TRAIÇÃO DAM - THE EVOLUTION OF THE ALKALI AGGREGATE REACTION (AAR) IN THE LAST 20 YEARS

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ABSTRACT

The Traição Dam, situated on the Pinheiros river in the city of São Paulo, was built in the period of 1938–1940. After a few years of operation, fissures, leakage and deformations occurred in the concrete causing problems with the operation of the machines. In 1995, the presence of alkali-aggregate reaction (AAR) was diagnosed as a cause of the concrete expansion. The analysis of the readings from the instrumentation installed in the last 20 years and the studies carried out recently indicate that the AAR phenomenon has already passed its peak and is in the course of declining. A program of monitoring is being implemented to follow up the phenomenon, and preventive and repair measures were recommended for the most affected regions.

Keywords: Traição Dam, Alkali-silicate reactivity, Monitoring instrumentation, Treatment recommendations

1 INTRODUCTION

The Pinheiros channel (Fig. 1) originated from the correction of the Pinheiros River, which started during the 30's and was concluded in 1957. Its main objective was to increase the generating capacity of the Henry Borden Power Plant, by means of the reversion of the water of the Pinheiros and Tietê Rivers, flowing them to the Billings Reservoir.

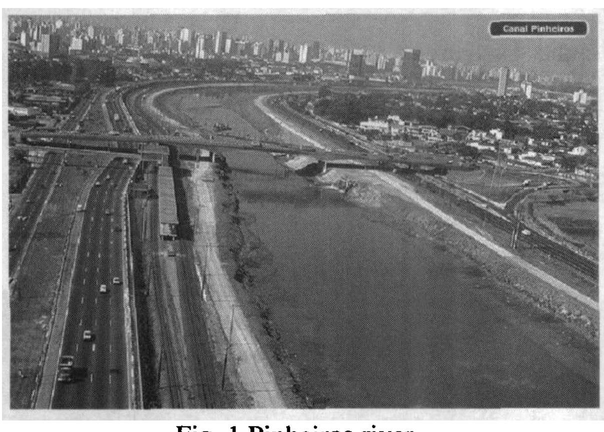

Fig. 1 Pinheiros river

The Traição Pumped Storage Power Plant (Fig. 2) was built in the period of 1938 – 1940 and is situated in the Pinheiros river, close to the Cidade Jardim Bridge, in São Paulo (SP), within the urban zone. The plant was constructed by the (at that time) Light company, and at present is operated by the EMAE.

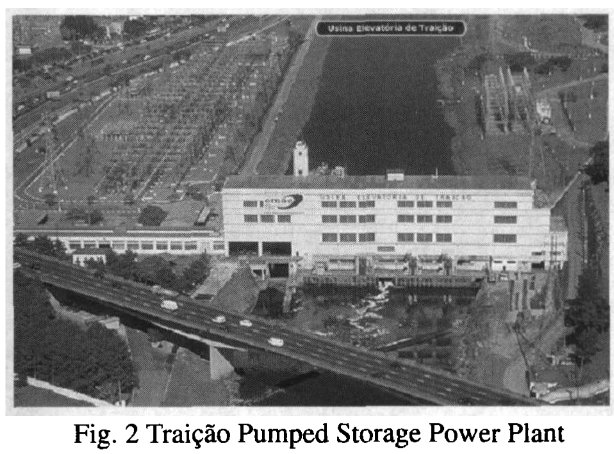

Fig. 2 Traição Pumped Storage Power Plant

Its basic function is to maintain control of floods, attend decrees of concession, by pumping water from the lower canal to the upper canal, with a rated head of 6 m and a maximum flow of 280 m3/s, pumped through 4 reversible Kaplan units, installed respectively in 1940, 1950, 1962 and 1977. In their turn, the waters of the upper canal are again pumped by

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the Pedreira Pumped Storage Power Plant to the Billings Reservoir, with a rated head of 25 m, thus permitting generation of electricity by the Henry Borden Power Plants in Cubatão, with a head of around 718 m (Fig. 3).

The power plant is a mass concrete gravity structure (Fig. 4) with a maximum height of 24 m, comprising 4 blocks housing the four units, a central block with a bottom sluiceway, a navigation lock in the hydraulic right bank and the erection area in the left bank. The blocks of the units are 13 m in width and that of the spillway is 6.80 m.

The foundations (Fig. 5 and Fig. 6) are composed of sandy silt to stiff clay, residual soils produced by the weathering of the magmatic rock. The sound rock dives in the direction of the eastern (right) abutment, being found at a depth of 4 m in the western shoulder and 22 m in the eastern abutment.

The stretch of the foundations with least favourable characteristics is situated in correspondence with the right bank, where there are recent alluvial deposits.

Figs. 4, 5 and 6 show the simple and multiple vertical extensometers installed in the structures, that allow measuring the expansion of the concrete and the settlement the foundations.

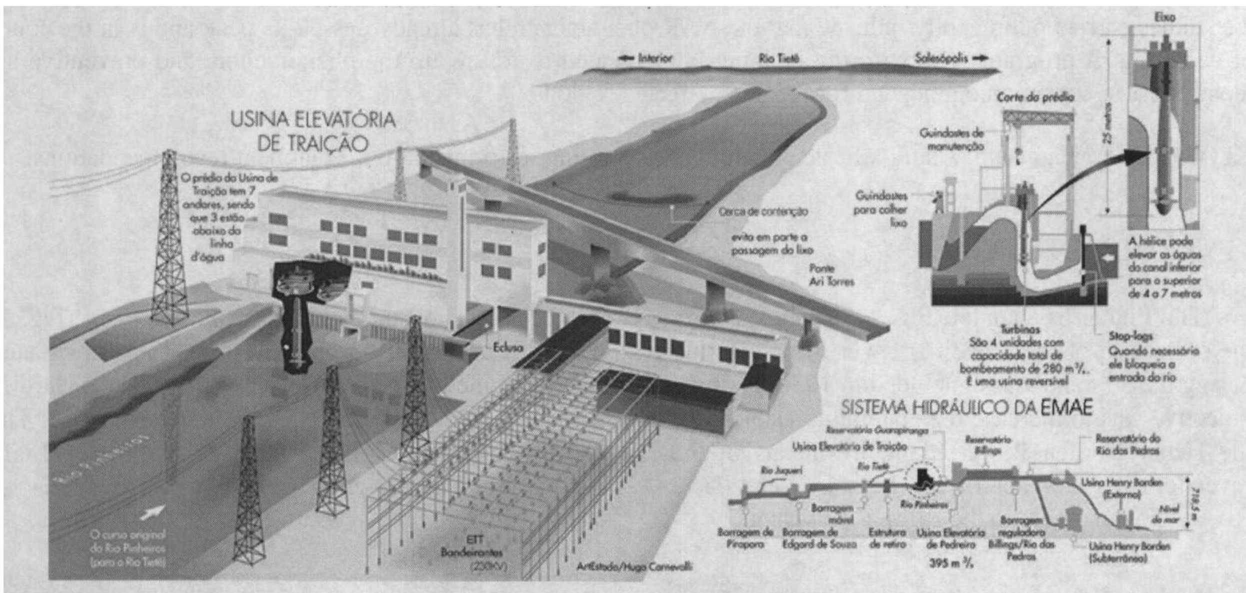

Fig. 3 EMAE Hydraulic System

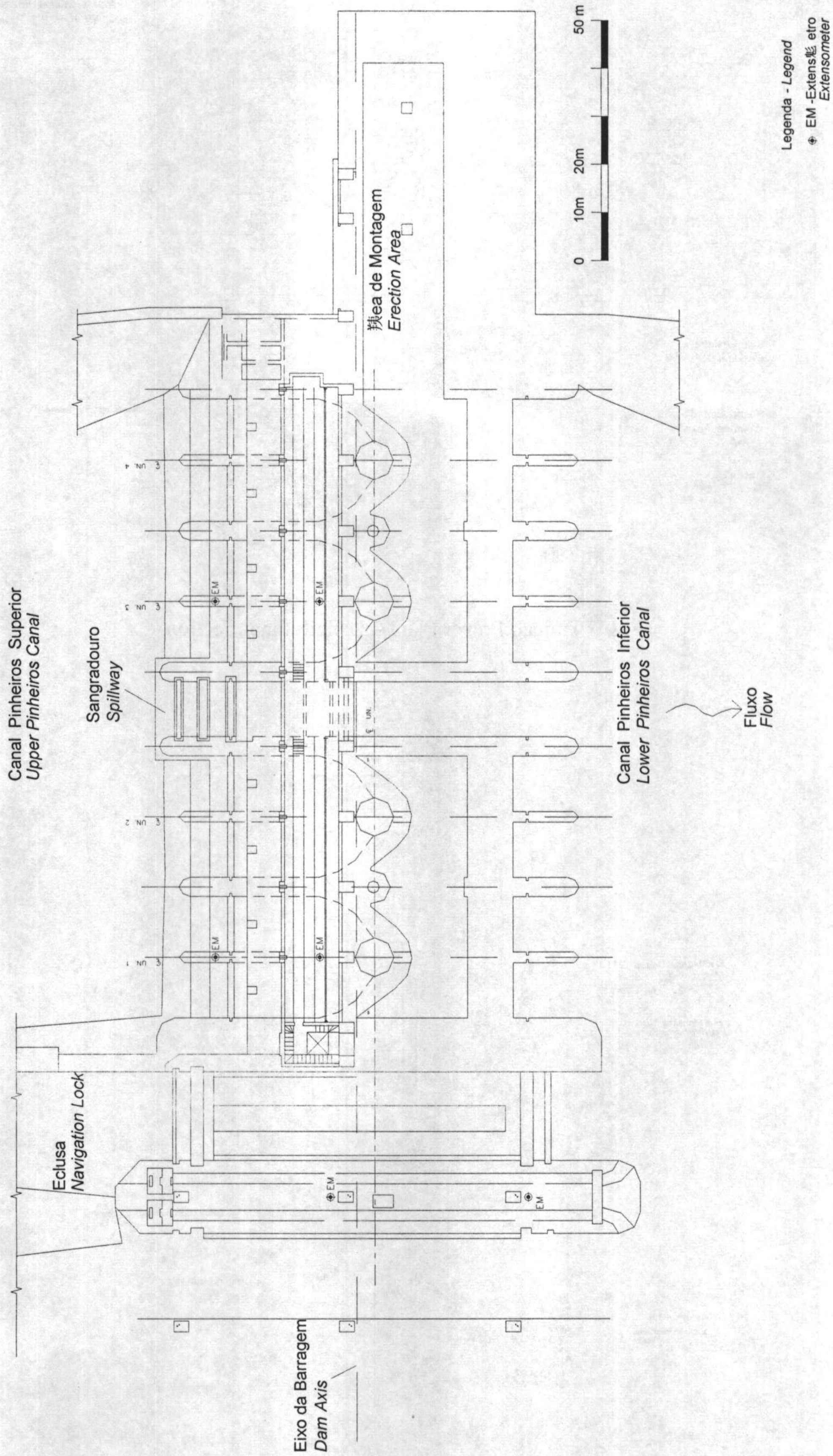

Fig. 4 Traição Power Plant – Plan View

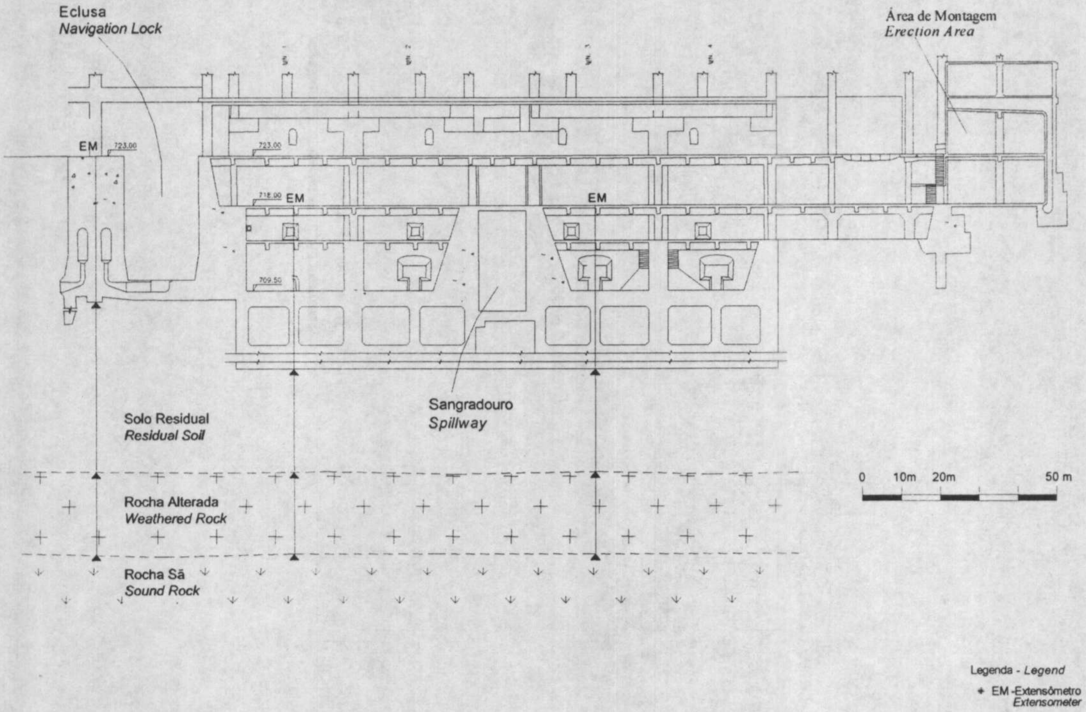

Fig. 5 Traição Power Plant – Longitudinal Section

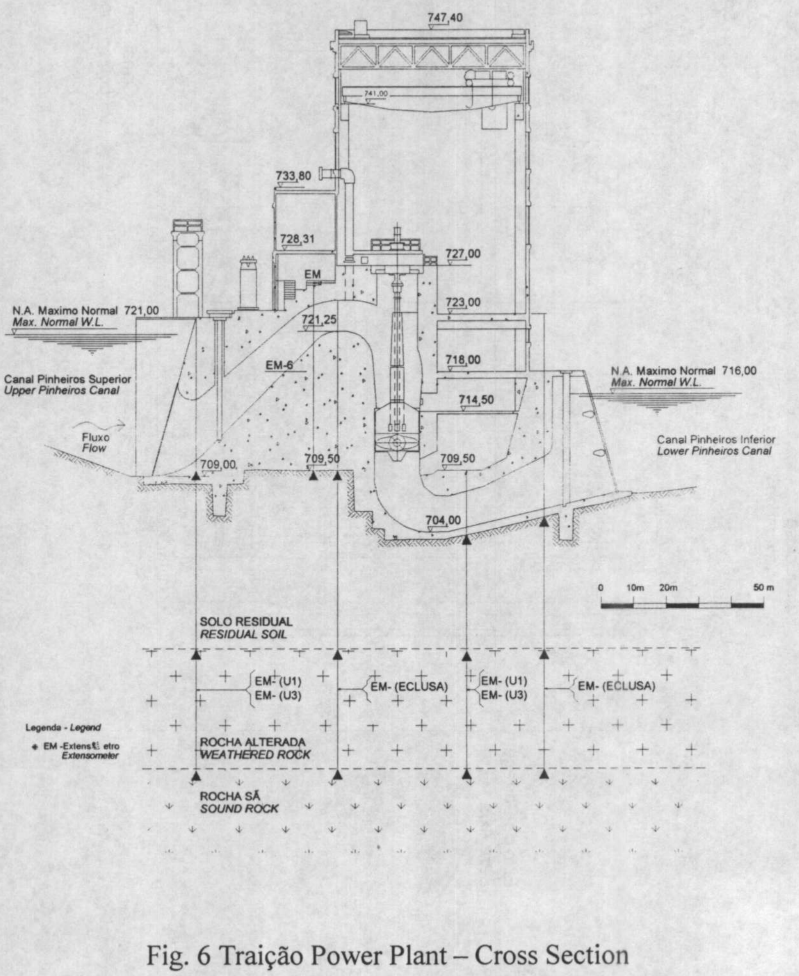

Fig. 6 Traição Power Plant – Cross Section

2 BACKGROUND

2.1 Problems that occurred

From the first years of operation, mechanical problems were recorded, in the majority of cases successive misalignments in the main shafts of the pumps, located principally in the Unit 1 of the eastern bank. Subsequently, fissures, cracks and seepage of the concrete occurred. The problems were initially attributed to the differential settlements of the foundation, to the bad quality of the canal water, to the vibrations and loads caused by the operation of the units, and even to supposed seismic activity.

An analysis of the available documentation also revealed:

- Frequent breakages of the bolts attaching the rotor ring of Unit 1 to its seat, anchored in the concrete;
- Generalized fissures in the diffuser of Unit 1, requiring its replacement;
- Ovality of the pit of Unit 1 (3 mm), entailing the problems of seizure of the diffuser ring, breakage of the attachment bolts to the concrete, fissures in the rotor peripheral ring (wear ring);
- On at least two verified occasions (1970 and 1994), the operation of erecting the rotor on Unit 1 was impaired by the relative change in the position of the plumb line employed to align the shaft of the pump, probably caused by deformations in the structure during operations of the rolling bridge crane and of the lock;
- Heating and asymmetrical wear of the guide bearings of the motor-generator;
- Jamming of the steel door to the mechanical workshop, probably caused by distortion of the concrete structures;
- Increased seepage through the inspection covers of the turbines and the covers of the shaft-guards, causing leaks of the water for cooling the bearings.

The tests carried out to obtain a quantitative evaluation of these influences consisted in successive operations of loading – unloading the lock, as well as loading tests of the rolling bridge crane through parking a particular load at pre-determined points of the superstructure while closely following its influence upon the displacements of the structure, of the foundation and upon the mechanical equipment.

However, the load tests failed to reproduce the phenomenon of the plumb line displacement and the instrumentation installed merely recorded small variations due to the daily temperature cycle.

The analysis of the geological and geotechnical aspects of the foundations revealed that the settlements that had occurred in the course of the last 10 years presented modest values, of the order of a few millimeters, with a tendency towards stabilization. Therefore, the problems relating to the behaviour of the structures and the functioning of the equipment of the Power Plant cannot be exclusively linked to the settlement of the foundations.

2.2 Diagnosis of the expansive reaction

The expansive reactions of the concrete were confirmed in 1995 through the petrographic-mineralogical analysis of sample cores extracted from the concrete.

The macroscopic observation of the samples showed the presence of diffuse borders in the paste/aggregate contact, with a whitish colour and a thickness of 1-2 mm, pertaining to aggregates from rocks that were intensely deformed after crystallization (mylonites), and cataclastically reactive.

The microscopic analysis indicated the following main characteristics:

- The porosity is around 1-2%, with up to 10 mm of extension; rare voids, filled with whitish secondary minerals – etringite, alkaline litharge gel (rare), calcium hydroxide, white alkaline calcium gel;
- The predominant aggregate corresponds to rocks subjected to a strong deformation, shearing and re-crystallization of minerals subsequent to the primary crystallization (blastomylonite of granitic to granodioritic rock); aggregates originating from gneisses occupy subordinate positions;
- The aggregate presents various components with the potential to generate alkali-silicate reactions: deformed quartz, pearlitic and micro granulated portions of deformed feldspar;
- The fractures possess a maximum length of 20 mm and an estimated thickness of up to 0.02 mm;
- The alkaline gel also fills fractures in the aggregate, comprising the most typical feature of the expansive reaction; the colour goes from clear to brownish, little crystallized and at times colloform. It was possible to observe the passage from alkaline gel to needlelike etringite.

The analyses confirmed, therefore, that an AAR phenomenon was occurring in the structures of the Traição Power Plant, in this case of alkali-silicate reactivity, specifically involving the deformed quartz as the reactive mineral, characterizing a reaction of the slow type.

3 MONITORING INSTRUMENTATION

The first instruments at the Traição Pumped Storage Power Plant were some topographic levelling marks installed on the south wall, whose readings weretaken from the topographic stations located close to the Rio Pinheiros River.

These measurements commenced in November of 1980, with the readings being taken by the topographic survey team of the owner.

In 1983, the I.P.T. carried out five exploratory soundings in the abutments of the above plant, using four of them as observation wells, two of which were placed in the right abutment and two in the left. At this same time some Tensotast bases were also installed in the fissures observed in the concrete, although of a provisional nature.

During the second semester of 1985, the monitoring instrumentation at the plant was complemented by the following apparatus, in accordance with the project prepared by Promon:

- 3 multiple extensometers (3 rods each);
- 5 standpipe type foundation piezometers;
- 4 triorthogonal joint meters in the contraction joints between blocks;
- 16 triorthogonal joint meters in the principal fissures of the concrete.

In 1999, some multiple extensometers and triorthogonal joint meters were replaced due to the advanced state of corrosion of their metallic parts. In consequence, in the year 2000, the auscultation instrumentation comprised the following instruments:

- 6 multiple vertical extensometers with 3 rods;
- 2 simple vertical extensometers;
- 5 horizontal extensometers;
- 8 convergence bases;
- 19 triorthogonal joint meters.

4 ANALYSIS OF THE RESULTS

4.1 Triorthogonal joint meters in the fissures

All 15 triorthogonal joint meters installed in the fissures indicate stabilization or opening, with a single exception. The fissures indicate, in general, an opening varying from 0 to 0.25 mm/year (mean value of 0.09 mm/year) with a tendency towards stabilization in recent years.

4.2 Triorthogonal joint meters in the contraction joints

The transversal contraction joints are situated in the floor of the slabs at El. 718 and 732 between block U2 and the bottom spillway and between block U4 and the erection area. With a single exception, the four meters indicate opening of the contraction joints with maximum values around 2 mm.

The mean rate of joint opening varied from 0.08 to 0.25 mm/year between January 1995 and January 2000.

4.3 Piezometers

The piezometers indicated abrupt drops in the uplift pressures corresponding to the maintenance periods of the units when they are emptied. This phenomenon in the past could have induced settlements in the foundation.

4.4 Extensometers

The settlements of the foundations have generally stabilized in the last three years, barely indicating settlements of less than a millimeter in two instruments located in the right abutment (navigation lock and block 1).

The horizontal extensometers, embedded in the concrete, were installed at the beginning of the year 2000 and with 3 years of operation indicate mainly the seasonal variations and small expansions in the horizontal direction with the sole exception of the blocks 3 and 4 where an expansion of 1 mm was recorded, equivalent to a rate of 21 microstrains/year in the direction of the axis of the power plant.

4.5 Analysis of deformations in the concrete throughout the years

An analysis was made of the deformations of the concrete throughout the lifetime of the plant, including the results of the topographic leveling marks installed at El. 727 and all the vertical extensometers, both old and new. The results are summarized in the following Table 1, which provides the mean rates of deformation in microstrains/year by block and by period of observation.

Table 1 Mean rates of deformation in microstrains/year

Period	Lock	U1	U3	U4	Mean
Dec80/Oct84	-	69*	-	25*	47
Dec85/ Sep92	-	42*	-	15*	28,5
Oct85/Oct94	29**	34**	58**(?)	-	40
Jan95/Oct99		23**	23**		23
Aug96/Aug99	13**				13
Jan00/Feb03	4**	12**	21 **	-	12

* Levelling marks

** Extensometers

(?) Doubtful result

These results indicate a constant and coherent decreasing tendency of the deformations in all the blocks.

The accumulated total values of the expansions of the concrete since installation, measured with the ME-01 and 02, are of around 400 microstrains.

Table 2 presents the calculated mean values of the expansion rates attributed to the year situated in the middle of the corresponding period.

The minimum and maximum values are also indicated.

The values of this table are shown in the graph of Fig. 7, where the straight line of the mean values trend clearly indicates the decrease in the expansion rate of the concrete with present values below 20 microstrain/year.

Table 2 Mean values of the expansion rates

Middle year	Expansion rate (microstrain/year)		
	mean	maximum	minimum
1982	47	69	25
1988	28.5	42	15
1989	31.5	34	29
1997	23	23	23
1998	13	13	13
2002	12.5	21	4

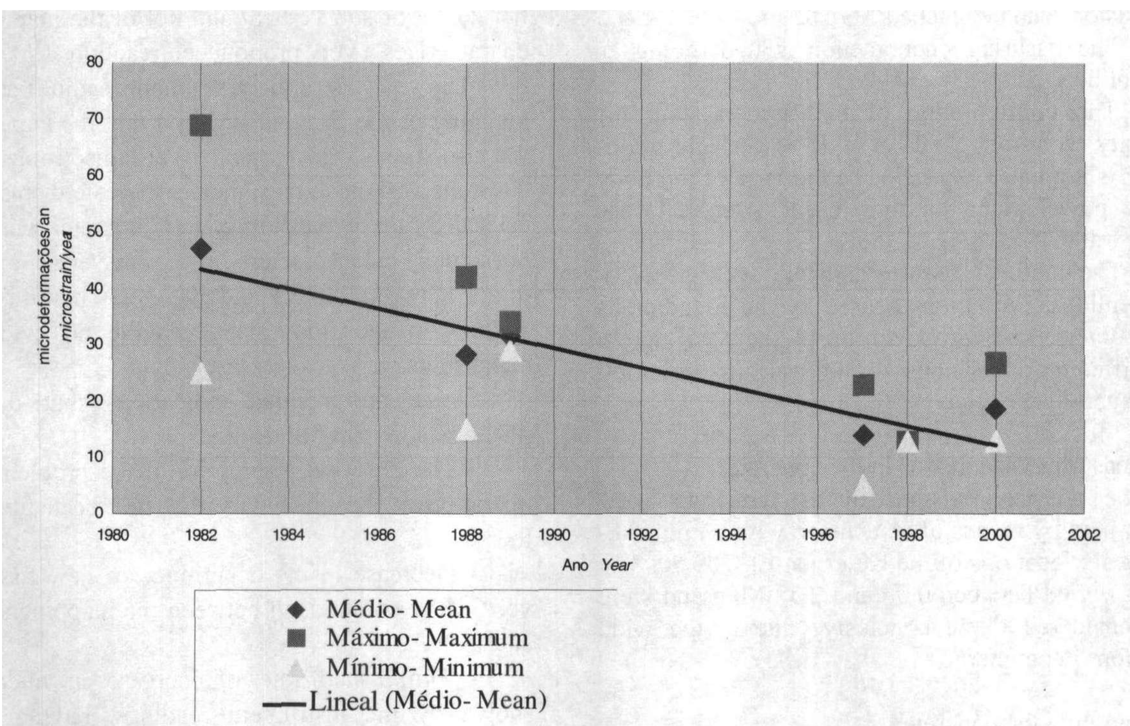

Fig. 7 Expansion rate of the concrete

5 OTHER INVESTIGATIONS

5.1 Mapping the fissures

Mapping of the fissures was carried out in January 1995 and August 1999. The quantitative analysis of these fissures indicates that:

- The great majority of the fissures is prior to 1995;
- All the new fissures have openings of less than 0.5 mm;
- The largest number of the fissures is located in the walls and particularly the downstream walls;
- The largest number of the new fissures appears in the floors, with the greatest incidence in the lower floors, diminishing in the upwards direction.

With regard to the location and type of the fissures, the following was verified:

- The fissures in the walls are more frequent at the lower elevations;
- The fissures in the walls of the lower floors are predominantly sub horizontal;
- The fissures in the upper elevations are horizontal and vertical, and some are inclined 45°.

Based on the above observations, the following conclusions can be reached:

- The fissuring phenomenon is undergoing an evident decrease;
- The configuration of the fissures with the majority sub-horizontal at the lower elevations suggests a greater expansion in the base of the body of the power plant, causing tensile stresses in the lower walls;
- The inclined fissures indicate settlements or differential deformations caused by the foundations or by diverse rates of expansion by the AAR due to the different dimensions of the various structural elements.

5.2 Measuring the stresses in the concrete

The stresses existing in the concrete were determined by means of tests made with a mini flat-jack at six locations of the gallery at El. 709.50. The results varied between 0.06 and 2.32 MPa and were not considered to be conclusive due to the wide variations encountered.

5.3 Sampling the concrete

Laboratory tests conducted on sample cores, 15 cm in diameter, withdrawn by rotary drills, showed that the concrete possesses normal properties with mean values for unconfined compressive strength of 35.2 MPa, varying from 47.3 to 21.8 MPa.

6 CONCLUSIONS

The studies and investigations carried out indicate that the fissure scenario must have been caused by the following factors:

- In the first place due to expansion of the body of the power plant, caused by the AAR over various years;
- Second, in order of importance, from the differential settlements between the navigation lock and the structures of the adjacent units, due to the significant increase in the thickness of the residual soil layer along the longitudinal axis of the power plant. This caused stress concentrations in certain regions.

The occurrence of the alkali-aggregate reaction is well demonstrated by the laboratory petrographic tests.

The reactivity phenomena, causing the expansion of these concrete structures, explain many of the problems observed in them and in the equipment installed.

The reactivity phenomenon, characterised by a slow type of reaction, didn't significantly affect the quality of the concrete, since:

- The drilling performed plus the laboratory tests showed that the concrete possessed normal properties, similar to those of other concretes manufactured in the region;
- The fissures are isolated, preferably sub horizontal or sub vertical and not of the map type that characterizes a very pronounced reaction.

The analysis of the instrument readings and of the mapping of the fissures suggests that the expansion of the structures is developing in an anisotropic fashion, since the vertical extensometers indicate displacements caused by the expansion of the concrete, whereas the horizontal extensometers, the transversal expansion joints between blocks and the great majority of the fissures in the floor slabs provide no evidence of expansions.

There are various indications that the AAR phenomenon is in full decline:

- The absence, at present, of the problems in the operation of the machinery that had been frequent in the past;
- Decrease in the occurrence of new fissures, as verified by comparison between the mappings of 1995 and 1999;
- Diminished rate of increase in microstrains shown by the instrument readings, having reached mean values below 20 microstrains/year, which is considered to be low;
- The low alkali content verified in the concrete samples;
- The presence of the mineral (etringite), detected by mineralogical analysis, that indicates the stabilization of the expansive phenomena.

7 RECOMMENDATIONS

The treatment recommended is as follows:

- Injection of epoxy resin into the fissures of the slabs where structural implications may exist;
- Injection of polyurethane into the fissures presenting infiltrations;
- Waterproofing the areas presenting infiltrations by means of polyurethane injections or treatment with a superficial waterproofing agent;
- Channelling the remaining flow.

The lock wall must be treated to eliminate the seepage to the interior of Unit 1. The fissures to be treated are those with openings > 0.3 mm in the presence of reinforcement or with openings > 0.5 without reinforcement, especially in the environments considered to be aggressive, such as the galleries of El. 709.50 and 718 m of the lower floors with high humidity. The treatment should preferably be administered during the cold season when openings are greatest, thus facilitating the injection.

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