A High RCC Dam with Low Grade Aggregates

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Abstract:

The Koudiat Acerdoune RCC dam (H=120m, RCC volume = 1,55million m^3) is presently under construction in Algeria.
Huge changes in the project were found to be necessary after commencing construction to adapt the dam to the geological foundation conditions and to the actual quality of aggregates. The paper describes the problems encountered when using RCC with weak alluvial marly shale aggregates.

At Koudiat the RCC aggregates are natural alluvium, which comprises a mixture of shales, marls, limestone and sandstone. Some of the materials proved to be alterable under wet conditions after processing and when stockpiled. The RCC mix was designed to be as workable as possible in order to prevent any further alteration of the aggregates and creation of plastic fines when transported, spread and compacted. Additional fines to meet the RCC mix requirements were added to the mix, these were milled on site from limestone supplied from an existing quarry 60km from the site.

Due to the unavoidable creation of some natural plastic fines during RCC production and placing, the desired workability of the mixed RCC was observed to decrease rapidly and to compensate for this and also achieve cement reductions, a set retarder and superplasticiser were introduced to the mix.

The creation of natural fines when handling RCC, plus the rounded shape of the alluvial aggregate, made lift surface preparation difficult and time consuming. By implementing the Slope Layer Method, the contractor has been able to reduce these problems to some degree.

RCC placed to date (50%) is very consistent in quality. Several in-situ shear tests were made along lift joints, both in the full scale trial and in the dam itself, confirm friction angles above 45°being achieved in the dam

A lot of coring has been undertaken which shows that the compressive strength of the cores is 35% less than the corresponding test samples manufactured in the site laboratory . This is considered to be due to several factors that are discussed in the paper.

The actual properties of the placed RCC to date fulfils the requirements of the design.

Key words: aggregate-shale-marls-cores

1. Presentation of the Project

The Koudiat Acerdoune RCC dam, presently under construction, is located 60km South East of Algiers on the Wadi Isser. The dam is 120m high and creates a reservoir capacity of 640 million m^3

which will supply 170 million m^3 of water per year. The design flood (1/10000years) is $8600m^3/s$ and the spillway capacity is $7000m^3/s$

2. Site conditions and design changes

2.1. The original design

The crest (elevation 321m) length was 425m and width 8m. The faces were sloped:

- U/S face was vertical from el. 321 to el. 299,76, then sloped 0.4H/1V
- D/S face was sloped 0.5H/1V.

Specified compressive strength of manufactured RCC samples was 11Mpa at 28days and 19MPa at 90days. The RCC mix was expected to include fly ash.

River diversion comprised two culverts (8 x 8m each), one of which was to be used as the bottom outlet.

2.2. Geological and geotechnical conditions

2.2.1. Dam foundations

During the foundation excavation works several landslides occurred (one of which was $100,000m^3$) and cracks were observed on the left bank, far above the footprint. Concrete lining of a drainage gallery was also cracked. Permanent automatic survey of the left bank was implemented which showed general movement of the left bank towards the valley.

Additional geological and geotechnical studies was ordered and performed in 2004, which showed that a new design of the foundation and of the dam to reduce the stresses transmitted to the rock, was necessary.

The foundation rock (shale) proved to have very low mechanical characteristics (friction angle is 19° in marly, sandy seams and 29° in general). Furthermore, its compressibility is high (some elastic moduli are lower than 1 GPa and heterogeneous). With the original design of the dam, crest displacement was estimated up to 25 cm.

As a result it was necessary was to re-design the dam itself in order to better distribute the stresses on the rock foundation and to direct the stresses more steeply into the foundation. This has led to a more symmetrical profile of the dam.

2.2.2. Construction materials

2.2.2.1. Aggregates

Aggregates were to be sourced from natural alluvium in the river valley upstream of the dam. The alluvium comprises a mixture of shales, marls, limestone and sandstone. Relative density of alluvium varies between 2,57 and 2,49. In the alluvial deposit, shales and marls constitute 11% of coarse particles (>31,5mm) and 27% of remaining materials. In the processed alluvium, shales and marls constitute 7% of coarse material (>31,5mm) and 34% in the less than 1,6 - 5 mm materials.

The actual designation of the shales and marls is siltstone (with a high content of quartz, a significant content of calcite and kaolinite and a low content of plagioclase, illite and chlorite). The siltstone is not a swelling material.

The individual coarser particles deteriorate easily under wetting and drying, whilst the finer particles deteriorate under mechanical stress. This deterioration results in an increase in clayey particles, the Plastic Index being 15 to 16%.

Mechanical tests show that sandstone and limestone particles have good characteristics, whereas the siltstone has very poor characteristics.

Tests on CVC made with these aggregates confirm that:

- there is a good bonding between aggregates and cement
- the cement demand is higher than usually observed, for a 20MPa concrete an additional 29kg/m^3 of cement is necessary than with standard limestone aggregates.

Several tests have been made to check the stability of CVC made with these aggregates, i.e.

- ageing tests (submitting concrete samples to temperature cycles for several months),
- erosion tests (submitting concrete slabs to high pressure water jet),.

They have shown that the long term behaviour of concrete made with these aggregates was no different from the behaviour of a reference concrete made with limestone aggregates. It was decided to use these alluvial aggregates for CVC and RCC on the basis that once enclosed in cement paste the aggregates are no longer able to degrade.

2.2.2.2.Cementitious materials

As there are no naturally occurring milled pozzolanic materials in Algeria and since it is impossible to import fly ash (because Algeria has not signed the Bâle convention about waste material) it was decided to use local cement and to provide fines by milling limestone aggregates on site supplied through an existing quarry 60km away

The cement used is CEM II cement (European standard), which is a blend of 85% clinker, 8% limestone powder and 7% natural pozzolan. It is a moderate heat of hydration type cement.

2.3. The revised design

The consequences of the actual geological and geotechnical site conditions resulted in changes to the design of the dam, which can now be described as follows:

- stepped U/S and D/S faces (1,2m high steps). U/S face vertical from el.321m to el. 288.5m, then sloped 0.65H/1V. D/S face sloped 0.65H/1V up to el.282.2m and 0.5H/1V from 282.2m to el.321m.
    - U/S face: CVC (1.2m thick to 0.8m thick), reinforced.
    - D/S face: CVC (0.4m thick) or RCC under the spillway reinforced CVC surfacing.
- GeRCC is used only inside the dam (against conveyor belt pit for example) and between U/S face CVC and RCC and adjacent to the abutment rock
- RCC compressive strength based on cores: 11MPa at 90days below el. 242m, then 10MPa at 90 days from el.242m to el. 260m, then 9MPa at 90 days above el. 260m.

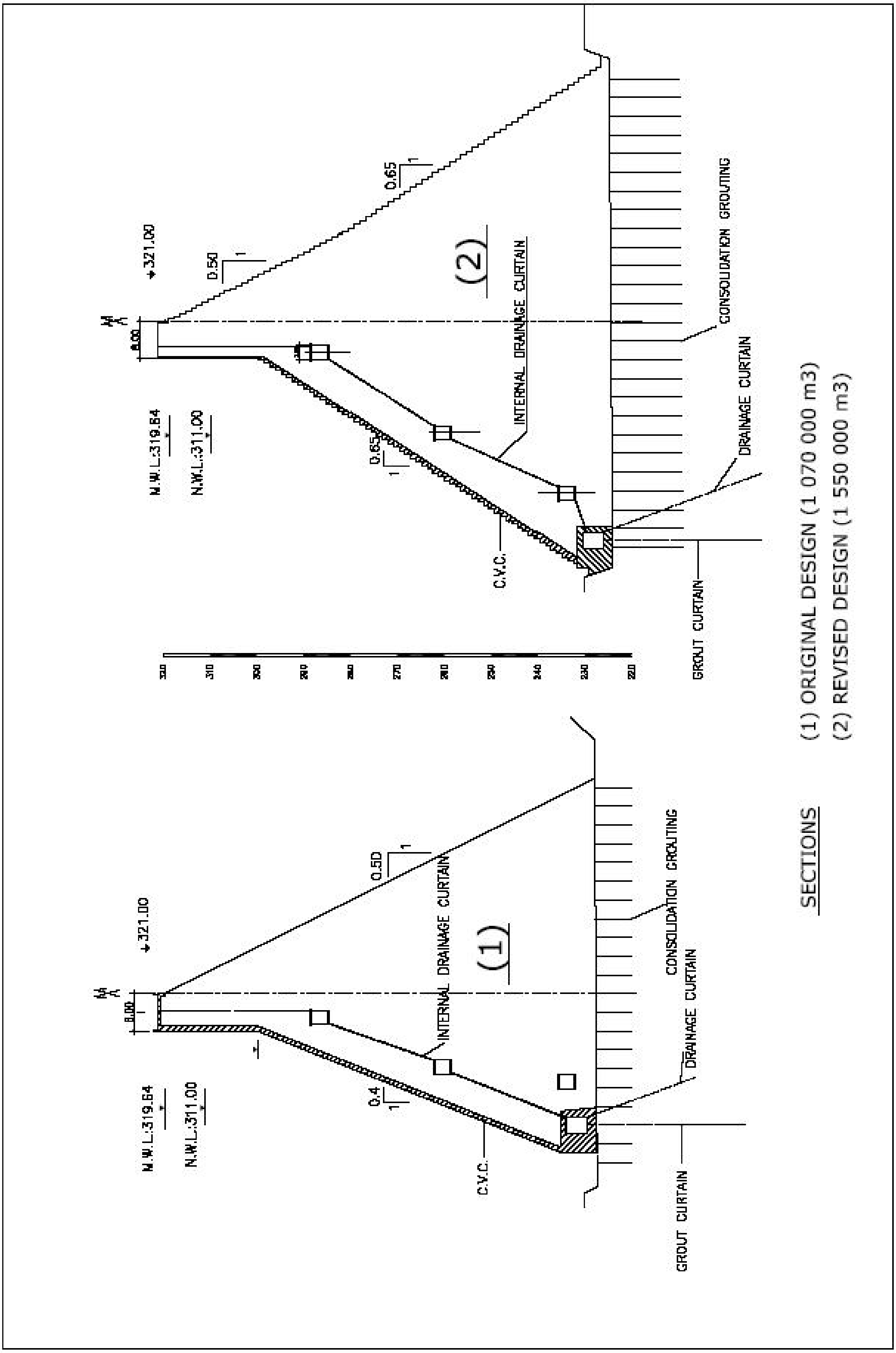
(for practical works control it has been established that the compressive strength on cores at 90 days was equal to the compressive strength measured on cylinders samples at 7 days).
- RCC mechanical requirements: lift joint friction angle 29°, no cohesion
- bedding mortar used on the U/S 7m.
- sloping internal drainage galleries.
- a third diversion culvert added above the original 2 diversion culverts (all 8m x 8m) to become the bottom offtake.
-new design of the spillway chute arrangement to avoid D/S bank erosion.
-consolidation grouting on 100% of the footprint, done from an unreinforced concrete slab in the bottom of the valley. On the abutments, the consolidation grouting is done either:
  - from a concrete slab, or
  - in two stages, the deeper stages from the the excavated foundation level and the upper stage, later, from the surface of RCC

As a result of these design changes introduced during the construction period, there was a significant increase in the scheduled quantities of the:

- excavation works: +2.5 million m^3
- anchor bars into the abutment slopes: + 200,000m
- shotcrete: + 20 000m^2
- RCC: + 500 000m^3
- CVC: + 100 000m^3

The main characteristics of the dam are now:

- height above foundation: 120m
- RCC volume: 1.55 million m^3
- CVC volume: 330 000m^3



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C.V.C.
INTERNAL DRAINAGE CURTAIN
CONSOLIDATION GROUTING
DRAINAGE CURTAIN
GROUT CURTAIN
SECTIONS
(1) ORIGINAL DESIGN (1 070 000 m3)
(2) REVISED DESIGN (1 550 000 m3)

2.4. Construction period

The construction works commenced in November 2002.

Excavation and slope stabilisation works were completed by April 2006. First RCC was placed in May 2006 but RCC placement was stopped to address the following issues:

- very high requirement for cleanliness of aggregates,
- the observation that the core compressive strength was 35 % lower than the that obtained from manufactured samples lead to change the specifications for RCC strength; instead of 11MPa on samples it was changed to 11MPa on cores
- very high requirements regarding the surface preparation.
- very high requirement regarding the maturity index (MI lower than 150°CxH).

Continuous RCC placing started in October 2006. RCC completion is now scheduled for June 2008 and completion of the overall works is scheduled in September 2008.

3. Construction details

General view of the works (January 2007)

3.1. Aggregates

It was found, that the clayey fines content of the processed sand and the aggregates increased by up to 2% as a consequence of the height of the stock pile at the processing plant, transportation by conveyor belt, and by their storage in the mixing plant bins.

As storage of damp sand and aggregates after processing proved to be causing an increase in fines content, the following procedures were adopted:

-extract and bulk store the raw alluvial material, reduce the storage time of processed materials to a few days only and increase the processing plant capacity (1000t/h) to equal the mixing plant capacity (500m^3/h),

-intensive treatment of the aggregates to eliminate as far as possible weaker clayey particles (by use of logwashers and several hydrocyclones) resulting in up to 20% loss of material,
-vigorous washing of the aggregates (water consumption being 3,5m^3/ tonne of aggregate).

Aggregates are transported to the mixing plant by conveyor but are re-washed before introducing them in the mixing plant, The sand however is transported by trucks, which has proved to be less damaging.

3.2. Fines

Fines (minus 0.08mm) are produced on site by a milling plant. Production capacity is 40t/h.

3.3. Cooling & Mixing

Coarse aggregates (5 - 20mm and 20 - 50mm) are air cooled in the silos at the head of the mixing plant. The cooling system can produce RCC at 250 m^3/h at 20°C ex mixer, starting from aggregates at 30°C.

As cement is delivered in bulk as well as in big bags to provide the specified stored quantity, a plant to unload big bags has been set up with a capacity of 40t/h.

The continuous mixing plant consists of two Simem mixers, each 600t/h capacity.

3.4. Delivery & placing

RCC is delivered to site by conveyor belt and then placed by crawler placer for 40% of the area and dumpers for the remaining 60%.

Four large tower cranes are used for handling forms, concrete and rebar for construction of the intake tower and the spillway and also the dam.

Access tracks onto the dam are provided as a continuous process as the dam height rises.

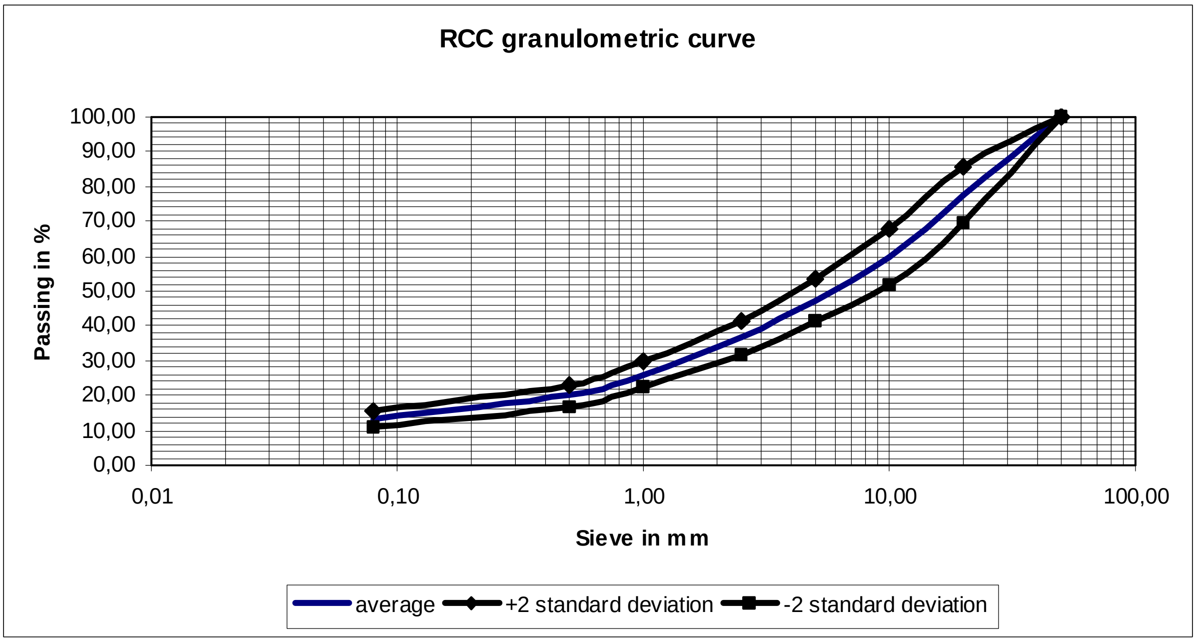
RCC placement commenced in blocks defined by the transverse contraction joints, each being 1.2m high comprising four 300mm thick horizontally placed lifts to match the 1.2m step height. The Sloped Layer Method was adopted using 1.2m high lifts from el.243,20m in March 2007 after the first 480,000m^3 RCC had been placed, . At the time of writing (June 2007) a total of 750,000m^3 RCC has been placed, with the following achieved to date:

- Peak hourly placement rate - 450m^3.
- Peak daily placement rate - 7,000m^3.
- Maximum monthly placement rate – 92,000m^3/month

4. RCC mix and placing

4.1. Mix design

The RCC mix was designed to achieve a granulometric distribution, including cement, as shown below



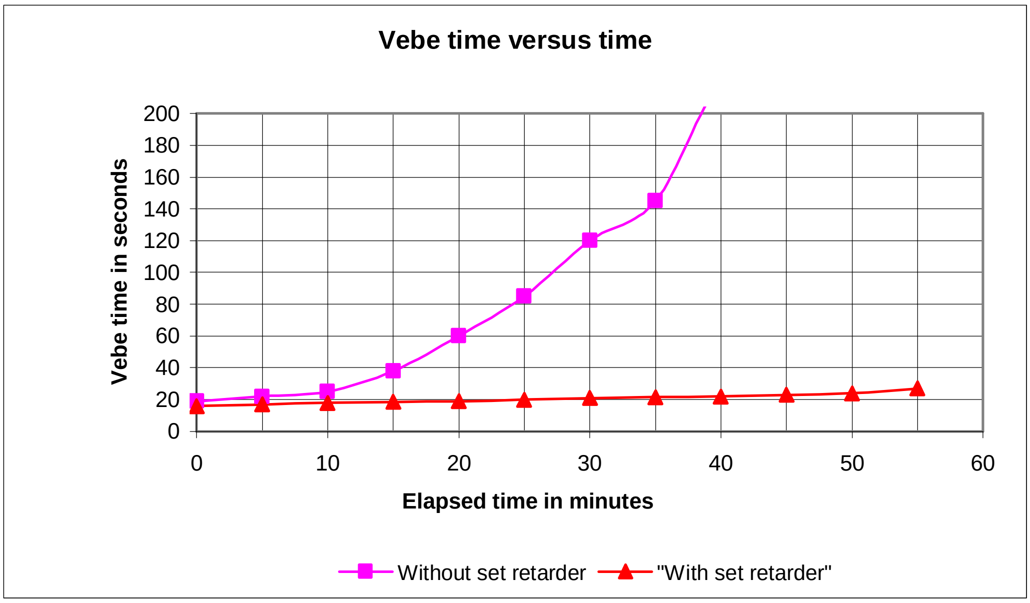
RCC granulometric curve

RCC mix was designed to achieve the following principal characteristics:

- 12 to 14 % less than 80µ (including cement and limestone fines)
- Maximum size aggregate: 50mm
- Sand content (+4.75mm) 45%
- Vebe time: 18 to 20s
- Theoretical air free density: 2.499 t/m^3

It was not possible to use the fines contained in the natural alluvium because of their clay content, as described above. Furthermore there was no available, locally occurring pozzolanic material, nor was it permitted to import fly ash. It was therefore necessary to use ‘manufactured’ fines ground on site from high quality limestone aggregates supplied from an external quarry. These fines were introduced as a very fine sand (with 80% less than 0.08mm). The amount of ’manufactured’ fines used in the RCC mix is 100kg/m3.

Due to the weakness of marl and shale particles included in the aggregates, and to their capacity to create fines when handled, including during the RCC mixing process, the Vebe time increased rapidly with time and RCC progressively lost its workability, as shown below.



Change of Vebe time versus time

To compensate for this phenomenon, a set retarder was introduced into the mix (0.5 to 0.8% of cement weight) which held the Vebe time reasonably constant for about one hour, giving enough time for delivery, placing and compaction of the RCC.

To reduce the required water content and thereby minimize the cement content, a superplasticiser was also added to the mix (0.4% of cement weight). This saved approximately 20kg of cement per m^3.

4.2. RCC as placed

RCC was placed in 30cm thick lifts and compacted with 8 passes of a 12t vibrating roller.

In situ density, measured with a nuclear densimeter, was generally between 2,45 and 2,50t/m^3, being 98 to 99% of the TAF density of the RCC.

Slight reductions in cement content were able to be made as the works progressed and the results shown to be consistent with a low coefficient of variation, as shown in the table below.

Cement content (per m3)	140	140	140	130	130	130	125	125	125
Compressive strength at	7d	28 d	90 d	7d	28 d	90 d	7d	28 d	90 d
N° of tests	191	191	191	82	82	60	53	32	0
Average (MPa)	13,5	17,3	19,8	11,2	14,5	16,6	11,3	14,9	
Coefficient of variation	11,1%	11,9%	12,2%	10,4%	11,7%	13,3%	8,7%	9,6%	

Summary of RCC compressive strength test results on manufactured samples

Grain size analysis of RCC sampled when delivered and after compaction showed that an additional 1,5% fines (<0.08mm) was created during the placing (spreading and compacting) process, confirming the weak, low strength nature of the alluvial aggregates used for the RCC.

Thermocouples embedded in the placed RCC show that the temperature increase, due to cement hydration and ambient heat gains/losses etc, is in the range of 12°C.

4.3. RCC Core strengths

Compressive strength measured on cores average 65% of the compressive strength measured on manufactured samples.

Possible reasons include:

- coring machine,
- popping out of rounded aggregates,
- thermal shock giving micro cracks,
- effect of the increase in plastic fines content due to placing and compaction stresses

Samples densities	2.415-2.425	
In situ measured density (Troxler)	2.45-2.50	
Cores density	2.42-2.48	(average2,45)

It is not unusual that the compressive strengths on samples are higher than those of core samples from the same concrete pour. For example, the German Standard for reinforced concrete uses a value of 85% for core samples with a maximum aggregate sizes of 32 mm and core dimensions of 100x100mm. Taking into account the influence of the diameter : length ratio, when raised from 1:1 to 1:2, the strength would be reduced by about 15 % for the 1:2 ratio. In theory the total reduction is about 72%, which is close to the 65% found at Koudiat. This is explained in the German Standard by the different methods of compaction, with vibration compaction giving lower strengths, than compaction by tamping with a steel rod.

Factors that influence the strength of in-situ RCC are numerous, some are discussed below as seen at Koudiat e.g.

- Differences in the compaction of samples and in-situ RCC
  RCC samples are manufactured in 3 layers, compacted by tamping followed by vibration of each layer on a vibrating table. The surplus of mortar on the top of each layer is removed. On the dam the in-situ RCC is spread by dozer and compacted by the vibratory roller.
  Following the belief, that equal densities will result in equal strengths, the densities of the two compaction methods have been compared.
  RCC densities of manufactured samples are determined by weighing, the 'maximum' density of the RCC as mixed, and prior to placing, is measured by the Vebe apparatus and after roller compaction it is measured in-situ by Troxler nuclear density probe. The Troxler results show higher densities than the manufactured samples, which seems reasonable for the more intensive roller compaction of the RCC, but the strengths results are lower.
  During RCC placing and compaction, especially when over compaction occurred, some breakage of aggregate particles, mostly sandstone, was observed. With fresh clean fractured aggregate surfaces, without a covering of cement mortar paste, compressive (and particularly tensile) strength of the in-situ RCC, and cores, would be reduced.
  Any vibrations from compaction energy, introduced to the RCC soon after setting, could result in micro cracking and reduced bonding of the aggregates to the cement paste. In general the critical period would be from initial set until a compressive strength of about 5MPa is reached.

- Aggregates
  Aggregate particles larger than 50 mm are removed by screening during sample preparation, whereas they remain in the core samples.
  The diamond bit coring the RCC cuts through aggregates, leaving a portion of an individual particle embedded in the RCC core, often as a smaller particle that is poorly restrained in the

body of the core. These were seen to 'pop' out when the core is loaded in the compression test, especially if the particle is rounded, or smooth surfaced, as alluvial aggregates often are. Furthermore, if 2 or 3 large aggregate particles occur close together at one level, then the cross section of the core at that location is likely to be weaker compared to more homogeneous zones of the core.
The shape of the aggregates at Koudiat are mostly flaky, with only a few round shaped particles. During spreading of the RCC by bulldozer, the flat and elongated particles become horizontally orientated. Whereas during sample manufacture, the elongated particles are more randomly distributed and orientated. When horizontal shear stresses are introduced during compressive strength testing, any accumulation of elongated and large particles in one zone of the core will result in a reduced compressive strength.

- Testing
  - Retained portions of cut aggregate tend to 'pop-out', have the rock to cement paste bond disturbed during the diamond bit cutting action, effect is worse with rounded alluvial aggregates, and more so with polished aggregate surfaces – which is the case on Koudiat – all leading to a reduced <u>effective</u> core diameter. An 18 mm reduction in effective diameter of a 145 mm diameter as cut core will result in a 30% apparent strength reduction.
  - Cores contain 50 mm size aggregate, whereas the samples have the + 40 mm size aggregate screened out of the sampled RCC to comply with the requirement that sample diameter => 4xmaximum aggregate size. A grouping of large particles would tend to create a zone of weakness in the core
  - Samples are water bath cured whereas cores are 'dry' cured in place, when tested the samples are in a saturated condition, whereas cores are in a drained condition, unless they have been immersed in a water bath for some days beforehand
  - RCC material is sampled on delivery to the placement area, the effect of the vibrating drum roller may be causing more particle breakage than the laboratory compaction process.
  - Where cores are extracted from depth and the hydration temperature of the RCC is still high, in the 40-450 C range say, and the drilling water is in the range 20-250 C, hence the perimeter of the cut core would be subjected to 'thermal shock', potentially sufficient to cause micro cracking of the core surface with a reduced effective diameter of the core when tested. An 18 mm reduction in effective diameter of a 145 mm diameter as cut core will result in a 30% apparent strength reduction.

4.4. Surface preparation

With the widened profile, internal stability of the dam requires only 29° friction angle and no cohesion on lift joints. Several in situ shear tests were made to confirm this was achievable.

In situ shear test

These tests showed that the friction angle was generally above 45°. In some cases the strain measured before reaching failure was judged to too large and, in these cases, it was assessed that a 30° friction angle was more realistic if large deflections were to be avoided.

Some tests were done to measure RCC setting time based on the DARC method. The results were variable - between 6 and 10 hours – with little or no influence of ambient temperature. Consequently the lowest value of the Maturity Index (MI) allowed in the technical specifications was adopted, i.e. 150°CxH, which is equivalent to 4-6 hours for 25-38°C

Lift joint surface treatment was accordingly defined as follows:

-upstream 7m : bedding mortar, irrespective of the time between lifts.

-downstream 10m: bedding mortar, irrespective of the time between lifts.

-central portion of the dam: no treatment when MI is lower than 150 (corresponding to 6 hours during summer night time placing), green cutting of the surface when MI exceeds 150.

- CVC upstream facing: green cut when time between lifts exceeded 2 hours.

5. Conclusions

1. Use of weak alluvial aggregates was necessary in the absence of other economical materials. With a significant washing and screening process, minimum period of stockpiling and careful transportation to minimise further breakage, the aggregates have been able to be used in a RCC mix which has been designed with a high workability and reduced coarse aggregate quantity to limit further breakage during the placing process. Acceptable strengths are being achieved with a low Coefficient of Variation although the sample strengths are 35% higher than the required core strengths.

2. RCC quantities have been increased significantly due to design changes to the cross section and foundation levels as a result of poorer than expected foundation conditions. The recent change to using the Sloping Layer Method of placing has accelerated the placing rates. It is now anticipated that the 1.55 million m^3 RCC and 0.33 million m^3 CVC will be placed in under than 2 years.

3. The requirement for green cutting RCC lift surfaces older than 6 – 8 hours (‘cold’ joints) and a high early strength of the RCC, requires high pressure air-water jetting, rotary wire brushing, vacuuming etc all of which destroy the weaker aggregate particles thereby generating a large quantity of fines and mud which has to be removed considerably delaying the placing process; use of the Sloping Layer Method has reduced the frequency of such ‘cold’ lift joints. A final, further, clean up, just prior to RCC placing over ‘cold’ joints, is necessary due to weathering of the weaker particles.

4. Incorporating reinforcing in the upstream CVC facing has been difficult due to the inclined face, which is constructed in 1.2m high steps. The CVC is placed by crane and bucket on either side of the reinforcing, which is a slow process. In order to proceed ahead with the RCC a transition zone of GE-RCC placed between the CVC and RCC which permits the roller compaction of the RCC.

6. Acknowledgements

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