ROLLER COMPACTED CONCRETE DAMS

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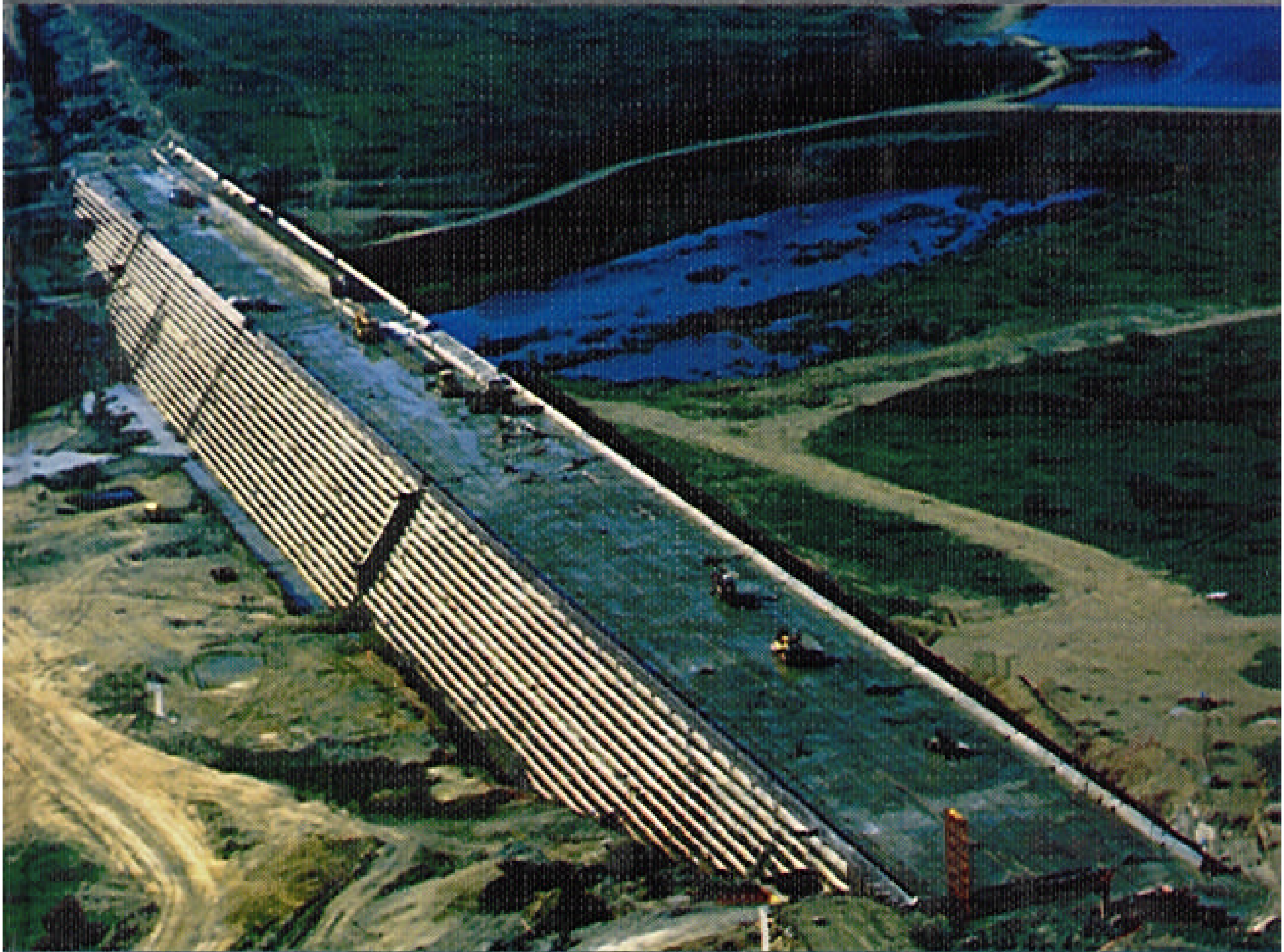
CAPANDA-ANGOLA HYDROELECTRIC DEVELOPMENT - Quality Control of Materials and Conventional and Roller Compacted Concrete



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CAPANDA-ANGOLA HYDROELECTRIC DEVELOPMENT - Quality Control of Materials and Conventional and Roller Compacted Concrete

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ABSTRACT

The data obtained through Quality Control of Materials and Concrete practiced during the construction of the Capanda Dam Development in Angola are presented in this report .The Contractor, Construtora Norberto Odebrecht S.A. was responsible for the Quality Control Plan of the Capanda Dam, with a height of approximately 110 m, a volume of Roller Compacted Concrete totaling approximately 800,000 m3. GAMEK - The Médio Kwanza Development Cabinet, an Angolan government organization, was responsible for the supervision thereof. The data obtained are presented, and the low cement content design mixes and the Coefficients of Variation show that a noticeable degree of quality and security has been achieved. Test data taken from the body of the dam is compared with the test control and study data.

1- INTRODUCTION

Capanda- Hydroelectric Development is located in the middle reach of the Kwanza river, in the central-north region of the People’s Republic of Angola, distant around 450 km by road from the capital, Luanda. The Project belongs to the Angolan government, represented by the Middle Kwanza Development Cabinet - GAMEK. The Brazilian-Soviet Consortium constituted by Construtora Norberto Odebrecht S/A and V/O Technopromexport have been commissioned for execution of the works.

When completed, the Development will be equipped with four Francis turbines 130 MW each for an average annual electric power production of 2400 GWh. When filling the reservoir to the 950 m elevation (a.s.l.), a water volume of 4,8 km3 will be stored in an area of 110 km2. The dam will also serve regulating purposes for the Cambambe Power Plant, located 140 km downstream, plus agricultural benefits. The dam is constructed in a deep gorge, crossed by the river through sandstone Upper Cambrian formations of the Malanje plateau.

The Development consists of a RCC gravity Dam incorporating in its central part a Spillway and a Bottom Outlet; Water Intake structure; Underground Penstocks; Power House and adjacent Erection Bay Area; Power Switchyard with 220 kV transmission lines, interconnecting Capanda to the Regional Power System; Diversion Tunnel and temporary cofferdams.

2 - CHARACTERISTICS OF THE RCC DAM

The RCC gravity dam is specified as follows:

- Maximum height over foundations:.........................110 m
- Total Length: ....1200 m
- Concrete volumes:

  Roller Compacted Concrete (RCC):................ 764.000 m3

  Conventional Concrete for the Dam:............. .290.000 m3

  Total:................................. ....1.054.000 m3

Design concept for the dam includes the following characteristics:

- Downstream slope with declivity of 0,74:1 (h:v);
- Upstream impervious zone (PVC membrane + face mix + bedding mix between RCC layers);
- Central and downstream Zones with guarantee of mechanical properties (cohesion, friction and strength) and drainers;
- Roller Compacted Concrete (RCC) with minimum required characteristic compressive strength (fck) of 80 kgf/cm2 at 180 days, and minimum specific gravity of 2400 Kg/m3.

On the upstream zone, encompassing the whole rock foundation, a layer of conventional concrete as a “plinth” was applied, with 70 cm thickness and 5,0 m width.

The upstream face design is totally vertical, consisting of precast concrete panels, containing in the internal face turned towards the dam inside an impervious PVC membrane, with 2,4mm thickness. Directly downstream from the precast panels, an impervious barrier was made using conventional concrete (facing mix), with thickness ranging from 1,50m near foundation deeper elevations, to 0,60m near to the dam crest.

Facing Mix and RCC were poured in layers 40 cm height after compacting. To comply with the strength parameters specified for the dam body, the use of RCC was forecast with a cement content between 60 and 80 kg/m3, added with **140** kg/m3 of meta-sandstone CRUSHED ROCK POWDER "Filler", with some pozzolanic activity.

The stability studies concerning sliding between RCC layers have recommended the use of “beding” conventional concrete between them; this concrete being called “bedding-mix", to be applied to a section equivalent to 0,25 the dam’s base wide in the layer considered, counted from the upstream facing and limited to a minimum of 5,0m. Downstream from this section, “Bedding Mix” was applied if the time elapsed between pouring the successive layers should exceed 8 hours. Stability analysis have determined declivity of the downstream slope in the spillway area, as 1:0,74 (v:h), with the RCC dam body having minimum specific gravity of 2400 Kg/m3.

To ensure a better performance against adverse climatic conditions and to improve visual aspect, the downstream slope is lined with conventional concrete similar to the facing mix, except for the spillway chute which is lined with highly abrasion resistant concrete. To avoid uplift pressure at the dam body, drains were provided between face and RCC concrete joints.

3 - PREVIOUS STUDIES OF MATERIAL CHARACTERIZATION AND QUALIFICATION

Previous studies of the materials and concrete mixes for the Capanda Project were made by Itaipu Binacional Concrete Laboratory. In the planning of these studies in 1987, the following conditioning factors were considered:

- CEMENT: complicated logistics for supply to the jobsite, 450 km far from the factory located in Luanda;
- POZZOLANIC MATERIAL: no industrial mining of this material in the country; no raw-material availability near the jobsite;
- NATURAL SAND: sparse deposits with small utilization potential, low fineness modulus and undesirable contamination of clayey-silt and organic material;
- ROCK SUPPLY: arkosian meta-sandstone sound and compacted, cemented by hydroxides and/or iron oxides;
- CONCRETES: there are not studies on concrete properties (thermal, mechanical-elasticity and permeability), with suitable extrapolation and compatible with the works magnitude.
- MISCELLANEOUS MATERIALS: (steel, elastomeres and admixtures), non-available in the local market;

Based on these conditions the studies were directed towards the following objectives:

- To optimize cement consumption in mixes;
- To evaluate throughly the characteristics of the rock available, in particular concerning its possible reaction with cement alkalies and the real need for using pozzolanic materials;
- To maximize the use of crushed sand obtained by meta-sandstone crushing;
- To investigate and use to their maximum extent the benefits of “CRUSHED POWDER” both as regards its action against possible alkalies-aggregate reactions as well as improvement of strength and impermeability properties.
- To characterize typical concrete mixtures as to: proportioning; compressive strength; tensile

strength; modulus of elasticity; triaxial compression; strain capacity; creep; permeability; adiabatic temperature rise; thermal diffusivity; specific heat and thermal coefficient of linear expansion.

- Characterize and qualify industrial products procured abroad (such as, steel, metallic splices, elastomeres and admixtures), before sending these to Angola.

Studies were presented in detail in references [1] and [2], with their main aspects described as follows:

- The cement available, CIMANGOLA, produced in Luanda, was qualified as suitable for the works.
- Crushed material when submitted to various methods for potential reactivity evaluation (petrographic analysis; ASTM-C-289 chemical test; ASTM-C-227 physical test; accelerated NBRI test; and thermal-"Ossipov" test), behaved as “innocuous”.
- The use of CRUSHED POWDER (material smaller than 0,075 mm) resulted beneficial whereas it reduced possible expansions due to alkalies-silica reactions, acting with pozzolanic material of specific activity in addition to reducing greatly concrete permeability.
- Coarse aggregate when submitted to abrasion tests (Los Angeles) and soundness tests (natural, artificial and accelerated cycling, with glycol ethylene), has shown results which enable its classification as durable and resistant.
- Concrete mechanical, thermal and elastic properties were consistent and compatible with the magnitude of the works and have provided parameters for the study of thermal behavior and structural dimensioning.
- Miscellaneous materials such as steel, metallic splices, elastomeres and admixtures have been previously qualified avoiding supply and refusal on site of materials and products non-compliant with specifications.

4 - PLANO DE CONTROLE DE QUALIDADE DOS MATERIAIS E CONCRETOS

Quality control of the material and concrete to be employed for the Capanda Project, was the Constructor’s responsibility. To perform these activities, a “Quality Control Plan” was devised, in order to comply with Design and Specifications requirements. Logistic conditions for construction of the Development were also considered such as, procurement of basic materials, distance from site to production centers, quantity and quality of labor available, schedules, and assurance of quality parameters compatible with the magnitude of the works. Figure 1 shows, in schematic form, the Quality Control Plan established.

MATERIAL OR SYSTEM	SAMPLE POINT	STANDARD REFFERED	TYPE OR INTENTION	FREQUENCY	LABORATORY	TESTS OR EVALUATION
REINFORCING STEEL	STOCKS	ABNT-NBR-7480	RECEPTION	EACH TRUCK (30t)	JOB SITE	WEIGHTLINEAR, YELD STRENGTH, RUPTURE STRENGTH, ELONGATION, BENDING
REINFORCING SPLICES	STRUCTURES	ABNT-NBR-7480	CONTROL	2 % OF TOTAL SPLICES	JOB SITE	RUPTURE STRENGTH
WATER	BATCH PLANT	LCAP- 1 - 10	CONTROL	WEAKLY	JOB SITE	SOLIDS, pH, O2, SO4, Cl
ADMIXTURES	BATCH PLANT	LCAP - 2 -1	CONTROL	ONE / 1000Kg	JOB SITE	SOLIDS, pH, SPECIFIC GRAVITY
WATER STOP	SUPLIER	LCAP - 5 - 1	DELIVERY	ONE / 200m	ITAIPU BINACIONAL BRAZIL-PARAGUAY	ALKALIES, HARDNESS, TENSILE STRENGTH ELONGATION AT RUPTURE
CEMENT	SUPLIER	BS - 4550	DELIVERY	ONE / 2HOURS OR ONE / 100t	CEMENT FACTORY	FREE LIME, FINENESS BLAINE TIME OF SET, LOSS ON IGNITION
			CONTROL	ONE / DAILY ONE / 500t	CEMENT FACTORY	SiO2; Fe2O3; Al2O3; SO3; CaO,MgO, FREE LIME; LOSS ON IGNITION, INSOLUBLE RESIDUE; TIME OF SET,RESIDUE ON # 200, # 325 SPECIFIC GRAVITY, AUTOCLAVE EXPANSION EXPANSION "LE CHATELIER" COMPRESSIVE STRENGTH -
	CONTAINERS	ABNT - NBR - 5781	RECEPTION	ONE / 100t	JOB SITE	
	BATCH PLANT		CONTROL	ONE / WEAKLY	JOB SITE	
			INTER-LABORATORY	ONE / 5000t	OFFICIAL LAB. AND ITAIPU	
AGGREGATES	CRUSHER SYSTEM	LCAP- 10 - 2	PRODUCTION	ONE / WEAKLY	JOB SITE	GRAIN SIZE; APPARENT AND ABSOLUTE DENSITIES ABSORTION, FLATNESS
	BATCH PLANT	ABNT - NBR - 7216	CONTROL	ONE / SHIFT	BATCH PLANT	UMIDITY; ADJUSTMENT MIXES
				ONE / WEAKLY	JOB SITE	GRAIN SIZE, APPARENT AND ABSOLUTE DENSITIES ABSORTION, FLATNESS
CONCRETES CVC	BATCH PLANTS	LCAP - 4 - 1	CONTROL	ONE / 200m3	JOB SITE	SLUMP, AIR; TEMPERATURE; SPECIFIC GRAVITY COMPRESSIVE STRENGTH
				ONE / 2000m3	JOB SITE	SLUMP; AIR; TEMPERATURE; SPECIFIC GRAVITY COMPRESSIVE STRENGTH, MODULUS, TENSILE SPLITTING
CONCRETE RCC	BATCH PLANTS	LCAP - 7 -1	CONTROL	ONE / SHIFT	BATCH PLANT	GRAIN SIZE; CEMENT CONTENT, CONSISTENCY (VeBe) COMPRESSIVE STRENGTH, SPECIFIC GRAVITY
	DAM BODY	LCAP- 10 - 3	CONTROL	ONE / 100m3	DAM SITE	SPECIFIC GRAVITY, COMPACTION RATIO, UMIDITY
DRLLED CORES	DAM BODY	LCAP - 11 - 5	CONTROL	ONE / 10000m3	JOB SITE	SPECIFIC GRAVITY; MODULUS, PERMEABILITY COMPRESSIVE STRENGTH
CRUSHER PLANT		LCAP - 10 - 1	INSPECTION	DAILY	SYSTEM	CHECK LIST
BATCH PLANT		LCAP - 10 - 7	INSPECTION	DAILY	SYSTEM	CHECK LIST

FIGURE 1- Control Quality Plan for Materials and Concrete

5 - QUALITY CONTROL OF MATERIALS

5.1 - Aggregates

Aggregates control was established using two types of samples - Production and Control:

- Production samples were taken weekly at the aggregates belt conveyor, between crushers and stock-piles. These samples allowed for routine checks of the crusher system classification and conditions and provided information also on control and balancing of stored materials. During initial production phase, these samples were taken at daily and sometimes hourly intervals until the system was quality and quantity adjusted.
- Control samples were taken weekly at each of concrete the batch plants allowing characterization of the aggregates on their immediate application to concrete.

Granulometric ranges considered in the production of aggregates for conventional and RCC concretes are shown in Figure 2, where it is noted that the RCC was produced from the various granulometric ranges available. This was because RCC was produced both at conventional concrete plants (Batch) and also in continuous mixing plants (Pug Mill).

DENOMINATION	AGGREGATE SIZE(mm)	USED FOR - CONCRETE TYPE	
		RCC	CVC-CONVENTIONAL
CRUSHED SAND	5 – 0	YES	YES
COARSE 1	19 – 5	YES	YES
COARSE 2	38 – 19	YES	YES
COARSE 3	76 – 38	YES	YES
AGGREGATE G1	19 – 0	YES	NO
AGGREGATE G2	64 – 19	YES	NO

FIGURE 2- Granulometric Ranges for Aggregates Production

Combined aggregate "G1" (0-19mm) was obtained by combining crushed sand with Coarse 1, at the crusher system. In the same way the combined aggregate "G2" (19-64mm) was obtained from the combination of Coarse 2 and 3, with a small reduction in size of Coarse 3. This reduction although requiring more crushing effort, had the purpose of improving performance of the RCC Pug Mill, ensuring less segregation both of the "G2" and of the RCC itself. Because the sand content of "G1" was insufficient for completion of RCC total granulometry, an additional amount of crushed sand was supplied directly from the recrushers for fillers, conveniently located within the system. Data obtained on aggregates control are presented in Figure 3.

PROPERTY	UNITY	CRUSHED SAND	AGGREGATE				
			G1-(19-0)mm	G2-(64-19)mm	B1-(19-4.8)mm	B2-(38-19)mm	B3-(76-38)mm
APPARENT SPECIFIC GRAVITY	g/cm3	1,59	1,61	1,6	1,42	1,43	1,41
ABSOLUT SPECIFIC GRAVITY	g/cm3	2,65	2,65	2,66	2,65	2,66	2,66
ABSORTION	%	0,9	0,77	0,33	0,6	0,42	0,45
ABRASION LOSS-LOS ANGELES	%	(ON THE METASANDSTONE ROCK FOR AGGREGATES = 13,8)					
NUMBER OF SAMPLES	N	259	134	122	145	162	125

FIGURE 3: Physical Characteristics of Capanda Aggregates.

As already demonstrated, the use of crushed sand was of fundamental importance for the Capanda Project concretes especially because it was possible to benefit from the use of CRUSHED POWDER FILLER. On proportioning of RCC mixes, it was prescribed that concrete total granulometry should have a minimum 10% content of particles less than 0,15mm (at sieve mesh # 100), and 7% of particles less than 0,075mm (at sieve mesh # 200). To better characterize the actual amount of CRUSHED POWDER, in the crushed sand, comparative grain size analysis were carried out, with dry and wet screen on twin samples, obtaining the results as shown in Figure 4. These comparison tests have evidenced that on wet screen granulometry tests the retained accumulated material content on sieve mesh # 200 results about 80% more than the results obtained with dry screen testing.

CONDITION OF TEST	*% RETAINED ACCUMULATED ON SIEVE (mm)*						
	4,8	2,4	1,2	0,6	0,3	0,15	0,075
DRY SCREEN	6	39	58	69	78	87	94
WETT SCREEN	8	39	58	68	76	84	89

FIGURE 4- Comparison granulometric results with dry screen and wet screen (Average value for 31 samples)

5.2 - Cement

On the Capanda Development the only brand of cement used was Cimangola, Common Portland type, supplied in bulk. According to the supply contract, the manufacturer carried out quality control himself and was responsible for the dispatch of his product. To this end, a procedure was established for the Delivery of samples every 2 hours or 100 t produced, to determine Free Lime, Blaine Fineness, Setting Time and Loss on Ignition. Supplementary factory control samples were taken daily every 500 t, for complete physical-chemical tests. Manufacturer's tests were made to British Standard BS 4550. On site, the Quality Control Plan established that Control and Reception samples be taken. .Reception samples were taken from each batch received on site, at the rate of 1 sample for every 100 t or fraction thereof. Control samples were taken weekly from each concrete batch plant, characterizing the cement immediately on application to concretes. Eventually, a sampling at every 5000 t was also established for inter-laboratory testing, allowing checking of the procedures used by the Laboratories involved. Figure 5 supplies all data obtained through control made (with samples taken at the concrete batch plants) as well as the requirements as specified, based on methods of ABNT-NBR 7215 (Brazilian Method of Test).

REQUIREMENT	UNITY	NUMBER OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
% RETAINED ON # 200	%	371	5,7	23,9	
% RETAINED ON # 325	%	318	20,6	21,9	< 30
SPECIFIC SURFACE BLAINE	cm2/g	392	3430	12,5	> 3200
APPARENTE SPECIFIC GRAVITY	g/cm3	187	1,1	2,7	
ABSOLUT SPECIFIC GRAVITY	g/cm3	349	3,12	0,6	
TIME OF SETTING - INITIAL	h : min	600	2:07	23,2	> 1,0 h
- FINAL	h : min	567	3.23	22,3	
LE CHATELIER - EXPANSION	mm	252	1	18	< 5,0
AUTOCLAVE - EXPANSION	%	167	0,5	258	< 0,8
COMPRESSIVE 3 DAYS	Kgf/cm2	154	177	23,6	> 100
STRENGTH 7 DAYS	Kgf/cm2	155	267	18,1	> 200
(AGE) 28 DAYS	Kgf/cm2	193	349	14,5	> 320
HEAT OF 7 DAYS	cal / g	23	78,1	7,7	
HYDRATION (AGE) 28 DAYS	cal / g	23	88,3	5,9	
LOSS ON IGNITION	%	212	1,13	32,7	
INSOLUBLE RESIDUE	%	214	0,53	39,6	
SiO2	%	214	20,5	3,4	
Fe2O3	%	202	3,58	13,3	
Al2O3	%	202	6,31	10,8	
CaO	%	214	64,3	1,4	
MgO	%	214	0,89	38,2	< 3,5
SO3	%	600	1,99	19,6	< 3,0
FREE LIME	%	601	1,51	39,7	< 2,0
C3S	%	202	44,9	14,2	
C2S	%	202	24,2	22,6	
C3A	%	202	8,96	19,6	< 9,0
C4AF	%	202	11,5	11,3	

FIGURE 5: Tests carried out on Cimangola Cement (Samples from Concrete Plants)

5.3 - Admixtures for Conventional Concretes

No admixtures were added to the RCC used on site. For conventional concretes facing mix and bedding mix types, air entrained plasticizer, set retarder and super plasticizer admixtures were used. Admixture samples had Control purpose only, since these had been pre-qualified during the initial studies [1][7]. Furthermore, these products were sent to site backed by manufacturer's quality certificates. Control samples were taken weekly at each of the concrete plants admixture batching. The results are shown in Figure 6.

ADMIXTURE TYPE	REQUIREMENT	*UNITY*	*NUMBER OF SAMPLES*	*AVERAGE*	*COEFFICIENT OF VARIATION %*	***LIMIT***
RETARDER / WATER REDUCER	SOLID RESIDUE	mg /	118	31,1	12,2	32 to 37
	SPECIFIC GRAVITY	g / cm3	118	1,15	3,5	1,15 to 1,17
	pH		118	6,9	17,4	4 to 7
AIR ENTRAINING	SOLID RESIDUE	mg /	117	8,8	20,5	7,5 to 9,5
	SPECIFIC GRAVITY	g / cm3	117	1	1	1,01 to 1,02
	pH		117	12,5	6,2	11 to 13
SUPER PLATICIZER	SOLID RESIDUE	mg /	16	32,2	6	32 to 37
	SPECIFIC GRAVITY	g / cm3	16	1,17	0,4	1,15 to 1,18
	pH		16	7	2,2	5 to 8

FIGURE 6: Tests with admixtures with limits as recommended by manufacturers.

5.4 - Mixing Water

At the concrete plants the water from the Kwanza river was used after decantation in the raw water reservoirs on site, with no chemical treatment. Sampling of the mixing water had Control purposes only with samples taken at the batching outlet in the concrete plants once a week. Results obtained are shown in Figure 7.

REQUIREMENT	*UNITY*	*NUMBER OF SAMPLES*	*AVERAGE*	*COEFFICIENT OF VARIATION %*	***LIMIT***
O2	mg /	186	2,5	92,8	< 3
SOLID RESIDUE	mg /	181	48 4	53,7	< 5000
CLORIDES	mg /	185	3,6	66,7	< 500
SULPHATES	mg /	186	5,2	136 5	< 300
pH		186	7,6	11,8	5,8 to 8

FIGURE 7: Control Tests of Mixing Water

5.5 - Steel

Most of the steels used for reinforced concrete were types CA-25 and CA-50 made in Brazil. A-30 type steels of Cuban origin and type III of (ex-) Soviet origin similar to ABNT CA-40 were also supplied to a lesser extent.

Brazilian steels were sent to site backed by manufacturer's respective quality certificates. On site the material was sampled as per ABNT NBR-7480, for Reception control; the results obtained are shown in Figure 8.

PROPERTY	UNIT	STEEL GRADE			
		CA-25 (NBR-BRAZIL)	CA-50 (NBR-BRAZIL)	A-30 (CUBA)	III (ex-URSS)
YELD STRENGTH	Kg/mm2	33	57	32	43
RUPTURE STRENGTH	Kg/mm2	49	85	52	66
ELONGATION AT RUPTURE	%	25	14	22	20

FIGURE 8- Results of Reinforcement Steel Control Tests

5.6 - Membrane PVC

P.V.C.Membrane used as supplementary safety element for impermeabilization of upstream facing, has been studied in detail [2] and developed to comply with the specific conditions of the Capanda Dam. The Quality Control Plan determined that Delivery factory samples be taken before this was sent to site. Frequency set was for one sample to be taken for every 1000m2 of membrane produced. Tests were made at Itaipu Binacional Laboratory, and the results obtained are shown in Figure 9.

REQUIREMENT	UNITY	NUMBER OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
THICKNESS	mm	23	2.49	0.96	> 2
HARDNESS	Shore "A"	23	91	0.56	
RUPTURE STRENGTH	Kgf/cm2	23	181	3.96	> 150
ELONGATION AT RUPTURE	%	23	351	10.01	> 200
TEAR RESISTENCE	Kgf/cm2	23	14	5.28	
HYDROSTATIC RESISTENCE	Kgf/cm2	23	16.3	6.47	> 14
WATER ABSORTION	%	23	0.39	4.13	< 0.5
SPECIFIC GRAVITY	g / cm3	23	1.24	0.53	1.2 to 1.3

FIGURE 9: Results of P.V.C. Membrane Control

5.7 - PVC - Water Stops

Same as for the PVC membrane, the Quality Control Plan determined that Delivery factory samples be taken of the water stops before these were sent to site.Frequency set was for one sample to be taken for every 200 linear m. produced. The water stops were sent to site backed by manufacturer's respective quality certificates. In addition, Control samples were taken on site with tests carried out by Itaipu Binacional Laboratory. The results obtained are shown in Figure 10.

REQUIREMENT	UNITY	NUMBER OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
HARDNESS	Shore "A"	10	83	0 74	75 to 85
RUPTURE STRENGTH	Kgf/cm2	10	143	4 96	> 120
ELONGATION AT RUPTURE	%	10	306	7 32	> 280

FIGURE 10: Results of Control tests with P.V.C. Seal Joints.

6 - QUALITY CONTROL OF CONVENTIONAL CONCRETES PRODUCTION

Conventional concretes were produced in two batching-mixing plants with tilting conical mixer with 3 m3 capacity per mixer. Nominal production of each plant was 120 m3/h, with production reaching 130 m3/h during peak periods. Quality control of conventional concretes production was made by taking routine samples of the concrete and its mixing materials. Sampling was made at the concrete plants where small field laboratories were installed. Moisture of the aggregates, for correction of mixing water, was determined every 2 hours for the small aggregates and at least twice a day for coarse aggregates. Tests were carried out on concrete samples fresh mix (slump, % of entrained air and temperature), aiming at controlling homogeneity and to enable mixing corrections and adjustments.

Moldings of ⌀15x30 cm test specimens for strength tests were made for every 200 m3 produced or fraction thereof. At every 2000 m3, additional test specimens were molded for modulus of elasticity and diametral compression tensile strength tests. Tests over hardened concrete enable statistical evaluation of compliance to design requirements, based on the reliability established and dispersions obtained. To check production equipment, all batchers were checked monthly, during maintenance or long shutdown periods or on occurrence of any anomaly. The following figures have been established as maximum deviations for each batching: water and cement 1%; sand 2%; coarse aggregates 3%; admixtures 5%.

For preventive control, periodical check-lists were run on each equipment, to inspect the following items: mixing water piping system; storage conditions of the various materials; cement supply system conditions; mixing and batching plants conditions.

Mix design of the conventional concretes mainly used in the dam construction and their respective control parameters are shown in Figure 11.

USED AS	UNIT	*FACING MIX*	*FACING MIX*	*BEDDING MIX*	*BEDDING MIX*	*PLINTH*
REQUIRED STRENGTH	Kgf/cm2	120	120	120	120	160
AT AGE	Days	90	90	90	90	28
IDENTIFICATION		E 38 03	E 38 04	E 19 07	E 19 08	C 38 01
SLUMP	cm	5 +/- 1	5 +/- 1	14 +/- 2	14 +/- 2	5 +/- 1
AIR ENTRAINED	%	4 +/-1	4 +/-1	4+/-1	4+/-1	4 +/-1
		PROPORTIONING MIX				
CEMENT	Kg/m3	230	200	260	230	265
WATER	Kg/m3	166	165	218	220	168
CRUSHED SAND	Kg/m3	740	840	1100	1155	675
COARSE B1(19-4.8)mm	Kg/m3	560	530	695	650	560
COARSE B2(38-19)mm	Kg/m3	600	570			630
RETARDER	Kg/m3	0.9	0.8	1	0.9	0.8
AIR ENTRAINING	Kg/m3	0.11	0.1	0.12	0.11	0.12
		COMPRESSIVE STRENGTH - STATISTICAL DATA				
3 DAYS SAMPLES		39	286	71	89	89
AVERAGE	Kgf/cm2	85	80	66	59	124
COEFFICIENT OF VARIATION	%	26.4	25.1	21.1	26.4	24
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*0.37*	*0.40*	*0.25*	*0.26*	*0.47*
7 DAYS SAMPLES		45	293	72	94	91
AVERAGE	Kgf/cm2	142	128	112	103	193
COEFFICIENT OF VARIATION	%	26.8	21.1	21	25.4	19.8
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*0.62*	*0.64*	*0.43*	*0.45*	*0.73*
28 DAYS SAMPLES		82	545	143	174	84
AVERAGE	Kgf/cm2	217	188	177	154	276
COEFFICIENT OF VARIATION	%	20.2	18	17.1	18.6	15.9
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*0.94*	*0.94*	*0.68*	*0.67*	*1.04*
90 DAYS SAMPLES		78	433	139	150	
AVERAGE	Kgf/cm2	256	215	210	181	
COEFFICIENT OF VARIATION	%	17.6	17.3	16.7	17.1	
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*1.11*	*1.06*	*0.81*	*0.79*	
PERMEABILITY	*m/s*	*10 E-10 to 10 E-12*				

Figure 11: Mix design and statistical data on conventional concretes mainly used.

7 - QUALITY CONTROL OF RCC CONCRETE PRODUCTION

Mix design and statistical data on RCC mixes mainly used in the dam construction and their respective control parameters are shown in Figure 12.

7.1 - Production Equipment and Checking

Between October 1989 and June 1992 650.000 m3 of RCC were produced. For the CCR, conventional concrete plants (batch) were initially used, as mentioned in item 5, and these produced about 150.000 m3 of CCR. As from May 1990, two other production plants entered into operation (Pug-Mill type) and each double horizontal shaft Mixer enabled various ranges of production of up to a maximum 120 m3/h.

All aggregates were gravimetrically proportioned using belt conveyors with variable speed and provided with rotation meters. Under each proportioning belt weigh-bridges were mounted with load cells that generated electrical signals proportional to the load of material. An integrator panel processed all the information of the speed variator and weigh-bridge, indicating the instantaneous proportioning of the mix flow (t/h). After proportioning, the aggregates were conducted to another belt conveyor which, after receiving cement, fed the mixers.

Cement proportioning was made in the same way as for the aggregates, except for the addition of an automatic correction device. Inside the mixers, the water was sprinkled through bored internal piping., after volumetric proportioning using hydrometers. Proportioning of all materials was monitored with digital indicators under which potentiometers were installed for speed adjustment of respective batchers.

For checking batchers, initial recommendations had fixed the same maximum deviations as allowed for conventional concrete batch plants. Later, based on practical findings helped by laboratory analysis information, maximum deviations were extended to as much as 3% for all materials. For checking batchers, standard weights were used coupled to the weigh-bridge with the batcher empty. Operating the proportioning belt at various speeds, the integrator panel made automatic calibration. After completion of automatic calibration, a direct check was made by sample collecting and timing process. For water, only this last procedure was used. For controlling production equipment, periodical inspections running a check list were carried out as described in item 5 (Figure 1).

7.2- Correction of Mixing Water

Aggregates moisture was determined every 2 hours for crushed sand and for G1 aggregate, and at least twice daily for the remaining aggregates. At intervals with the aggregate tests, the moisture of the RCC mixing was also determined in the retained fraction of sieve mesh 19mm.

Moisture test made on the passed fraction resulted more convenient, precise and efficient compared with the test for full mass concrete, as this considered mainly the fraction containing fine matrix which accounts mainly for RCC compactability.

PRODUCED BY(TYPE OF MIXER)	UNIT	*BATCH PLANT*	*BATCH PLANT*	*CONTINUOUSPLANT*	*CONTINUOUSPLANT*
		GENERAL DATA			
REQUIRED STRENGTH	Kgf/cm2	80	80	80	80
AT AGE	Days	90	180	90	180
IDENTIFICATION		F 76 BT	G 76 BT	(F 64 PM)-(F 76 1 B)	(G 64 PM)-(G 76 2B)
		RCC - PROPORTIONING MIX			
CEMENT	Kg/m3	80	70	80	70
WATER	Kg/m3	102	102	102	102
CRUSHED SAND	Kg/m3	1075	1085	294	348
COARSE B1 (19-4,8)mm	Kg/m3	520	520		
COARSE B2(38-19)mm	Kg/m3	470	470		
COARSE B3(76-38)mm	Kg/m3	200	200		
AGGREGATE G1 (19-0)mm	Kg/m3			1200	1240
AGGREGATE G2(76/64-19)mm	Kg/m3			768	660
		FRESH RCC MIXTURE - STATISTICAL DATA			
SAMPLES		50	20	17	308
SPECIFIC GRAVITY-AVERAGE	Kg/m3	2415	2462	2460	2442
COFFICIENT OF VARIATION	%	1 1	0 7	0,7	0,1
SAMPLES		115	25	28	356
CEMENT CONTENT-AVERAGE	Kg/m3	77,6	68,4	82	70,2
COEFFICIENT OF VARIATION	%	6,3	5,6	10,3	9,2
DEVIATION FROM NOMINAL VALUE	Kg/m3	-2 4	-1 6	2	0,2
		COMPRESSIVE STRENGTH - STATISTICAL DATA			
3 DAYS SAMPLES		29	17	9	66
AVERAGE	Kgf/cm2	41	36	42	40
COEFFICIENT OF VARIATION	%	19,9	25		27,7
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*0,51*	*0 54*	*0,53*	*0,57*
7 DAYS SAMPLES		48	15.	9	74
AVERAGE	Kgf/cm2	62	54	67	54
COEFFICIENT OF VARIATION	%	19 1	18 8		22,9
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*0 78*	*0 77*	*0 84*	*0 77*
28 DAYS SAMPLES		53	16	9	57
AVERAGE	Kgf/cm2	86	78	93	78
COEFFICIENT OF VARIATION	%	17,2	13,1		18,1
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*1,08*	*1,11*	*1,16*	*1,11*
90 DAYS SAMPLES		141	51	26	152
AVERAGE	Kgf/cm2	100	93	115	95
COEFFICIENT OF VARIATION	%	15 9	9,3	14 9	14
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*	*1,25*	*1,33*	*1 44*	*1,36*
180 DAYS SAMPLES			18		13
AVERAGE	Kgf/cm2		95		111
COEFFICIENT OF VARIATION	%		8 4		11,1
MIX EFFICIENCY	*(Kgf/cm2) / (Kg/m3)*		*1,36*		*1,59*
DRILED CORES FROM DAM BODY TESTED BETWEEN 128 AND 223 DAYS AGE - STATISTICAL DATA					
SAMPLES AND AGE		***48 (from 128 to 223 days age)***			***127 (360 days)***
COMPRESSIVE STRENGTH	***Kgf/cm2***	***138***			***127***
COEFFICIENT OF VARIATION	***%***	***19,50***			***24,40***
SAMPLES AND AGE		***9 (from 361 to 419 days age)***			
MODULUS OF ESLASTICITY	***Kgf/cm2***	***255000***			
SAMPLES		***8***			
PERMEABILITY	***m/s***	***10 E-9 to 10 E-11***			

FIGURE 12-Statistical Data for Control of RCC produced at Conventional Gravimetric Plants (Batch) and at Continuous Mixing Plants with Gravimetric Batchers (Pug-Mill).

In laboratory studies, the optimum quantity of water for the RCC was set as 102 kg/m3, which is the equivalent for moisture content (in mix) for full mass concrete of 4,1%. For the fine RCC fraction of sieve mesh 19mm this moisture content corresponds to 6,2%. However, this moisture measured at the concrete plants could only be practiced during the night. It was noted that during warmer days, with wind blowing and low relative moisture content in the air, the passing CCR fraction moisture content needed to be raised about 8,5%, in order to compensate for strong evaporation after spreading. Tests on RCC samples taken after spreading and before compactation have confirmed this elevation.

7.3 - Correction of Filler Contents in Total RCC Granulometry

Crushed sand accounted for about 47% (in mix) of total aggregates. As already mentioned, part of this sand was incorporated to Coarse 1 in the crusher system forming aggregate G1, with the supplementary sand content being supplied by the filler recrushers, located near the continuous mixing plant (Pug Mill). Taking into consideration balance of aggregate requirements for the whole Project, aside from performance of the crusher system, the equipment were adjusted so that the sand content of aggregate G1 were between 55% and 60%. Granulometric homogeneity of aggregate G1 had a strong effect on mix performance. Despite preventive and corrective actions, sometimes deviations from the limits of sand content as set above, were found in this aggregate. Under these circumstances, proportioning of aggregate G1 and sand were adjusted, trying to keep to the total filler quantity as set in the theoretical mix. To this end, a simplified screening test was carried out in the field laboratory, using the same routine sample taken for determining moisture content, after cooling down. Once the sand content in aggregate G1 was established, the necessary corrections were made, with calculation procedure somewhat similar to that used for mixing water correction due to free moisture of the aggregates. The process was simplified by using appropriate tables.

7.4 - Remolding Time " modified VeBe "

Remolding-consistency time test “Modified VeBe” was introduced in the hope of monitoring RCC workability (consistency), as an indicator of deviations concerning moisture and/or filler contents. The suffix “modified” is due to the two main differences in this test as compared to the original VeBe, namely :

- Non-utilization of the conical-trunk form, the cylindrical recipient being totally filled with RCC in bulk state, leveled at the surface;
- Application of an overload of 22,7 kg, over the bulk mix.

It was tried to check the influence that non applying the overload would have to this test results by making tests with the same sample of RCCR this indicating a smaller dispersion in tests made with overload. Technique achieved with the Capanda RCC did NOT produce evidence of absolute applicability of this method, probably due to low plasticity of the RCC, due to the cement consumption adopted and low cohesiveness of fine aggregates also. It was found that extreme remolding-consistency time values do not always correspond to RCC with deficient compactability.

7.5 - Cement Content in RCC Fresh Mix

To check homogeneity of cement proportioning or mixers efficiency, daily tests were made with reconstitution of cement contents in the RCC fresh mix. This reconstitution was made by titration chemical process, determining the cement amount indirectly, from the calcium content present in the sample. This procedure required previous calibration with laboratory preparation of various RCC mixes with variable and strictly known cement proportioning, with always the same proportion among its various components, water included. For each mix, the necessary E.D.T.A. (Ethylene-Diamine-Tetra-Sodium Acetate) volume was determined for total consumption of CaO. Since the volume of E..D.T.A. spent, was directly proportional to the quantity of CaO (and therefore of cement) contained in the mix, a linear correlation was established between these two parameters. This correlation was called test calibration standard. Data obtained during control made through this determination are shown in Figure 12. Figure 13 also shows the results obtained in other RCC applications[3 to 6].

DAM - SITE	BATCHER TYPE	THEORETICAL CEMENTITIOUS MIX CONTENT Kg/m3	CONTROLS										
			CEMENT CONTENT			COMPRESSIVE STRENGTH - STATISTICAL DATA							
			AVERAGE Kg/m3	COEFFICIENT OF VARIATION (%)	DEVIATION FROM NOMINAL VALUE (Kg/m3)	AVERAGE VALUES - Kgf/cm2				COEFFICIENT OF VARIATION - %			
						3 DAYS	7 DAYS	28 DAYS	90 DAYS	3 DAYS	7 DAYS	28 DAYS	90 DAYS
SACO NOVA OLINDA BRAZIL	VOLUMETRIC	75	53 4		-21,6		26	29	42				16
	CONTINUOUS	70	50 4		-19.6		26	29	34				18
SERRA DA MESA COFFERDAM - BRAZIL	VOLUMETRIC CONTINUOUS	60 + 140	188	23.5	-6	76	142	265		31	24	17	
URUGUA-I DAM ARGENTINE	GRAVIMETRIC	60	61,5	5,2	1,5		56,5	74	98		16	12	10
	CONTINUOUS	90	91,1	6.8	1,1		75	96	121		12	10	12
CAPANDA DAM ANGOLA	GRAVIMETRIC BATCHER	80	77,6	6,3	-2,4	41	62	86	100	19,9	19,1	17,2	15.9
		70	68,4	5.6	-1,6	38	54	78	93	25	18.8	13,1	9.3
	GRAVIMETRIC CONTINUOUS	80	82	10,3	2	42	67	93	115				14.9
		70	70,2	16.2	0,2	40	54	78	95	27,7	22 9	18.1	14

FIGURE 13-Reconstitution data of Capanda RCC Cement Content compared with contents of other Applications. Note the proximity of the values measured, compared with the theoretical values when using Gravimetric Batchers.

7.6 - Granulometry Reconstitution of RCC Mix

The RCC mixes used in Capanda Dam, were proportioned with aggregates having specific gravity of about 2,65 t/m3, combined so as to obtain the smaller void index. To achieve this, a reference granulometric curve was initially adopted for aggregates with D_{max}= 76 mm, as follows: **p= $(d/D_{max})^{1/3}$ x 100%**. To minimize segregation, it is common practice to adjust the coarse fraction of this curve, reducing lightly the aggregate content of D_{max}= 76 mm. Alternatively, reduction of the aggregate D_{max} itself is resorted to.

In Capanda it was decided to reduce the D_{max} from 76mm to 64 mm, for RCC produced by the continuous mixing plants (pug mill).For RCC produced in conventional concrete plants (batch), it was decided to reduce content of the aggregate D_{max}= 76 mm (Coarse 3), not interfering with the specifications of aggregates for mixing conventional concretes of other structures for the Development.

Figure 14 shows granulometric range specified for the RCC, together with the ranges effectively obtained and their dispersions, in batch andcontinuous mixing plants. The granulometric range specified was determined by the equation mentioned before, with small adjustments for fractions less than 0,3 mm.

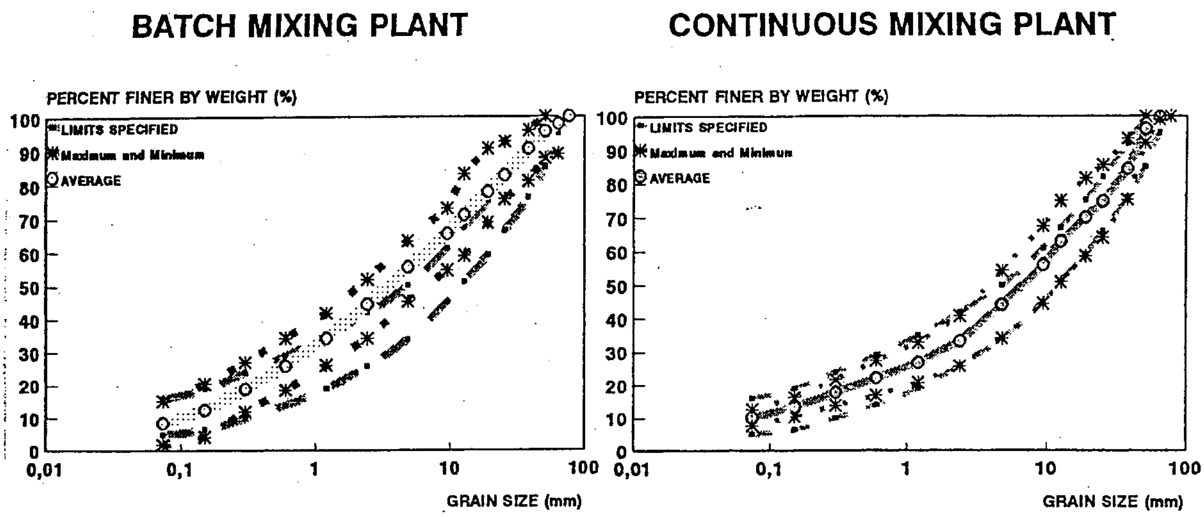

FIGURE 14- Granulometric Curves for RCC Mixes from reconstitution tests. Note the proximity of average values compared with theoretical value used.

7.7 - Molding and Tests of RCC cylindrical test specimens

After each work shift of 12 hours or approximately at every 1000 m3, a series of cylindrical test specimens ⌀25x50 were molded with full mass RCC mix. Compacting of test specimens was made with manual pneumatic compactor, with ramming of 4 layers in 25 seconds each. After compacting and levelling of test specimens, specific gravity of fresh RCC mix was determined at the field laboratory. Because the metallic molds are dismountable and are roughly finished, perhaps this determination is somewhat lacking in accuracy in view of small volume variations after assembly and disassembly. 24 hours after molding, test specimens were removed from the molds and sent to the main laboratory for simple axial compressive strength tests at various ages. For the RCC to be used in Capanda, minimum compressive strength specified was (fck) of 80 kgf/cm2, at age of 180 days, with a deficient quantil of 20% (reduced normal variable "t"= 0,84). For supplementary assurance, initial compression evaluation were concentrated at the age of 90 days. Statistical data obtained are shown in Figure 12.

Figure 15 shows coefficients of variation obtained in the control of RCC for Capanda, compared with the same parameters for other projects, as well as with same control parameters for conventional concretes (CVC) with cementitious consumption (cement + pozzolanic material) between 84 kg/m3 and 134 kg/m3, used in projects for Ilha Solteira, Tucurui and Itaipu [6 and 10]. Parameters of these conventional concretes refer to an universe of approximately 25.000 samples representing about 8.800.000 m3.

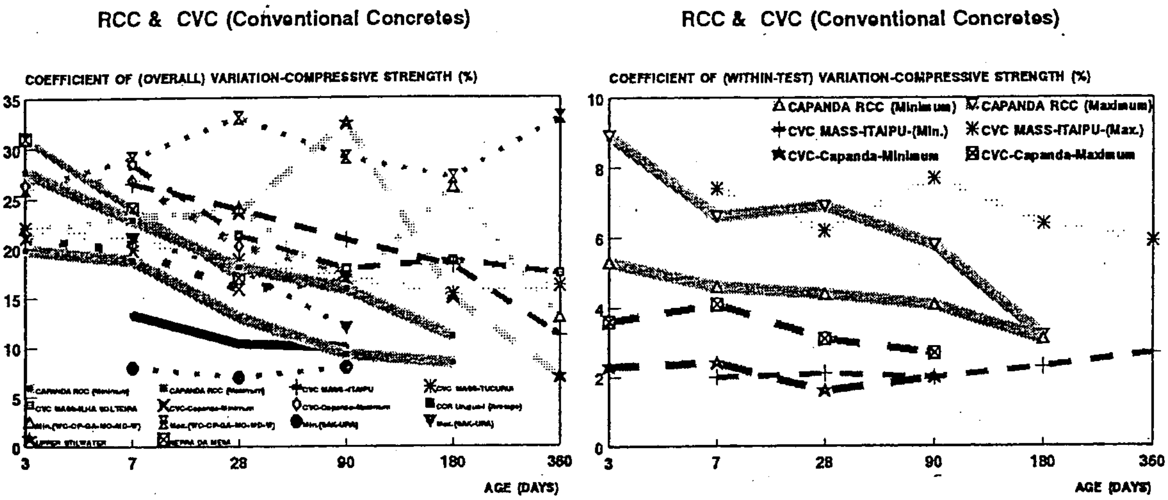

FIGURE 15-Data on Coefficients of Variation obtained in RCC control in Capanda, compared with values of Coefficients of Variation for compressive strength of Conventional Concretes and RCC in other Projects..

Figure 15 also shows comparison values for coefficients of variation, for compressive strength for conventional concretes mainly used in Capanda.

Determination of the specific gravity for these test specimens has resulted in the values as shown in table of Figure 12.

Quality performance of Concrete Plants, concretes and operators control may be evaluated from dispersion in the results for compressive strength obtained for the concretes produced by them. In the same way, quality of the strength tests may be evaluated from its own internal dispersion from control. Internal dispersion of the test is evaluated from the difference between the individual values obtained for strength tests in specimens of the same series, broken at the same age.

This analysis may adopt both the criteria of Norm ACI 214-65 - "Recommended Practice for Evaluation of Compression Tests Results of Field Concrete"[8], and of Norm ACI 214-77 - "Recommended Practice for Evaluation of Strength Tests Results of Concrete"[9].

Detailed studies [10] in statistic control of concrete quality have demonstrated that the coefficient of variation (Vn) is a little representative parameter for concretes with medium strength of up to 210 kg/cm2. Therefore, dispersion measure by coefficients of variation as recommended by ACI 214-65 is more appropriate for concretes with low cementitious consumption mixes. These same studies have revealed also that standard deviation remains practically constant for concretes with strengths higher than 210 kg/cm2. In this case, dispersion measure from Standard Deviation, as recommended by ACI 214-77, becomes more appropriate for structural type concretes or for concretes with high cementitious consumption. For dispersion measure within the test, (i.e., variety of molding process, handling, cure, coating and application of compression load to test specimens) the Coefficient of

Variation is recommended by both Norms. Figure 16 shows the various control standards and application criteria.

STANDARDS OF CONCRETE CONTROLS - (ACI 214 - BEFORE MAY/ 76)						
CLASS OF OPERATION		COEFFICIENT OF VARIATION (%)				
		EXCELLENT	GOOD	FAIR	POOR	
OVERALL VARIATION	GENERAL CONSTRUCTION TESTING	< 10	10 to 15	15 to 20	>20	
	LABORATORY TRIAL BATCHES	<5	5 to 7	7 to 10	>10	
WITHIN-TEST VARIATION	FIELD CONTROL TESTING	< 4	4 to 5	5 to 6	> 6	
	LABORATORY TRIAL BATCHES	< 3	3 to 4	4 to 5	> 5	
STANDARDS OF CONCRETE CONTROLS - (ACI 214 - AFTER MAY/ 76)						
CLASS OF OPERATION		STANDARD DEVIATION (Kgf/cm2)				
		EXCELLENT	VERY GOOD	GOOD	FAIR	POOR
OVERALL VARIATION	GENERAL CONSTRUCTION TESTING	< 28,1	28,1 to 35,2	35,2 to 32,2	42.2 to 49,2	> 49,2
	LABORATORY TRIAL BATCHES	< 14,1	14 1 to 17 6	17 6 to 21,1	21 1 to 24,6	> 24 6
WITHIN-TEST VARIATION	FIELD CONTROL TESTING	< 3	3 to 4	4 to 5	5 to 6	> 6
	LABORATORY TRIAL BATCHES	< 2	2 to 3	3 to 4	4 to 5	> 5

TABELA 16: Standards of concrete production controls and tests [8 and 9]

8- QUALITY CONTROL FOR PLACEMENT OF ROLLER COMPACTED CONCRETE

RCC methodology has established the convenience of adopting additional controls on site during placement and compacting phases.

8.1 - Construction Joints Treatment

Prior to placement of CCR over foundation all semi-loose rock debris were removed and foundations were washed out with water. In the deeper elevations of the old river bed, placement of dental concrete was required at various cavities. As a general rule, conventional concrete was applied to all contact foundation rock surfaces prior to RCC placement. Requisites for treatment of horizontal joints between RCC layers refer to superficial cleaning and application of bedding mix in order to comply with minimum bonding conditions between layers.

Cleaning was made using compressed air, an activity better performed with the surface reasonably dry. Immediately after cleaning, cure process recommenced, executed with water sprinkling and compressed air. The concrete surface was treated with removal of cement slurry. This activity was started after partial hardening of the concrete.

As mentioned already, application of Bedding Mix was mandatory in a section equivalent to 0,25 of the dam breadth in the layer to be executed. Downstream from this section, bedding mix was applied whenever the time of bedding the CCR layers exceeds 8 hours. Interconnection of the various segments of the PVC membrane to the upstream facing constitute a particular type of joint treatment. Membrane were incorporated to pre-cast plates, with dimensions 2,0m x 4,0m.

Joining of these was made on site at the dam, by bonding a strip also made of PVC, using a bonder specially designed for this purpose. In some cases, the classic vulcanization process with hot air jet was used. Before bonding, all surfaces were cleaned with steel brushes and solvents. Checking the quality of bonding was done during execution of the works or later, by means of a sharp point tool.

8.2 - Concrete Placement

Prior to placement of a layer, horizontal reference strips were painted indicating the layer height on the various elements which define its contour. In extensive layers, auxiliary landmarks were placed near the spreading area border. Facing mix was placed directly from the concrete mixers which moved parallel to the upstream facing. This concrete was previously compacted to a height of 40 cm, supplying the bulldozer tractor operator with the required level reference for spreading RCC at this same height. To ensure the required binding of facing mixing and RCC, the first was proportioned with setting retarder admixture at a ratio variable according to climatic conditions, extension and particular placement conditions. Bedding mix was also placed directly from the concrete mixers which moved at low speed while a labor-hand maneuvered the discharge nozzle attempting to cover the largest area possible. Bedding was completed with wood or metallic rakes, up to a final thickness of 2 to 3 cm.

Transportation of RCC from the mixing plants to placement front was made by 3-axle Rear Dump trucks with 10m3 capacity. A belt conveyor was also used from the mixing plants to the transfer hopper which fed two near vertical pipes anchored to the rock slope which unloaded RCC to the trucks which were 45m below, at the placement front. RCC placement was done in layers of approximately 45 cm of loose thickness which turned to 40 cm after compacting.

On warmer and windy days it was necessary to sprinkle water “fog” even before compacting, to compensate for surface drying due to evaporation. Placement of all concretes was done with the surface as near as possible of “saturated dry surface” condition.

8.3 - Compacting Control of RCC layers

For RCC compacting, basically two types of rollers were employed: Double Drum Roller with two 10t static weight drums and Drum Roller with one 10t static weight drum and 31 t dynamic impact, under 1770vpm frequency.

Figure 17 illustrates typical behavior of Capanda RCC compaction (in terms of compaction ratio) in function of the number of passes of a double drum roller. In addition to the rollers mentioned, a static 9t pneumatic roller sometimes was also used for superficial sealing of the layer in order to reduce the work and prevent excessive removal of material during construction joint cleaning

Finally, an evaluation of performance of the tamping drum roller was also made to check density behavior in the middle and base of each layer. Values for compaction ratio in these evaluations are shown in Figure 17.

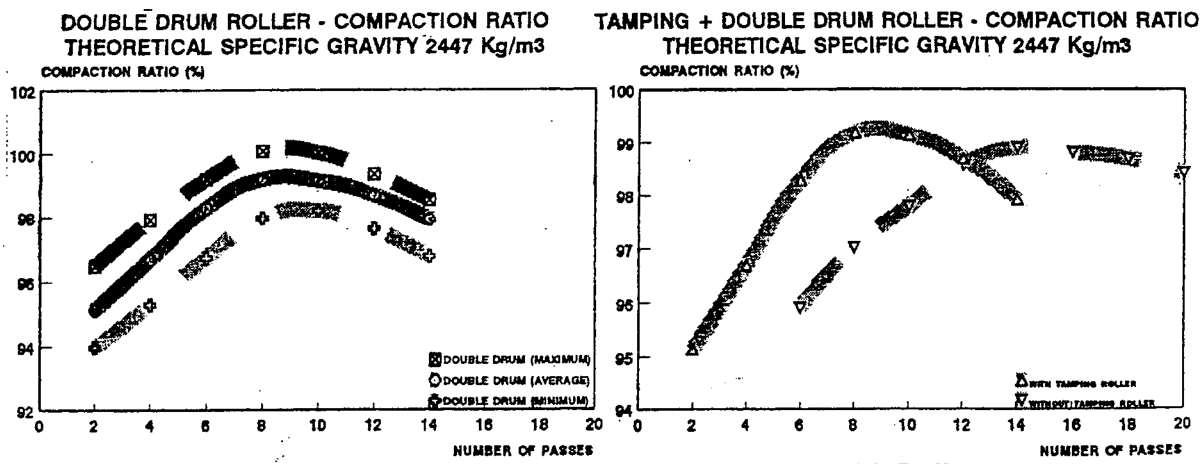

FIGURE 17 - Compaction Ratio with different number of passes with Rollers.

RCC density of compacted layers may be determined using various procedures. It is however advisable that the procedure used enables not only determination of the compaction value but possibly a supplementary or corrective action of the compacting operation based on the results obtained. Therefore, process swiftness and safety are fundamentally important. For the Capanda project, compacting control was made using nuclear densimeter. Three methods however have been evaluated and studied and these are described in the following sub-items:

8.3.1 - Method using a Nuclear Densimeter

This is the most popular process used for the compaction control of RCC layers. It provides a gamma ray source of known intensity in the interior of the compacted layer. Measuring the emerging radiation volume at the surface, density is inversely proportional to that volume. Commercial equipment available in the market, the "densimeters", are factory gauged to measure materials with ranging densities between 1600 and 3000 kg/m³ and special gauging is seldom required. Such devices also determine the moisture content, based on the measurement of hydrogen ions of the material. Special gauging may be required for humidity, depending on the chemical composition of the materials. The layer to be tested will have a vertical hole made by means of a hardened steel pointing chisel. A metal template helps to maintain the chisel vertical during the spiking. Three measurements are taken for every test. The device is turned around the stem containing the radioactive source. This is the procedure to obtain a representative average value for a cone with 50 cm diameter, approximately. The practice observed in Capanda provides the following information:

- Test duration: 10 to 12 minutes, approximately, which makes it a quick and efficient test.
- Inconsistent Results: in some cases, the test hole is not vertical and this causes the loss of results. This aspect is related to the hardness and dimension of the coarse aggregate used in RCC.
- Systematic Errors: affected by the material roughness being tested. Such roughness refers to cavities outside the material under tests and within the Gamma Rays path. They may occur between the base of the device and the layer's surface, and also between the device stem and the wall of the test hole. Taking into consideration that the cavities are fulfilled with air, the roughness

tend to minimize the result of the material being tested. Normally, for every millimeter of cavities' thickness corresponds a negative deviation of about 10 kg/m^3 in the density value.

- This hypothesis may be reinforced by the analysis of the results presented in Figure 18 which were obtained through measurements in various depths for 40 tests samples.
- It is observed that the average density value measured in the first 10 cm of the layer was 2419 kg/m^3. Nevertheless, as per tests carried out with RCC samples, and representing this same layer region, it was found the average value of 2446 kg/m^3.
- It is still observed that the variation of the measurement factor decreases according to the depth. This leads to the conclusion that there is a greater variance for tests carried out near the regions of greater roughness.

Alternatively, when maintaining the nuclear densimeters, it was normal to use the "water volume method". Density tests results obtained are also summarized in Figure 18. To meet the understanding requirement of the compacted RCC behavior, some densities were additionally determined for the RCC "seam" regions that meets the conventional concrete of the Dam waterproofing face, hereto named "interface".

COMPARISON OF SPECIFIC GRAVITY AT VARIOUS DEPTH				
DEPTH (cm) OF LAYER	*NUMBER OF SAMPLES*	*SPECIFIC GRAVITY AVERAGE (Kg/m3)*	*COEFFICIENT OF VARIATION (%)*	*COMPACTION RATIO RELATED NOMINAL RCC*
0 to 10	40	2419	0,8	98,86%
0 to 20	40	2421	0,4	98,94%
0 to 30	40	2413	0,3	98,61%
COMPACTION CONTROL OF EACH LAYER				
TOTAL RCC VOLUME (m3)	*NUMBER OF SAMPLES*	*SPECIFIC GRAVITY AVERAGE (Kg/m3)*	*COEFFICIENT OF VARIATION (%)*	*COMPACTION RATIO RELATED NOMINAL RCC*
650.622	5240	2412	0,5	98,57%
CONTROL OF THE FRESH MIXES OF RCC				
TOTAL RCC VOLUME (m3)	*NUMBER OF SAMPLES MOULDED*	*SPECIFIC GRAVITY AVERAGE (Kg/m3)*	*COEFFICIENT OF VARIATION (%)*	*COMPACTION RATIO RELATED NOMINAL RCC*
650.622	395	from 2415 to 2462	from 0,1 to 1,1	from 98,69 % to 100,6%
CONTROL OF COMPACTION AT THE INTERFACE OF FACING MIX AND RCC				
NOMINAL VALUE FOR FACING MIX	*NUMBER OF SAMPLES*	*SPECIFIC GRAVITY AVERAGE (Kg/m3)*	*COEFFICIENT OF VARIATION (%)*	*COMPACTION RATIO RELATED NOMINAL RCC*
2303 Kg/m3	92	2364	3,7	96,61%
COMPARISON OF SPECIFIC GRAVITY FROM VARIOUS METHOD OF TEST				
METHOD OF TEST	*NUMBER OF SAMPLES*	*SPECIFIC GRAVITY AVERAGE (Kg/m3)*	*COEFFICIENT OF VARIATION (%)*	*COMPACTION RATIO RELATED NOMINAL RCC*
VOLUME OF WATER	16	2470	2,3	100,94%
NUCLEAR DENSIMETER	16	2413	0,3	98,61%
VOLUME OF SAND	45	2408	0,3	98,41%
NUCLEAR DENSIMETER	45	2410	0,2	98,49%
COMPARISON OF SPECIFIC GRAVITY FROM CORES HORIZONTAL AND VERTICAL DIRECTIONS				
DIRECTION OF CORING	*NUMBER OF SAMPLES*	*SPECIFIC GRAVITY AVERAGE (Kg/m3)*	*COEFFICIENT OF VARIATION (%)*	*COMPACTION RATIO RELATED NOMINAL RCC*
VERTICAL	103	2418	0,9	98,81%
HORIZONTAL AT TOP	21	2446	0,7	99,96%
HORIZONTAL AT BASE	19	2355	0,7	96,24%

FIGURE 18: Tests and statistical data about Density - MISCELLANEOUS PROCEDURES.

8.3.2 - Water Volume Method

This process was adopted at the beginning of the works, parallel to the use of the nuclear densimeter. It comprises basically the execution of a manual cavity in the material being tested and afterward the hole volume is measured, deducting the weight of the material. The cavity was coated with a plastic film and then filled with water provided in a gauged container. Cavities were executed for a diameter of 30 cm and vertical walls from the base to the layer being tested. Such test provided a volume of 25 liters, and 60 kg of RCC, approximately. The practice resulting from this test in Capanda make possible the following comments:

- Test duration: 50 to 60 minutes; this is considered to be a hard and slow test in terms of RCC technology;
- Inconsistent Results: due to the angular aggregate;
- Systematic Errors: due to the aggregate's dimensions and hardness, the irregularities of the hole walls make difficult the conformation of the plastic film, tending to minimize the measured volume. Consequently, densities result bigger than what they really are.

8.3.3 - Sand Volume Method

This method presents the same basic concept of the Water Volume Method: the only change is the measurement process of the cavity volume which, in this case, is performed with a standardized and calibrated sand. Standardized sand shall mean a monograin sand with a known and countable density. Cavity dimensions and those from the sample were the same of the previous process. The practice resulting from this test in Capanda make possible the following comments:

- Test duration: 70 to 80 minutes; this is considered to be a hard and slow test in terms of RCC technology;
- Inconsistent Results and Systematic Errors: the effect of the cavity walls' irregularities is less identifiable in this test because there is no coating. If negative slopes are avoided for walls and if the test area is isolated from vibrating equipment, the precision of this method is considered satisfactory.

8.3.4 - Direct method on samples extracted from the Dam

This method allows to determine the density directly from the sample, using the ARCHIMEDES postulate. This method allows to check and confirm control data because it can be only carried out after the sample extraction.

8.4 - Correlation between the various Densimeter processes

The compaction control of the RCC layers is basically executed by means of a nuclear densimeter, currently accepted as the most quick and efficient method to control big masses of this material. However, the densimeter available at the site had a stem with no more than 30 cm. Taking into consideration that the RCC layers are poured from a height of 40 cm, the density of the last 10 cm are disregarded. So it was necessary a criteria for the evaluation of the average density in the entire layer depth (up to 40 cm), based on the results obtained for the maximum depth available of 30 cm. To synthesize, the initial tendency of the nuclear results of presenting positive deviations because they do not cover the layer bottom is it really offset by the general tendency for negative deviations caused by the surface irregularities (cavities) found in the Gamma Ray path. When determining the density in laboratory from the extracted samples, the RCC samples' weight was determined by precision scales and the volume determined by the water dipping process (Archimedes). Since this is a typical laboratory process, time, risk and precision factors are irrelevant.

The reduced number of available samples may be mentioned as an impediment to becoming a routine, due to the limits and difficulties inherent to the cost of samples' extraction. Figure 18 shows the tests with samples horizontally extracted, containing the construction joint in its intermediate plan. Such samples presented in their lower part the top of a given layer, and in their upper part, the base of the next layer. Due to the internal dimensions of the extracting ring (200 mm), each half represents an average of 100 mm from top and base of two consecutive layers. All of the tested samples were extracted from layers joints without "bedding-mix" treatment. Theoretically, he layers' base treated with "bedding-mix" have a tendency to present higher density values due to the sealing of the RCC cavities, because of the rising of the fluid mortar from the "bedding-mix". The average value of 2.406 g/cm³ was found for the vertical samples, as per Figure 18, it is verified that the average density of the RCC layers corresponding to the first construction phase of the dam meet the minimum value specified. At the interface region, the conventional concrete application and the RCC, the density obtained showed the ratio of 2364 kg/m³ (interface) to 2412 kg/m³ (for the layers' control).

8.5 - Compressive Resistance from the Extracted Samples

One of the final stages of the planned quality control for Capanda was to obtain the RCC resistance from the tests executed on the samples extracted from the dam and the embankment itself. Based on the arrangement existing at the time of samples' extracting, the concrete typology and the control age, it was impossible to standardize the samples' rupture ages due to their extraction chronology. Values obtained for samples aging between 128 and 223 days are shown in Figure 12.

9 - COMMENTS

Data and information collected and presented in this text make possible to affirm that:

- The available equipment ensured the production of RCC concretes of low cement content (60 to 70 kg/m³ approximately) with the same dispersions observed for conventional mass concretes of works controlled according to the standards internationally used.
- The precision obtained allow to observe the strength homothetic values as regards the low cementitious content adopted and measured;
- The grading uniformity obtained through the recovery test is similar to the theoretical parameters

and it points out the batchers condition and the quality control established;

- The various methods available attest the proximity of the density values as regards the nominal value and also the small dispersions;
- Values demonstrated by the samples attest the compliance with the design parameters;
- Deviation observed through the Variation Factors are reduced according to the controlling age;
- The small deviation (variation factor in the samples' universe) of the RCC strength to the Controlling age (180 days) between 8.4% and 11.1% allow to classify the control system operation between GOOD and EXCELLENT grades, according to the American Concrete Institute Standards;
- The small deviation (variation factor within the test figures) of the RCC strength to the Controlling age (around 4%) allow to classify the control system operation as EXCELLENT, according to the American Concrete Institute Standards;
- The reliability obtained in the control to meet the specifications and design required values, and also the small dispersions found demonstrate that the Quality Control provided by the Contractor matched the planned objectives.

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