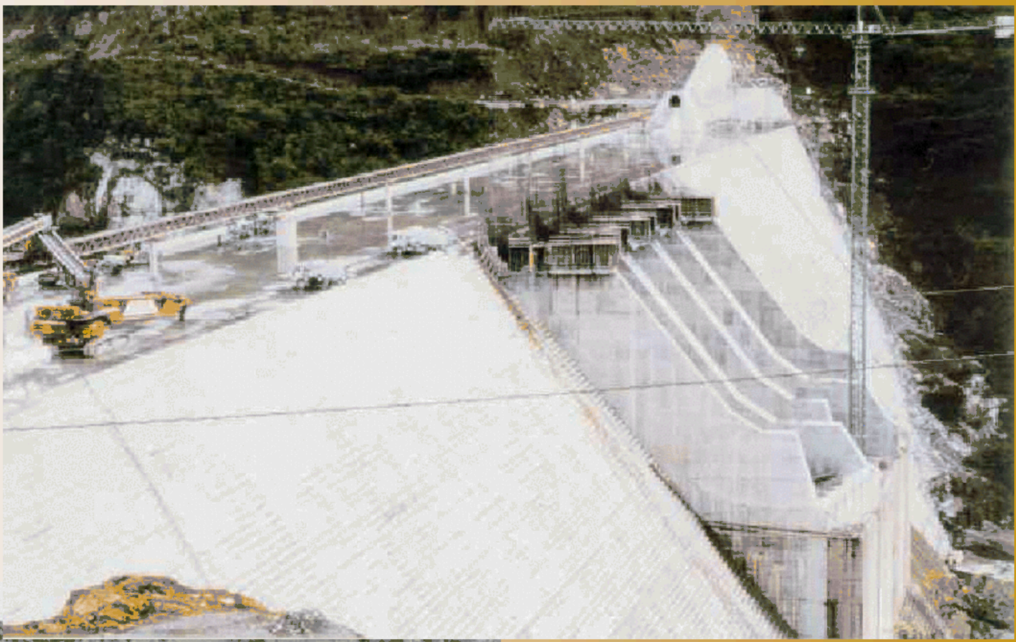
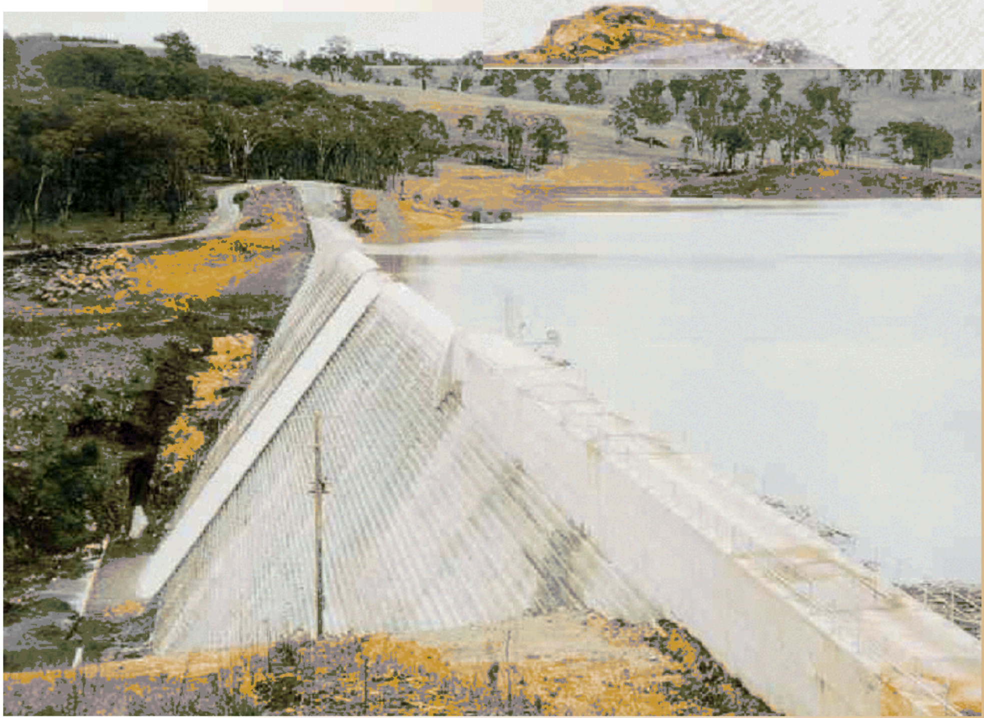
Understanding the Continuum….
Design, Equipment & Construction

RCC – From Whence to Where.





ARAN

TECHNICAL EXPLANATION TE-156

Roller Compacted Concrete Dams
From whence to where?

Roller Compacted Concrete for dams, known everywhere as RCC, has come from relative obscurity to prominence in less than twenty years. RCC is used in many variants. Some of these differences are explored with reference to the equipment needed to mix RCC.

There are competing claims as to who first applied the material to dam construction. Variants of what is commonly known as RCC had been used in Italy, Pakistan and China for sections of dams before it became widely used for the total dam structure in the early eighties.

The term RCC is unfortunate. Applied to RCC pavement materials, low paste dams, medium paste dams, and high paste dams it describes four quite different materials. When does RCC become concrete, and at what point does concrete become RCC are questions of definition. Roller Compaction refers only to a means of compaction. Any form of force densification which is achieved by impact from above does the same thing. RCC therefore is mixed at OMC, or a moisture content optimum for compaction.

Conventional slump concrete is really compacted by gravity under the influence of high frequency vibration. It relies on additional water and added fines (paste) for this to occur. Concrete mixed at OMC cannot be compacted in that way without additional paste. One of the innovations discussed in this article involves that transition.

An early low paste RCC dam, Copperfield Northern Queensland, Australia. The upstream face was conventional concrete placed against forms. The downstream face of the dam was unformed except for the spillway which was conventional concrete. This 40 metre high dam contained 140,000 cubic metres of RCC and 16,000 cubic metres of conventional concrete. It was built in 1984 over a period of 16 weeks. The RCC was mixed with excellent uniformity by two ARAN ASR200 continuous mixing plants.

Concrete is essentially a matrix of stone particles of different sizes bound together by a cementitious binder. When used for a road, a clean, non plastic, well graded crushed rock, mixed with 125 kg per cubic metre of cement, force densified with a high compaction paver or roller, is only "cement treated base", (CTB or CBM). In a dam, the same material is low paste "concrete". For that same material to become "RCC", or "concrete" in a pavement application it needs more like 300 kg of cement per cubic metre!

Early RCC

Some early RCC dams were really like a multi layer cement treated base roads and were constructed using the same equipment as would be used for a road. Of course, special attention was paid to layer joints, upstream face surface, water tightness, and management of shrinkage. The low amount of cementitious material minimizes heat and shrinkage problems. High density was achieved by a relatively high natural fines content.

It was the use of readily available high output equipment which gave RCC dams a speed and cost advantage over more conventional concrete structures.
Willow Creek dam in the USA was widely credited with being the first all RCC dam. The low moisture concrete for this dam was mixed with somewhat indifferent results in a traditional drum type batching plant designed for slump concrete. Such mixer types are water sensitive for efficient mixing.

The second all RCC dam was Copperfield in Northern Queensland, Australia. It was designed and built during the 1984 dry season. Two Aran mobile continuous mixing plants mixed the RCC accurately and thoroughly. They substantially contributed to the speed and cost effectiveness of the project.

That was fifteen years ago. Debate still rages over the specification of RCC and how it should be mixed, handled, and placed.

Early on, RCC dam philosophy divided into distinctly divergent streams. It is not the purpose of this article to extol the merits of one or the other, but to discuss the construction implications of these different approaches and to describe some recent developments which merge the concepts and help to return to RCC to the cost effective material which it set out to be.

RCC, SAME NAME, VERY DIFFERENT MATERIALS.

There are several different types of RCC. Whilst each type of RCC belongs to a "concrete" family which has low moisture content, and which is able to be force densified, their mix proportions and characteristics are quite different.

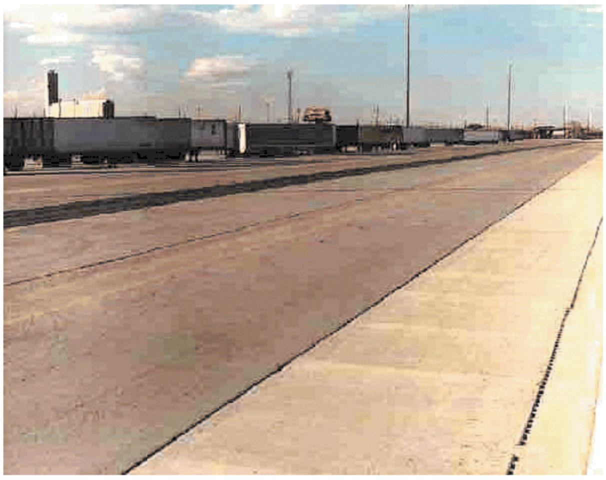
Above: An RCC pavement. This material has very much more cement than RCC for Dams.

The workability of low paste RCC is very much like road base material. It has only enough moisture for compaction, and relies on a continuous dense grading envelope right down to the fine fraction for its density. These materials typically have natural non-plastic fines of 5-7% and a cement content of 3.5-5%. Sometimes flyash is used as a substitute for absent natural fines. Low paste RCC takes on the colour of the parent stone, presents a relatively loose edge to its compacted layer, and is able to be trafficked without noticeable impression by construction vehicles immediately after rolling. Various techniques have been developed for upstream and downstream faces. These include precast panels with and without membranes, and various implementations of concrete placed against forms. The low paste school of thought has stayed with the concept of processing materials more like road materials.

High Paste RCC has typically used relatively large quantities of flyash as a substitute for natural fines. This material generally uses a washed fine and coarse sand. The cement content may be as low as 2% to 3%, and the flyash content 6% to 10% of the dry weight. The response of flyash to water is quite different from that of "natural" fines, and when mixed, the concrete takes on a glistening grey appearance. The presence of the flyash makes the RCC more workable, and when compacted it will still evidence impressions if trafficked by construction vehicles. It presents high rolling resistance to construction vehicles. Flyash is more sensitive to variations in moisture content than fine silt, so small variations in the addition of either flyash or water have a more noticeable effect.

Slip formed concrete facing elements for upstream and downstream faces have been common in dams of this style. This treatment gives a pleasing appearance and good erosion resistance, but can be more costly than other options. As the dam rises towards the crest, the length increases and the trafficable width decreases. Placing of the facing becomes the time constraint to each lift of RCC. Proponents of high paste RCC present the material as a premium concrete, and deal with it as they would a no slump conventional concrete.

Between these somewhat polarized positions is a range of RCC mixes which draw from the benefits of both and allow the advantages of the material to be realized. Most RCC dams constructed in Australia have occupied this middle ground.



Above: An RCC pavement used for large freight transfer terminal USA.

Left and Below: New Victoria dam in Western Australia is of the high paste design with slipformed facing. Impressions left by construction traffic are visible.

MIXING RCC

Two questions arise in mixing any kind of concrete. Firstly, how are the different ingredients proportioned one relative to the other? Secondly how are they intimately mixed on both a macro and a micro basis with each component uniformly distributed throughout the matrix, and so that the cementitious binder particles coat fully that which they are to bind?

The approach to these issues is often prejudiced by the view of the material held by the specifiers. The subject is shrouded in mystery and frequent misconceptions.

A unit volume of concrete (say one cubic metre) and what it contains are essentially geometric relationships. Even the grading curve is established so that voids between larger stones are filled by progressively smaller stones such that a dense matrix is achieved. This is all about stone size, shape, and particle count for each size. Assurance of compaction and absence of voids is evaluated by measuring the density. When the ingredients of a unit volume of concrete are defined, they are usually described in weight terms. Here in lies a conundrum. Concrete is bought and sold in compacted volume, but usually the basis of defining it during manufacture it is by weight of individual ingredients. Whether the prescribed weight of a particular aggregate size contains the appropriate number of stones of the desired shape to fill the required volume and leave the anticipated voids is another question.

Provided that the compaction characteristics of the feed materials are controlled at the metering point, it is equally, if not more correct to proportion the individual components on a geometrical basis. In fact defining ingredient proportions in weight terms is nothing more than a convenient label which is easy to read in a batching process. On that basis, all concrete should be sold strictly in tonnes.

It is believed by some that only if ingredients are individually batch weighed, are they always the same. This is a half truth. It may be generally so on a macro basis for each batch, but even then each batch is a new project and is different by degree from its predecessor.

In reality, a well developed continuous or "through mixing" plant delivers ingredients to the mixer, in the correct proportion one to the other, on a ribbon feed basis. At any moment in time, a section through the feed stream reveals that the proportions are correct and remain so. There is no distinct variation or step between each "batch".

The author has been involved in the development of Aran "through mixing" plants for more than twenty years. Not all continuous metering systems are created equal. There are many subtleties to management of material flow within feed hoppers and silos, and to the control of the metering devices themselves which make the difference between an accurate and repeatable system, and a mediocre one. The same applies to batching systems.

The principal difference between RCC and slump concrete is the amount of water in the mix. In a slump concrete, the water acts as a mobilizing agent during mixing. Water aids with the free migration of fine particles, particularly cement and flyash, during the mixing process. For this reason drum type mixers, and even truck mounted drum mixers can satisfactorily mix higher slump concrete, given sufficient time. By contrast RCC has sufficient water to retard the disbursement of the fine particles and not sufficient to aid it. It is very unlikely to be thoroughly mixed in any drum type mixer unless left mixing for an intolerably long period of time. Other types of twin shaft batch mixers and pan mixers which operate at relatively low speed can mix RCC, however the mixing time must be greatly increased, typically 50% or more than the time required for a slump concrete, or some compromise in the outcome tolerated.

When a "batch" of assorted aggregates, sand, cement, flyash, water, and additive is dumped into a batch mixer, the ingredients are anything but uniformly distributed. The batch mixer must deal with both macro mixing and micro mixing. Typically dry mixes require more interactions for this to be achieved. In a high demand situation, such as an RCC dam, a compromise must be reached between thoroughness of micro mixing and acceptable output. Mixer cycle times are even longer for larger mixers.

The most suitable type of mixer for this material is a high intensity twin shaft "through mixer" as is used in Aran Continuous Mixing Plants. These mixers run at much higher speeds than typical batch mixers, even those of the twin shaft type. In the batch type mixer, mixing is mostly accomplished by turning and division. In a high intensity Aran mixer, the process is higher velocity collision and division. Because a ribbon fed, "through mixer" receives its ingredients already macro mixed, the primary task of the mixer becomes one of micro mixing and thorough coating of the particles with binder. Compared with a typical batch type twin shaft mixer, each element of material passing through an Aran high intensity "through mixer" encounters four times the number of interactions at four times the velocity in a quarter of the time. Almost all such interactions are essentially dedicated to micro mixing in the "through mixer" whereas in the batch mixer, the lesser number of lower velocity interactions are largely devoted to distributing the various sized stones uniformly around the mixer body.

In the authors experience it has become apparent that the strength of either paving concrete or RCC mixed in this way is normally measurably greater than that predicted by lab mixed samples of the same material. The superior disbursement of the binder and finer coating of the stones also has compaction benefits. The 300 mm thick layers of the 43 metre high Cadiangullong dam recently constructed in Australia and mixed with an Aran MODUMIX II-4 were able to be fully compacted in two to three roller passes compared with other RCC dams where six to ten passes are common. This in significant measure resulted from the mix design, however the ease of compaction of RCC mixed in this plant was noticeably better than trials made with the same mix and an older model Aran plant.

Contactors having used both mixer types universally comment on the easier handling and compaction of RCC mixed through Aran continuous or "through mix" plants.

Although a batch system may superficially seem to give repeatability, strength, yield, and workability, differences are easily overlooked.

The literature suggests that a coefficient of variation (COV) for compressive strength of manufactured samples:

- 0% to 10% is considered as excellent.
- 10% to 15% is considered as good
- 15% to 20% is considered average.

This standard has been proposed by Malcolm Dunstan in a recent ICOLD (International Committee on Large Dams) draft bulletin as appropriate for evaluating RCC for dams.

It is possible to find cases which justify either argument. This basis of evaluation is affected by the uniformity of input materials, site variables, management, equipment maintenance, and the unspoken temptation to some contactors to tweak the settings to their benefit. The method of making test cylinders or cubes has also been shown by Geoff Ayton of the NSW RTA in Australia to have a major effect on the COV results.

Data collated by the author from a variety of projects using both batch type mixers, Aran continuous mixers, and other continuous mixers demonstrates a wide range of COV results. Mostly the results correlate more closely with management competence and equipment maintenance than with machine type. This view is supported by specifying authorities known to the author.

For the recent Cadiangullong dam the Aran MODUMIX II-4 achieved COV figures of between 7% and 10% during period when input was the same. The particular flyash available at that site was very variable and unusually difficult to handle. The same machine has achieved COV results in the range from 5% to 8% on a current concrete road project. Other results for Aran "through mixing" plants have ranged from 3.7% to 8% for slip formed concrete roads, and have been in a similar range for well managed dam projects.

Right: RCC produced at 360 cubic metres per hour for the Cadiangullong dam, NSW, Australia.

Batch plant COV data available to the author ranges from 8% to 19.3% for RCC dams, and from 3% to 18.3% for a wide range of slipformed concrete roads, the majority being in the 7% to 11% range.

If anything, the data suggests that well developed "through mixing" plants offer superior uniformity. They clearly offer more thorough mixing with low moisture RCC materials and a greater degree of versatility for mixing all types of concrete found in a dam including the structural and slip formed facing concrete if used.

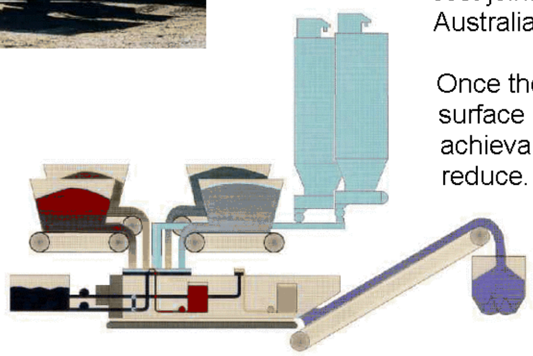
Many RCC dam specifications recommend continuous mixing plants. The data and engineering considerations do not support an argument for limiting mixing to a batching approach.

MIX DESIGN.

Dams built in Australia have included both low paste RCC, (Copperfield), and high paste RCC, (New Victoria). Most others have followed a more independent design stream. Because they are of relatively small size (15 to 30 metres high and 15,000 to 120,000 cubic metres) they have offered opportunity for development of improved techniques.

The predominant construction and placement difficulty with RCC mixes is the tendency for the mix to segregate during handling and upon placement. A key objective is to achieve a mix which is contractor friendly with respect to placement and avoidance of segregation in addition to achieving normal strength and good lift joint cohesion requirements.

Above: The Aran MODUMIX II-4 mixing plant producing RCC. The same machine can mix structural and slipform concrete with equal efficiency.



Right: "Through Mixing" System. Ingredients are ribbon fed and micro mixed in a "Through Mixer". All ingredients enter the mixer together.

For the Cadiangullong dam, the designer GHD Pty Ltd developed a mix which contained approximately 2,200 kg per cubic metre of aggregate comprising 45-55% sand, 4-7% fines, and a maximum aggregate size of 53 mm. The sand was manufactured in the quarry on site. Binder was 90 kg/m³ of slagment, a 60/40 blend of portland cement and ground granulated blast furnace slag, and 90 kg/m³ of flyash. To best fit with compaction behaviour, the moisture content was set at 5.6%. As a result of the achievement of better than predicted strength results, part way through the construction, the dose rates were reduced by the designer by 5 kg/m³ for each binder material.

The resultant mix design was easily mixed at 360 compacted cubic metres per hour in an Aran MODUMIX II-4 and handled and compacted well in two to three roller passes. There was little or no segregation. Because of the apparent ease of achieving full compaction, cores from the 300 mm thick lifts were examined in 38 mm layers. The density difference between the top 70 mm and the lower 70 mm of the lift was only 0.1% or 3 kg/m³.

Local availability of materials has a major effect on the mix design. Although philosophical similarities may exist, each dam is a new project and should be engineered as such.

JOINTING.

Bonding between layers is of critical importance to the structural stability of the dam as well as to water retention performance. It is particularly important in seismically active regions. Bond between lift joints is strongly influenced by segregation and by the age and condition of the lift joint at the time of placing the next layer. Approaches to this problem vary, but generally rely on strict cleanliness of the surface prior to placing the next layer within defined time limits. High paste mixes are proposed as aiding this bond. The subject remains the source of controversy within RCC dam circles.

A survey of the published papers on RCC dam construction reveals many frustrations with the various approaches to this issue in terms of both mix characteristics and method. A simple and low cost joint slurry has been used on recent Australian dams.

Once the initial set of an exposed RCC surface has occurred, the bond achievable between the lifts begins to reduce. For Cadiangullong dam, a 6mm thick layer of high slump mortar was spread over surfaces more than 2 hours old and less than 36 hour old immediately before the placement of the next layer.

The high slump slurry was designed to have the same 15 MPa strength as the parent RCC. Without large stones, it is easy to produce and spread to the required thickness. The cost of this treatment is comparable to the addition of a further 20 kg of cement or a further 50 kg of flyash, neither of which, according to design engineer Brian Forbes would have achieved the same bond between the un-bedded lift joints. Use of additional binder dose rates adds to heat generation and can result in additional shrinkage joints as well as costly concrete cooling requirements. The results of two vertically cored 100 mm holes through the full height of the dam showed 90% of the lift joints were intact upon recovery. This compared well against other projects using alternative methods where as few as 60-70% are sound and intact and free of porosity above the joint.

Mean cohesion strengths of 3,500 kPa for the RCC body and 3,300 kPa for the lift joints compare favourably with published data for other dams using alternative approaches.

Above: Placement of the mortar layer between RCC lifts for Cadiangullong dam.

GROUT ENRICHED FACING.

An interesting recent development has been the use of a grout to modify the characteristics of the RCC at the faces. Rather than use slipformed concrete facing, or placing conventional concrete against forms, the standard RCC mix was placed right up to forms on both the upstream and downstream faces.

When conventional slump concrete is used for facing structures, there is some doubt as to whether it forms a well bonded monolithic mass with the RCC behind it, particularly as the smooth slip formed facing ages. Concerns have been raised by some about differential shrinkage between the conventional concrete and the RCC. For Cadiangullong dam, the RCC was placed right up to forms without differentiation from the rest of the layer. Before compaction, the RCC adjoining the form is coated with a grout designed to maintain or marginally increase the RCC strength in the facing area. A hand held poker vibrator is used to work the grout into the RCC after it has penetrated the loose RCC. The grout and its application rate are established so that the grout works its way into the RCC and so that the underlying bedding mortar on the lift joint rises in such a way that the entire layer is modified. The rest of the RCC layer is then rolled.

Above: Application of grout to facing RCC for GE-RCC. The facing RCC modified by grout and vibration can be seen against the forms,

The amount of grout required is small and can be hand mixed at the placement location. The result is a smooth and tight surface with a pleasing appearance. Horizontal cores demonstrated that the grout enriched RCC transitioned into the RCC, both mid lift and at lift joints, without any sign of structural discontinuity.

This material was also successfully used for encasing the PVC water stops at the upper levels of the dam.

Grout enriched RCC, or GE-RCC as it has now been called, eliminates the need for a separate source of concrete for facing, special transport for that concrete, and special placement machines for the facing. It resulted in a significant cost saving over alternatives as well as offering an excellent result.

ONE HIGH PRODUCTIVITY MIXING PLANT.

The adoption of these recent innovations of mortared joints and GE-RCC substantially reduces the amount of time and effort required for clean up, and for non-RCC placing activities. All concrete for a dam can be produced in one mixing plant.

Aran "through mixing" plants are capable of mixing both RCC and structural concrete at high quality and large output. Capacities of up to 800 compacted cubic metres per hour are possible for very large dams.

The outcome is an improved product, faster, and at lesser cost.

Although RCC for dams is more than fifteen years old, there remains much potential to make it more cost effective. Innovative design and construction methods combined with the right equipment are bringing the original "fast and economical" characteristics back to RCC dams whilst achieving the surface appearance and structural characteristics desired.

The Cadiangullong dam in Australia, constructed with Grout Enriched RCC facing. The surface is smooth and impervious.

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About the Author:

Trevor G. Dunstan BE, M.I.E. (Aust) has been closely involved with the mixing and application of RCC both to dams and to pavements from the outset. Dunstan's company, Aran International Pty Ltd has specialized in the development of mixing plants for these materials for more than twenty years. The company's machines are used around the world, not only for RCC but for other types of binder modified materials and for high quality paving concrete. Trevor Dunstan has taken a personal and professional interest in RCC dam projects and has concerned himself with both civil and mechanical engineering issues. He has contributed to a number of improved construction techniques.