Managing unprecedented RCC challenges at Gibe III dam, Ethiopia

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The Gibe III hydroelectric project, nearing completion on the Omo river in Ethiopia, features a 249 m-high RCC dam, currently the highest of its type in the world. The narrow gorge where the dam is sited and the height of the dam required unprecedented solutions for efficient RCC placement. Optimization of the cements and RCC mixes also involved interesting innovations. Gibe III stands as a successful example of a strategic partnership to deliver a key piece of infrastructure for Ethiopia's economic growth.

Hydroelectric potential, estimated at around 160 TWh/year (economically feasible), has been recognized for decades as the single most valuable resource in Ethiopia. The existence of large rivers flowing in deeply incised valleys provides very attractive conditions for medium to large-scale hydroelectric schemes. Ethiopia's hydrological setting requires storage reservoirs to harvest the high flows during the rainy season, which lasts for three to four months a year, for release during the remaining dry months. The Gibe III hydro project will fulfill that requirement, by creating a regulating reservoir with an active storage capacity of 11 750 $\times 10^6$ m^3. With an installed capacity of 1870 MW, the project will generate 6500 GWh/year of electricity.

(a) Aerial view of the Gibe III dam site from the right abutment.

Fig. 1. Location of the Gibe III project in Ethiopia.

The project's owner is Ethiopian Electric Power (EEP), a public enterprise owned by the Government of Ethiopia, which is the employer of the EPC (engineering, procurement, and construction, FIDIC Silver Book) contractor, Salini-Impregilo SpA of Italy. The designer is Studio Ing. G. Pietrangeli, also of Italy. Tractebel Engineering of France and ELC of Italy have the function of Employer's Representative. Salini-Impregilo SpA acts as General Contractor for the coordination of the whole scheme.

The Gibe III project is located in the middle reach of the Omo river basin, 450 km, by road, southwest of the capital city Addis Ababa. Fig. 1 shows the project area, and Photo (a) is a photo of the site

The scheme includes a 249 m-high gravity dam with a total volume of $6.2 \times 10^6 m^3$ of roller compacted concrete (RCC). It is currently the highest RCC dam under construction in the world. Water control works include a surface spillway, on the crest of the dam, with seven 12 × 17 m radial gates. Major underground works include three river diversion tunnels of 3.2 km total length, twin headrace tunnels, two intake towers, two underground penstocks, two 18 m-diameter surge shafts in rock, and two steel manifolds.

1. Site conditions and selection of the dam type

In the area of the future reservoir, the Omo river flows through narrow valleys and deep canyons, which are very favourable for the creation of a reservoir, but present extremely challenging logistical conditions for dam construction. The remoteness of the site and seismicity of the area increase the challenge. Access required the construction of an airport, a 120 m span bridge, 75 km of new national roads and 40 km of project site roads. Providing workers with camps, along with sanitation, health and recreation facilities, in such a remote location was taken very seriously and proved extremely important for the success of the project.

Several dam types were considered at the basic design stage: concrete arch, concrete faced rockfill (CFRD), and RCC gravity.

The rock mass conditions on the right abutment discouraged the adoption of the arch type.

The rockfill dam solution was studied, with either a bituminous or concrete upstream facing. Both were discarded for the following reasons:

- There would be risks of damage to the dam embankment in the event of overtopping during construction, which were considered unacceptable to financiers and insurers.

• Impounding of the reservoir was planned to begin before completion of the entire dam wall, to allow for power generation to start as early as possible.

The concrete gravity alternative can resist temporary overtopping and fulfills the second requirement. Besides, abundant construction materials (alluvium, basalt, and ignimbrite) in the project area favoured the RCC option.

The three layout options for the RCC dam shown in Table 1 were then studied.

Although alternative 1 featured lower costs, the choice fell on alternative 3, mainly as a result of aspects related to locating the powerhouse at the toe of the dam. Fig. 2 shows the final layout adopted.

Trachytic-basalt of adequate rock mass quality, under reasonable overburden depths, provided adequate foundation conditions for the 249 m-high gravity dam. The presence of sub-vertical joints, occasionally affected by hydrothermal alteration, required careful foundation treatment.

2. Foundation treatment

Two main features made foundation conditions more challenging than anticipated. These were: extensive areas of intensely fractured and/or weathered rock; and, the occurrence of hot springs at riverbed elevation.

Foundation areas of intensely fractured/weathered rock required treatment with respect to:

• foundation seepage and erosion control; and,
• structural behaviour associated with local variations in rock mass deformability.

The treatment measures involved:

• excavation deepening and reshaping, with local rock reconstruction;
• shotcrete protection of extended weathered surfaces;
• provision of an upstream cutoff curtain, 40 m deep, achieved by high pressure washing and grouting;
• dental concrete and extensive consolidation grouting along the main sheared and weathered bands, see Photo (b); and,
• bespoke design of grouting and drainage galleries to follow critical rock lineaments, making future access possible for additional treatment, as necessary.

During foundation excavation, hot water springs were encountered at the riverbed elevation. These are considered to be associated with the hydrothermal alteration observed along the vertical joints, and are expected to be in hydraulic connection with a deep trachyte aquifer underlying an 80-100 m-thick layer of largely impervious rock-mass.

The spring waters were intercepted, monitored and conveyed to the lowest drainage gallery network, see Photo (c). A widespread system of drains was added to intercept other possible water inflows that might occur after impounding, when the full reservoir level will affect the groundwater regime. Drains, V-notches, and dedicated piezometers, at different locations and depths, will constantly monitor spring inflows during operation.

3. Cements for the RCC

During the early stages of the project, Ethiopian cements proved to be inadequate, because only the pozzolanic cements exhibited low heat, but their reactivity was unsatisfactory. In addition, problems associated with the variability in quality and the intermittent supply of national cement led to the Ethiopian Government's decision to open up to the importation of special cement. Initial research focused on two main properties: low heat of hydration; and, high reactivity. These steered the choice towards high quality cement,

Table 1: The three options considered for the layout at Gibe III

Layout	Advantages	Disadvantages
Dam crest spillway; dam toe powerhouse.	No power tunnel, no surge shafts.	Penstocks inside dam body; dam toe powerhouse questionable.
Right bank spillway; dam toe powerhouse.	No spillway flow above powerhouse structure.	Penstocks inside dam body.
Dam crest spillway; left bank powerhouse.	Powerhouse independent from the dam body.	Powerhouse location controlled by spillway jet; power tunnels and surge shaft.

Fig. 2. The final layout adopted for Gibe III, showing: the dam crest spillway; and, the left bank powerhouse.

(b) Dental treatment along a large subvertical joint parallel to the riverbed.

(c) Hot spring inflows conveyed inside the dam inspection gallery.

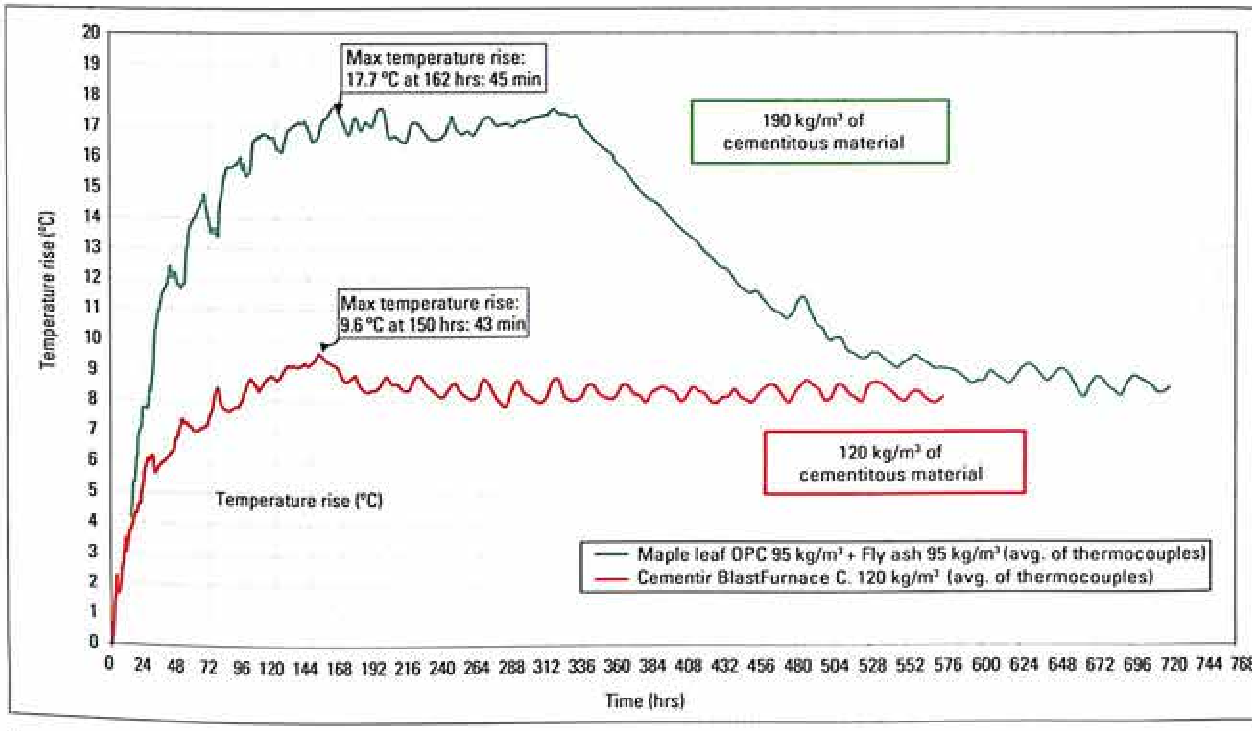

Fig. 3. RCC temperature rise behaviour.

from Pakistan, and flyash from South Africa. However, not surprisingly, the transportation costs for these materials proved unsustainable. The mix design was therefore oriented to the use of blast furnace (BF) cement produced in Italy, which ensured a steady quality associated with high strength and low heat of hydration. The test results proved very satisfactory:

• As regards the material's reactivity, 120 kg/m³ of BF cement proved to be equivalent to 95 kg/m³ of OPC (Pakistan) cement and 95 kg/m³ of flyash.

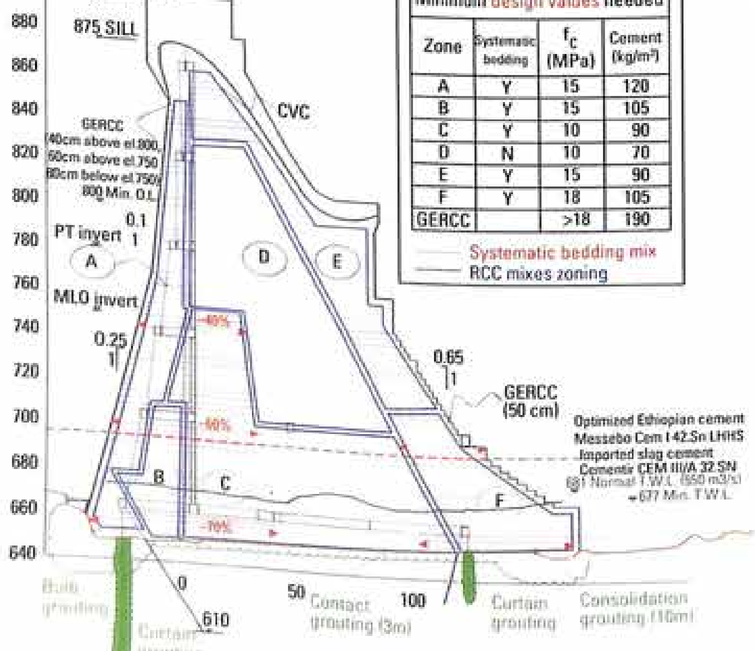

Fig. 4. The dam zoning. The red dotted line indicates where Ethiopian cement started to be used.

• The BF cement exhibited much more favourable RCC temperature rise behaviour (see Fig. 3).

These results led to the choice of an Italian BF cement (ENN Cem III 32.5N), which was used to build the lower part of the dam, up to some 40 m above foundation level (see Fig. 4).

Maximizing the use of national resources for project implementation is an essential element for harvesting both direct and indirect economic benefits from the large investment associated with Gibe III, therefore both EEP and Salini-Impregilo continued looking for solutions to revert to locally produced cement. To that end, tests on national cements continued, in parallel with construction, in cooperation with Ethiopian cement factories, and carried out by local technicians and international experts. Extensive laboratory and field tests finally led to the identification of suitable RCC mixes based on improved Ethiopian cements. The turning point was the addition of an iron ore-rich soil formation in the composition of an ordinary Ethiopian Portland, producing an EN OPC LH HS 42.5. The mix proved to perform like a Portland ferric cement, with very low hydration heat, high sulphate resistance, and high reactivity. This cement has been used for the main body of the dam (see Fig. 4). This experience, achieved in co-operation with the major Ethiopian cement producers, contributed to improving the cement manufacturing process, and the quality of cement available on the local market, resulting in beneficial effects for the overall Ethiopian economy.

4. RCC mixes and tests

The RCC mixes were optimized to satisfy design requirements in terms of compressive strength, modulus of elasticity, cohesion, friction angle, and so on, as indicated in the dam zoning (Fig. 4).

A systematic bedding mix has been used in areas where lift joint cohesion was required, and in the upstream part of the dam, to ensure low permeability values.

The composition of the RCC aggregates is: 71 per cent alluvium; 24 per cent basalt; and, 5 per cent ignimbrite. The sand has a size of 0-6 mm, the medium gravel is 6-25 mm and the coarse gravel is 25-50 mm (see Fig. 5).

The river alluvium consists of trachyte, basalts, and rhyolite. The ignimbrite is a deposit of pyroclastic flows, and is characterized by a poorly sorted mixture of ash and pumice lapilli, with lithic fragments. Ignimbrite has been used for the production of both sand and filler; the latter increases the paste content and adds a slight pozzolanic effect to the RCC mix.

Natural fines present in the combined grading make up approximately 6 per cent of the total. The paste content of the mixes used for the Gibe III dam ranges from 21.4 per cent for the mix with a lower cement content (70 kg/m^3) to 24.2 per cent for the mix with a higher cement content (120 kg/m^3). This paste content contributes to the workability and to segregation control of the mix during spreading and compaction. Cores drilled through hardened RCC revealed good aggregate distribution, see Photo (d). Quality control of the RCC components involved the tests shown in Table 2.

Results of 1 year compressive strength tests ranged from 23 MPa (cement content 70 kg/m^3) to 27 MPa (120 kg/m^3), which are in full compliance with the design parameters (see Fig. 6).

5. RCC placement issues

As mentioned earlier, Gibe III is, to date, the highest RCC dam under construction in the world. The site did not offer ideal conditions for the scheme, particularly for the stocking of aggregates. Crushing plant yields varied between 1200 and 1400 t/hr. For temperature control, major cooling plants had to be provided.

The narrow gorge and the height of the dam required special solutions to ensure reliable and efficient placement of the RCC mixes in the various zones of the dam. Negotiating a drop in elevation of 250 m between the production plants and the dam foundation levels required unprecedented solutions. Representing a unique case at world level, 17 conveyor belts, for a total length of 960 m and placed at a 22° inclination, were necessary to reach the lower elevations of the dam, see Photo (e); placing capacity was up to 820 m^3/hr (compacted RCC), which is a world record.

The steep conveyor belts were erected on the dam abutments thanks to a cable crane (Blondin) and expert climbers, while a network of challenging roads built on the dam abutment allowed access to every level of the dam. Conveyors discharged RCC to 'tripper lines', supported by steel towers on the rising placement

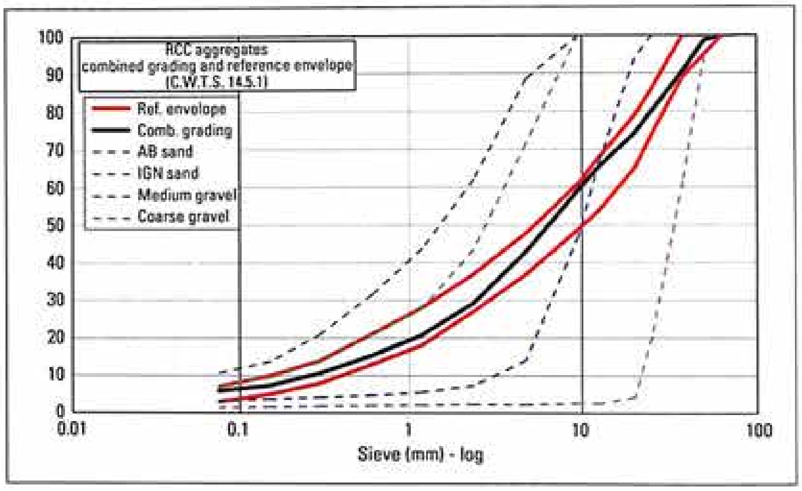

Fig. 5. Typical Gibe III RCC combined grading.

Table 2: Quality control tests for the RCC at Gibe III	
RCC component	Quality control tests
Coarse aggregates	Sieve analysis, specific gravity, absorption, flakiness, elongation, limit liquid, plasticity index and Los Angeles abrasion.
Cement	Compressive strenth, flexural strength, heat of hydration specific gravity, fineness, setting time, residue by air-jet sieving and x-ray spectrometer chemical analysis.
Filler	Specific gravity, fineness, residue by air-jet sieving and X-ray spectrometer chemical analysis.

(d) RCC cores, showing the good distribution of aggregates and absence of segregation.

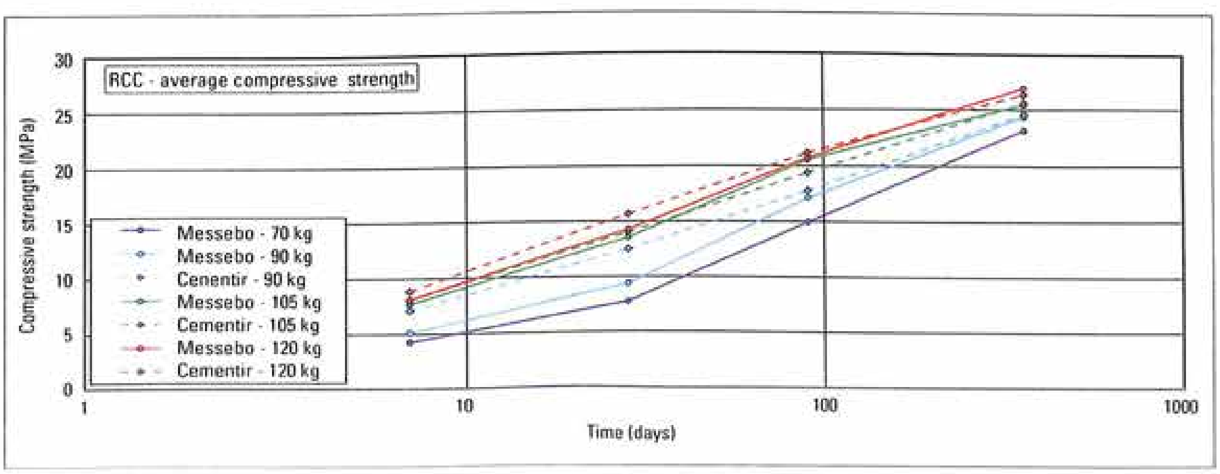

Fig. 6. Gibe III RCC compressive strength with different cement types and cement contents.

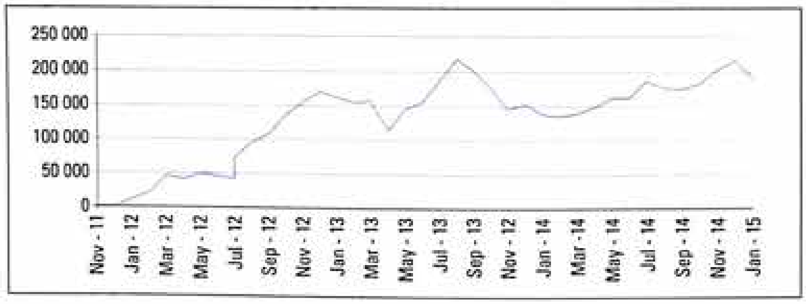

Fig. 7. RCC monthly placement rates.

(e) Conveyor belts on the canyon slopes.

level, and from there a crawler placer delivered RCC to the planned placing area, see Photo (f). This arrangement minimizes vehicular traffic on the surface of freshly laid RCC, preserving the RCC quality and bonding between the layers. This configuration had to be progressively adapted, as the dam height increased; a 70 m offset downstream of the dam axis had to be

(f) Tripper lines and the crawler placer at the dam placing level.

Table 3: Managing changed conditions at major dam projects; examples at Gibe III

Changed condition	Management response
Dam type	Adapting the dam type to actual geo-mechanical conditions and complying with the Owner's requirement for early startup
Foundation conditions	On-the-spot foundation treatment and high pressure washing/grouting
Headrace tunnel lengthening	Unfavourable rock conditions forced to shift portal location 500 m upstream with a corresponding increase of length for the twin tunnels
RCC ingredients	Optimizing the type of cement according to availability and design requirements
Adverse weather	Installing a short range rainfall radar prediction system on site
Project financing	Revised financial architecture, during implementation, with the introduction of a major sub-contractor. This entailed design harmonization and coordination of site activities in an integrated programme of works

(g) Application of the bedding mix.

introduced, which was somewhat unconventional.

Application of the bedding mix (cement mortar), in design-defined areas, improved the layer-to-layer bonding, see Photo (g). These areas are typically close to the upstream and downstream dam facings. Vacuum trucks proved very effective in maintaining a neat and clean RCC surface.

Spreading and compaction was carried out by dozers and rollers respectively. Grout-enriched RCC, with the consistency of conventional concrete, was placed near the formwork, in areas beyond the compaction roller's reach. Compaction of these areas was accomplished by immersion vibrators.

Fig. 7 shows sustained RCC placement rates in the range of 150 000 to 200 000 m^3/month. The increasing average achievement is related to the difficulty of placing RCC in the lower part of the dam, because of the laborious treatment of foundations and abutments.

On 11 December 2014, a new world record was set when 18 519 m^3 of RCC was placed within 24 hours, see Photo (h).

6. Management of 'changed conditions'

Satisfactory execution of a turnkey job requires the EPC contractor to be able to manage situations during construction which deviate from the initial design assumptions. Such conditions inevitably occur in large civil engineering projects, and more so in major dam projects like Gibe III. Table 3 lists a few examples.

7. Conclusions

Gibe III stands as a showcase of how large, multi-party projects can be managed and brought from inception to operation within a comparatively short period of nine years, despite complex financial and geological problems. Gibe III is testament to the fact that 'technical flexibility' with a spirit of partnership, along with the willingness to deliver, are the keys to responding to

(h) Celebration of a new record being set for daily RCC placement rates.

the changing conditions which are inevitably associated with large hydropower schemes. That spirit was the main driver for delivering a key piece of infrastructure for Ethiopia's economic growth. ◊

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Bruno Ferraro has been Project Coordinator at Gibe III for Salini-Impregilo. He has 40 years of work experience. After pioneering the RCC application at Tarbela, he was involved in large RCC dam projects such as Conception, Porce II, Balambano, Ralco, Gibe III. Overall these projects have involved around 12 these projects have involved around 10^6m^3 of RCC, excluding the Grand Renaissance dam.

Eugenio Zoppis is the Contractor's Site Manager at Gibe III. He has more than 25 years' site management experience in roads (more than 1200 km), bridges, tunnels (more than 45 km) and dams (more than 15 × 10^6m^3 of RCC, concrete, and rockfill embankments), at projects such as Bumbuna dam, Port Sudan-Gedaref Road, and the Gilgel Gibe hydropower project, Phase I and II.

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