DEVELOPMENT OF PLASTIC CONCRETE FOR DEEP CUT-OFF WALLS AND STUDY ON QC TESTING

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ABSTRACT

A robust plastic concrete design is decisive at long-term cut-off wall construction sites to minimize scatterings in relevant fresh and hardened material properties. A mix design can be characterized as robust, when ambient unavoidable influences lead only to minor variations in resulting material properties.

Before the commencement of construction activities of the recently completed cut-off wall at Polavaram dam project, a such robust mix design of plastic concrete was developed and optimized in intensive suitability tests. At this project, a 1500 m long cut-off wall with depths up to about 100 m was executed. The entire wall was completed in two dry seasons over a net period of 11 months.

The material properties of the plastic concrete were successfully verified by Quality Control. Exemplarily, the material scattering concerning UCS can be revealed by evaluating the project database.

This paper presents a general approach to develop a robust plastic concrete and reports on Quality Control analysis based on gained results from laboratory testing as per project specifications. Furthermore, a comparison of the project specifications with the international standard EN 1538 is drawn. Accordingly, it was determined that a reduction of the QC frequency is reasonable at other long-term projects in future achieving the same safety level.

1. PROJECT OVERVIEW

The Polavaram Project is a multifunctional irrigation project on Godavari River and it is treated as a „National Project" in India since multiple provinces are expected to benefit extensively from its construction.

The special foundation works comprise the execution of a plastic concrete cut-off wall with a minimum rock embedment of 2 m with a total area of 67.500 m². The cut-off wall with a thickness of 1.5 m and a length of 1500 m reaching to depth of up to approximately 100 m. For the execution of the cut-off wall elements, hydraulic grabs and trench cutters BAUER BC40 und BAUER BC32 were used.

2. REQUIREMENTS ON PLASTIC CONCRETE AT POLAVARAM PROJECT

According to DIN EN 1538:2015 the plastic concrete is described as „low strength, low Young's modulus concrete capable of sustaining larger strains than normal concrete". By using a plastic concrete, in particular the horizontal and vertical deflections due to the fluctuating water levels in reservoir and resulting settlements on the dam foundation can be endured without crackings (ICOLD, Bulletin 51 1985).

A robust "Mix Design" of plastic concrete was developed and optimized in intensive suitability tests. The conformity of plastic concrete to the "Technical Specification" was verified during project implementation with a comparatively high frequency (see Table 1).

Table 1 : Requirements on Plastic Concrete acc. to Technical Specification

Type of Test	Testing Frequency	Acceptance Criteria
Max. Aggregates Particle Size	each 300 m³	max. 12.5 mm
Slump Slump-Flow	each 60 m³	240 ± 20 mm 400 - 600 mm
Air content	each 60 m³	< 1.7 %
Temperature	each 60 m³	5° - 35°
UCS (28 days)	3 Cylinder each 60 m³	2.0 ± 0.5 MPa
CCS (28 days) σ_c = 0.4 MPa	3 Cylinder each 60 m³	2.5 - 6.0 MPa
Strain at Failure	3 Cylinder each 60 m³	0.375 - 1.25 %
Young`s Modulus	each 300 m³	200 - 400 MPa
Permeability	each 200 m³	< 1 x 10-8 m/s

At dams, deformations are slowly induced. Therefore, stress relaxation plays a huge impact on resulting stress condition. For this reason, calculated stresses as calculated by Hooke's Law shall not occur. Such good-natured behavior consequently has a positive effect on the durability of plastic concrete and could also lead to a more economical design through the use of a realistic material model (Beckhaus et al. 2015).

3. SUITABILITY TESTS FOR DESIGN OF A ROBUST PLASTIC CONCRETE ON POLAVARAM PROJECT

In accordance with requirements on plastic concrete, sufficient workability / workability life, compressive strength, deformability and permeability of hardened plastic concrete were intensively examined during the suitability tests.

3.1 Selection of Plastic Concrete Constituents

Raw materials used for the plastic concrete are basically similar to the conventional concrete with an exception of use of bentonite.

Aggregates maximum size, grain distribution and proportion in plastic concrete play an important role for the stability of fresh plastic concrete. For plastic concrete commonly a smaller maximum aggregates size is chosen, in this case maximum aggregates size was limited to 12.5 mm and a proportion of coarse aggregate to sand was selected 40% / 60%. Coarse aggregate was obtained from local excavated material and sand directly from the riverbed. Also the mixing water for plastic concrete was obtained directly from Godavari River.

As the cementitious material a composite cement from portland clinker and fly-ash was used.

Bentonite provides a better workability and necessary resistance against sedimentation of aggregates at relatively high water and low cement contents, while improving the ductility and filling the air voids (Shepherd et al. 2018). Generally, the bentonite is added to the plastic concrete mix as pre-mixed bentonite slurry. A sufficient pumpability of bentonite slurry should be given.

3.2 Fresh Concrete Properties

A realistic assessment of the concreting time including transport time of concrete and possible delays is decisive for the adjustment of workability and sufficient retention time especially for high concreting volumes.

Primarily, the most important properties of fresh concrete (EFFC/DFI, 2018):

- Workability: the general term defining the ability of the concrete to fill the excavation, self-levelling and self-compacting under gravity
- Workability retention: defining how long the specified fresh properties will be retained
- Stability: defining how long the specified fresh properties will be retained

As sufficient workability, slump values of 240 ± 20 mm or slump-flow values of 400 to 600 mm and workability retention times up to 12 hours were set to be achieved at trial tests. To design a robust plastic concrete, all suitability tests were conducted using original materials from the construction site, at expected ambient temperatures (30-35°C). The fresh concrete properties were repeated several times in order to assess possible scatterings in laboratory condition. Another critical step to design a robust plastic concrete is the type and amount of admixtures to be used. For the plastic concrete, a ligninsulphonate based retarder with slight plasticizing effect was used. It was further aimed that also considering very high ambient temperatures, the sufficient workability of plastic concrete mainly to be provided by mixing of sufficient water. Therefore, a slump-flow value of 450 to 500mm was initially set (slightly lower than the target slump-flow), for the case that no admixture was yet added. In further suitability tests, where the admixture was considered, due to the plasticizing effect of the retarder, slump-flow values 500 to 600mm could be achieved. Also during construction activities, in general consistencies in the same range could be achieved. Despite its very flowable consistency, the concrete shall be stable against segregation, bleeding and filtration. The stability of the plastic concrete was specifically tested and it was concluded that a slurry quantity of 350 l/m3 achieving the best properties that meet the requirements of fresh concrete properties.

3.3 Hardened Concrete Properties

Consequently, using the above mentioned slurry quantity (350 l/m3) various plastic concrete mixes were produced with varying cement contents between 160 to 220kg/m3 (see Table 3).

Table 3 : Determination of required cement content

Mix	**1**	**2**	**3**	**4**
Slurry quantity [l/m^3]	350			
Cement [kg/m^3]	160	180	200	220

The mix (Mix 2), which fulfills the requirements of the Technical Specification could be used at the construction after a long approval processes.

Table 4 : Properties of hardened Plastic Concrete with various cement contents

Mixes acc. to cement content	**ConfinedCompressive Strength σ_c = 0.4 [MPa]**	**Strain at Failure at CCS [%]**	**Unconfined Compressive Strength [MPa]**	**Permeability Coefficient [m/s]**
Mix 1 c 160 kg/m³	2.6	5.7	1.2	1.0 x 10-8
Mix 2 c 180 kg/m³	3.5	4.9	1.8	8.0 x 10-9
Mix 3 c 200 kg/m³	3.9	4.2	2.9	3.0 x 10-9
Mix 4 c 220 kg/m³	4.7	3.1	3.4	5.2 x 10-9
Requirement	2.5 - 6.0MPa	-	1.5 - 2.5MPa	< 1 x 10-8

As it can be clearly seen at Table 4, with a higher compressive strength, a lower strain at failure at Confined Compressive Strength (CCS) test is achieved, which leads to opposing requirements on the composition of the plastic concrete. Taking the additional plastic deformations into account, Mix 2 with a dosage of 180 kg/ m^3 was selected, whereas a strain at failure value of (rounded) 5% was considered as satisfactory.

4. QUALITY CONTROL OF PLASTIC CONCRETE

During the execution of plastic concrete cut-off wall, the quality control of plastic concrete was carried out in three steps.

(1) Incoming material control

(2) Testing on fresh plastic concrete

(3) Testing on hardened plastic concrete

The testing on marsh-time, yield point, filtrarion loss, pH-value, tempereature and the density of the bentonite slurry was checked for each delivery and regularly during production. The chemical properties of cement were tested externally physical and mechanical properties were tested at the construction site laboratory. The sieve analysis and moisture content of used fine and coarse aggregates were determined twice a day. As per client's request, the chemical properties of aggregates and mixing water were tested in an external laboratory.

An extremely challenging task was the enormous number of tests to be carried out. Despite reference to other internationally recognized standards with significantly smaller sampling quantities, the frequencies of the tests were carried out according to the original project specification. The test frequencies and the resulting total number of tests on hardened plastic concrete are shown in Table 5:

Table 5 : Scope of Quality Control testing

Type of Test	Testing Frequency	No of Test per day	No of Tests Total
Unconfined Compressive Strength (28 Days)	3 Cylinders each 60 m³	30 – 50	6071
Confined Compressive Strength (28 Days) σc = 0.4 MPa	3 Cylinder each 60 m³	30 – 50	6071
Permeability (28 Days)	1 Cylinder each 200 m³	3 – 5	712

This tremendous large number of laboratory testing required also enormous man power and a comparatively large laboratory facility. In the site laboratory, two testing machines for triaxial tests, a compressive strength testing machine and a system for permeability testing, which enabled simultaneous testing of 6 samples, were installed.

In the period of construction activities and as a results of extensive quality control testing, the conformance of parameters was verified. In addition to the conformance of parameters, also a relatively low standard deviation and coefficient of variation could be achieved. These parameters point out a consistent plastic concrete production and a constant material quality. An overview for statistical presentation of results of laboratory testing is shown in Table 6.

Table 6 : Statistical parameters of quality control

Type of Test	Unconfined Compressive Strength	Confined Compressive Strength	Coefficient of Permeability	Young`s Modulus
No of Tests	6071	6071	712	883
Average Value	1.98 MPa	3.29 MPa	2×10^{-9} m/s	286 MPa
Minimum Value	1.00 MPa	2.10 MPa	2×10^{-8} m/s	201 MPa
Maximum Value	3.54 MPa	6.01 MPa	9×10^{-11} m/s	439 MPa
Standard Deviation	0.31	0.59	n.d.	53
Coefficient of Variation	16 %	18 %	n.d.	19 %

In consequence of above mentioned outcomes, it was further investigated, if a reduction in QC testing frequencies would be reasonable.

As can be seen from the table above, a reduction in quality control frequency from each 60 m³ to each 300 m³ (as suggested by EN 1538) the difference in average value for UCS is only in 3rd decimals and negligible. Similarly, reducing the standard deviation and the coefficient of variation would only lead to a marginal difference (see Table 7).

The statistical evaluation of the tests shows that an effective quality assurance would have been possible even with a lower number of tests as given in EN 1538-2015, see Table 7.

Table 7 : Statistical parameters from the evaluated quality control database

Type of Test	Evaluation of Unconfined Compressive Strength – as per Technical Spec.	Evaluation of Unconfined Compressive Strength – as per EN 1538 (2015)
Testing frequency	Each 60m³	Each 300m³
No of Tests	6071	1214
Average Value*	1.9848 MPa	1.9876 MPa
Minimum Value	1.00 MPa	1.00 MPa
Maximum Value	3.54 MPa	3.54 MPa
Standard Deviation*	0.3113	0.3137
Coefficient of Variation	15.68 %	15.78%

* Additional decimals are used for better explicitly

Consequently, it can be concluded that for similar mega-projects, where extremely high testing numbers are expected, reduction in testing frequencies may result in a safety level at same range. This would lead to significant work and cost savings for all the parties.

5. SUMMARY AND OUTLOOK

With the locally available raw materials, a robust plastic concrete mix was developed within the scope of extensive suitability tests that meets the requirements for a highly deformable cut-off wall concrete.

Despite the extensive challenges, in view of the particular location and the climatic conditions, including the sample storage and testing, very uniform plastic concrete properties could be achieved over the entire project. The specified plastic concrete properties were verified by means of extensive quality control in every phase of cut-off wall construction.

An evaluation of Quality Control analysis based on gained results from laboratory testing as per project specifications was done. Furthermore, a comparison with the international standard EN 1538 is drawn. Accordingly, it was determined that a reduction of the QC frequency is reasonable at other long-term projects in future achieving the same safety level.

Based on this data, for such projects, where very high volumes of plastic concrete used, the testing frequencies can be reduced, which lead to significant work and cost savings for all the parties. Of course, this statement is valid for the case that the contractor possesses adequate experience and expertise in special foundation works.

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