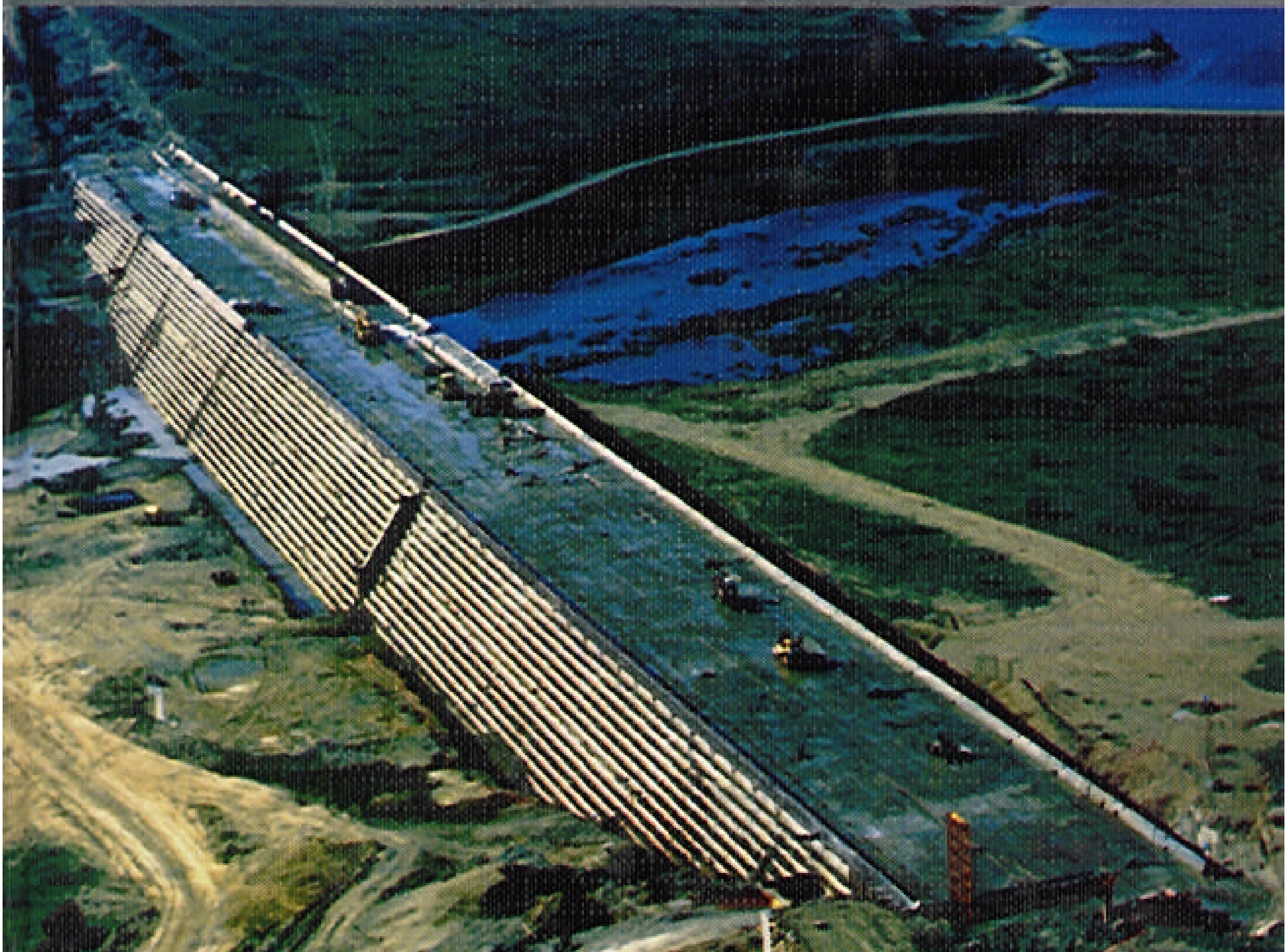
ROLLER COMPACTED CONCRETE DAMS

Proceedings of the International Symposium held in Santander, Spain, on 2 - 4 October 1995

RCC PROPERTIES



IECA Spanish Institute of Cement and its Applications (IECA)

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RCC PROPERTIES

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ABSTRACT

This report contains laboratory test data, test fill data and the results obtained through quality control during the construction of Dam projects .Data on the following are included: Compressive Strength, Direct and Indirect Tensile Strength, Shear Strength - Cohesion and Friction, Triaxial Compressive Strength, Modulus of Elasticity, Strain Capacity, Permeability, Thermal Expansion Coefficient, Diffusivity, Conductivity and Adiabatic Temperature Rise. Shear Strength test data on test fills carried out "on site" are presented for the characterization of the treatment of construction joints are presented.

1- INTRODUCTION

Roller Compacted Concrete - RCC- dams structures, since the completion of Shimajigawa Dam in Japan in 1980, have gained wide acceptance world-wide. Since 1973 [1] a lot of test results, from laboratories and test-fill studies were published. Beside this some doubts and questions remains.
Questions like :

- Are there RCC Dams higher than 100m ?
- Which is the maximum high that could be reached by a RCC Dam?
- How does RCC compare with CVC as a material suitable for building high and large gravity or arch-gravity dams with same durability and quality as existing dams wich have performed well for several decades?
- How need be the construction joint treatment ?
- And so on !;

in a general point of view comes from the inexperience of some technicians in the coorelation and comparison of the RCC data with those on of Conventional Concrete (CVC- concrete) , or in terms of dams, with the Conventional Mass Concrete.

It means that, beside the available data, there are no familiarity with the RCC Properties. Based in those doubts, this paper intends to discuss the RCC properties and quality in comparison with CVC properties , considering the same kind of materials used for proportioning-mix studies.

2- PROPERTIES

RCC is a **concrete**, and so, the significant materials properies of hardened RCC can include specific gravity, compressive strength, tensile strength, shear strength (monolitic and joint construction), modulus of elasticity, creep, tensile strain capacity, adiabatic temperature rise, thermal coefficient of expansion, specific heat, thermal diffusivity, thermal conductivity, and permeability, as described in sequence.

2.1- Specific Gravity - Density

The specific gravity of RCC is either the same or somewhat (2% to 4%) greater than that of CVC with the same materials. The aggregate volume in a concrete mix is about 80%, so the concrete specific gravity depends mostly of the aggregate specific gravity. The main reason for higher RCC specific gravity is its lower water content and the compaction ratio. Figure 1 shows some typical RCC and CVC test-values, used at some projects [37, 38, 39, 40, 41, 42, 43, 44, 45, 46].

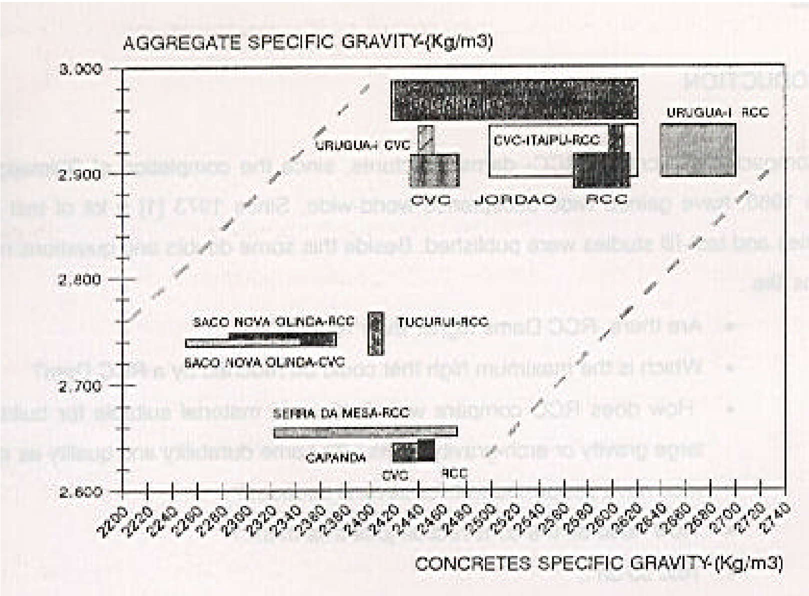

FIGURE 1- SPECIFIC GRAVITY OF CONCRETES RELATED WITH AGGREGATE SPECIFIC GRAVITY

2.2- Compressive Strength

To discuss the compressive strength in a general way is very dificult because it depends of the cementitious content (cement + pozzolanic materials) . A normal way that can be used to compare these parameter is based on " **mix efficiency = h** " that is a factor:

η = [Compressive Strenght (Kgf/cm2)] / [Cementitious materials (cement + pozzolanic materials in Kg/m3)].

"Mix Efficiency " at various ages for 28 RCC and 8 CVC dams or studies [2, 3, 5, 6, 10, 11, 12, 14, 15, 20 a 46] are plotted in Figure 2 where data for Capanda, Itaipu, Upper Stillwater, Urugua-i, Jordão and Salto Caxias could compare RCC and CVC using the same constituents. Generally, “mix efficiency” at lager ages is higher for RCC than comparable CVC, meaning that desired compressive strength of RCC can be obtained using lower cementitious content, particularly Portland Cement, and higher pozolanic material content. These type of mixes can develop more strength due to the best combination of cement and pozzolanic material.

2.3- Tensile Strength (Splitting Test)

Like compressive strength, tensile strength of RCC and CVC , also depends on the cementitious content and age. For CVC , tensile strength is considered to be 10% to 15% of compressive strength. Data from 22 dams or testing programs [6, 10, 11, 14 a 17, 19 a 21, 23, 25, 26, 28, 29, 33, 34, 37 a 46, 48], showing the ration of splitting tensile strength to unconfined compressive strength presented in Figure 3, indicates that the average tensile strength of RCC is also 10% to 15% of its compressive strength.

2.4- Shear Strength

These tests are donne to get the Mohr Envelope, and so the cohesion-C- (shear strength) an friction angle -□. The laboratory tests on monolitic- RCC- specimens could be donne in:

- Triaxial Chamber similar in aspect, but greater in dimensions than that used for soil-mechanics, or rock-mechanics. In this way it is possible to change the confining pressure and determine the axial compressive value, as shown in Figure 4; or
- Direct Biaxial Shear test, is normaly used in rock-mechanics, when it is applied a normal load and measure the shear (with a litle angle of the plane - due the metodology) load (see Figures 5 to 7); or
- Direct Unconfined Shear test , based in the CRD- C- 90, Corps of Engineers Method of Test , where the shear load is aplied in a single and uncofined plane.

DAM	Cement	Poz. Mat.	TOTAL	Mix	Efficiency	[(Kgf/cm2)/(Kg/m3)]		
	Kg/m3	Kg/m3	Kg/m3	7 days	28 days	90 days	0,5 year	1 year
TAMAGAWA	91	39	130	0,85	1,36	1,52	1,94	2,25
SAKAIGAWA	91	39	130	0,39	0,87	1,54		
MYAGASE	91	39	130			2,54		
URAYAMA	91	39	130	0,61	1,15	1,85		
YUGOSLAVIA	100	60	160		0,88			
URUGUA - I	60		60	0,94	1,24	1,53		
WILLOW CREEK	47	19	66	0,43	0,85	1,25		2,81
WINCHESTER	104		104		1,7		2,06	
MIDDLE FORK	66		66		1,5	2,22		
GALESVILLE	54	52	106					1,45
MONKSVILLE	64		64	0,52	0,73	0,78		1,65
UPPER STILLWATER	80	173	253	0,35	0,58	0,96	1,28	1,42
NORTH LOOP	119	56	175	0,67	0,82	1		
CEDAR FALLS	140	92	232	0,66	0,95			
LOWER CHASE	64	40	104	0,69	0,98			
COPPERFIELD	95	15	110		0,42	0,67		
CRAIGBOURNE	70	60	130		0,66	1,22		
BUCCAWEIR	90	90	180		0,67	1,11		
MISTRAAL	58	58	116		1,81			
ZAAIHOEK	36	84	120		1,67			
OLIVETTES	88	47	135	0,39	0,94	1,14		
RWEDAT	60		60	0,4	0,8	0,88		
ITAIPU	91	26	117	0,41	1,11		1,27	
SACO NOVA OLINDA	75		75		0,65			
TUCURUI	58	34	92		1,11	1,43		
CAPANDA	70		70	0,79	1,15	1,35	1,48	1,62
JORDAO - COPEL	75		75	0,5	0,7	1,1		
RCC - Average				0,57	0,99	1,33	1,81	1,90
ITAIPU				0,4	0,9	1,38	1,58	1,62
ILHA SOLTEIRA				0,82	1,45	1,76	1,83	2,1
TUCURUI				0,75	1,05	1,33	1,38	
MYAGASE						1,76		
URAYAMA				0,65	1,25	1,9		
UPPER STILLWATER				0,55	0,9	1,25	1,42	1,5
URUGUA-I				0,75	1,03	1,27		
CAPANDA				0,62	0,94	1,1		
JORDAO - COPEL				0,5	0,75	0,9		
Conventional -Average				0,63	1,03	1,41	1,56	1,74

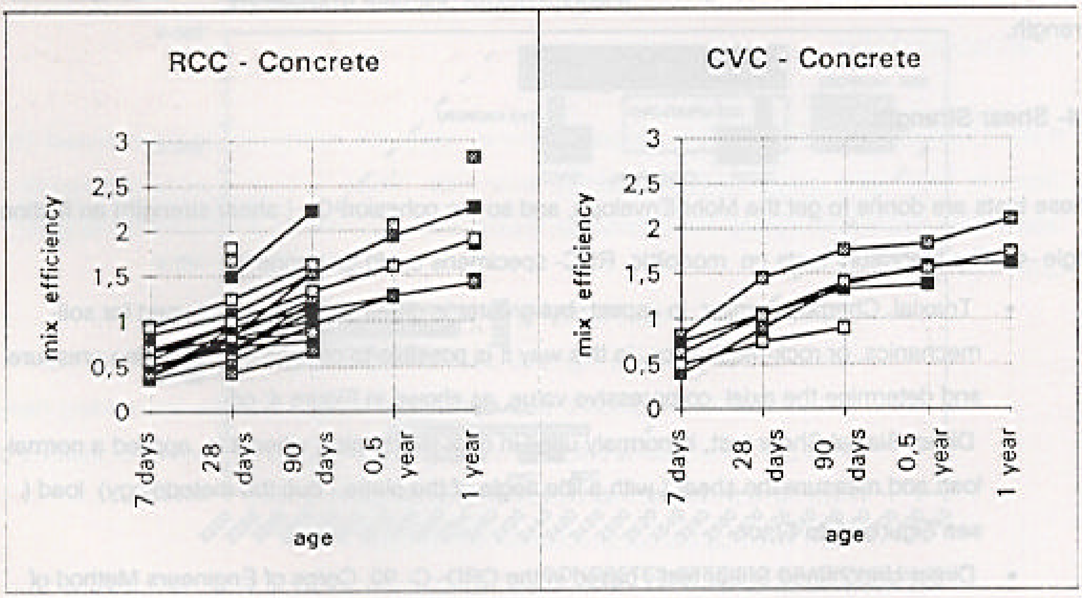

FIGURE 2- "MIX EFFICIENCY" OF RCC IN COMPARISON WITH CVC CONCRETE

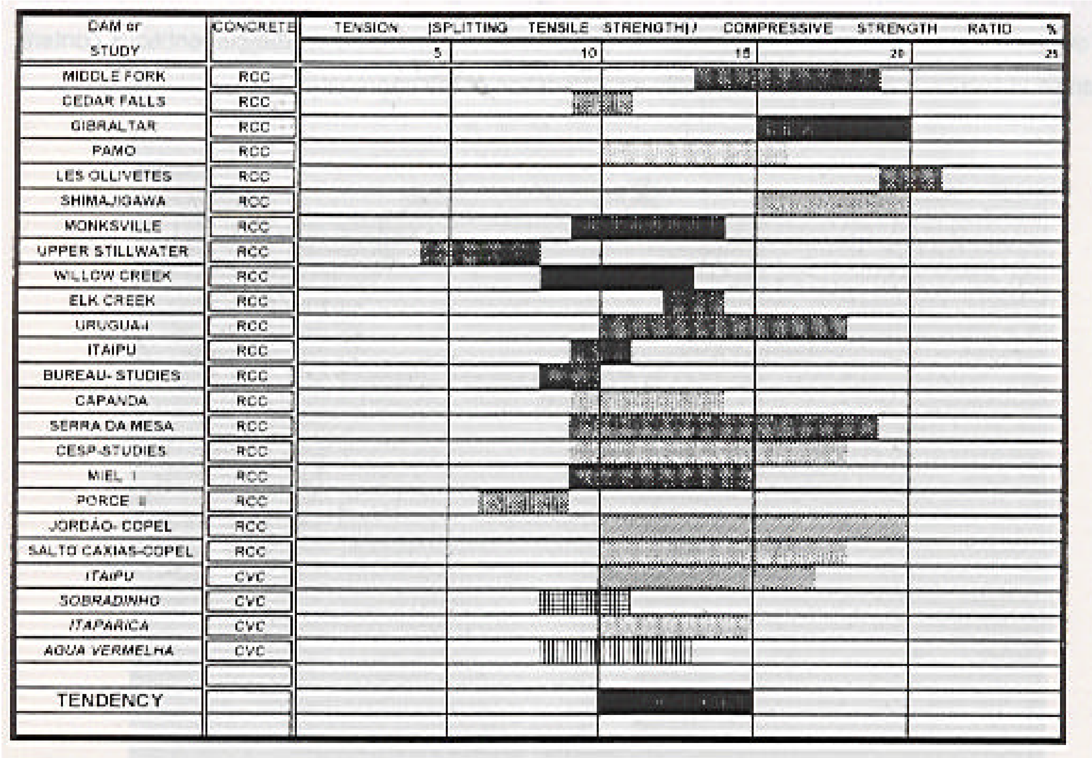

FIGURE 3- SPLITTING TENSILE STRENGTH AS PERCENTAGE OF COMPRESSIVE STRENGTH, OF RCC AND CVC CONCRETES

The specimens from the RCC-Construction Joints, could be tested in:

- Direct Biaxial Shear test - "***in laboratory"-*** as shown in Figures 5 to 7, on specimens drilled core from a trench, or from a large scalle test-fill, or from a large specimen (for instance cast a 45x90cm specimen with a contruction-joint in the central part, and after drilled a core throughout the construction-joint); or
- Direct Biaxial Shear test - ***"in situ"***- in a large scalle test-fill, as donne at Urugua-i and Capanda dams and as shown in Figures 8 to 11.

Typical values of shear strength parameters for some RCC and CVC dams and studies [10, 11, 18, 19, 21, 23, 25 a 27, 38, 42, 44, 46, 47] are shown in Figure 14. Figures 15 shown some values from Figure 14, comparing with shear tests from the rock (meta-sandstone) foundation contact at Capanda dam. It is very important to show this, because it is possible to see that:

- The shear (cohesion and friction) values at construction-joint, (normaly well treated and with "Bedding-mix"), are greater than that one obtained for the rock-foundation contac ;
- The shear values at construction-joint,without "Bedding-mix", are in the same range that one obtained for the rock-foundation contact.

Results of direct, biaxial and triaxial tests performed on cores obtained from test fills and completed dams, and "in situ" tests, indicate that the shear strength components - C- and φ - are comparable to that of CVC made from similar aggregates. While cohesion is dependent on the cementitious content, the angle of friction is affected by the quality and gradation of the aggregates.

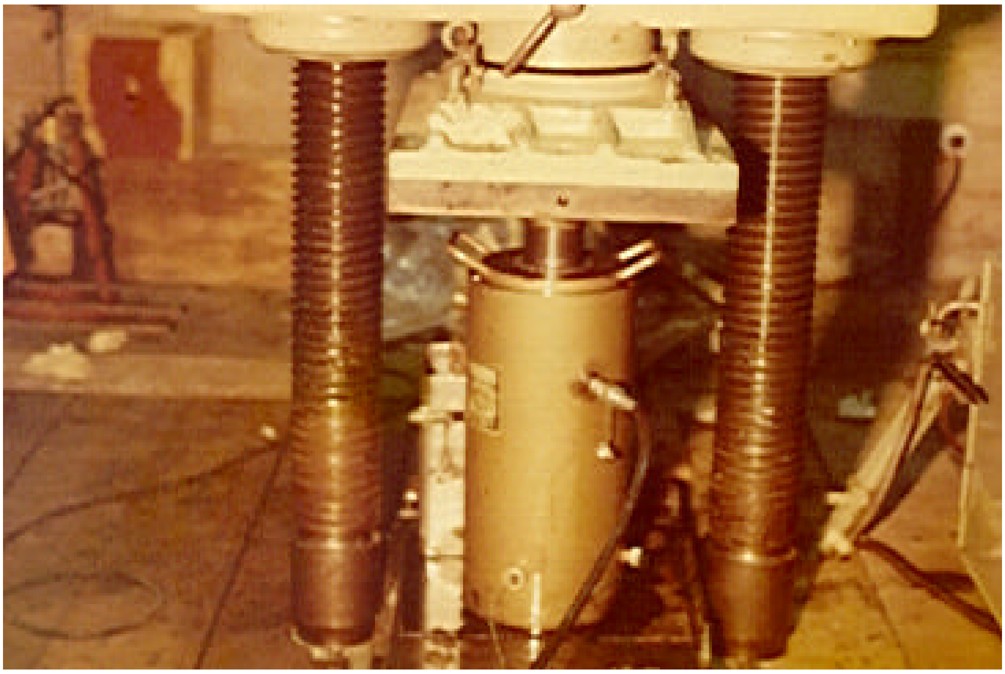

FIGURE 4 - TRIAXIAL CHAMBER USED FOR CONCRETE TESTS AT ILHA SOLTEIRA AND ITAIPU LABORATORIES.

From the shear tests it can be learned that when it is "riched", increasing unnecessarily the cementitious content of the Bedding-mix , the shear values, generally, not increase, because the surface failure will be just near the construcion-joint (closely above or bellow) in the weakest point or surface of RCC, as could be seen in the Figures 12. The values in this case will be around the same as the monolitic-RCC values.

2.5- Modulus of Elasticity

The main factors that can affect the modulus of elasticity of RCC and CVC values are:

- age of tests - The modulus increase with age up to maximum value that correspond to the maximum that could be reached by the mortar or the aggregate (wich is lesser);
- aggregate type (and its modulus) - At large ages the concrete modulus could be symilar that one of the aggregate if was used a rich mortar;
- water cement ratio (or the "paste" proportioning).- As concluded from the above mentioned, rich mix - high values, and poor mix - low values.

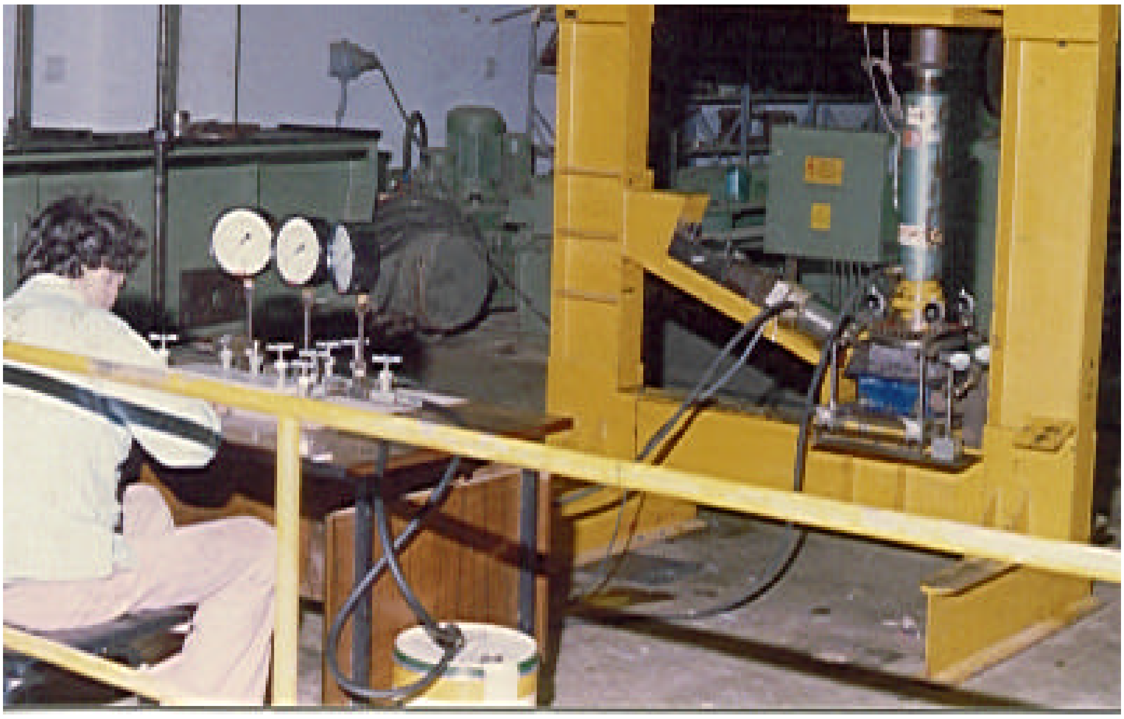

FIGURE 5 - SYSTEM USED FOR BIAXIAL SHEAR TEST, ON ROCKS AND CONCRETE SPECIMENS, AT ITAIPU LABORATORY.

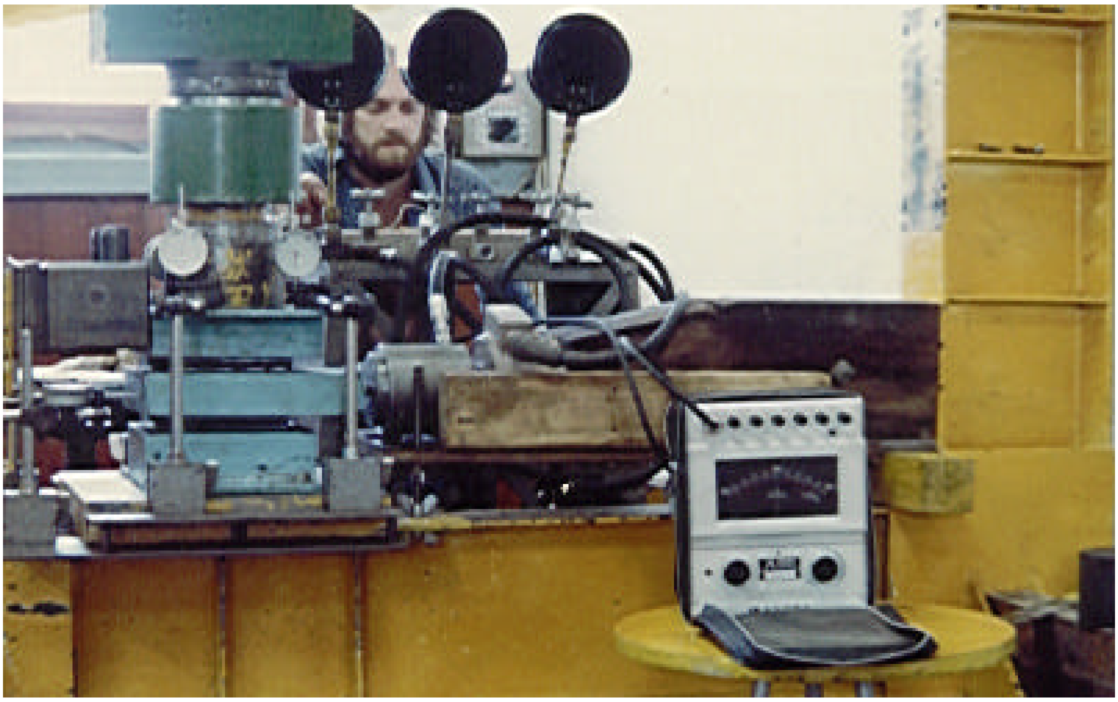

FIGURE 6- A MODIFICATION IN THE APPARATUS SHOWN ON FIGURE 5, CHANGING THE ANGLE OF THE SHEAR LOAD, AT ITAIPU LABORATORY, AS SUGESTED BY BUREAU OF RECLAMATION [18]

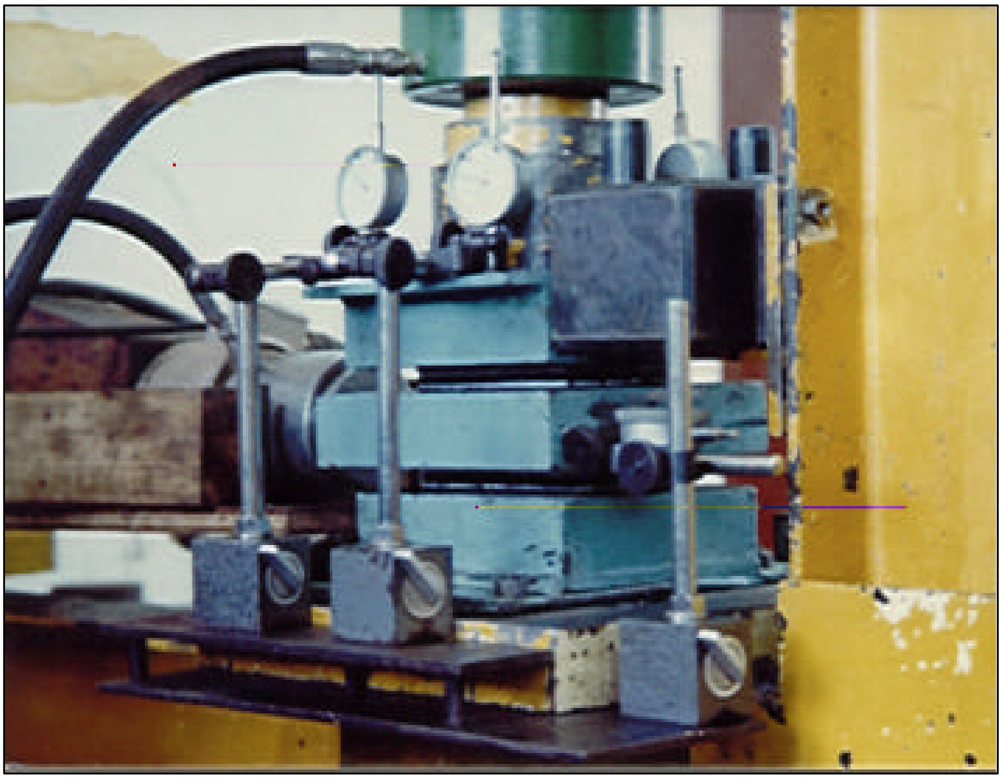

FIGURE 7- DETAIL FROM THE TEST SHOWN ON FIGURE 6.

FIGURE 8- ROCK SURFACE PREPARATION FOR RCC-TEST FILL , AT CAPANDA JOB SITE

FIGURE 9- RCC PLACEMENT AT THE TEST-FILL, AT CAPANDA JOB SITE

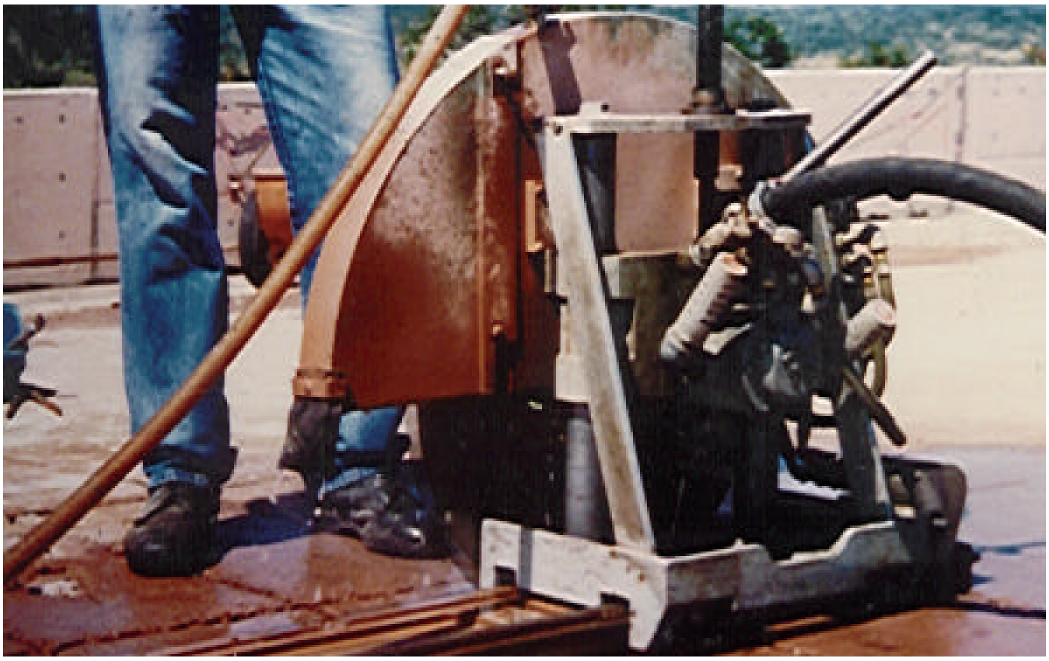

FIGURE 10- RCC BLOCK-SPECIMENS BEING CUTTING BY DIAMOND SAW BLADE, AT CAPANDA JOB SITE

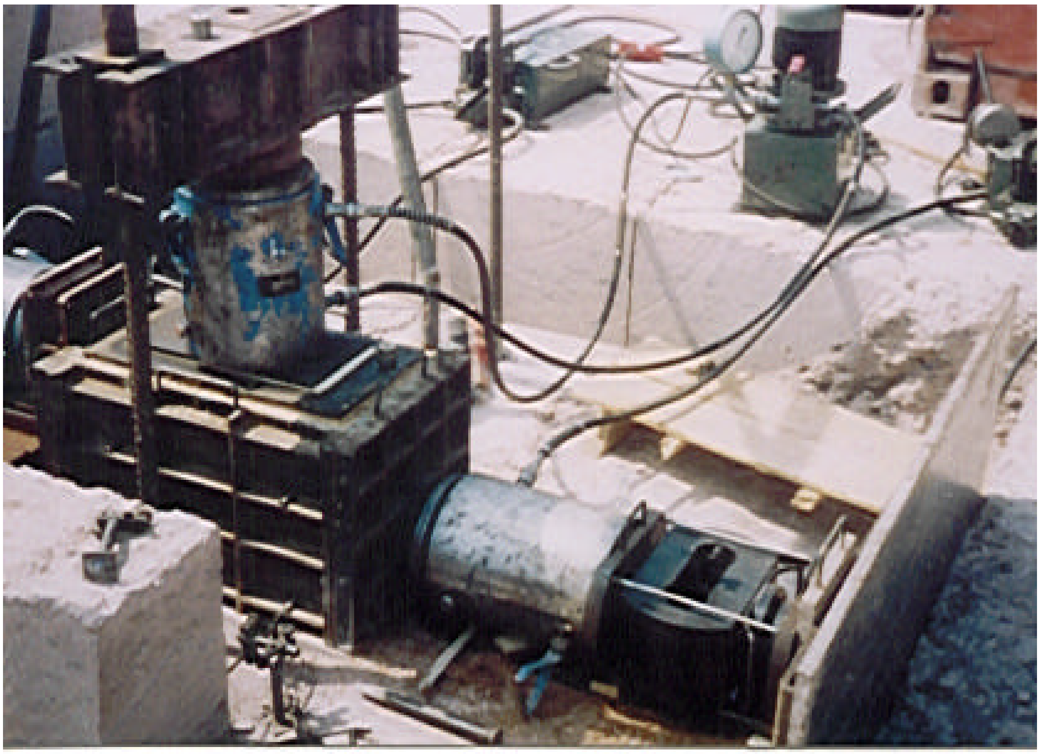

FIGURE 11- BIAXIAL SHEAR -IN SITU- TEST GOING ON, AT CAPANDA TEST FILL

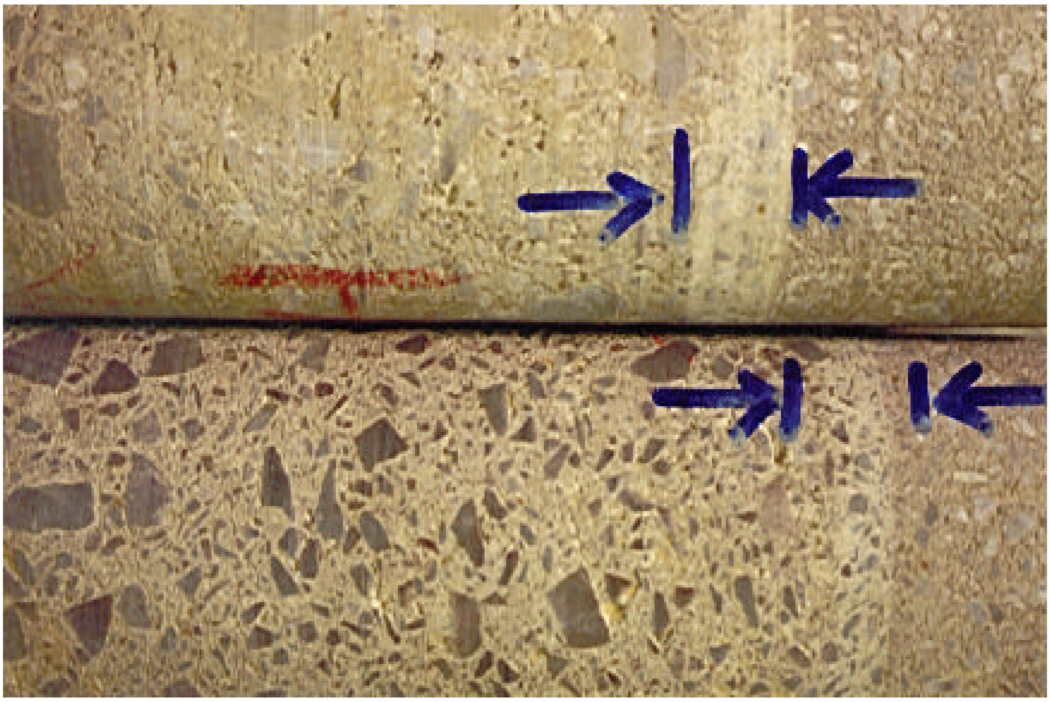

FIGURE 12-CORE DRILED FROM THE RCC TEST FILL, SHOWING THE ACTION OF THE BEDDING MIX PLACED ON THE CONSTRUCTION-JOINT OF CAPANDA DAM

FIGURE 13 - RCC BLOCKS SPECIMENS AFTER TESTED,SHOWING THAT THE BEDDING MIX " WORKS WELL" AND THE SURFACE OF RUPTURE OCURED IMEDIATELY BELLOW THE CONSTRUCTION-JOINT

Figures 16 and 17 ilustrates the increase in modulus of elasticity with age for 5 CVC and 13 RCC dams or test programs [11, 14 a 16, 19 a 26, 28, 29, 33, 34, 37 a 46] . It is seen that the modulus of elasticity of RCC is considerable lower than that of CVC; about **50% at 7 to 28** days and about **65% to 90%** days and later. Tests on core samples obtained from RCC used as backfill at Itaipu Project showed (Figure 11) the same modulus at the age 3090 days as CVC with the same mix materials.

2.6- Creep

The total creep is mainly affected by the aggregate modulus of elasticity and by the filler material that was used in the concrete proportioning mix. The schem adopted for the creep test at CESP (Ilha Solteira- São Paulo- Brazil) and ITAIPU Laboratories could be seen in Figure 18. The main diference when compared with creep tests on CVC, is that the deformations of the RCC-specimens under load were measured on the surface,instead by strain-meters embedded in the specimen body, as normaly used for CVC specimens. This is due from the dificulties that could occur during the compaction of the RCC (by pneumatic hammer) .

DAM	CODE	CONCRETE TYPE	Cement Kg/m3	Poz Mat Kg/m3	TOTAL Kg/m3	JOINT TREATMENT	PEAK RUPTURE COHESION	PEAK RUPTURE FRICTION	APPARENT COHESION	APPARENT FRICTION
TAMAGAWA	1	RCD	91	39	130	MORTAR	30	49		
TAMAGAWA	2	RCD	91	39	130	MONOLITIC	33	52		
UPPER STILLWATER	3	RCC	80	173	253	NO TREATED	34	64	2,5	47
UPPER STILLWATER	4	RCC	80	173	253	MONOLITIC	21	57	2,3	44
COPPERFIELD	5	RCC	95	15	110	GLOBAL VALUES	0,2 - 1,5	46 - 51		
GALESVILLE	6	RCC	54	52	106	WITHOUT BEDDING MIX	7,8	67	5,6	40
GALESVILLE	7	RCC	54	52	106	MONOLITIC	23,3	52	4,9	43
GALESVILLE	8	RCC	54	52	106	NO TREATED	26,6	33	6,7	45
ELK CREEK	9	RCC	70	36	106	NO TREATED	1,1	41		
ELK CREEK	10	RCC	70	36	106	NO CLEAN + MORTAR	6	62		
ELK CREEK	11	RCC	70	36	106	WATER JET + MORTAR	4	56		
ELK CREEK	12	RCC	70	36	106	MONOLITIC	8,5	67		
URUGUA-I	13	RCC	60		60	WITHOUT BEDDING MIX	3,8 - 4,6	54 - 59	3,2 - 3,5	40 - 47
URUGUA-I	14	RCC	60		60	200 C + WITHOUT BEDDING MIX	2,9 - 3,1	40 - 44	3,3 - 3,4	36 - 40
URUGUA-I	15	RCC	60		60	500 C +WITHOUT BEDDING MIX	4,2 - 4,4	33 - 37	3,6 - 3,9	30 - 35
URUGUA-I	16	RCC	60		60	780 C + WITHOUT BEDDING MIX	2,5 - 2,7	39 - 42	3,6 - 3,7	32 - 37
URUGUA-I	17	RCC	60		60	MONOLITIC	24,6	48		
SERRA DA MESA	18	RCC	60	140	200	MONOLITIC	22	58		
CAPANDA	19 - (1)	RCC	100		100	MONOLITIC	31,7	42		
CAPANDA	19 - (2)	RCC	60		60	MONOLITIC	15,7	49		
CAPANDA	19 - (3)	RCC	100		100	MONOLITIC	38,3	46		
CAPANDA	A - (1)	CVC	140		140	MONOLITIC	36,5	42		
CAPANDA	A - (2)	CVC	140		140	MONOLITIC	29,9	43		
CAPANDA	A - (3)	CVC	180		180	MONOLITIC	38,5	41		
ILHA SOLTEIRA	B - (1)	CVC	200 / 350		200/350	MONOLITIC	55 - 70	31 - 44		
ILHA SOLTEIRA	B - (2)	CVC	109		109	NO TREATED	5,5	57		
ITAIPU	C - (1)	CVC	100 / 350		100 / 350	MONOLITIC	22 - 96	40 - 42		

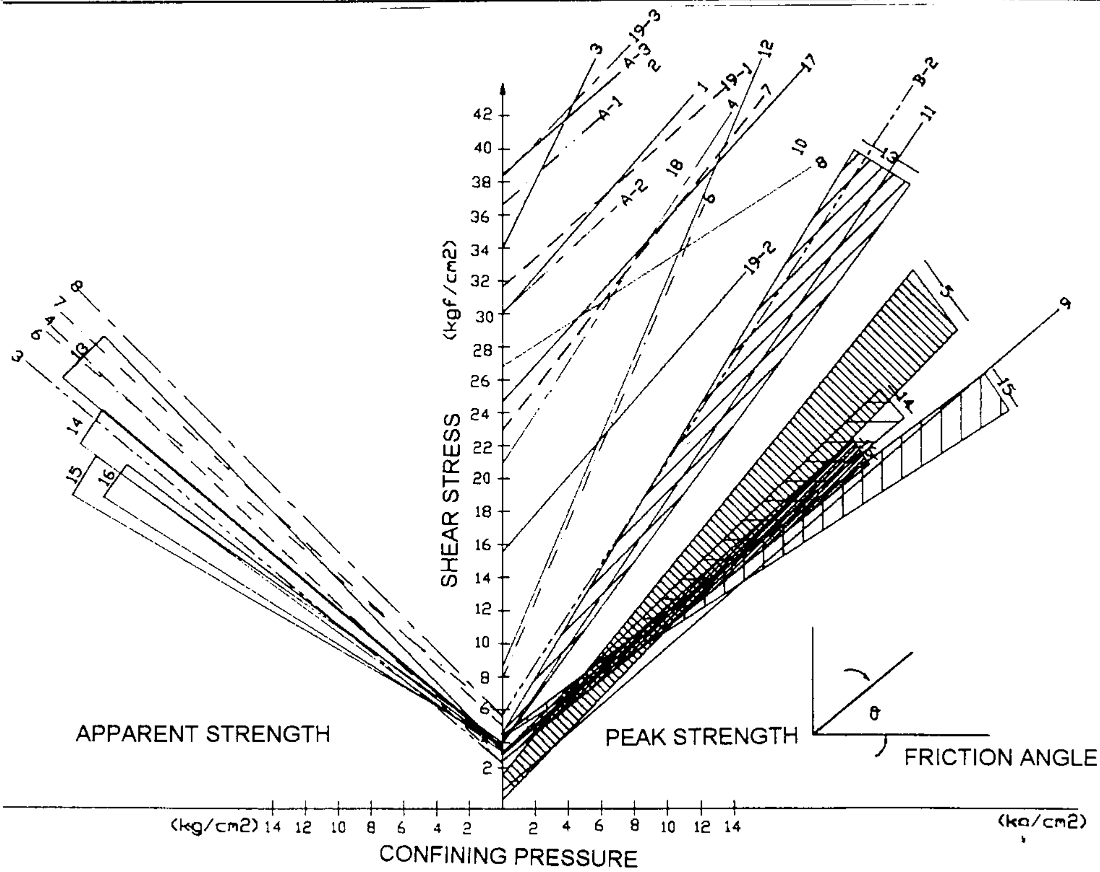

FIGURE 14- SHEAR STRENGTH VALUES OF RCC AND CVC CONCRETES

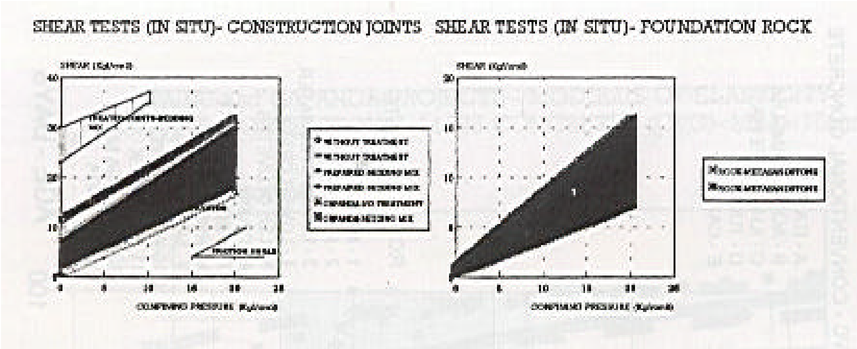

FIGURE 15 - SHEAR STRENGTH VALUES FROM RCC AND CONTACT WITH ROCK FOUNDATION

The Figure 19 shows some [28, 38, 39, 42 a 46] values in comparison with creep values of CVC. It can be note that from the creep equation $\mathbf{E = \{[1/E] + [f_{(k)}] x [\log (t+1)]\}}$**,** normaly used, the ratio 1/E of RCC mixes - at early ages- is grater than that of CVC mixes , due to the higher mortar content of RCC . Due to the larger content of mortar in RCC mixes than that of CVC mixes the coefficient of creep " $f_{(k)}$ " of RCC is larger than that obtained for CVC made of similar aggregates.

2.7- Tensile Strain Capacity

The strain capacity is considered as the ultimate deformation under tension before the rupture.

Test data for tensile strain capacity for RCC for Capanda and Urugua-i dams [38, 42, 43, 44] as compared to that for CVC are ploted in Figure 20. It appears that the strain capacity of the two types of concrete using the same amount of cementitious materials, at various ages, is about the same.

2.8- Adiabatic Temperature Rise

The adiabatic temperature rise due to the heat of hydration , for both types of concretes is obtained by the same way, using a large dimension calorimeter.

The adiabatic temperature rise for both types of concrete is essentialy proportional to the cementitious content of the mix.

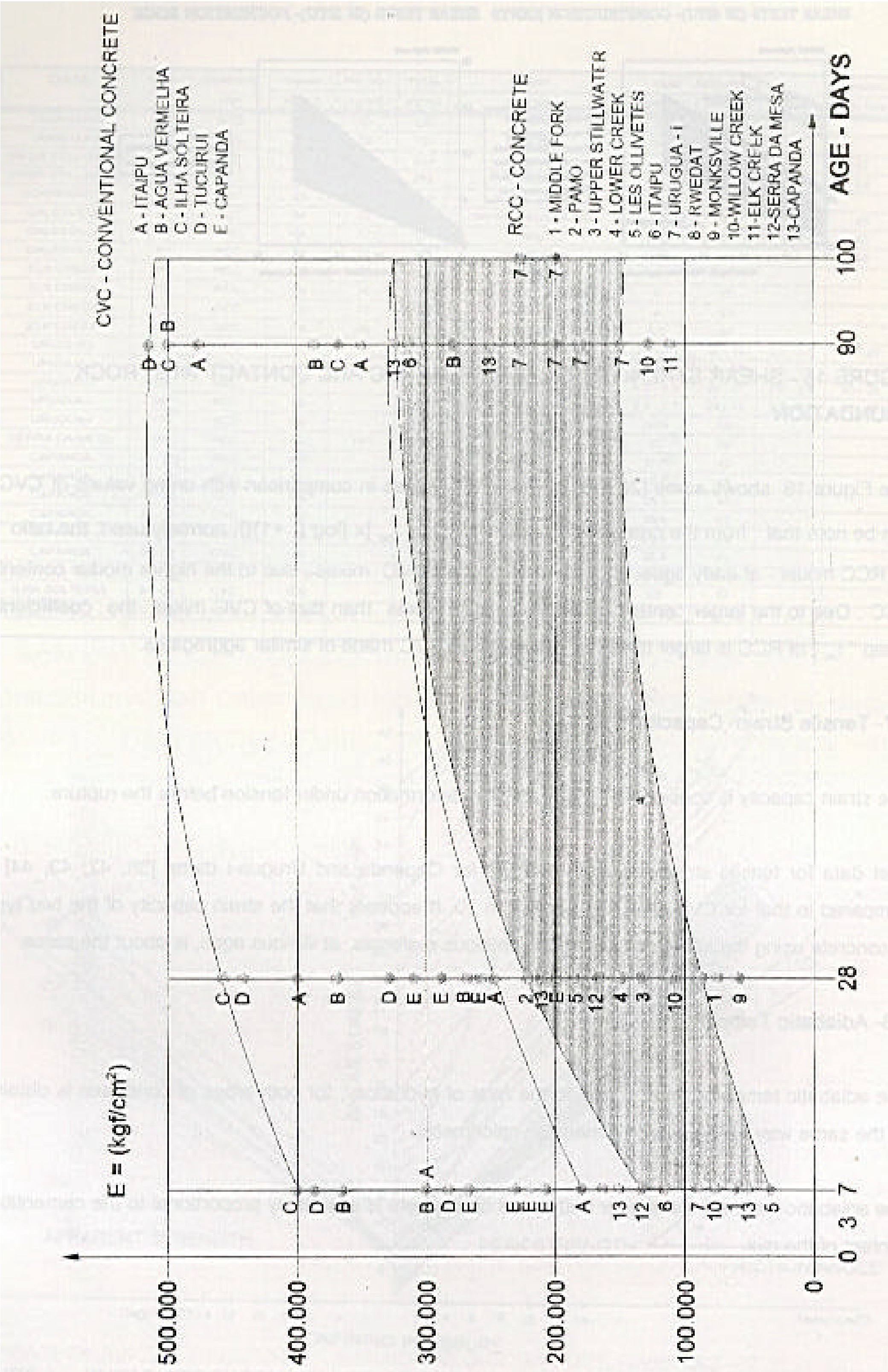

FIGURE 16- MODULUS OF ELASTICITY VALUES FROM RCC AND CVC CONCRETES

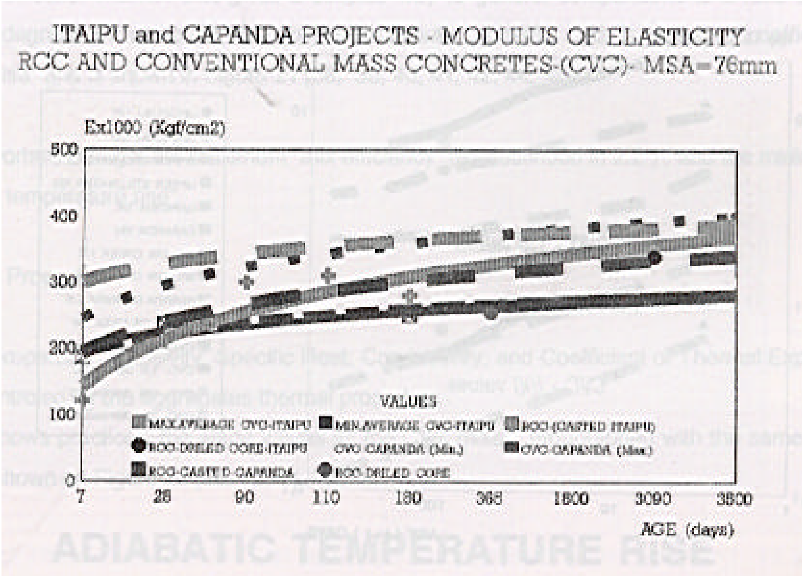

FIGURE 17- RCC AND CVC MODULUS OF ELASTICITY AT VARIOUS AGES OF TEST

FIGURE 18- CAPANDA RCC AND CVC SPECIMENS UNDER CREEP TEST, AT ITAIPU CONCRETE LABORATORY.

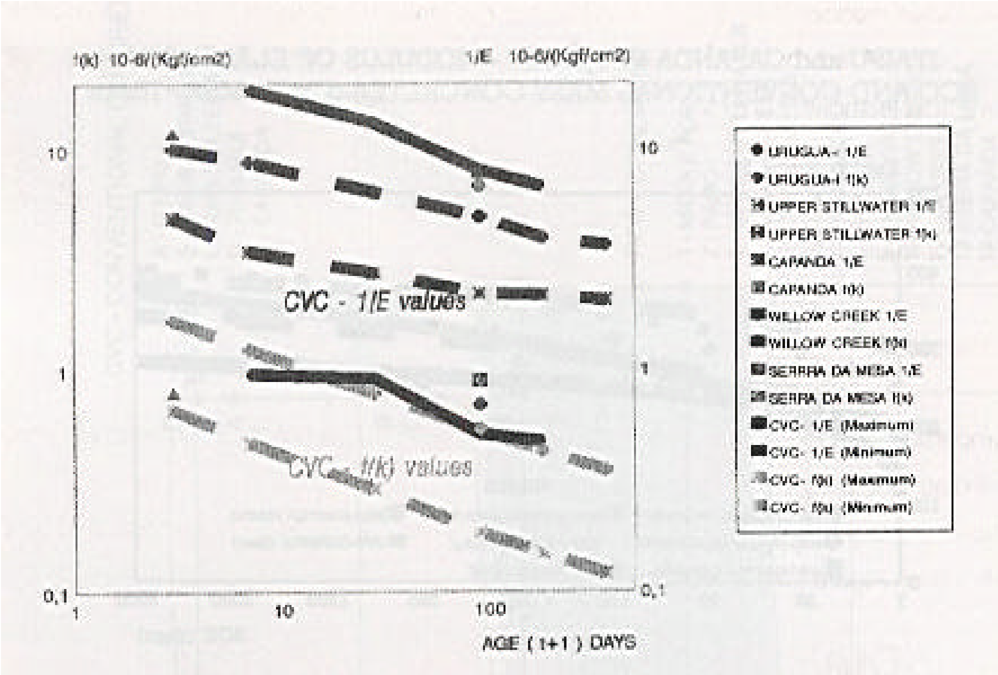

FIGURE 19 - CREEP VALUES FROM RCC AND CVC CONCRETES

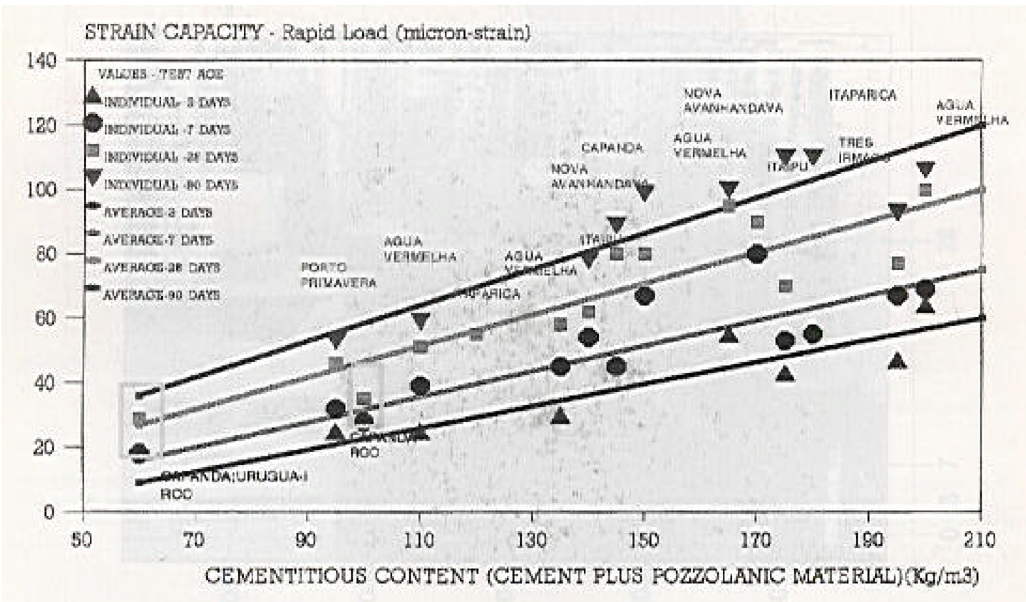

FIGURE 20- TENSILE STRAIN CAPACITY FROM RCC AND CVC CONCRETES

The values can be shown in two diferents manner.One in terms of temperature degrees, in an absolute value. Other manner that gives a simples way to general comparisons is a ratio between temperature degrees of adiabatic rise ,per cementitious content, that is called "coefficient of temperature rise" and is shown in Figure 21 [38, 39, 40, 41, 42, 44, 45].

The most important is to get the maximum "mix efficiency" (as described in 2.2) , and the minimum "coefficient of temperature rise".

2.9- Thermal Properties

The thermal properties - Difusivity; Specific Heat; Conductivity; and Coefficient of Thermal Expansion- are mainly controled by the aggregates thermal properties.
RCC mixes shows practicaly the same values as the CVC mixes ,proportioned with the same type of materials as shown on Figure 22 [38, 42, 44,45].

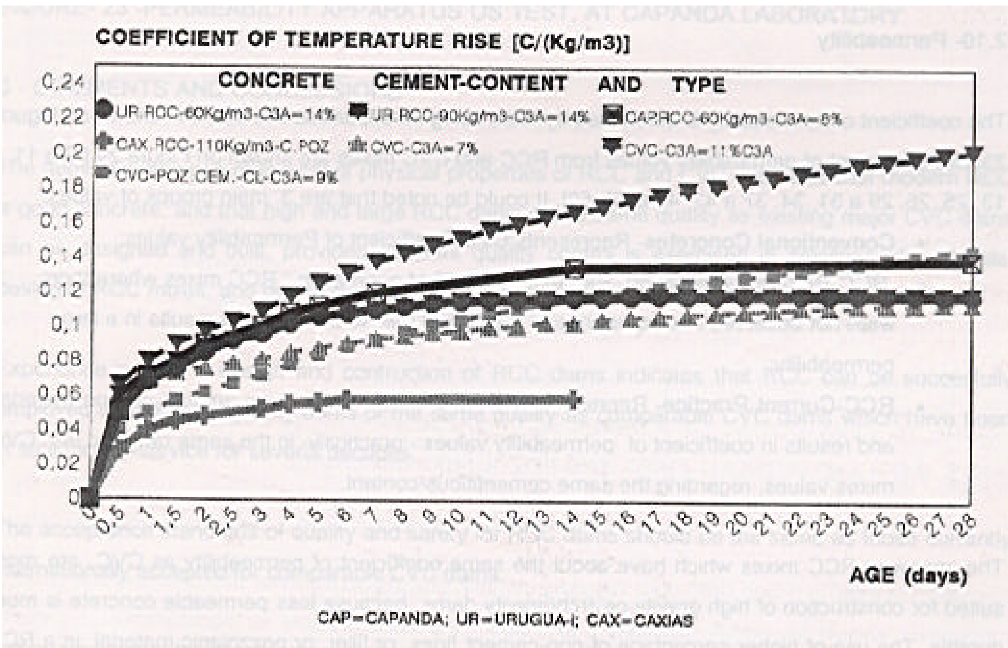

FIGURE 21- ADIABATIC TEMPERATURE RISE IN TERMS OF COEFFICIENT OF TEMPERATURE RISE VALUES FROM RCC AND CVC CONCRETES

COEFFICIENT OF THERMAL EXPANSION					
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS CONTENT Kg/m3	COEFFICIENT OF THERMAL EXPANSION 10-6/C
URUGUA-I	PM - 60	RCC	BASALT	60	7 41
URUGUA-I	PM - 90	RCC	BASALT	90	8.33
ITAIPU	76 - D - 04	CVC	BASALT	189	8
ITAIPU	76 - D 04	CVC	BASALT	162	7 71

SPECIFIC HEAT					
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS CONTENT Kg/m3	SPECIFIC HEAT cal / g C
URUGUA-I	PM - 60	RCC	BASALT	60	0 238
URUGUA-I	PM - 90	RCC	BASALT	90	0,233
ITAIPU	76 - D - 04	CVC	BASALT	189	0 243
ITAIPU	76 - D -04	CVC	BASALT	162	0 252
CAPANDA	RC - 60	RCC	META-SANDSTONE	60	0.221
CAPANDA	152 - 150 - B	CVC	META-SANDSTONE	150	0 228
CAPANDA	152 - 100 - A	CVC	META-SANDSTONE	100	0 223

THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY						
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS CONTENT Kg/m3	THERMAL CONDUCTIVITY 10-3(cal /cm s C)	THERMAL DIFFUSIVITY 10-3(m2 / day)
URUGUA-I	PM - 60	RCC	BASALT	60	4 76	0,066
URUGUA-I	PM - 90	RCC	BASALT	90	4 22	0.06
ITAIPU	76 - D - 04	CVC	BASALT	189	4,41	0,062
ITAIPU	76 - D -04	CVC	BASALT	162	4 8	0,063
CAPANDA	RC - 60	RCC	META-SANDSTONE	60	6	0 093
CAPANDA	152 - 150 - B	CVC	META-SANDSTONE	150	7	0,111
CAPANDA	152 - 100 - A	CVC	META-SANDSTONE	100	7 4	0 116

FIGURE 22- THERMAL PROPERTIES VALUES FROM RCC AND CVC CONCRETES

2.10- Permeability

The coefficient of permeability is detemined by tests using an apparatus like that one shown on Figure 23.The coefficient of permeability values from RCC and CVC mixes are shown on Figure 24 [3 a 11, 13, 25, 26, 29 a 31, 34, 37 a 42, 44 a 47, 50]. It could be noted that are 3 main groups of values.

- **Conventional Concretes**- Represents CVC Coefficient of Permeability values;
- **RCC-Pioneer Generation**- Represents the "first generation " RCC mixes where there were not observed the importance of the filler in the RCC mixes,and results in a large permeability;
- **RCC-Current Practice**- Represents the RCC mixes with a large amount on fine material, and results in coefficient of permeability values - practicaly- in the same range of the CVC mixes values, regarding the same cementitious content.

The improved RCC mixes which have about the same coefficient of permeability as CVC, are more suited for construction of high gravity or arch/gravity dams, because less permeable concrete is more durable. The use of higher percentage of non-cement fines, or filler, or pozzolanic material, in a RCC mix, contribute to its low permeability, without increasing the potential for thermal cracking.

FIGURE- 23 -PERMEABILITY APPARATUS OS TEST, AT CAPANDA LABORATORY

3 - COMMENTS AND CONCLUSIONS

The above comparison of important physical properties of RCC and CVC, indicates that modern RCC is good concrete, and that high and large RCC dams of the same quality as existing major CVC dams can be designed and built, provided excelent quality control is exercised in selection of materials, design of RCC mixes, and during construction.

Experience gained in design and contruction of RCC dams indicates that RCC can be succesfully employed to build high gravity dams of the same quality as comparable CVC dams which have been in satisfactory service for several decades.

The acceptance standards of quality and safety for RCC dams should be the same as those currently internationally accepted for comparable CVC dams.

Adequate bond at the construction joints can be obtained with a treatment. This comprises a thin layer of bedding mix of suitable properties, regardless of the time interval between placement of layers of RCC.

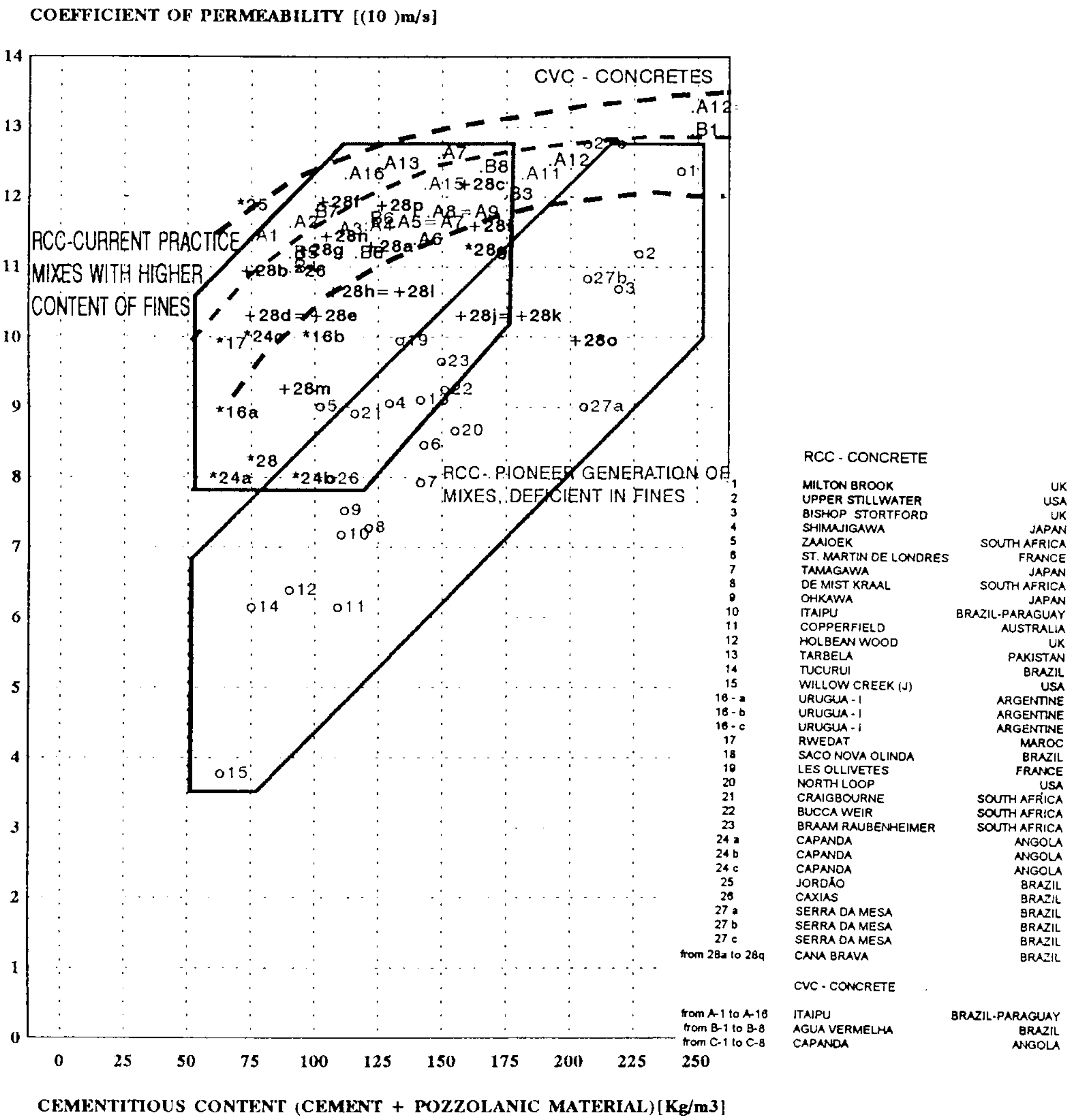

FIGURE 24- COEFFICIENT OF PERMEABILITY VALUES FROM RCC AND CVC CONCRETE MIXES, WITH AND WITHOUT FINES AND POZOLANIC MATERIALS

All matetrials used in a high RCC dam including cement, pozzolanic material, filler and fine and coarse aggregates, should be similar in quality , as those considered suitable for comparable CVC dam. Particularly important are physical properties related to specific gravity, susceptibility to alkalli-aggregate reaction or excessive thermal expansion.

The RCC mix should be design with lowest cementitious content necessary to obtain the desired consistency and specified strength in compression and shear at prescribed ages, and with the lowest practicable rise in temperature.

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