TECHNOLOGICAL INNOVATION IN THE DESIGN AND CONSTRUCTION OF DE HOOP DAM

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Abstract

The construction of De Hoop Dam was approved by the Cabinet of the Government of South Africa in June 2004. Dam Type Selection Studies as well as the Design of the dam commenced in 2005 by the Department of Water Affairs: Chief Directorate: Engineering Services.

De Hoop Dam is situated in the Steelpoort River, on route from the town of Stoffberg to Steelpoort, next to the existing provincial road R555. The dam wall is constructed immediately downstream of the confluence of the Steelpoort and the Klip Rivers, a tributary joining from the eastern side.

De Hoop Dam will be one of the biggest dams in South Africa with a total concrete volume of more than 1 mil m³ of concrete. Site establishment for the dam commenced in June 2007, the First (1st) Stage River Diversion was in place in December 2007 and the first concrete placed in June 2008. The Second (2nd) Stage River Diversion was in place in July 2009 and consisted of a diversion culvert constructed immediately next to the Outlet Works. The Second (2nd) Stage River Diversion would remain in position until commencement of Impoundment.

In order to keep South Africa at the forefront of Roller Compacted Concrete dam construction, the Contractor utilized international expertise in order to assist with concrete mix development. This resulted in the Department becoming a world leader in RCC (Roller Compacted Concrete) Construction Technology in effectively developing IV-RCC (Immersion-Vibrated Roller Compacted Concrete).

IVRCC is a high-paste concrete mix that can be placed by means of large equipment such as Bulldozers and Vibratory Rollers (10T) but can also be vibrated against the formwork by means of hand-held Poker Vibrators. This eliminates the need for “skin concrete”.

The development of IVRCC is truly recognized in world of RCC as a ground breaking achievement and will change RCC dam construction as we know it.
1. Introduction

The Olifants River Water Resources Development Project (ORWRDP) consists of a number of phases. Phase 1 was the raising of Flag Boshielo Dam that was completed in 2006. Phase 2A is the construction of the new De Hoop Dam that is currently underway in the Limpopo Province. Phases 2B to 2H includes bulk water infrastructure consisting of pipelines, reservoirs, pump stations, balancing dams and river gauging structures. From that point onwards, the municipalities would be responsible for further distribution.

The purpose of the Olifants River Water Resources Development Project is mainly to unlock economic potential and improving social development within the Limpopo Province of South Africa. Phase 2A of the project, Construction of the new De Hoop Dam, will essentially be the heart of the system providing life to the project as a whole.

The President of South Africa in his 2003 State of the Nation Address announced the construction of a dam in the Olifants River system to unlock the rich mineral deposits in the Limpopo Province and with such a catalyst, also economically supply water to towns, industries and poorly serviced communities in the Sekhukhune area. The De Hoop Dam was found to be the only feasible option to supply water to the Nebu Plateau where about 800 000 people reside.

The construction of De Hoop Dam was then approved by the Cabinet of the Government of South Africa in June 2004. Applications for environmental authorisation commenced in 2004 and initial planning and dam type investigation studies also commenced. Towards the end of 2005 the Department of Water Affairs: Chief Directorate: Engineering Services commenced with the design process.

De Hoop Dam will be one of the biggest dams in South Africa with a total concrete volume of more than 1 million m$^3$ of concrete. Construction of the dam commenced in June 2007 and the project is currently nearing completion.

Significant improvements in the RCC mix design have been implemented at the beginning of the dam construction. These led to a vast simplification of the construction process and allowed the highest construction rates ever achieved in South Africa with a peak of more than 130 000 m$^3$ of RCC placed in one month. This furthermore resulted in the Department of Water Affairs (DWA) becoming a world leader in RCC Construction Technology in effectively developing IVRCC (Immersion-Vibrated Roller Compacted Concrete).

The first international experience with IVRCC at De Hoop dam has been extremely successful and has brought up one of the most significant contributions of the last years to the RCC dam construction technology. A very workable RCC mix could be designed that allowed placement with both roller compaction and with immersion vibration. During the preliminary trials in April 2009, it was proven that the new RCC mix did not require any additional grout at the point of placement and it could be directly consolidated by immersion vibration. IVRCC has been used against the formwork and rock abutment as interface concrete and in the main dam achieving an excellent finish and an extraordinary in-situ quality. Following this first experience IVRCC has been further implemented in other projects.
In addition to the key mix design aspects and specific placement procedures associated with this main topic, this paper provides a general description of the dam construction methodology and quality control. Some of the difficulties encountered throughout the construction period and lessons learned are also discussed.

The following is a photograph of the nearly completed De Hoop Dam.

![De Hoop Dam](image.png)

**Figure 1. Nearly completed De Hoop Dam**

2. Materials and RCC Mix Optimization

The experience at De Hoop dam has been extremely useful in developing a new approach to RCC materials and mixes in South Africa. Former RCC dams built in the past by the Department of Water Affairs had followed the low paste approach. RCC mixes were formerly placed at a water to cement ratio of about 0.9. Despite the relatively high water content these mixes tended to segregate and the concrete was generally of a poorer quality than the traditional conventional concrete. As a result of this, the design team at De Hoop decided to follow from the beginning a mix approach with a higher paste content that would also be easier to consolidate by roller compaction.

2.1 Main Properties of the initial RCC Mix

Crushed coarse and fine aggregate have been used from a quarry production installed in the future reservoir area. In the initial stages of the mix design the envelopes of the aggregate grading curves were revised and the allowance for the fine content of the sand was increased up to 10% passing 0.075 mm sieve. Coarse aggregate following the SANS standard and with a maximum size of 53 mm was used during the preliminary trials. In the original specified mix, the sand/total aggregate ratio was 41% and the workability was between 15 and 25 seconds. The total cementitious materials content ranged between 180 and 190 kg/m³ with 72% pulverized fly-ash. The water to cementitious ratio was 0.62.
The investigation of the initial mix at the laboratory and on several test sections concluded that there was still a need for improvement. Although the mix behaved well at the laboratory (in terms of compaction and strength parameters), the cores extracted from the test sections indicated some spots with segregation and in some cases lack of bonding between layers. During placement, the fresh RCC mix did not look as a typical high-pozzolanic workable mix. When placed there was still some signs of segregation at the bottom of the heap and the mix looked too dry. During compaction it was not possible to get much paste on the surface and there was no movement when walking on top of this concrete. These were all signs of a less workable and drier mix than desired.

The replacement of the conventional facing concrete by grout-enriched RCC was also tested in the early trials. Despite the fact that the surface finish was adequate, the vibration effort was high, even when adding a grout that had a water to cement ratio as high as 1.0. Some difficulties were experienced in achieving a good consolidation and bonding with the adjacent roller compacted concrete.

### 2.2 Mix Design Improvements

In order to overcome these problems a more workable mix was suggested during an external review of the construction methodology and the placement procedures (April 2009). The modifications that were suggested in the RCC mix design are summarised as follows:

- Maximum size of aggregate 38 mm (instead of 53mm);
- Slight modification of the overall gradation curve;
- Fine aggregate 38% of the total aggregate (instead of 41%);
- Cement (OPC) 60 kg/m$^3$ (instead of 56 kg/m$^3$);
- Fly-ash 140 kg/m$^3$ (instead of 130 kg/m$^3$);
- Mix consistency between 8 and 10 seconds VeBe. The water content was increased from 114 to 125 l/m$^3$ (water to cementitious ratio kept at similar value as before); and
- Use of a retarder admixture to achieve initial set of the RCC at around 20 hours, to improve bonding between layers.

The findings after testing the proposed mix design were quite positive. The segregation was eliminated, the fresh concrete was much more cohesive and with a higher volume of paste around the particles of aggregate. The placement and compaction were much easier and higher densities could be achieved with just a few passes of the vibratory roller. As a consequence of all this, the production could be increased and the time between layers could be reduced.

The analysis of cores showed that a good bonding and interpenetration between layers was possible to achieve. This was caused by a relatively high volume of paste on the surface of the compacted layers with a reduced setting time. Therefore the treatment of the horizontal joints could be significantly reduced compared to that required with the initial mix.

The mix could have been further optimised if some modifications could have been implemented in the aggregates processing plant. These adjustments would include replacement of a tertiary crusher (vertical impact instead of a cone) and the installation of a fines recovery unit. The aim was to improve the shape of the fine aggregate and to increase the amount of fines passing 0,075 mm sieve up to 14 – 15%.
Unfortunately it was too late to implement these measures at the time. Therefore the water content was maintained at a relatively high level to ensure a good workability. This is a much more limiting factor to guarantee the in-situ quality of the RCC than the compressive strength.

Preliminary laboratory tests indicated that if the proposed changes in the crushing plant could have been implemented a reduction of the cement and fly-ash content of more than 25 kg/m$^3$ might have been possible. Thus the total cementitious material content of the RCC mix that has been used for the construction of the dam could not be further reduced from the values mentioned above in order to meet the required compressive and tensile strength of the RCC at the long term.

### 2.3 IVRCC as a result of Mix Optimization

A relatively easy immersion vibration was possible with a 0.65 water to cement ratio. But the most extraordinary finding of the RCC mix design optimization developed in April 2009 was that the fresh RCC was so workable, rich in paste and cohesive that it could be even consolidated by immersion vibration without adding any grout at the point of placement.

The following photograph indicates the IVRCC’s ability to be full consolidated by means of immersion vibration:

![Immersion Vibration of Roller Compacted Concrete](image)

Figure 2. Immersion Vibration of Roller Compacted Concrete

This has brought up a significant simplification to the placement as no grout is required to be mixed, transported and placed against formwork and at the interfaces. The same RCC mix is directly vibrated against the formwork short after it has been spread. The shorter the elapsed time is between mixing and vibrating, the easiest is to achieve full consolidation. After stripping out the first formwork the finish of the surfaces were inspected. The achievements are as good if not better as those that are typical of conventional concrete.
The properties of the IVRCC are the same as the adjacent RCC. The traditional skin concrete has been replaced by IVRCC with same elastic and thermal behaviour as the concrete placed in the core of the dam. The potential discontinuity between skin concrete and RCC has been therefore eliminated.

The following is a comparative indication of the Original RCC mix vs IV-RCC as well as Conventional Vibrated Concrete:

Table 1: Comparative Concrete Mix Designs

<table>
<thead>
<tr>
<th>Concrete Mix Description</th>
<th>Original RCC (Grade 15/53)</th>
<th>IV-RCC Mix (Grade 15/38)</th>
<th>CVC (Grade 15/38)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC (Ordinary Portland Cement)</td>
<td>68 kg/m³</td>
<td>62 kg/m³</td>
<td>87 kg/m³</td>
</tr>
<tr>
<td>PFA (Pulverized Fly Ash)</td>
<td>172 kg/m³</td>
<td>145 kg/m³</td>
<td>203 kg/m³</td>
</tr>
<tr>
<td>Total Cementitious</td>
<td>240 kg/m³</td>
<td>207 kg/m³</td>
<td>290 kg/m³</td>
</tr>
<tr>
<td>53 mm Course Aggregate</td>
<td>316 kg/m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37,5 mm Course Aggregate</td>
<td>505 kg/m³</td>
<td>883 kg/m³</td>
<td>789 kg/m³</td>
</tr>
<tr>
<td>19 mm Course Aggregate</td>
<td>631 kg/m³</td>
<td>483 kg/m³</td>
<td>511 kg/m³</td>
</tr>
<tr>
<td>Sand</td>
<td>816 kg/m³</td>
<td>877 kg/m³</td>
<td>821 kg/m³</td>
</tr>
<tr>
<td>Water</td>
<td>120 l/m³</td>
<td>122 l/m³</td>
<td>145 l/m³</td>
</tr>
<tr>
<td>Additive (Superplasticizer)</td>
<td>2 400 cc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additive (Retarder)</td>
<td>2 500 cc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W:C Ratio</td>
<td>0.52</td>
<td>0.59</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The following is a photograph of IVRCC placement in progress:
3 Main Features of the Dam

The main features of the dam are as follows:

Table 2: Main Features of De Hoop Dam

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gross Storage Capacity [million m³]</td>
<td>347.4</td>
</tr>
<tr>
<td>2</td>
<td>Catchment Area [km²]</td>
<td>2865</td>
</tr>
<tr>
<td>3</td>
<td>Approximate Length [m]</td>
<td>1017</td>
</tr>
<tr>
<td>4</td>
<td>Approximate Height [m]</td>
<td>88</td>
</tr>
<tr>
<td>5</td>
<td>Total Excavation – Dam Footprint [m³]</td>
<td>415 000</td>
</tr>
<tr>
<td>6</td>
<td>Total Excavation – Quarry [m³]</td>
<td>1 300 000</td>
</tr>
<tr>
<td>7</td>
<td>Total Estimated Concrete Volume of the Dam [m³]</td>
<td>1 100 000</td>
</tr>
</tbody>
</table>

The First (1st) Stage River Diversion consisted of earth-fill embankments (diversion channel) constructed towards the left of the Outlet Works and Spillway, allowing for construction activities to commence in the position of the Outlet Works and a section of the Spillway.

The Second (2nd) Stage River Diversion consisted of a diversion culvert constructed immediately next to the Outlet Works and allowing for construction activities to commence towards the Spillway and Left Bank vicinity.
The Second (2nd) Stage River Diversion will remain in position until commencement of Impoundment. This implies that operation of the dam will commence although construction of the dam is not entirely complete.

The use of the outlet system for river diversion would be very limited. Only once the second stage diversion culvert has been closed, can the outlet pipes be used to divert the river flow through to the downstream section whilst the construction of the main dam wall is being completed.

4 Site Layout and Installations

Batching plants consisting of a 4.5 m³ Liebherr unit, a 2.5 m³ Icon unit, a double drum SGME, a single drum SGME as well as a 2.5 m³ Liebherr unit are used for concrete production. From the batching plants Articulated Dump Trucks as well as a conveyor system is used to transport concrete up to the point of placement.
5 CONCRETE PLACEMENT RECORD ACHIEVEMENTS

Further to this achievement, the Contractor attempted to break the South African record for the volume of concrete placed in a month during November 2010. The previous record of 40 600 m$^3$ of concrete placed in a month was bettered during this record attempt and a total concrete volume of 103 000 m$^3$ was placed in 21 days.

Figure 6. Record Attempt 2010 (Day 0)

Figure 7. Record Attempt 2010 (Day 5)
A further attempt to break this record was conducted during November 2011 and proved to be extremely successful. A total concrete volume of 131 000 m³ was placed in 28 days. Concrete placement of this magnitude was never attempted in the past and it is believed that this record will stand for the foreseen future.
1. **Conclusion**

Overall progress currently stands at approximately 90% complete. Construction of the dam provided employment opportunities for in excess of 1 100 employees of which 80% local labour were employed.

Numerous challenges were experienced in the construction process to date. Some of these challenges includes: deeper excavation requirement due to geological reasons, concrete mix development in order to ensure international best practice as well as procurement of construction materials and establishment of a quarry, sufficient in size, to provide for the vast amount of required aggregate.

The De Hoop Dam Project is truly a flagship project for the Department of Waters Affairs of South Africa and possibly one of the largest projects for the foreseeable future. Water needs will be addressed in the Limpopo Province and poverty will be greatly reduced. Lessons learned and technological innovations will change how future projects will be addressed.

2. **References**


