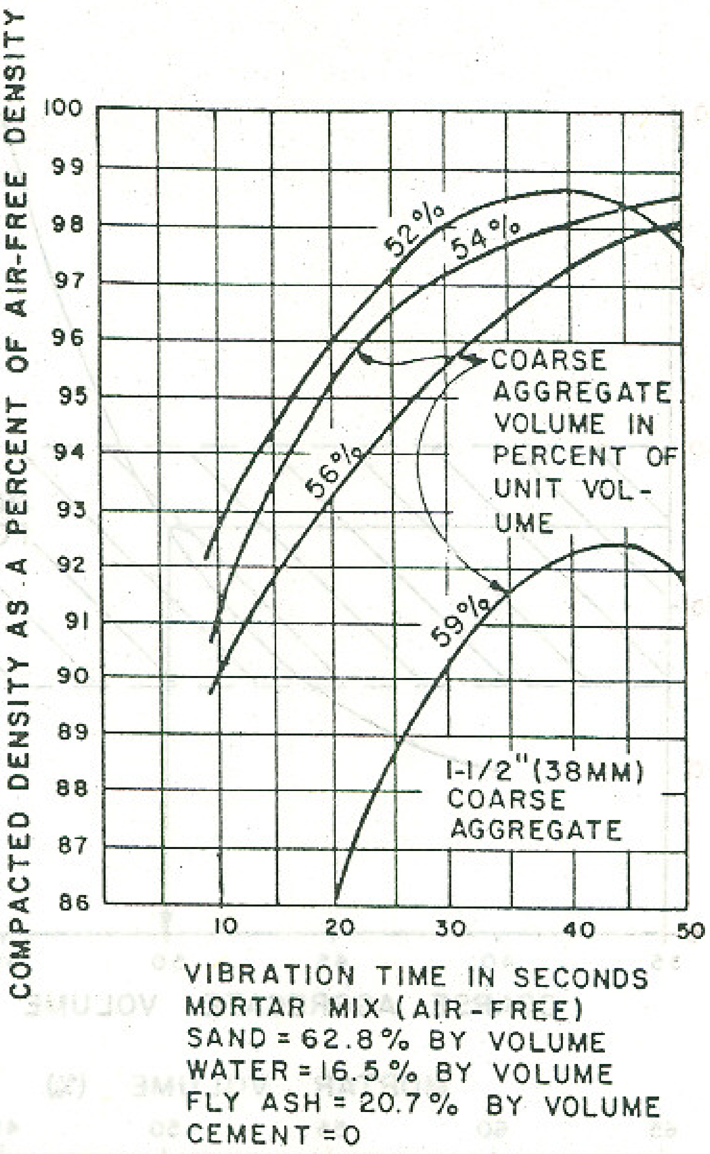


Figure-E - Effect of coarse aggregate volume on compaction. [ ]

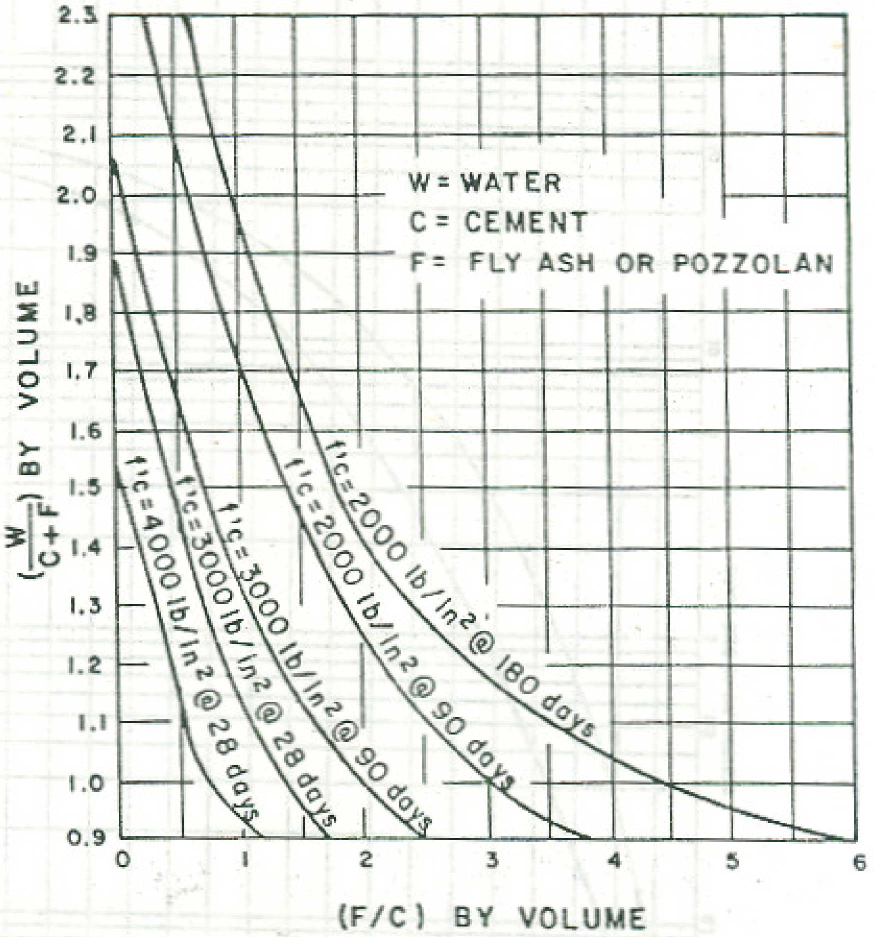


Figure-F. - Proportioning curves for equal strength concrete. [ ]

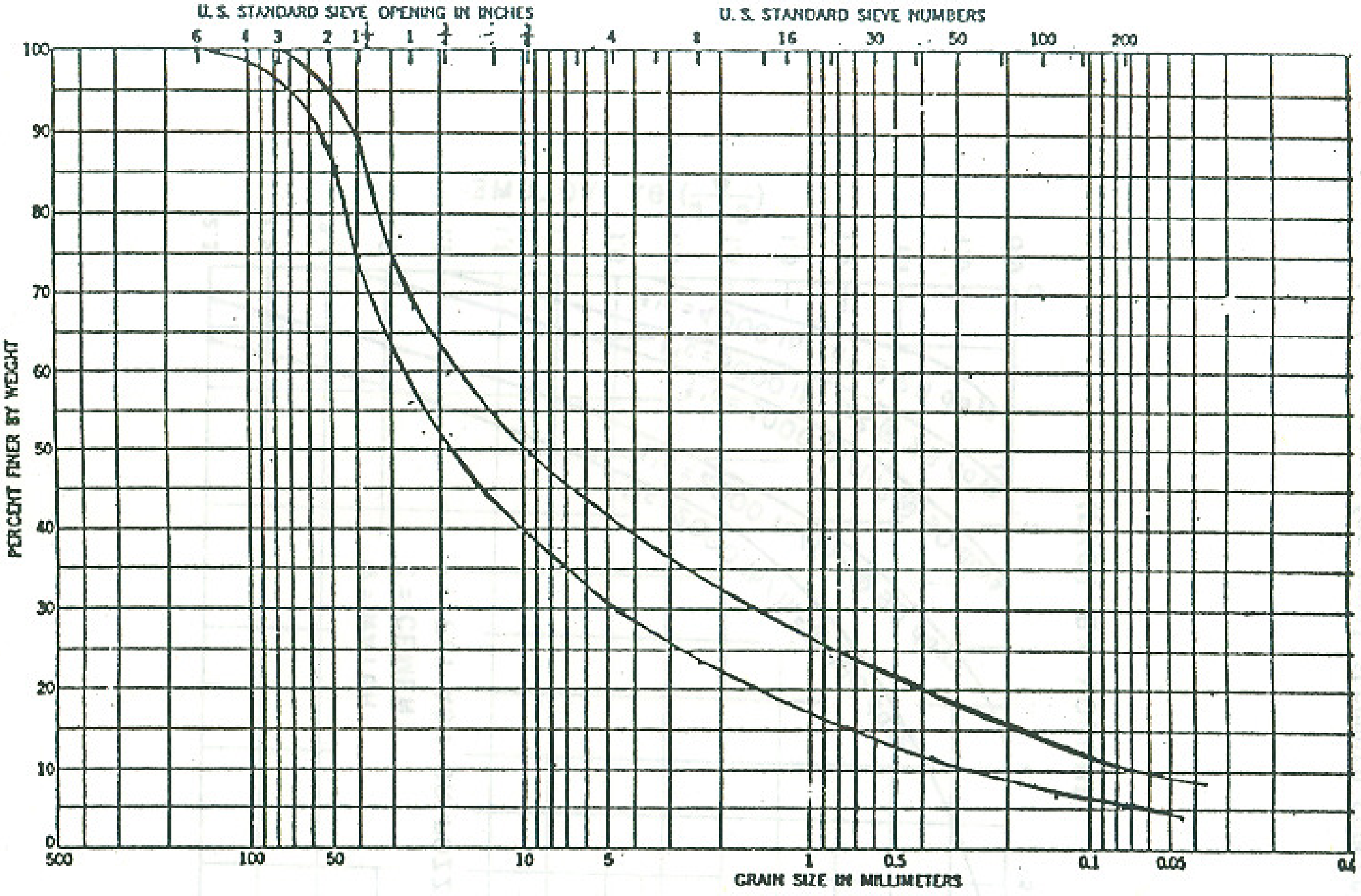
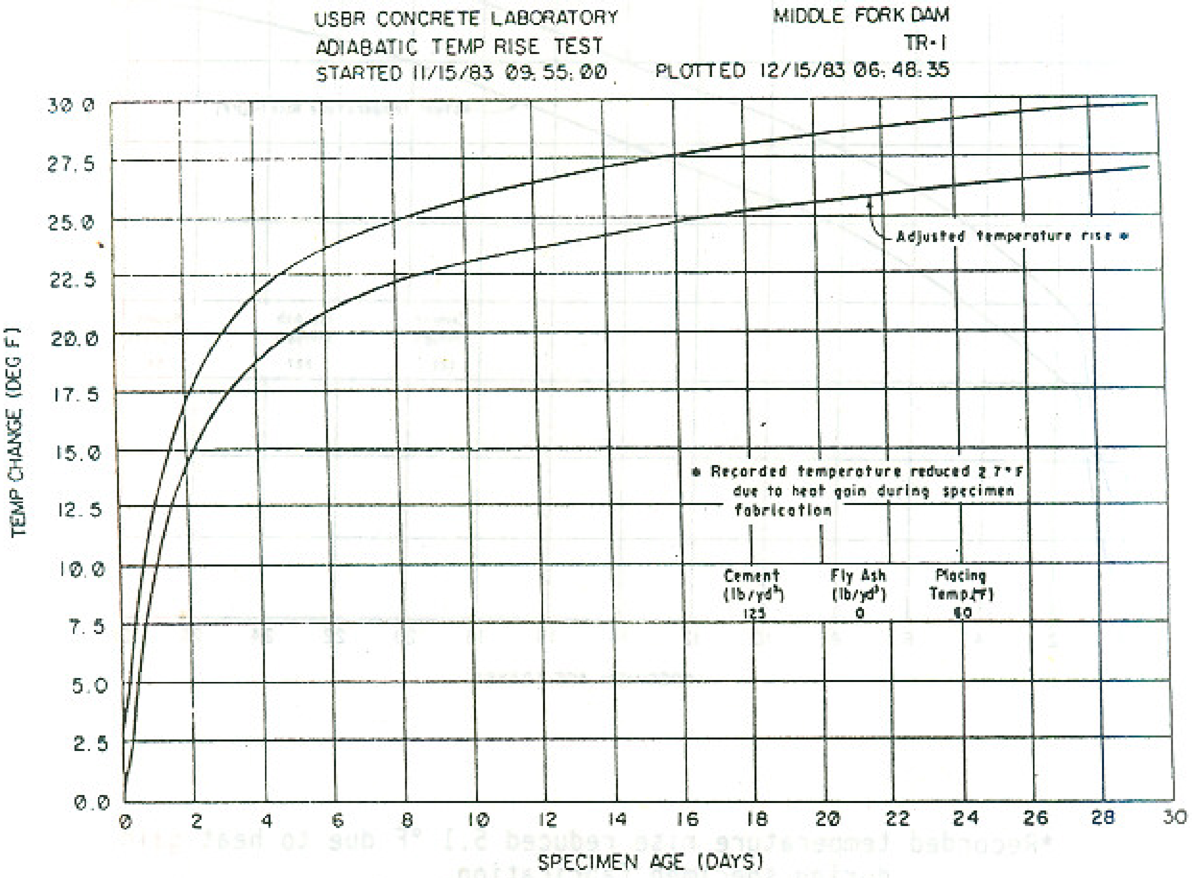
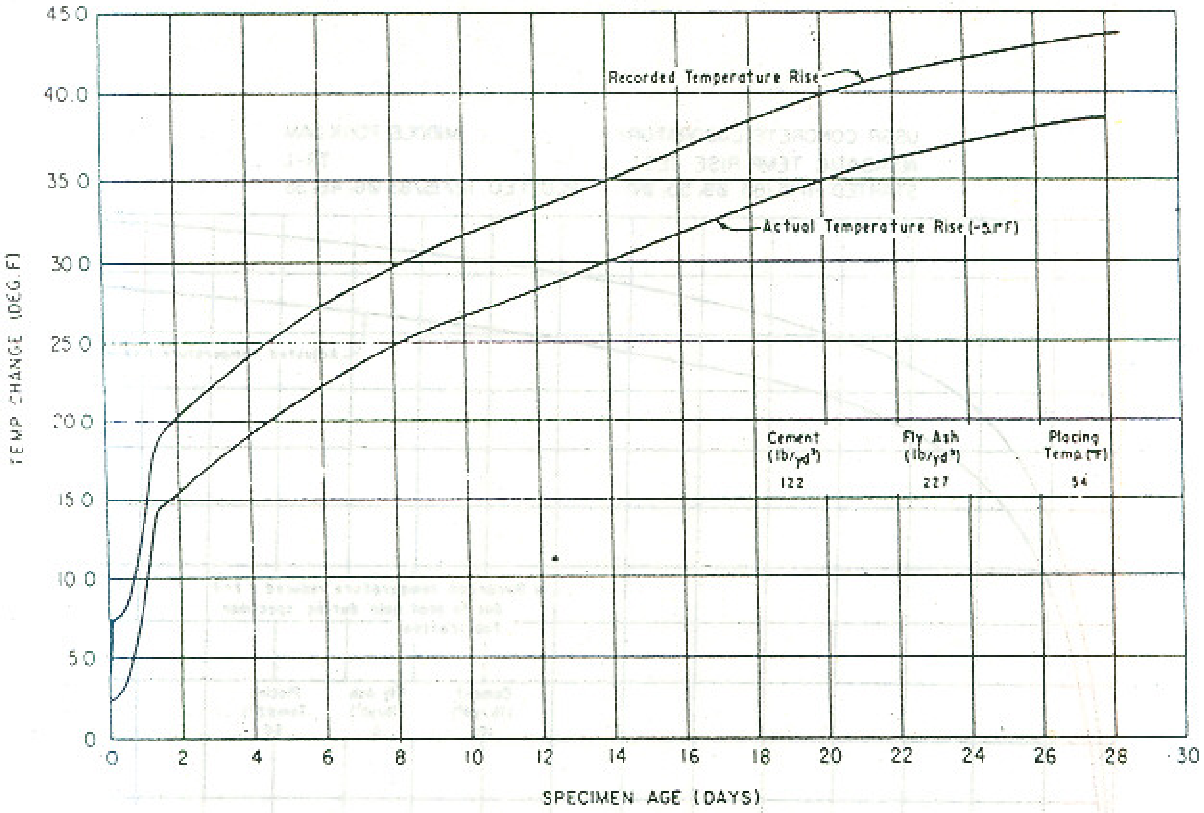


Figure-G. - Suggested grading band for lean RCC mixes.



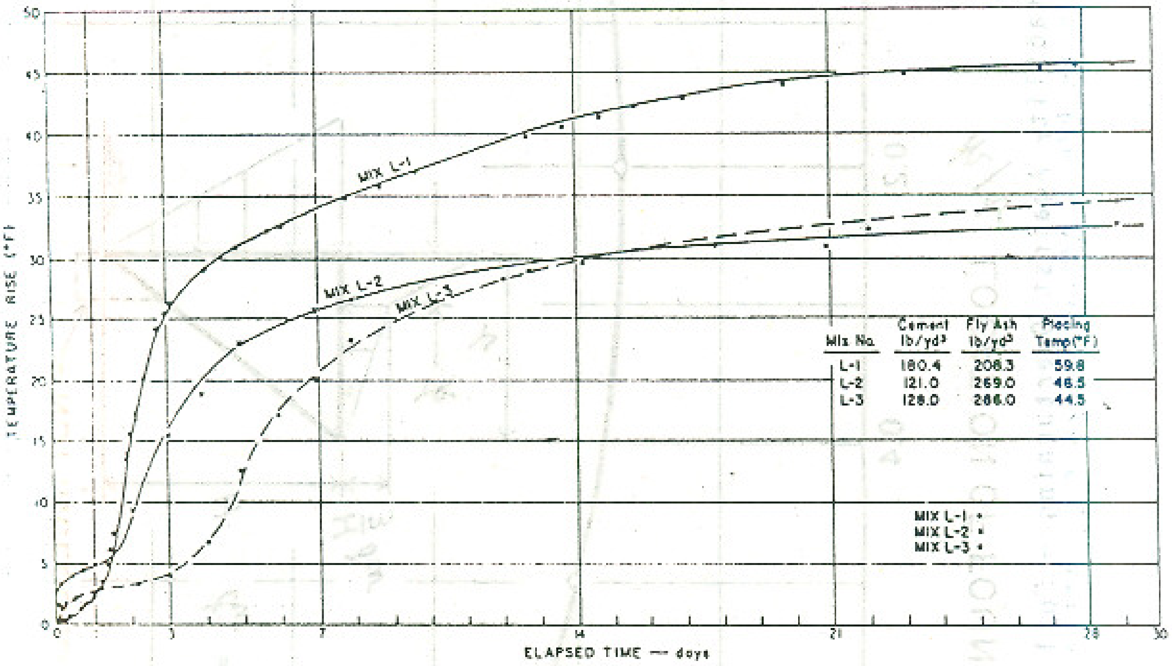
* Recorded temperature reduced 2.7 °F due to heat gain during specimen fabrication

Figure -H. - Adiabatic temperature rise, Middle Fork Dam, Colorado.



*Recorded temperature rise reduced 5.1 °F due to heat gain during specimen fabrication.

Figure-J. - Adiabatic temperature rise, Pamo Dam, California.



Mix No.	Cement lb/yd³	Fly Ash lb/yd³	Placing Temp(°F)
L-1	180.4	208.3	59.8
L-2	121.0	269.0	46.5
L-3	128.0	266.0	44.5

Figure-K. - Adiabatic temperature rise, Upper Stillwater Dam, Utah.

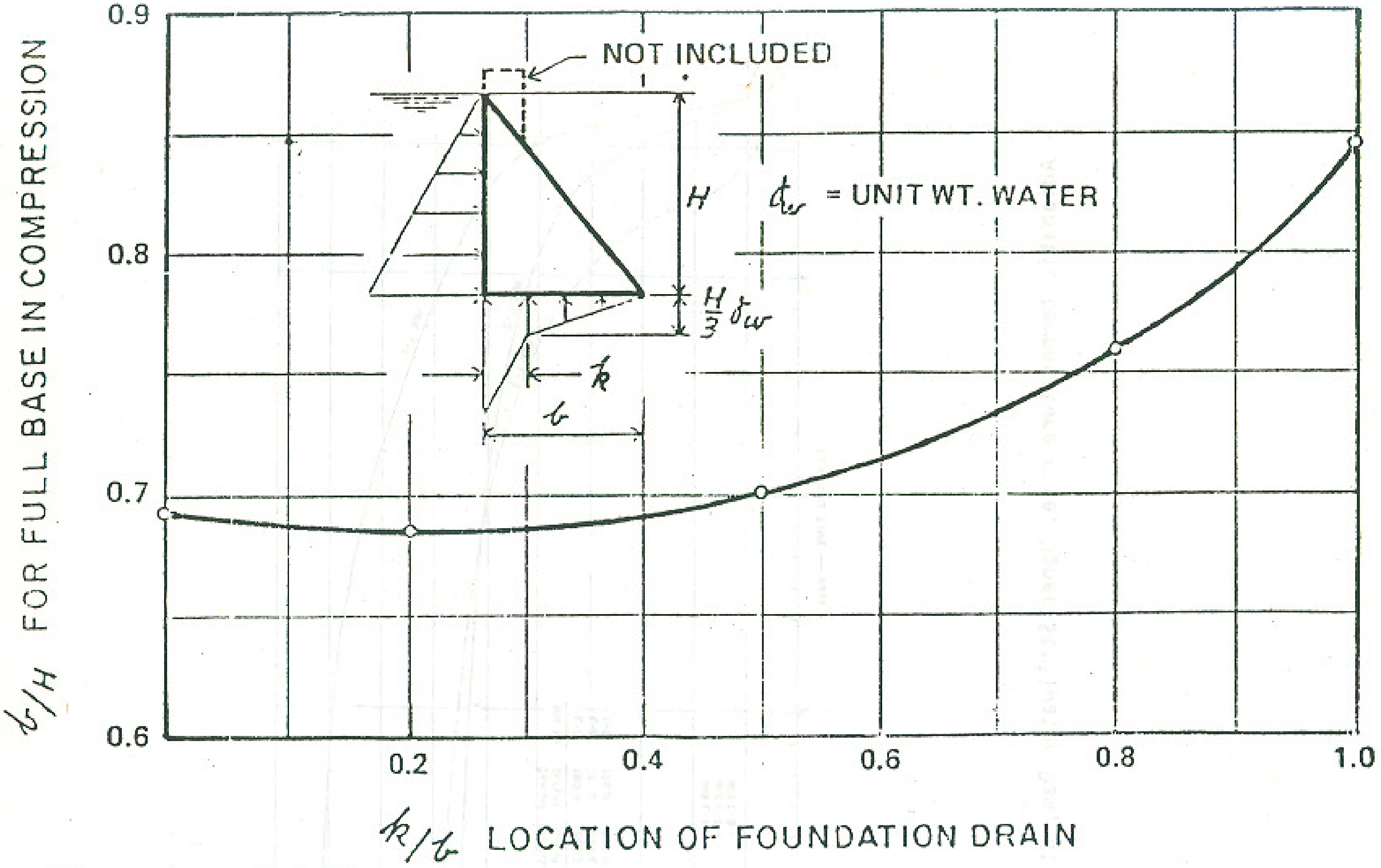


Figure L : Stability Against Overturning - Full Base in Compression - b/h vs k/b - After Figure 5.1, ACI 207 Committee Report( )

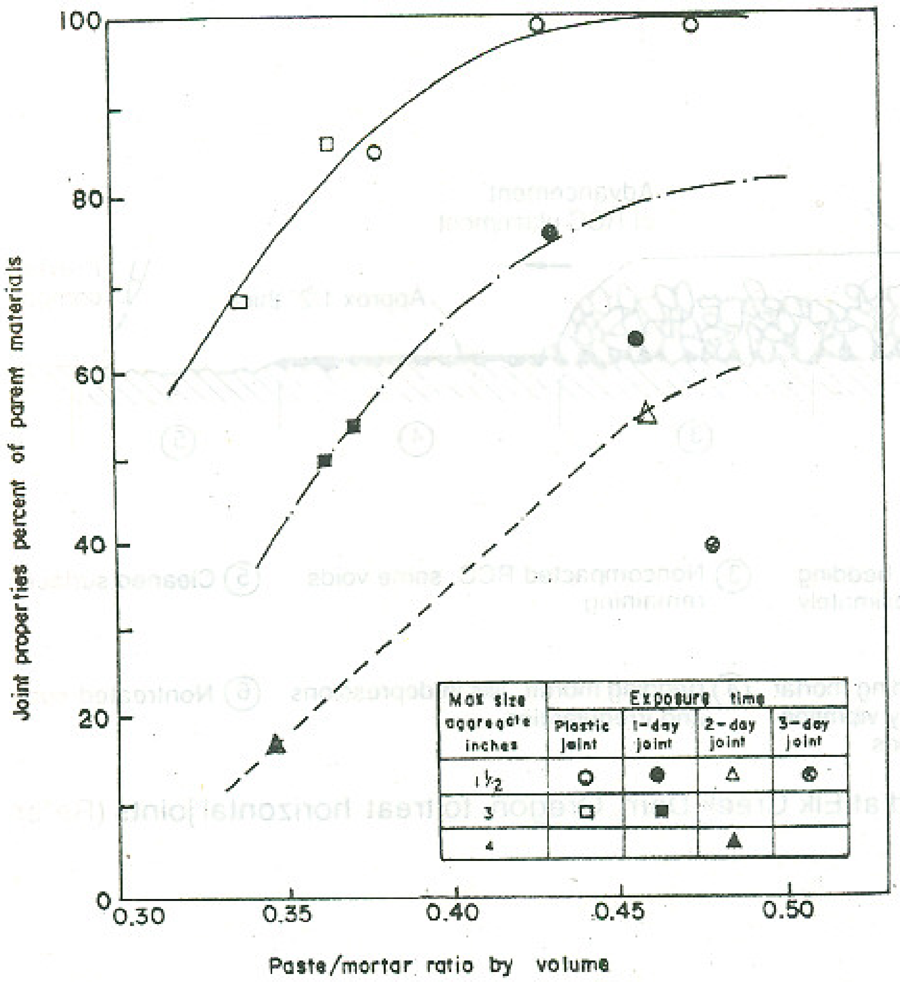
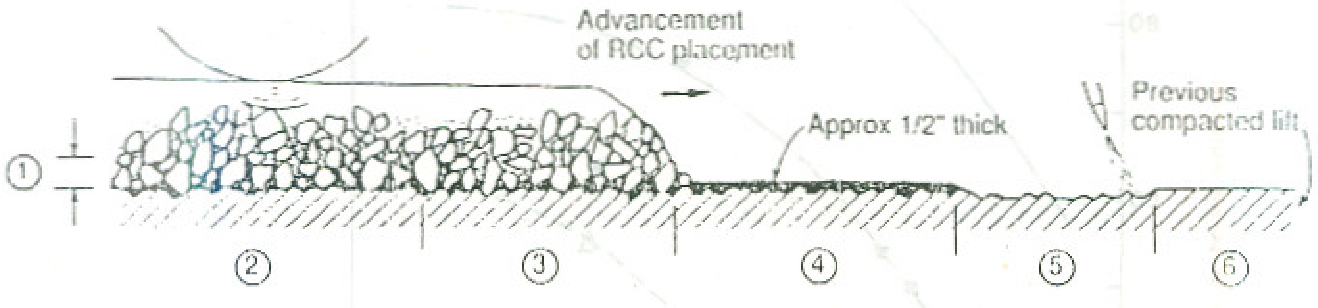


Fig-M. Relationship between RCC bonding and paste mortar ratio (Reference).



① Maximum penetration of bedding mortar into RCC is approximately 1-1/2 inches

② Compacted RCC – Bedding mortar squeezed up into RCC by vibration action. No remaining voids

③ Noncompacted RCC, some voids remaining

④ Bedding mortar, fills in depressions and irregularities

⑤ Cleaned surface

⑥ Nontreated surface

Fig. N. Procedure used at Elk Creek Dam, Oregon, to treat horizontal joints (Reference).

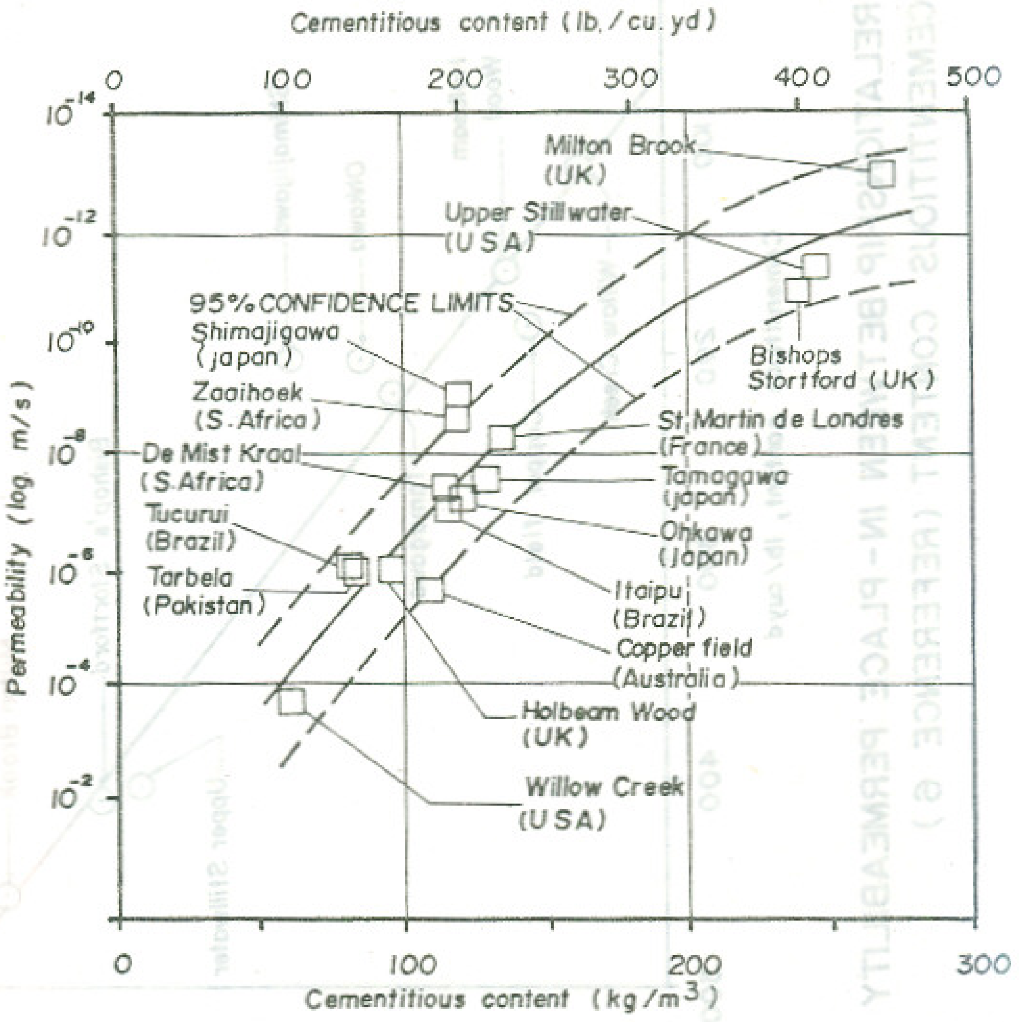
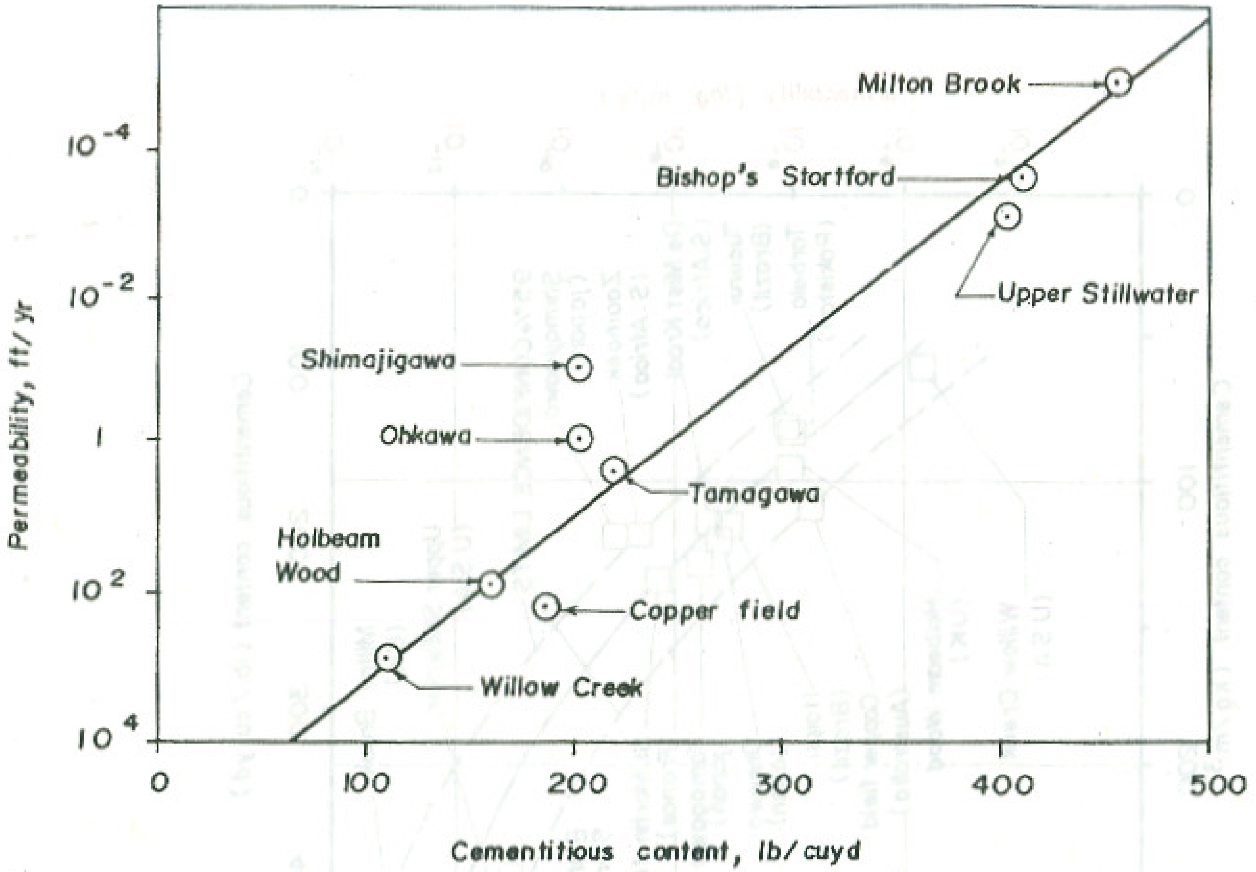


FIGURE-O RELATIONSHIP BETWEEN IN-SITU PERMEABILITY AND CEMENTITIOUS CONTENT.

Shabbir Ahmad



RELATIONSHIP BETWEEN IN-PLACE PERMEABILITY AND CEMENTITIOUS CONTENT (REFERENCE 6)

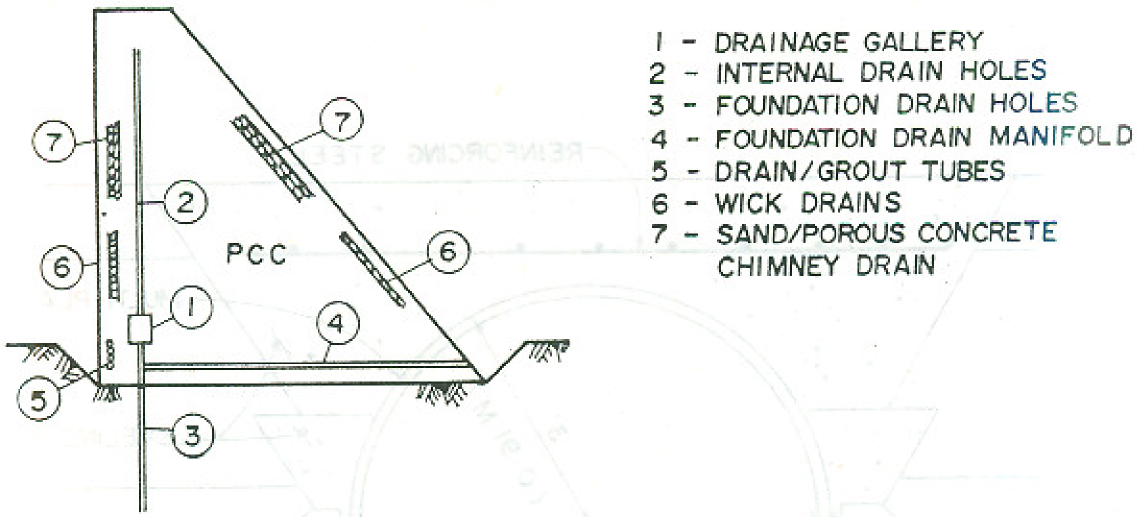


FIGURE-P METHODS OF COLLECTING SEEPAGE

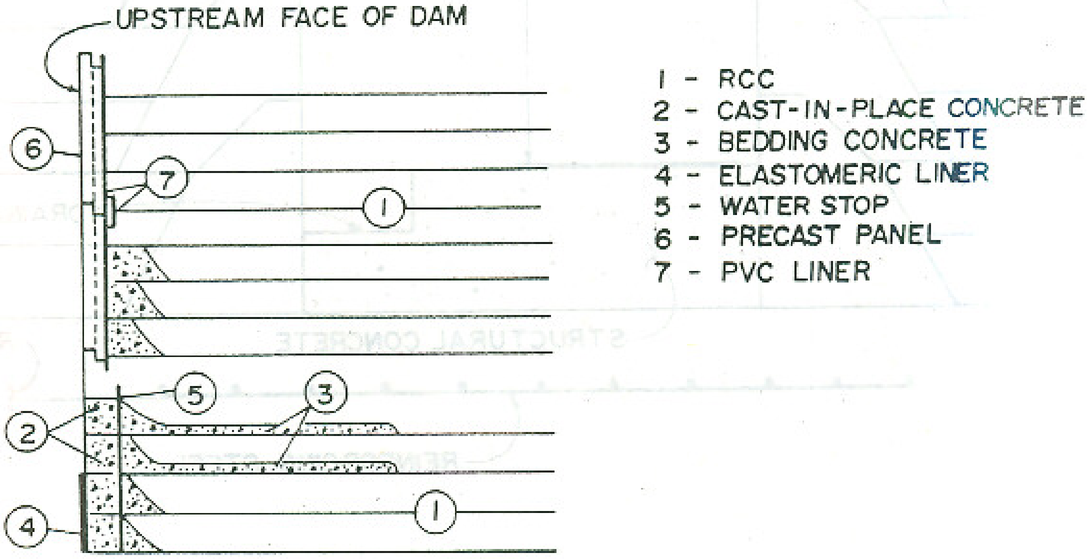


FIGURE-R METHODS OF REDUCING SEEPAGE

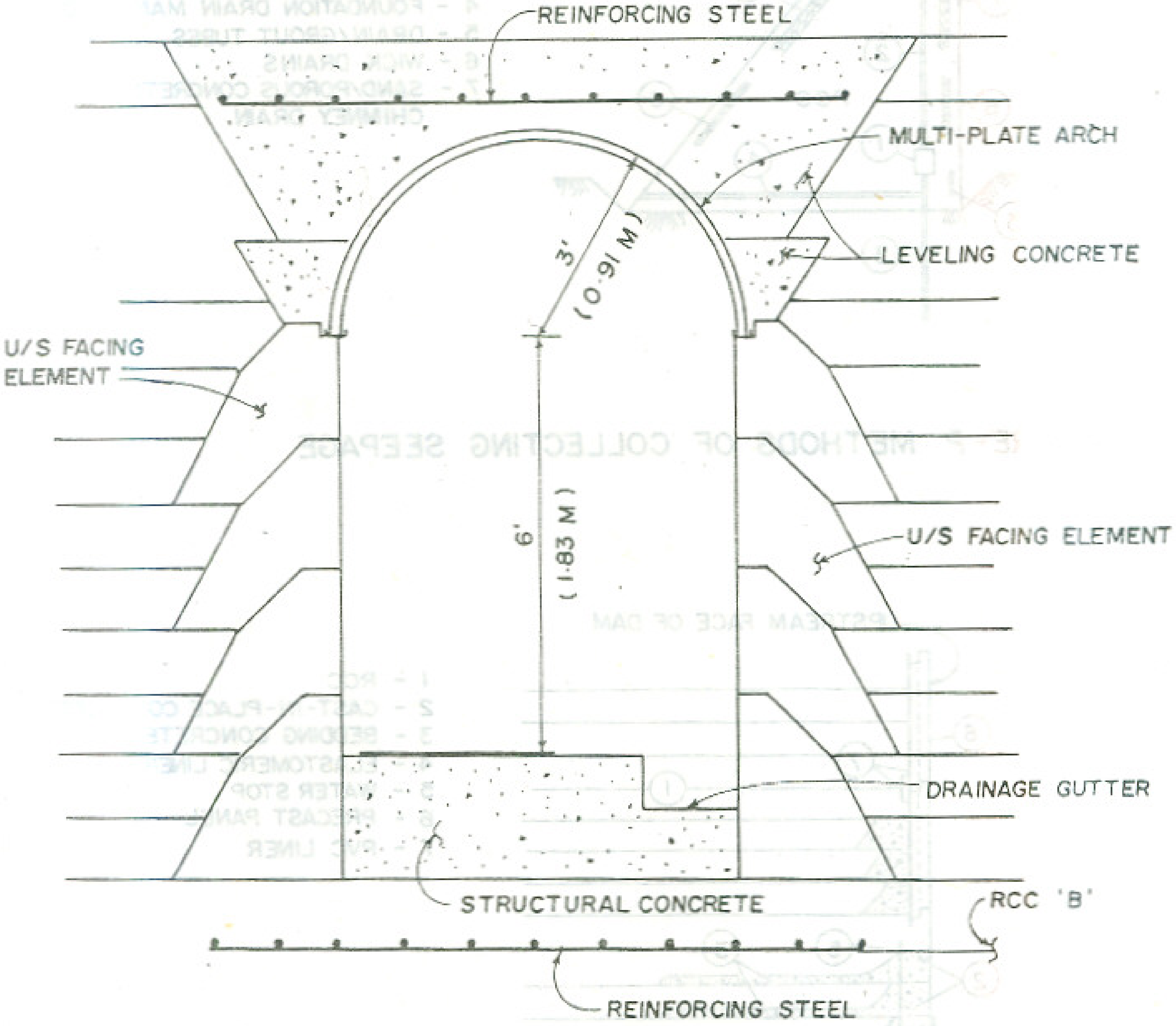
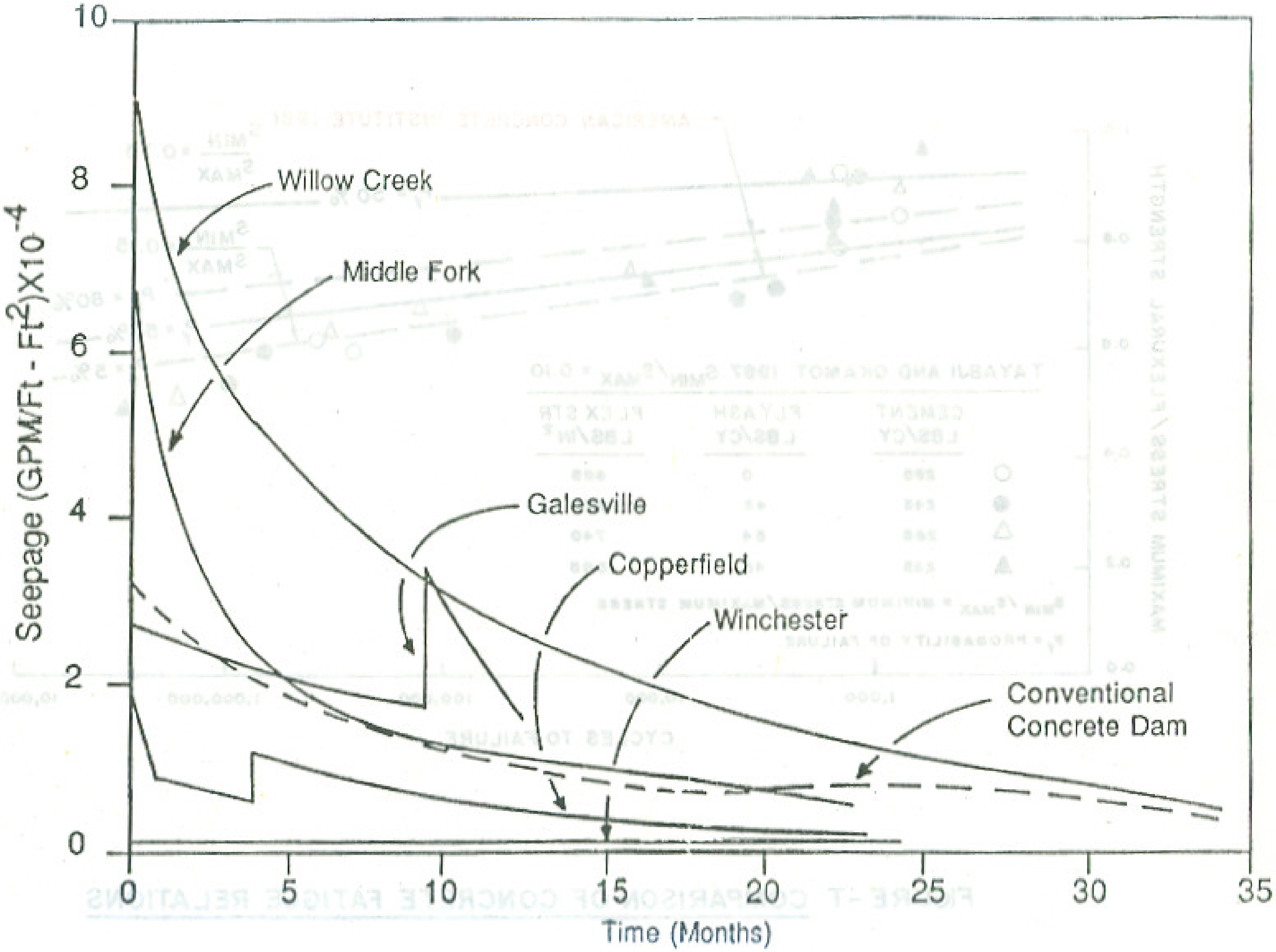


FIGURE-P-1 TYPICAL GALLERY CROSS-SECTION

Shabbir



NOTE: Seepage - gallons per minute per weighted average head pressure and upstream surface area

Figure - S Total Seepage After Reservoir Raise (   )

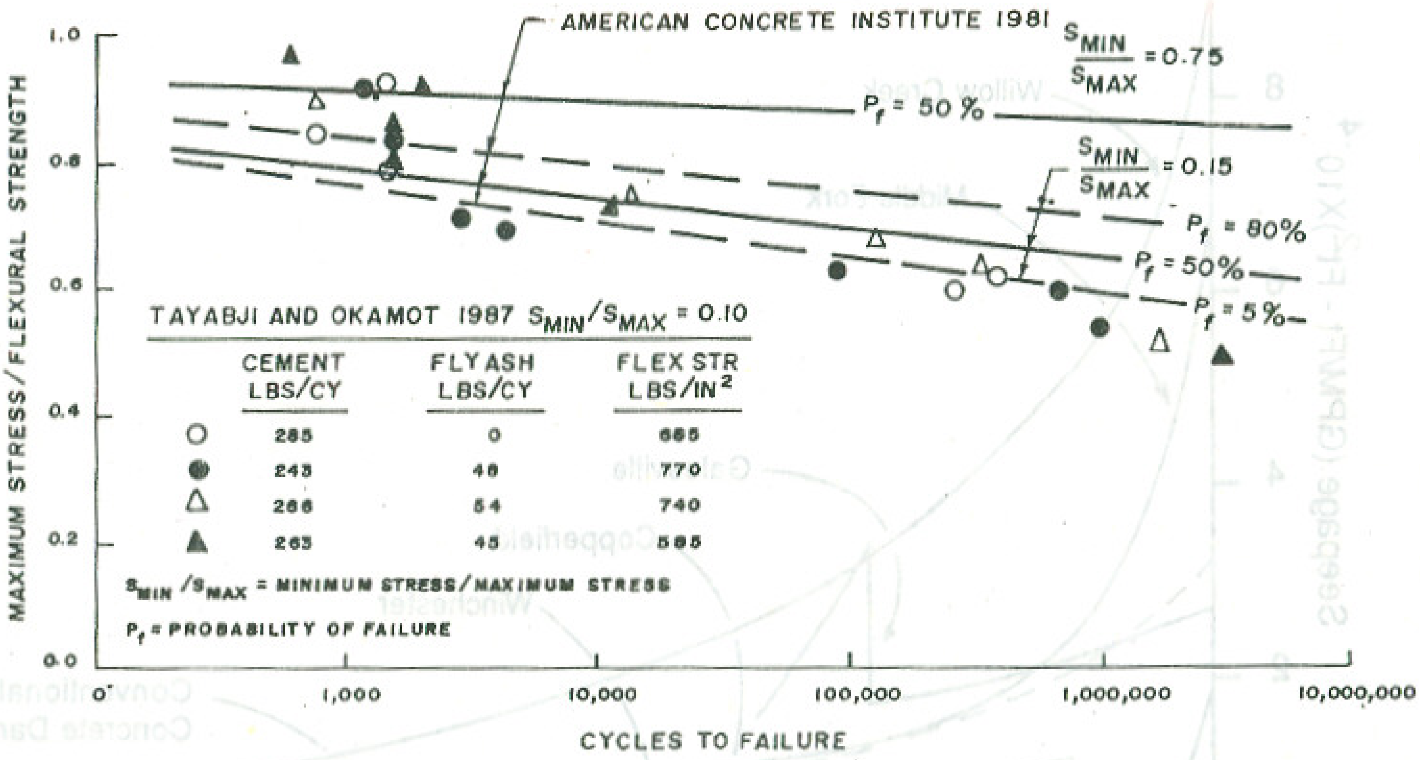


FIGURE-T COMPARISON OF CONCRETE FATIGUE RELATIONS