Development of rubble masonry concrete dam engineering in South Africa

By Michelle Blaeser

Rubble Masonry Concrete (RMC) technology for dams blends ancient manual construction methods with state-of-the-art design techniques to create a dam type that history missed, the RMC arch dam. Developing a concept first implemented in neighbouring Zimbabwe in the mid-eighties, new generation RMC arch dams were introduced in South Africa in 1995. Since then the obvious benefits of this technology have been confirmed by more than ten successfully completed structures.

Rubble Masonry Concrete (RMC) dam construction has been demonstrated to be an efficient, cost effective method for the labour-based construction of small and medium sized dams. This technology is likely to become increasingly prevalent in South Africa, particularly in light of our current need for job creation and skills development. In view of the fact that the design approach applied to date has been developed on largely empirical grounds and construction has included some fairly ambitious dam structures, there is a need for a more analytical and all-embracing approach to RMC dam design. This is particularly important to allow dams of this type to be applied in the diversity of environments inherent to South Africa and using a fairly broad spectrum of construction material types.

Labour intensive Construction

Rubble masonry has been used in dam construction for several hundred years. Using this technology (RMC) dam building material and method is not only extremely cost effective, but produces a durable, low maintenance dam wall, that is particularly labour intensive. Considering the training offered to previously unskilled labour in the production of dense, impermeable, high quality masonry work, the merits of the RMC technology are quite exceptional in South Africa at this time.

RMC dam construction usually gives five times more employment than equivalent embankment dam and the masonry skills developed through the application of this technology have been found to be of value in many other types of building. As compared to a conventional plant construction, RMC created an additional 8 000 person days of employment at Bakubung Dam, whilst saving 30% in costs.
New generation RMC
The majority of masonry dams constructed around the world in the past have been mass gravity structures that transferred load in a vertical plane into the foundations. It is only in Zimbabwe since the 1980’s that more ambitious arch designs have been constructed in masonry. Requiring impermeability from thin structural members, these arch dams have necessitated the development of a masonry of higher density and more uniform consistency than that applied on earlier gravity structures, where the seepage length to water pressure ratios are significantly higher.

New generation RMC was born out of a specific set of circumstances in Zimbabwe during a period of prolific dam construction in the mid-eighties. Bringing this technology to South Africa in the nineties, a different environment to Zimbabwe in many aspects, a dam building material and labour based technology that could be demonstrated to be extremely cost-effective, while producing a durable, low maintenance wall was found. With favourable conditions for a specific site, an RMC dam is the lowest cost dam type up to heights of around 25 m. The structures created are extremely durable and substantially less sensitive to exceptional flooding conditions than the common fill embankment. This durability significantly reduces the requirements of river diversion and in fact allows a dam to be built safely in phases over an indefinite period, or to be built for future raising.

The Apparent Behaviour of RMC in Dams
The dams constructed in Zimbabwe to date have universally demonstrated exemplary behaviour and the Zimbabwean engineers can be strongly commended for their impressive wide valley arch dams. Distinct differences, however, exist between the application of RMC for dams in Zimbabwe and in South Africa. Beyond climate and materials variations, a number of differences exist in relation to the respective approaches to dam design. These various differences require a greater understanding of the material, its behaviour, and indeed its likely variations in behaviour, before implementation on ambitious designs in South Africa. The Zimbabwean experiences of the behaviour of RMC was soon confirmed in South Africa and reflected a disparate drying and thermal shrinkage performance when compared to conventional mass concrete. Structures of several hundred metres in length can be constructed in summer without demonstrating the cracking that would be unavoidable for an equivalent, jointless concrete structure.
RMC dams seep, rather than leak, before sealing themselves and becoming watertight. In this process of sealing, efflorescence and calcite deposited in layers on the downstream face and the white streaking effects detracts from the finish of the wall. However as the seepage diminishes, the calcite deposits dry, weather and discolour to a greenish brown, depending on the dampness and extent of attached organic growth.

South Africa is home to a broader range of climates, geologies and construction materials than is the case in Zimbabwe and therefore greater extremes in RMC behaviour and performances are likely to be experienced in this country.

**Construction of RMC dams**

Rubble Masonry Concrete technology for dams, blends ancient manual construction methods with state-of-the-art design techniques to create a dam type that history missed- the RMC arch dam. The first “new generation” RMC arch dams were initiated in South Africa in 1995. Since then, the obvious benefits of this technology have been demonstrated on more than 10 successfully completed dams.

**RMC composition**

As a broad definition, RMC is a matrix comprising large stones, or plums, in a mortar binder. To minimise cost and optimise structural properties, it is necessary to ensure the correct rock or stone content. While a rock component content of 65-70% is achievable, 55% rock with 45% mortar is realistic. The mortar used will generally comprise one part cement and 4-6 parts sand (by volume), giving typical 28 day compressive strengths for the RMC of the order of 14 down to 9 MPa.

Rock used will vary in size from approximately 50 mm maximum dimension to 300 mm, the largest dimension being dependent on the thickness of the member under construction and the obvious restrictions of manageable weight.

**Placement and compaction**

A number of variations exist with regard to the placement and compaction of RMC. Whilst the Zimbabweans have developed certain methods and standard practices, various adaptions of these methods were applied for the Bakubung Dam until a uniform and effective final method was accepted.

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The quality and durability of the final structure produced in water retaining RMC is obviously inherently sensitive to the methods applied for placement and compaction, as can be witnessed when inspecting many of the leaking masonry dam walls in certain parts of Mpumalanga. It is clear that RMC for arch dams must
not be perceived as a series of stones cemented together using mortar, but rather as a monolithic matrix, containing large stones within a body of mortar. In essence, this is similar in concept to the difference between brickwork and concrete. The former comprises a series of individual entities cemented to each other, while the latter comprises a body, or matrix of material made up of component constituents, in the form of cement, aggregates and water. When a “rubble” masonry structure is built in a similar manner to brickwork, placing mortar as a receiving medium into which the surfaces of stones are embedded, the overall structural action of the final body of material is compromised. Stress transfer paths are predetermined and limited, local tension effects become significant, the mortar properties play a more dominant role and overall permeability is high.

The optimal structural performance of RMC would seem to be achieved when the stone content is maximised and this, in all likelihood, is a result of stone-on-stone contact playing the significant structural role, with mortar acting little more than to distributing stress over the stone surfaces.

Accordingly, the method adopted successfully for the construction of the Bakubung Dam involved the initial construction of dry stone walls on either side of a particular structural member to a height of approximately 200 mm, followed by the filling of the trough with a relatively flowable mortar, into which large stone plums were embedded. The stone plums were forced deep into the mortar by being stood on and by being pressed in using a customised hammer tool created from a length of reinforcing steel bar, which further effectively compacted the receiving mortar. Some stones were left projecting slightly above the top surface of each lift, to allow keying into the subsequent lift. The receiving placement surface was cleaned thoroughly and dampened between lifts, as this surface tended to be damaged and dirtied by pedestrian movement.

**Surface finish and appearance**

The approach to surface finish applied in Zimbabwe is generally one of producing plastered external surfaces, with the occasional stone partially visible. This requires a type of flush pointing technique, which produces a relatively flat and even surface. The overall impression of such a finish is one of poorly shuttered and discoloured concrete. However, once through seepage occurs in the process of sealing, the surface becomes covered by efflorescent lime deposits and correspondingly white-streaked. In various instances in South Africa, particularly when a local stone with surface discoloration has been used, it was considered advantageous to preserve a natural rock surface appearance as far as possible. This was achieved by applying recess pointing, whereby the mortar is recessed behind the exposed surface of the stone by approximately 15 mm. The result is a structure that blends well aesthetically into its natural surroundings and takes on an ancient appearance very soon after completion. Variation in appearance for a recess pointed surface is further
possible, depending on the stone-pointing method applied for the surface zones. While the surfaces of the Bakubang was finished relatively roughly, with uneven stone projections, the surface of the masonry on Genadedal and Hogsback Dams were recess-pointed very carefully, to produce a stone-pitched wall appearance. The approach adopted at Bakubang produced a more ‘ancient’ appearance and that applied at Genadedal a very neat and decorative finish.

**Construction and River Diversion**

The nature and extent of the necessary river diversion for an RMC dam will, as always, depend on the size and hydrology of the river to be dammed and the size and construction duration of the dam itself. However, specifically addressing small to medium sized RMC dams within the context of southern Africa, certain assumptions can be considered generally valid. For small- to medium-sized RMC dams, where catchment size is not excessive, as will generally be the case, river diversion and flood handling during construction are very straightforward. As RMC dams are constructed as monolithic structures, without joints, if the arches are constructed in relatively horizontal layers, then the structural integrity is assured at all times. Whilst early loading of RMC might be undesirable, hydraulic pressures incurred during the passage of a relatively short-lived flood event can be handled with ease and without any detrimental consequences.

**Design considerations**

General observation indicates that RMC does not crack, or does not exhibit drying shrinkage and thermal cracking in the same manner as conventional concrete. While this property is not widely understood and cannot currently be satisfactorily justified on engineering principles, heavy reliance in design is placed on the no-cracking performance of RMC. In an effort to derive an explanation for this behaviour, several hypotheses can be evaluated.

These hypotheses include the following:

- Mortar shrinkage is of little influence, as continuous contact between rock particles will prevent related shrinkage of the body as a whole;
- Micro-cracking may well occur within the mortar matrix in RMC, but the large random and interlocking stone particles prevent related continuity causing single, large cracks; and
- On a macro scale, the large stone particles and related interlocking produces a material of relatively high tensile strength.
Experience has shown that high mortar content RMC can crack and will undoubtedly exhibit less favourable behaviour than will a high rock content matrix. Whilst conventional concretes are proportioned to ensure that all surfaces of the coarse aggregate particles are covered in mortar and paste, high rock content RMC comprises a matrix of large rock particles in contact and surrounded and in-filled by mortar. In compression, it is likely that the rock properties will play a dominant role, whilst in tension the mortar and the interlocking of rock particles are likely to be more significant.

The only case of RMC cracking, which is known of, occurred when large rock particles were randomly inserted into a high cement content mortar. Undoubtedly, in this instance the RMC mortar / rock ratio was excessively high and negligible rock contact and interlocking of particles was achieved.

It is believed that a sensible evaluation of cracking in RMC, on the basis of the current level of material knowledge, might be summarised as follows:

- RMC exhibits negligible drying shrinkage;
- RMC in arch dams probably does crack at the heel of the tallest cantilevers, but as is the case with other dam types, this cracking is not visible as it is only present well beneath the water level, when the dam is at least relatively full; and
- Without sophisticated instrumentation and related measurement, the observance of structural deformation is not really possible, particularly on the small scale of the dams in question, and it is suggested that fairly large deformations allow the re-distribution of stresses reasonably effectively. The use of materials of relatively low elastic modulus is obviously significant in this regard.

**RMC Dam Projects Completed in South Africa**

**The first two South African RMC dams**

By coincidence, the first two RMC dams to be constructed in South Africa were initiated independently, but virtually in parallel, in 1995. Bakubung Dam in Pilansberg National Park is a 14.5 m-high RMC multiple arch buttress dam, while the Maritsance Dam near Bushbuck Ridge is an 18 m-high single curvature arch dam with an embankment flank. Both dams were completed in early 1996.

**Bakubung Dam**

Bakubung Dam comprises six 12 m radius, 120 degree aperture arches, with crest thickness of 0.8 m and a maximum base thickness of 1.6 m. The width of the five buttresses varies from 1.8 m to 3 m dependent on height, and each flank is completed by a short section of gravity wall and low embankment, where the
foundation competence deteriorated. The completed structure contains 2,650 m³ of RMC and required 900 person-days of labour to complete.

In this instance, a mechanical mixer was only brought in late on the construction and a shuttle dumper, with earth ramps and scaffold platforms, was used to deliver mortar to the point of placement. The dam was constructed with Walcrete masonry cement, local sand and surface rhyolite stones collected off the local hillsides and loaded by hand onto a tractor-driven trailer. The RMC dam further proved to be 30% lower cost than an equivalent earthfill embankment dam, providing an indication that sustainable labour based contracts were possible using RMC technology. The majestic structure further compliments the natural beauty of the Pilanesberg Park.

Maritsane Dam
Maritsane Dam comprises a single arch on a 60 m radius with an aperture of 105°, flanked on the right side by a massive thrust block, which also acts to retain a fill embankment. The arch has a uniform thickness of 2.4 m, which is flared out to 3.5 m immediately above the foundation contact. The arch and thrust block contains 5,600 m³ of RMC.

Scaffolding, ramps and wheelbarrows were used for the delivery of materials to the point of placement and mortar was mixed using two 300 litre mechanical concrete mixers. Granite rock particles were blasted from a dedicated quarry and sand was sourced from alluvial deposits in the dam basin. A total of 12,000 person-days of labour were required to complete the masonry construction.
The biggest South African RMC dam

With the preparatory work completed in 2012, 2013 saw the placement of RMC at Mdwaka Dam on southern Africa’s largest example of an RMC multiple arch-buttress dam. Situated close to Hole in the Wall, between Elliotdale and Coffee Bay in the Eastern Cape, Mdwaka Dam is being constructed as the storage component of the Mncwasa Water Supply Scheme, which will provide domestic water supply to 63 rural villages.

While its height of 30 m makes Mdwaka Dam the highest RMC dam yet to be constructed in South Africa, its RMC volume of approximately 30 000 m³ makes the dam the largest of this type yet constructed in southern Africa.

The Future of RMC in South Africa

The apparent benefits offered by RMC in terms of low construction costs, employment creation and skills development make it an appropriate solution for dams in South Africa.

Furthermore, RMC dams offer very cost-competitive solutions for domestic water supply projects in rural areas where deeply incised rivers with rock foundations are available, such as in KwaZulu-Natal and along the Eastern Escarpment of South Africa.