A BRIEF HISTORY OF THE RCC AT NECKARTAL DAM

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ABSTRACT

The construction of Neckartal Dam started in September 2013. The full-scale trial section was done in August 2015 and the first RCC was placed on the dam foundation in October 2015. The RCC placement was completed 32 months later in May 2018. This paper gives a brief history of the RCC through the various project phases. Two mixes were used, a 20/38 high cementitious mix for an impermeable zone (Zone 1) in the upstream face of the dam and two 10/38 low cementitious mixes for the main body of the dam (Zone 2). The Contractor produced a total of 3.12 million tons of aggregate for the project over 33 months at an average of 94 800 tons per month. The overall crushing plant efficiency over the 33 months of production was 33%. The Contractor produced a total of 836 000m^3 of RCC for the project over 32 months at an average rate of 26 127m^3 per month. The overall plant efficiency over the 32 months was 17%. Over the whole RCC placement period, there were interruptions for many reasons, some within the Contractor's control such as plant breakdowns, insufficient sand, cement and/or fly ash, waiting for shutters to be moved, preparing RCC surfaces, sequencing of the intake tower construction etc. There were also some delays beyond the Contractor's control such as strikes, break downs and late payments. The RCC cube tests indicated that the set RCC easily achieved the strength requirements of the project specification of 20MPa at 365 days for Zone 1 and 10MPa at 365 days for Zone 2.

1. INTRODUCTION

Neckartal Dam is located on the Fish River, a tributary of the Orange River. The project will supply bulk water to a new irrigation scheme located 40km south-west of Keetmanshoop in Namibia. Keetmanshoop has a desert climate. The daytime temperature often rises above 40°C during the summer and the mean annual precipitation is less than 150mm.

The construction of Neckartal Dam started in September 2013. The Employer is the Namibian Ministry of Agriculture, Water and Forestry. The Contractor is Salini Impregilo S.p.A and the engineering design and site supervision are being undertaken by Knight Piesold Consulting (Pty) Ltd. Neckartal Dam is the largest dam currently under construction in Southern Africa. The Neckartal dam will be 78.5m high, with a crest length of 518m and a gross storage capacity of 857 million m^3. The main dam wall contains 836 053m^3 of RCC. The dam outlet releases water through two Francis turbines to an abstraction weir and pumping station located 13km downstream. Neckartal Dam will be the largest dam in Namibia and the eight largest dam in Southern Africa by storage volume. It is an important development project for the Namibian government and is aimed at stimulating economic growth in the Southern Region of Namibia. This paper describes the development of the RCC from the dam design and specification to the completion of the RCC placement in May 2018. This paper is intended to give a brief overview of the RCC dam design, specifications, aggregate production, the full-scale trial, the RCC plant used, the RCC production rates and the quality assurance methods.

Neckartal dam is remotely located, approximately 1000km from the nearest cement factory located at Otavi in Northern Namibia and 1200km from the closest fly ash sources located in the highveld region of South Africa. A key objective for the RCC mix design was to reduce the cementitious content and therefore a significant proportion of the overall project costs. This was achieved by using the latest developments in RCC technology at that time to adopt mixes suited to this remote site. Two different RCC mixes were used in the dam, a higher cementitious mix for the upstream face to provide an impermeable barrier and a lower cementitious mix in the core of the dam. With the aid of an RCC expert, both the mix and aggregate specifications were carefully developed to ensure an economic solution. Through laboratory testing and a full-scale trial the design mixes were optimised. The RCC was placed in hot dry temperatures increasing the ratio of cold to hot joints and the potential of temperature induced cracking. This was mitigated by using a low cementitious mix for the dam core and by using retarders to increase the setting time. A thermal model of the dam was developed to determine the optimum joint spacing and to estimate surface and mass gradient thermal effects, thereby allowing a definition of the maximum allowable RCC placement temperature.

2. NECKARTAL DAM

2.1 Dam statistics

Neckartal Dam is 78m high with a crest length of 518m. The total volume of RCC used to construct the is 836 000m^3, which comprised of 368 000m3 of Zone 1 (20/38) and 468 000m3 of Zone 2 (10/38) RCC.

The long-term average temperature at Keetmanshoop is 21°C. The long-term average winter temperature is 15°C while the long-term summer temperature is 26°C (October to April). The average annual rainfall (MAP) is 138mm,

Figure 1: Neckartal Dam June 2018 (View from downstream - top of the left bank)

3. RCC SPECIFICATIONS

Neckartal dam is remotely located, approximately 1000km from the nearest cement factory located at Otavi in Northern Namibia and over 1200km from the closest fly ash sources located in the highveld region of South Africa. The daytime temperature often rises above 40°C during the summer and the mean annual precipitation is less than 150mm. These constraints required an innovative approach to the RCC mix design and specification. A key objective for the RCC mix design was to reduce the cementitious content and therefore a significant proportion of the overall project costs while having a mix which is still easy to work, that compacts to a high density and has a relatively long set time to minimise the number of cold joints. This was achieved by using the recent developments in RCC technology to specify and the develop RCC mixes suited to this remote and very hot site. The approach adopted was to use two different RCC mixes in the dam, a higher cementitious mix for the upstream face to provide an impermeable barrier and a lower cementitious mix in the core of the dam to reduce cost as far as possible. The RCC mixes and the aggregate specifications were carefully developed with the aid of an RCC expert to ensure an economic solution for the site. Through on-site laboratory testing and later a full-scale trial section, the specified design mixes were optimised and improved. These mixes were also further improved during construction. Set retarders were used in both mixes to increase the setting time. The retarder was used to increase the initial setting time to the maximum while ensuring the final setting time did not extend beyond 28hrs. This reduced the number of cold joints which aided both speed of construction and quality of the horizontal joints. The Consultant encouraged the Contractor to develop a procedure to adjust the retarder and the water content in the RCC mix to better suit changing day and night time temperatures as well as the winter and summer variations. However, the Contractor varied the retarder and water content only by visual inspection of the RCC.

The specifications for the RCC varied from the traditional "SANS1200 type" specification which generally specifies the engineering properties of the final product and not the equipment requirements and construction processes to achieve these. This gave the Employer control over the plant to be provided for the construction of the dam. It also made the comparison between Tenders easier as the Contractors all needed to provide the specified plant. The Neckartal Dam RCC specification included an RCC mix composition range for each zone, the coarse and fine aggregate requirements, plant requirements, detailed construction methods, a maximum placement temperature of 28°C and quality control methods including a coring programme. The specification required a batch plant with a minimum capacity of 300m^3/hr, a conveyor belt system to deliver the RCC from the batch plant to the dam surface, at least a CAT D4 to spread the RCC and a vacuum truck among other specific equipment.

4. RCC MIX PROPORTIONS

For Neckartal Dam, it was decided to use a 20/38 high cementitious mix for a 6m impermeable zone (Zone 1) in the upstream face of the dam and a 10/38 with a low cementitious but still with a relatively high paste content for the main body of the dam (Zone 2). For Zone 2 the fly ash content was increased by 25kg during construction to improve the workability and reduce the amount of bleeding in Zone 2. The specified RCC mix parameters and the values achieved are given in table 1 and 2 below. The Contractor changed the retarder from MAPEI to BASF during construction for commercial reasons.

Table 1: RCC Mixture specified ranges and adopted RCC mix parameters

RCC	Fines Volume (ℓ/m^3)	w/c ratio (by weight)		Vebe Grade (s)		Agg. Size (mm)	Sand / Agg. Ratio (by weight)		P / M Ratio (by volume)
	Min	Min	Max	Min	Max	Max	Min	Max	Min
Zone 1 (20 MPa)	20	0.60	0.65	8	15	38	0.39	0.42	0.40
RCC Mix 51	**118**	**0.64**		**13**		**38**	**0.42**		**0.45**
Zone 2 (10 MPa)	35	1.2	1.5	25	35	38	0.35	0.40	0.36
RCC Mix 52	**60**	**1.38**		**28**		**38**	**0.40**		**0.39**
RCC Mix 52B	**78**	**1.02**		**26**		**38**	**0.40**		**0.38**

Table 2: Specified Range of Mixture Proportions and adopted mixtures number 51 and 52 (52B)

Material	Range of mixture proportions (kg/m³)			
	Zone 1 Specification (Grade 20/38)	**Zone 1 - Mix 51 (Grade 20/38)**	Zone 2 Specification (Grade 10/38)	**Zone 2 - Mix 52 (B) (Grade 10/38)**
Type I Portland Cem.	60 - 65	**65**	65 - 80	**65 (65)**
Pozzolanic material	110 - 140	**120**	0 – 20	**20 (45)**
Free water	110 - 130	**119**	100 - 120	**117 (112)**
Coarse aggregate	1300 - 1400	**1370**	1350 - 1550	**1500 (1485)**
Fine aggregate	880 - 960	**990**	800 - 950	**1001 (991)**
Set retarding admixture	1 - 4	**1.1**	1 - 4	**1.2 (1.1)**

5. RCC AGGREGATE PRODUCTION

A detailed specification for the RCC aggregate requirements was part of the Neckartal Dam contract, which included specific grading for the coarse and fine aggregate. These gradings are quite different to the grading given in SANS 1083 *Aggregates from natural sources — Aggregates for concrete*.

5.1 Coarse aggregate

The specification required that the aggregate is divided into three groupings for quality control, two coarse gradings and one fine grading envelopes were specified. The coarse aggregate was grouped into two stockpiles a 4,75–19 mm and a 19–37,5 mm. The coarse aggregate required that the sum of the Flakiness and Elongation Indices (FI & EI) of the coarse aggregate shall be less than 25%. This was to ensure good workability of the RCC with reduced water content and therefore also reduced cementitious content.

The Contractor set up a 600 t/h crusher to produce both the coarse and fine aggregate and started to produce aggregate in April 2015. The contractor's crushing plant included four stages of crushing and screening. The parent dolerite was obtained from a quarry identified for the project. Initially, the crushing plant set up by the Contractor did not produce aggregate within the specified shape limits. The combined EI + FI of the coarse aggregate was about 65 during the first few months of production. The Engineer instructed the Contractor to make adjustments to the crushing plant to get the aggregate closer to the specification. After much discussion and various expert opinions from both the Contractor and the Engineer, the Contractor agreed to adjust the crushing plant. The Contractor started producing aggregate with a combined EI + FI of about 35 by July 2015. The Contractor improved the aggregate shape by feeding more material through their Vertical Shaft Impact (VSI) Crushers, increasing the rotational speed of the VSI crushers and changing some screens.

5.2 Fine Aggregate

The contractor had the option to process river sand or to crush sand from the quarry or to have a blend of river and crushed sand for the fine aggregate. The Contractor chose to crush the sand and included two rod mills into his crushing plant set up to produce the fine aggregate. The Contractor did on occasion run short of sand during the construction of the dam. For the fine aggregate, a tight grading envelope was specified with a high proportion of fines with a maximum void ratio of 32%, in order to improve the paste/mortar ratio while using small quantities of cement and fly ash in the RCC mix. In addition, the specification required that the fine aggregate grading is not deficient in the 0,150 to 1,18 mm fraction and at least 55% of the fine aggregate must lie within these grading limits. The Contractor was not able to achieve the required fraction of 0.15 to 1.18mm required in the fine aggregate with his crushing plant. After the full-scale trial, this requirement was relaxed from 55% to 40%. The fine aggregate that the Contractor produced was deficient in 0.6mm to 1.18mm as shown on the grading curve in the figure below. The crushing plant did produce sufficient fines < 0.075mm, however, this was difficult to control on windy days, as a significant portion of the fine material tended to blow away making it difficult to keep the proportion of fines constant. The figure 2 below shows the gradings specification limits and the actual gradings that the Contractor achieved.

5.3 Aggregate Production

The Contractor produced a total of 3.12 million tons of aggregate for the project over 33 months at an average of 94 800 tons per month. The overall plant efficiency over the 33 months of production was 33% (based on a 20-hour working day, a six-day week and a 4-week month). The overall efficiency percentage includes the slow start-up period while the Contractor was adjusting the crusher to meet the specifications, the holiday periods and plant breakdowns. During the peak production months from April 2016 to November 2017, the overall plant efficiency was closer to 40%. Figure 3 below shows the monthly production of aggregate, the cumulative production and the average monthly production.

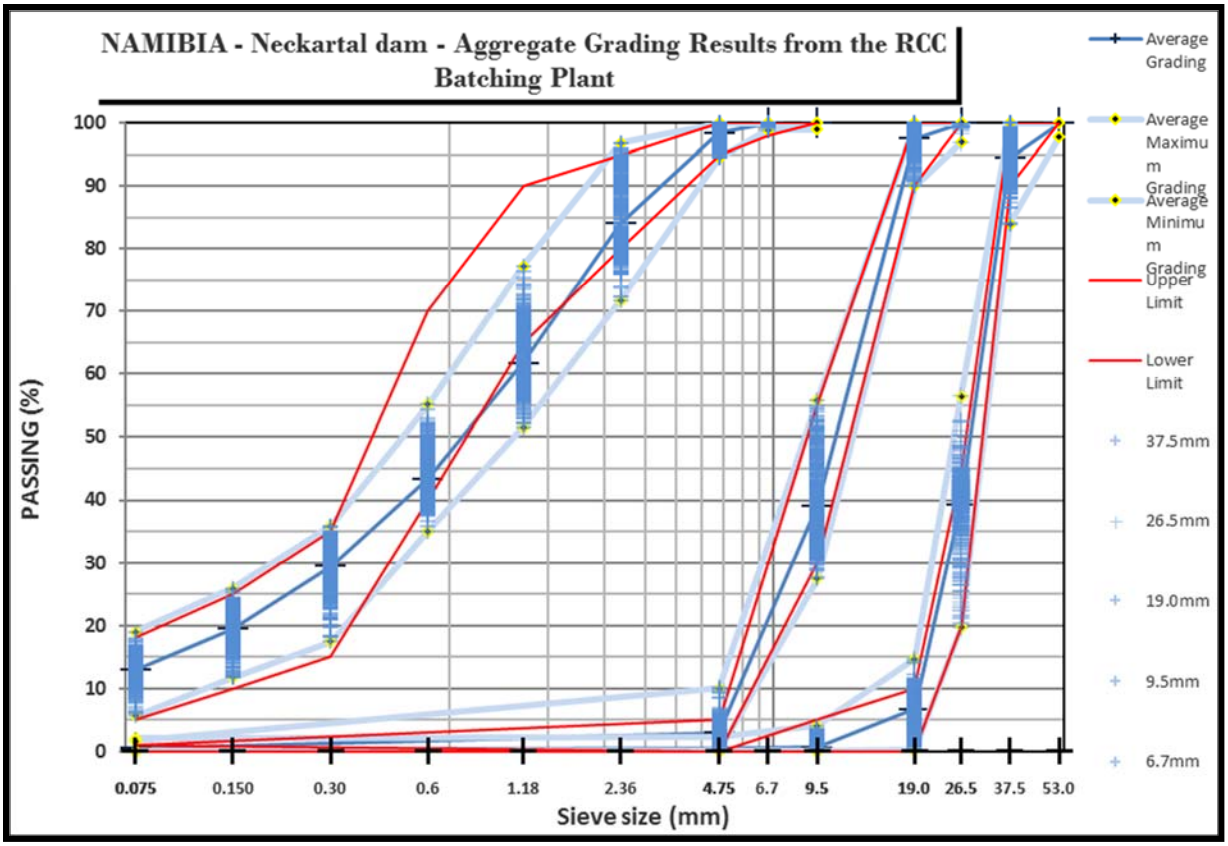

Figure 2: Fine and Coarse Aggregate Grading Specifications and Results

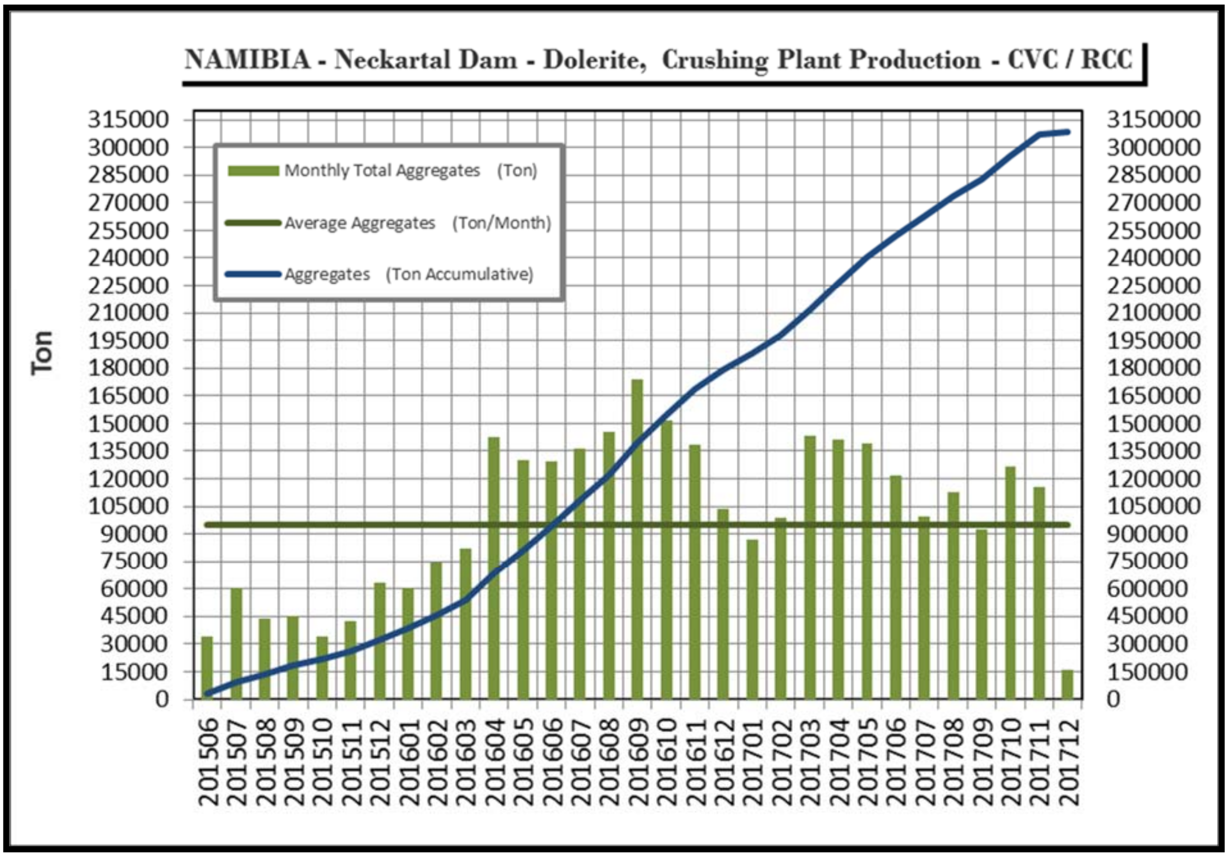

Figure 3: Monthly Aggregate Production

6. RCC TEMPERATURE CONTROL

During the design, the thermal analyses indicated that the maximum RCC placement temperature should not exceed 28°C to avoid thermal cracking in the dam structure with a maximum joint spacing of 20m. In order to achieve this requirement, the Contractor set up a cooling plant to cool both the coarse aggregate and the mixing water. The Contractor selected and designed a cooling plant consisting of two chiller units, four air blast units and four insulated aggregate silos through which the cold air was blown. It required 3MW of power to run the cooling plant. With ambient temperature over 30°C almost every day in summer and quite regularly over 40°C, the Contractor had to run his cooling plant in summer to meet the specified placing temperature. The average temperature for placed RCC was 22°C, which ranged from about 25°C in summer to about 16°C in winter. The cooling plant was designed to reduce the temperature of the mixing water from 25°C to 4°C and the19mm aggregate from 35°C to 16°C and the 38mm aggregate from 35°C to 12°C at an RCC production rate of 320m^3/hr. Figure 4 below shows the history of the RCC placement temperature and the ambient temperatures. The specified maximum RCC placement temperatures were achieved by the Contractor using the cooling plant.

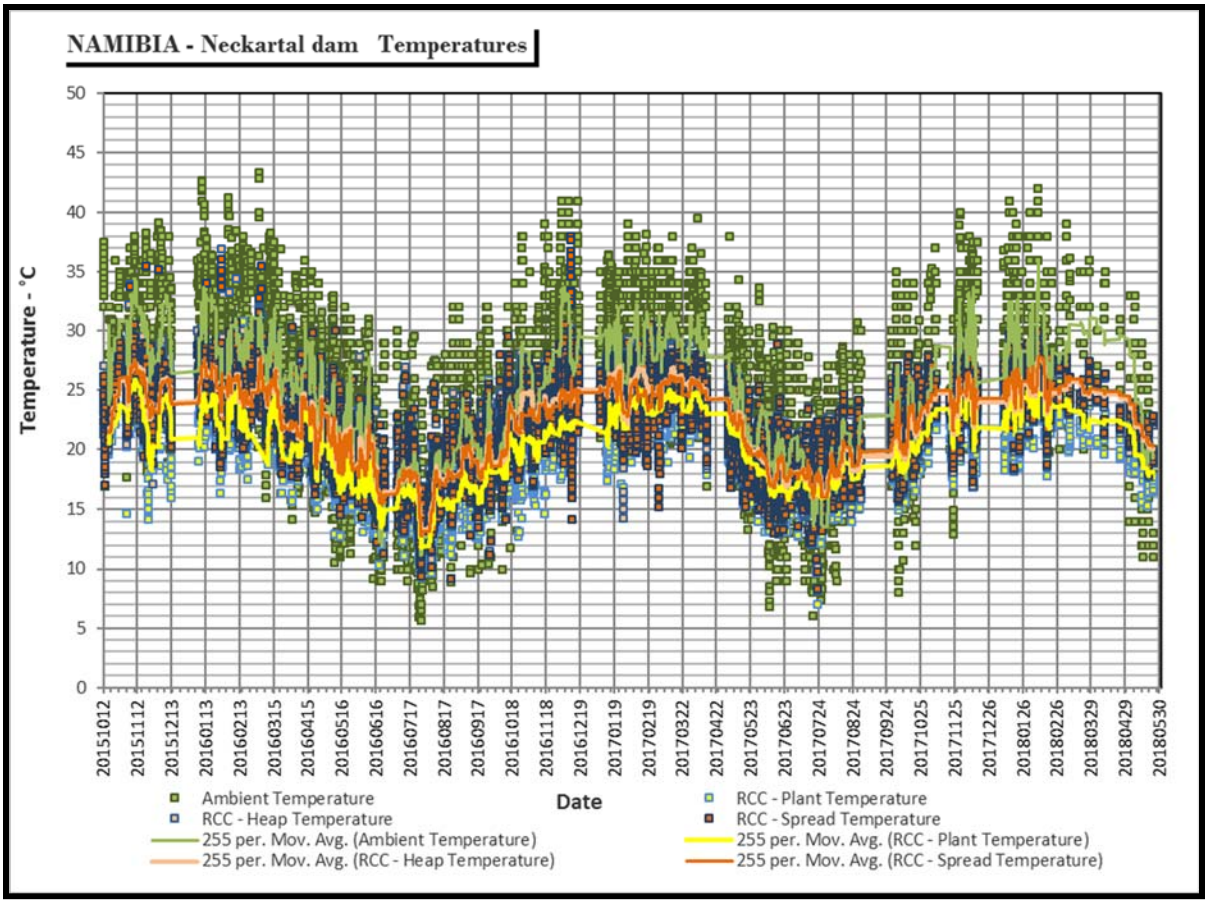

Figure 4: RCC and Ambient temperatures

7. RCC PRODUCTION

The Contractor's RCC batch plant included two Simen twin shaft mixers with a combined capacity of 320m^3/hour. Each mixer could mix 4m^3 of RCC within 90 seconds at a time. The maximum RCC batch consisted of 24 cycles x 4m^3 = 96m^3. To transport the RCC from the batch plant to the surface of the dam, the Contractor constructed a 300m long covered conveyor belt down the very steep left abutment. The conveyor belt had a large structural telescopic steelwork tower just upstream of the dam to raise the end portion of the conveyor as the dam increased in elevation. The batch plant could deliver RCC onto the conveyor or directly into trucks. The maximum volume of RCC delivered by trucks in a day was 3304m^3 and the maximum volume of RCC delivered in a day by the conveyor was 4988m^3.

The Contractor produced a total of 836 000m^3 of RCC for the project over 32 months at an average rate of 26 127m^3 per month. The overall plant efficiency over the 32 months was 17% (based on a 20-hour working day, a six-day week and a 4 week month). This efficiency percentage includes the slow start-up while the Contractor was preparing foundations, difficult areas to place RCC at the end of the project when the surface area was very restricted, a work stoppage due to late payment, holidays and breakdowns. During the peak production months from May 2016 to October 2017 the Contractor placed an average of 36 109m^3/month, the overall plant efficiency was closer to 24% for this period. Figure 5 below shows the monthly production of RCC, the cumulative production and the average achieved.

From the monthly RCC production graph, it can be seen that there was a slow start-up period when the contractor was busy placing RCC at foundation level. It can also be seen that the Contractor's production rates were significantly impacted by the December shut down, and also the April holidays. The production also slowed down significantly in August 2016, when the dam reached gallery height at elevation 730m. It was not only the gallery formwork but significant dam monitoring instrumentation that was required at this elevation. The RCC production was also impacted in September 2017 over late payment from the Client. From November 2017, production decreased significantly as the RCC conveyor was taken away and the access onto the dam was restricted. Over the whole RCC period, there were interruptions for many reasons, some within the Contractor's control such as mechanical breakdowns, insufficient sand, cement and/or fly ash at times, waiting for shutters to be moved, preparing RCC surfaces, sequencing of the intake tower construction etc. As is the case on many large projects, there were also some delays beyond the Contractor's control such as strikes and late payments. These delays were dealt with in terms of the Contract.

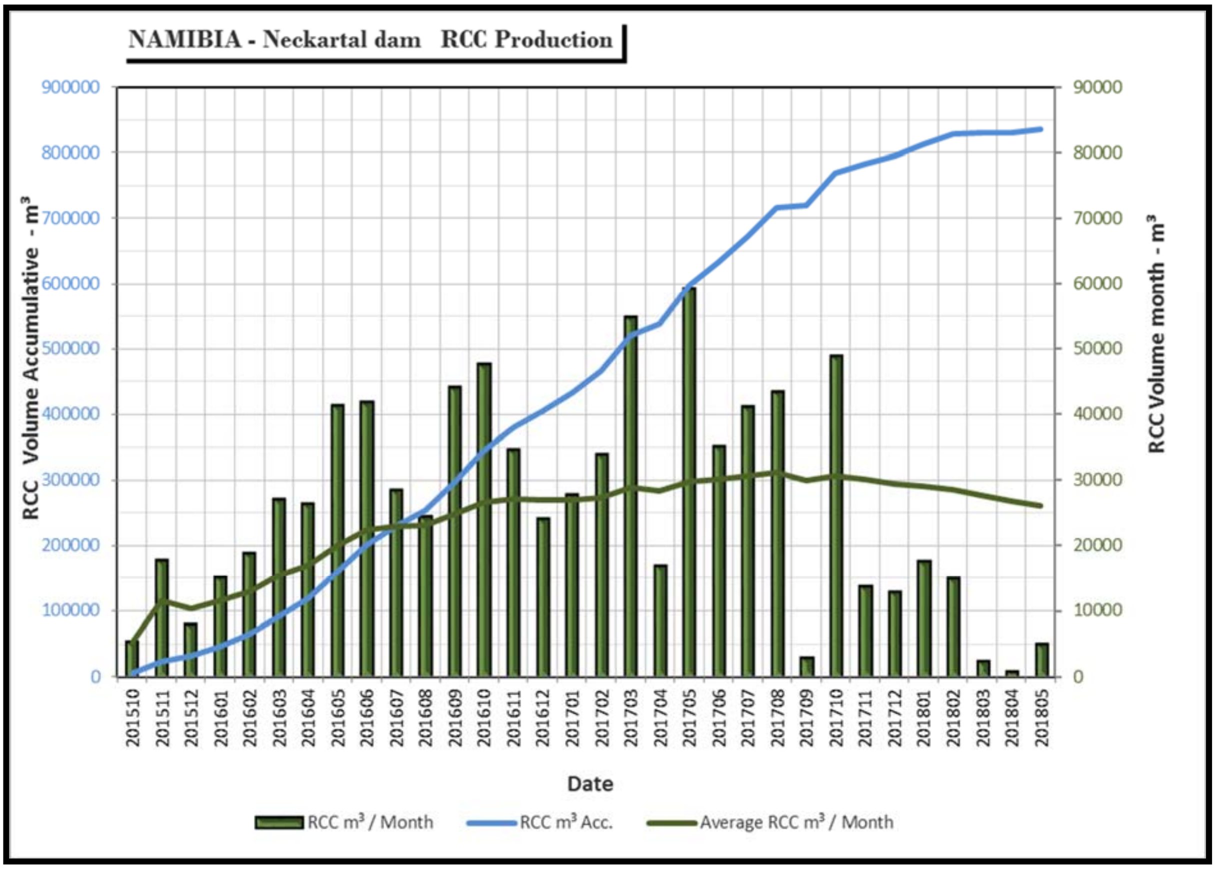

Figure 5: RCC Monthly Production

The two guideline parameters to target for efficient RCC production are peak month/average month should be less than 2 and peak month/peak day should be greater than 20 (QHW Shaw 2017). The actual parameters achieved for Neckartal Dam (and the Contractor's Tender Programme) were;

- **Actual** peak month/ average month of 2.3 over 32 months of the whole RCC placement period; or 1.6 over 18 months of peak production period. (**Tender Programme** peak month/ average month of 1.8 over 20 months of the whole RCC placement period.)

- **Actual** peak month/peak day of 12.3. (**Tender Programme** peak month/peak day of 16)

The Contractor did not manage to meet his Tender programme of 20 months for the RCC placement and the target monthly production/peak daily of 1.8. However, it can be seen that he did achieve the monthly production/peak daily of 1.8 during his peak production months. The Contractor's Tender programme indicated a planned peak production of 80 000m^3/ month, however he only managed to achieve a peak production of 60 000m^3/ month.

Another factor for estimating RCC construction efficiency (M Dunstan, 2015) is average monthly RCC placement over plant capacity per hour.

The actual parameters achieved for Neckartal Dam (and the Contractor's Tender Programme) were;

- **Actual** average monthly RCC placement/capacity of 82hrs per month for the whole RCC placement period; or 113hrs per month during peak 18 months of RCC placement. The **Tender Programme** indicated a planned average monthly RCC placement/capacity of 140hrs per month.

According to Dunstan's records, the average efficiency factor for all RCC dams completed up to 2016 was 94hrs per month, with a range for the worst case of 13.5hrs per month to the best case of 196 hrs per month. Neckartal Dam is below the world average; however, the Contractor did demonstrate that during the peak RCC periods, he could achieve production values well above the world average of 94hrs per month. The Contractor did not manage to meet the goals of his Tender Programme which targeted a value of 140hrs per month which is well above the world average of 94hrs per month.

The daily RCC production graph in Figure 6, shows more clearly the impact the holidays had on the overall RCC production. When studying the hourly RCC production rates, it is also apparent that the Contractor's choice to have two 10hr shifts as opposed to three 8.5hr shifts had a significant impact on the overall RCC production rate.

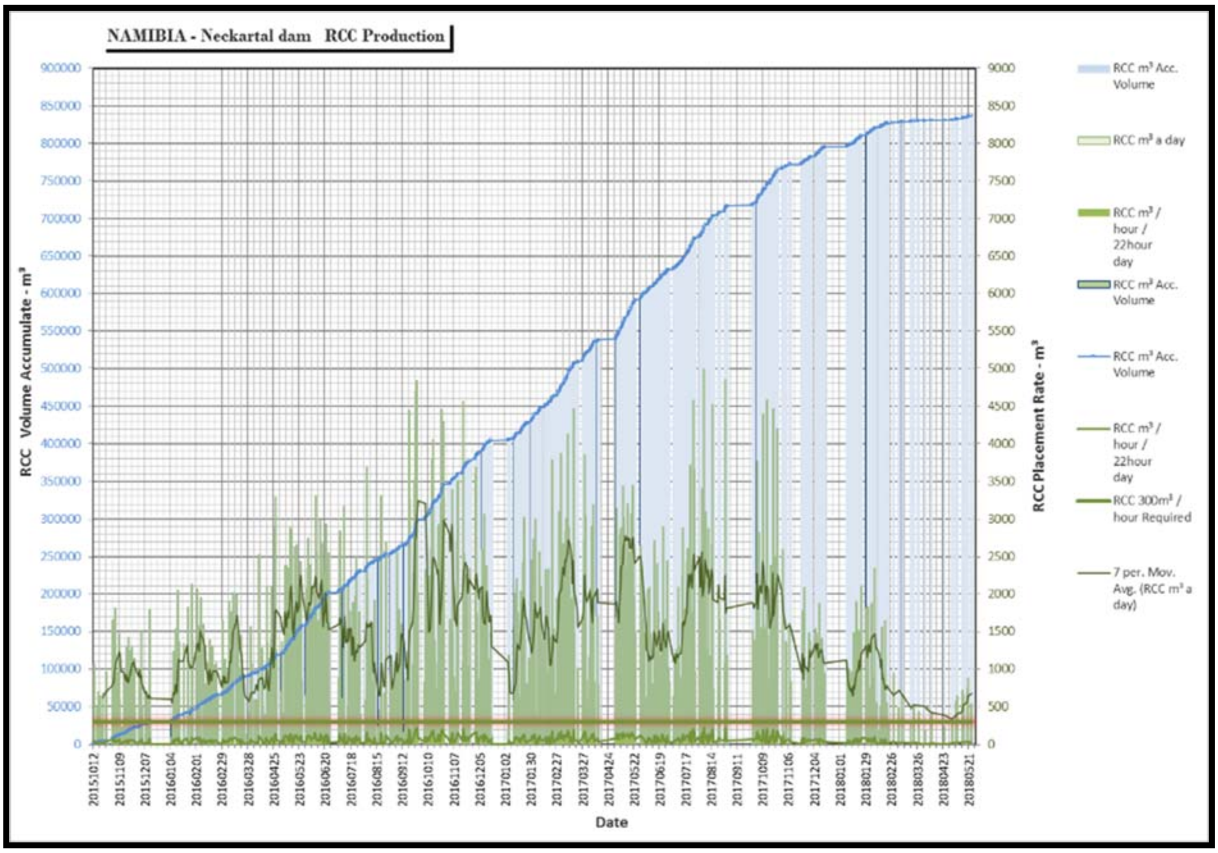

Figure 6: RCC daily and cumulative production

8. RCC QUALITY CONTROL

RCC cube/cylinder crushing/direct tensile tests and density tests after RCC compaction were done during RCC production and placement. A summary of the results of these tests is provided in table 3. The tests indicated that the set RCC easily achieved the strength requirements of the project specification of 20MPa at 365 days for Zone 1 and 10MPa at 365 days for Zone 2. The compressive strength achieved as well as the tensile strengths were very above the specified values.

Table 3: RCC Quality Control testing results and average values and (the standard deviation)

RCC Zone	Temperature spread (°C)	Vebe time (s)	Initial set (hr)	Final set (hr)	Compacted density (kg/m^3)	Compacted density (%)	Comp. Strength 28 day (MPa)	Comp. Strength 365 day (MPa)	Tensile. Strength 365 day (MPa)
Zone 1	22.6 (+/-3.5)	12 (+/-2.3)	10	20	2675 (+/-17)	99.3 (+/-0.6)	26.0 (+/-2.1)	49.5 (+/-3.4)	2.1 (+/-0.27)
Zone 2	21.7 (+/-3.6)	28 (+/-2.8)	8	17	2697 (+/-20)	98.9 (+/-0.7)	16.5 (+/-2.6)	27.9 (+/-4.5)	1.4 (+/-0.22)

A coring programme was undertaken to determine the insitu properties of the RCC, including the compressive, tensile and shear strength, the quality of the parent material and joints. Lugeon tests were also done to determine the permeability of the RCC. Testing of the cores is currently ongoing. Photographs of some typical cores are shown in the figures 7 and 8 below for the different Zones.

Figure 8: RCC Zone 1 (mix 51)

Figure 9: RCC Zone 2 (mix 52)

9. CONCLUSIONS

Neckartal Dam will be the largest dam in Namibia. The RCC gravity dam option was selected as the most economic dam type. The specification required a batch plant with a minimum capacity of 300m^3/hr and a conveyor belt system to deliver the RCC from the batch plant to the dam surface. A 20/38 high cementitious mix for an impermeable zone in the upstream face of the dam and a 10/38 with a low cementitious content for the main body of the dam was specified. The construction of Neckartal Dam started in September 2013.

The Contractor set up a 600 t/h crusher to produce both the coarse and fine aggregate and started to produce aggregate in April 2015. The Contractor produced a total of 3.12 million tons of aggregate for the project over 33 months at an average of 94 800 tons per month. The overall plant efficiency over the 33 months of production was 33%. The Contractor was not able to achieve the required fraction of 0.15 to 1.18mm required in the fine aggregate with his crushing plant.

The maximum RCC placement temperature should not exceed 28°C. In order to achieve this requirement, the Contractor set up a cooling plant to cool both the coarse aggregate and the mixing water. The cooling plant consisted of two chiller units, four air blast units and four insulated aggregate silos through which the cold air was blown. It required 3MW of power to run the cooling plant.

The Contractor's RCC batch plant included two Simen twin shaft mixers with a combined capacity of 320m^3/hour. The RCC was transported from the batch plant to the dam using a 300m long conveyor belt. The Contractor produced a total of 836 053m^3 of RCC for the project over 32 months at an average rate of 26 127m^3 per month. The overall plant efficiency over the 32 months was 17%. Over the whole RCC period, there were interruptions for many reasons, some with in the Contractor's control such as plant breakdowns, insufficient sand, cement and/or fly ash, waiting for shutters to be moved, preparing RCC surfaces, sequencing of the intake tower construction etc. As is the case on many large projects, there were also some delays beyond the Contractor's control such as strikes and late payments.

The RCC cube tests indicated that the set RCC easily achieved the strength requirements of the project specification of 20MPa at 365 days for Zone 1 and 10MPa at 365 days for Zone 2. The quality assurance tests indicated that the set RCC achieved the strength requirements. The RCC coring programme is ongoing.

10. ACKNOWLEDGEMENTS

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