ASSESSMENT OF ALKALI-AGGREGATE REACTION AT SABESP`S DAMS

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Abstract

Sabesp is the company that supplies water for almost 27 million people in the State of Sao Paulo, Brazil; from this total, nineteen million from the Sao Paulo Metropolitan Region get about 65m³/s of water. In the Greater Sao Paulo area Sabesp owns 28 dams of various sizes from 5 to 60 meters high. In 1989 several and severe cracks were discovered at the concrete intake of Tunnel 6, that links Cachoeira dam and Atibainha dam, of the Cantareira system. The diagnosis showed that alkali-aggregate reaction (AAR) was the origin of all cracks and instrumentation installed in 1996 confirmed that concrete is swelling and the magnitude of the cracks is continuously increasing and varies according to the existing confinement, to the local humidity and to the state of stress of the concrete elements.

Due to these facts the company decided to investigate its occurrence in fourteen other hydraulic structures comprising dams, tunnels, and water intakes where cracks are visible. Twenty four concrete specimens were extracted, subjected to petrographic evaluation using microscopic examinations and scanning electron microscope; eleven specimens presented evidence of AAR confirming the problem in eight of these structures. Two dams were built in the early 30`s while all other structures were built in early 70`s. Concrete was produced either using granite gneiss, gneiss or biotite gneiss as coarse aggregate. In one dam concrete expansion resulted in the jamming of the spillway`s steel stop-log, however this situation was rapidly solved.

This paper describes the studies that were performed in all structures, shows the testing results, presents the evolution of crack openings and the actions that are being taken to evaluate and follow-up these occurrences in order to avoid any future problems in the water supply of the Greater Sao Paulo.

Keywords: alkali-aggregate reaction, cracks, dam, tunnel, instrumentation

1. INTRODUCTION

The Companhia de Saneamento Basico do Estado de Sao Paulo-Sabesp is responsible for the water collection, treatment, supply and for the sewage collection, treatment and final disposal in 364 municipalities of São Paulo, Brazil, serving a population of 27.1 million inhabitants. To reserve the water to be further processed Sabesp has nearly 300 dams, retaining structures made of masonry, earth, rockfill and concrete, which require the highest levels of security and total operational availability. Water production in the São Paulo Metropolitan Network is 67 m³/s considering all production systems in the city and is supplied to 15.9 million persons. In 1989 Sabesp discovered cracks originating from generalized alkali-aggregate reaction (AAR) in the concrete of the water intake of Tunnel 6, Cantareira system [1]. A similar cracking pattern was observed in other structures built at the same time and in nearby regions.

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The conclusions of the work carried out in the intake of Tunnel 6 in 1996 [1], raised the need to investigate dams and other concrete structures in similar facilities, to identify which structures would be affected by the problem and thus guide the next steps in search of greater durability and safety of these facilities. This paper presents a brief description of the structures that show signs of AAR, the methodology used in identifying it, the results obtained in investigations and the actions taken by Sabesp.

2. STRUCTURES DIAGNOSED WITH AAR

The following describes some key characteristics of structures that were studied and presented AAR. They consist primarily of concrete structures from the three main water production systems in the Metropolitan Region of São Paulo-RMSP, the vast majority belonging to the Cantareira System, which is sketched in Figure 1. The other two systems that also present signs of AAR are the Rio Claro and the Alto Cotia.

2.1 Jaguari Dam - Cantareira System

It is a homogeneous earth dam with a maximum height of 62m and crest length of about 860m. The paved crest is 10m wide and is at elevation 847m. Has an ogee crest regulated spillway with Creager profile, equipped with three tainter gates, with total capacity of discharge 1.240m^3/s, located on the right abutment and a bottom outlet composed of 03 rectangular galleries 355m in length each; the gallery from the left is destined for access and inspection and the others (central and right) for the discharge of 38m^3/s, through two Howell-Bunger valves. It was built from 1977 to 1982. The AAR detected in the crest of the spillway concrete pillar, is of the alkali-silica type. However, ASR was not detected in specimens taken from the upstream face and neither from the central gallery.

2.2 Atibainha Dam - Cantareira System

It is a homogeneous earth dam with maximum height of 39m and crest length of about 430m. The paved crest is 10m wide and is at elevation 791.50 m in the central region. The morning glory spillway is located near the right abutment and has a capacity of 73m^3/s, and the flows are directed to a concrete gallery, which crosses the earth dam. The bottom outlet with a capacity of 25 m^3/s is embedded within the morning glory structure. The dam was built from 1969 to 1973. ASR was detected in the wall of the morning glory spillway. However no AAR was detected in specimens taken from the left wall or from the stilling basin.

2.3 Cascata Dam - Cantareira System

It is a homogeneous earth dam with steep curvature upstream and a channel-type spillway in its central portion, provided with baffle blocks for energy dissipation. The maximum height over the foundation is about 12m, the crest length is about 80m, the width is approximately 8m and is in elevation 774.0 m in the central section. There is a bridge over the spillway, allowing traffic in the direction of the downstream tunnel portal. The dam was built in 1976 and the AAR detected in the bridge is of the alkali-silica type.

2.4 Paiva Castro Dam - Cantareira System

It is a homogeneous earth dam built from 1968 to 1972, with a maximum height of about 22m over the foundations and crest length of 210m. The paved crest is 7m wide and lies on elevation 750.00 m. There is an ogee crest regulated spillway with Creager profile, a bottom outlet on the right abutment and a fuse plug in the left abutment. AAR was detected in the spillway, in the walls near the fuse plug and in the dissipation basin.

2.5 Pedro Beicht Dam - High Cotia River System

It is a concrete gravity-type dam, with a slight upstream arching, maximum height of 23m and crest length of 347.40m, built between 1929 and 1932. It has a side channel spillway, with a crest length of 25m and a bottom outlet composed by two tubes of 0.90m in diameter each, coupled to 3 gates located upstream, at different levels. AAR of the alkali-silica type was detected in the upstream face and was identified by the presence of expansive gel.

2.6 Ribeirao do Campo Dam - Claro River System

It is a concrete type-gravity dam, with a maximum height over the foundation of 26m. Its paved crest is 171m long. The ogee crest Creager type spillway is located on their central portion of the dam and there is also a bottom outlet operated from the equipment room, located next to the upstream face and to the spillway. The beginning of its construction was in 1950s and its completion in 1962. The reservoir has a volume of 13.9 x 10^6 m^3, regulating the discharge of $1m^3/s$, which is released on the Claro river, on the dams located downstream of Poco Preto dam and the dam called "76" and then captured by the Claro river water treatment plant. AAR of the alkali-silica type was detected in the drainage gallery.

2.7 Tunnel 2 - Cantareira System

This tunnel, built in 1973, connects the Aguas Claras dam reservoir to the Guarau water treatment plant. It has 4878m in length, steepness of 0.13% and cross-section of $20m^2$. AAR detected in the concrete of the tunnel portal is of the alkali-silica type.

2.8 Tunnel 7 - Cantareira System

The tunnel built from 1978 to 1981 connects Jacarei and Cachoeira dams from the Cantareira System. It is 5885m long, has a steepness of 0.50% and horseshoe cross section with $28m^2$. The upstream portal is a concrete structure that works as an intake for the water conveyed from the Jacarei reservoir to the Cachoeira reservoir located downstream. The AAR detected in the buttresses that are part of the concrete intake is of the alkali-silica type.

3. METHODOLOGY AND DIAGNOSIS OF AAR

Fourteen concrete structures where supposedly there would be more chances of occurrence of the phenomenon were chosen for the tests. They included dams and tunnel portals and 24 concrete specimens were extracted for assessment and analysis. These samples were sent to ABCP - Brazilian Portland Cement Association - where they were subjected to an assessment of concrete durability with an emphasis on the diagnosis of alkali-aggregate reaction.

3.1 Methodologies Employed

The main characteristics of concrete, as well as features on existence of alkali-aggregate reaction were identified macroscopically and by stereoscopic optical microscopes of transmitted light. As a result of these identifications the information regarding textural and structural aspects of the concrete were obtained as well as the general petrographic characteristics of the coarse aggregates and the microscopic characteristics of fine aggregates.

Characteristics relating to the existence of alkali-aggregate reaction, identified in macro and microscopic analysis allowed the identification of features suggestive of occurrence of the reaction such as the presence of reaction rims, pores filled with white material and existence of microcrackings. The analysis by scanning electron microscope equipped with EDS – Energy Dispersive Spectrometer was performed to obtain a more detailed microstructural of concrete and, especially, better characterize the products of the AAR reaction.

3.2 Diagnosis of Structures

The studies conducted with samples identified the presence of alkali-aggregate reaction in specimens belonging to eight of the fourteen structures analyzed. Of the 24 samples of concrete analyzed 11 had evidence of deleterious reactions, as shown in Table 1. It contains a list of structures, places where specimens were extracted and the diagnosis. Table 2 summarizes the main features found in the various concrete affected by alkali-aggregate reaction. It may be noted the summary of macroscopic analysis of the concrete, aspects related to alkali-aggregate reaction, some general characteristics and petrographic characteristics of coarse and fine aggregates. There were no cracks in any of the concrete specimens macroscopically analyzed. In all samples the type of coarse aggregate was crushed stone and its mineralogy consisted primarily of quartz and feldspar.

4. MONITORING OF STRUCTURES

Noting the occurrence of cracking in concrete structures, around 1992, Sabesp started to monitor some of these occurrences. For this purpose glass plates and plaster seals were installed as a preliminary step to qualitatively evaluate cracks movements. In some structures reference points were also placed across certain cracks in order to measure their opening movements. At the same time a reading frequency was established to be followed. After confirmation of the occurrence of AAR in the concrete of the intake of Tunnel 6, Sabesp performed the series of test mentioned above and increased the monitoring in some of the structures affected by AAR. Among them is the Paiva Castro, described below. The affected structures are accompanied by periodic inspections and instrumentaton readings are properly analyzed.

4.1 Paiva Castro Dam Case

The finding of cracks led the company's technicians to install in January 1992 bolts in the most significant cracks, to allow monitoring and tracking of their openings by monthly readings with analog caliper. At that time, 15 pairs of bolts were installed in the dam, 5 being located in the spillway (1-5) and 10 in the walls of the dissipation basin (1 to 10), as shown in Figures 2 and 3.

In November 2000, 11 crack-meter bases had been installed: called as "A", "B", "C" in the spillway and "D", "E", "F", "G", "H", "I", "J", "L" on the concrete walls of the dissipation basin. On this occasion the readings began to be performed with a digital caliper, whose precision is 0.01 mm and also with the elongameter with an accuracy of 0.001 mm. In addition, temperatures of the structures were recorded during the readings, through non-contact digital thermometer, whose values are obtained by infrared emission. In January 2001, during the preventive maintenance test involving the tainter gate number 02, the lifting beam of the stop-log showed evidence of being blocked, indicating a tendency of gap closure, something that never actually occurred previously. Because of this anomaly, underwater inspections were made, hydroblasting cleaning of the steel structures of the spillways number 01 and 02 was performed and measurements of the distance between guides of the stop-logs were started. Afterwards approximately 10mm at the end of the lifting beam and of the stop-logs were cut off. This prevented further blockage of the lifting beam and of the stop-log allowing their movement without difficulty. In 2004 three new elongameter bases called "M", "N" and "O" were installed in the concrete near tainter gate No. 02; also a triortogonal meter fixed with the aid of a beam was installed between the two walls of the spillway, to monitor an evolution of the gap closure. Figure 4 shows the triortogonal meter. As an example of values that have been obtained in the measurements, Figures 5 and 6 present variations of the opening of some cracks from Paiva Castro dam. Figure 7 shows detail of the cracks. It seems that at the spillway cracks evolution continues with different opening rates, according to its location. Those localized along the right wall on the crest of the spillway, measured by pins number 4 and 5 show opening rates of 0.41mm/year and 0.53mm/year, respectively. The remaining cracks in the spillway show lower opening rates: 0.20mm/year, 0.19mm/year and 0.20mm/year for cracks 1, 2 and 3 respectively. The crack opening evolutionary process in the dissipation basin seems to be concentrated at the end of the left wall as shown by the readings of the pins 3 and 4 (see Figure 6).

4.2 Other structures

Other Sabesp`s structures that have AAR are visually inspected more frequently highlighting some that have installed instrumentation: the intake of Tunnel 7 and Ribeirao do Campo dam.

5. CONCLUSIONS

Sabesp has some of its concrete structures affected by AAR, found through petrographic examination of specimens taken from them. It is known that, up to now, there are no technical and economic corrective measures that can stop for sure AAR in the mentioned structures. For this reason the approach has been adopted by the company to assess the phenomenon, follow its evolution through visual inspections, install and operate instrumentation and adopt remedial corrective measures where necessary, as in the case of Paiva Castro dam. Moreover, Sabesp has required the adoption of preventive measures in the planning and design phases, to avoid the appearance of AAR in new works.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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Table 1 – Structures that were investigated		
Structure	*Location of extracted cores*	*Diagnosis*
Jaguari dam	Upstream face (spillway)	No AAR
	Central gallery (spillway)	No AAR
	Crest (spillway)	ASR
Jacarei dam	Inspection gallery (bottom outlet)	No AAR
Tunnel 7 Intake	Butress 02	ASR
	Butress 05	ASR
Cachoeira dam	Left wall (dissipation basin)	No AAR
	Morning glory wall (at reservoir`s water level)	No AAR
Atibainha dam	Left wall (dissipation basin)	No AAR
	Morning glory wall (at reservoir`s water level)	ASR
Tunnel 5 Intake	Water intake gallery	No AAR
Cascata dam	Downtream bridge	ASR
Pedro Beicht dam	Upstream face	ASR (ettringite was also noticed)
	Crest	No AAR (ettringite noticed)
Ribeirao do Campo dam	Upstream face	No AAR (ettringite noticed)
	Drainage gallery	ASR
Paiva Castro dam	Spillway	ASR
	Left wall at dissipation basin	ASR
	Right wall	ASR
Aguas Claras dam	Morning glory wall (at reservoir`s water level)	No AAR (ettringite noticed)
Tunnel 2	Tunnel 2 portal	ASR
Guarau water treatment plant	Slab near tunnel 2 portal	No AAR (ettringite noticed)
	Slab	No AAR
Tunnel 3	Tunnel 3 portal	No AAR

Table 2 – Summary of petrographic analysis					
Characteristics		*Site*			
		Jaguari dam	*Atibainha dam*	*Cascata dam*	*Pedro Beicht dam*
Macroscopic analysis of concrete	Macroscopic porosity	3% of submilimetric pores and voids up to 5mm, filled with white material	1% of pores up to 2mm, partially filled with white material	1% of pores up to 10mm, partially filled with white material	1% of pores up to 2mm, voids or partially filled with white material (gel and/or ettringite)
AAR	Reaction rims	Existent	Unobserved	Unobserved	Seems that there are reaction rims around aggregates
	Filled pores	Filled pores with white material	Filled pores predominantly with white material	Predominantly empty	Partially filled with white material
	Microcracks	Unobserved	Unobserved	Unobserved	Unobserved
General and petrographic characteristics of coarse aggregates	Type	Crushed rock	Crushed rock	Crushed rock	Crushed rock
	Aggregate deformation	Deformation visible through the extinction angle of quartz and felspar	Deformation visible through the extinction angle of quartz and felspar; alignment and fine grains of cristals due to shear	Deformation visible through the extinction angle of quartz	Deformation visible through the extinction angle of quartz and felspar; alignment and fine grains of cristals due to shear
	Reaction rims	Unobserved	Unobserved	Unobserved	Observed
	Rock type	Igneous metamorphic	Metamorphic	Igneous metamorphic	Igneous metamorphic
	Petrographic classification	Gneiss milonitized	Biotite gnaiss cataclastic	Granite gneiss	Sheared biotite gneiss
	Potential reactivity	Reactive aggregate	Potentially reactive aggregate	Potentially reactive aggregate	Potentially reactive aggregate
Microscopic characteristics of fine aggregates	Main mineralogy	Quartz and felspar	Quartz and felspar	Quartz and felspar	Quartz and felspar
	Deformation	Deformed, with undulatory extinction	Deformed grains of quartz and felspar, undulatory extinction	Deformed grains of quartz and felspar, undulatory extinction	Deformed grains of quartz, undulatory extinction
	Reaction rims	Unobserved	Unobserved	Unobserved	Unobserved

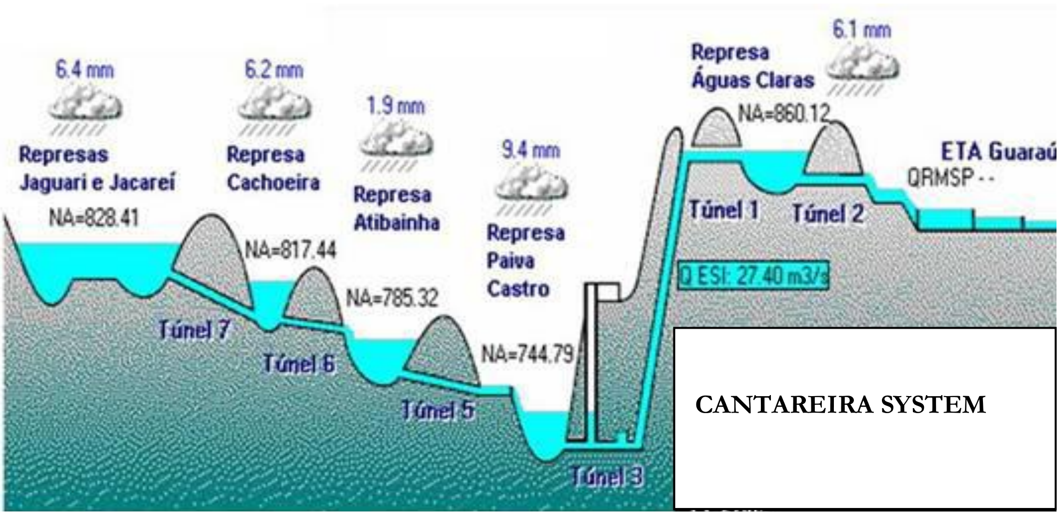

Figure 1- Scheme showing dams and tunnels of the Cantareira System that supplies water to Sao Paulo Metropolitan Region (not on scale).

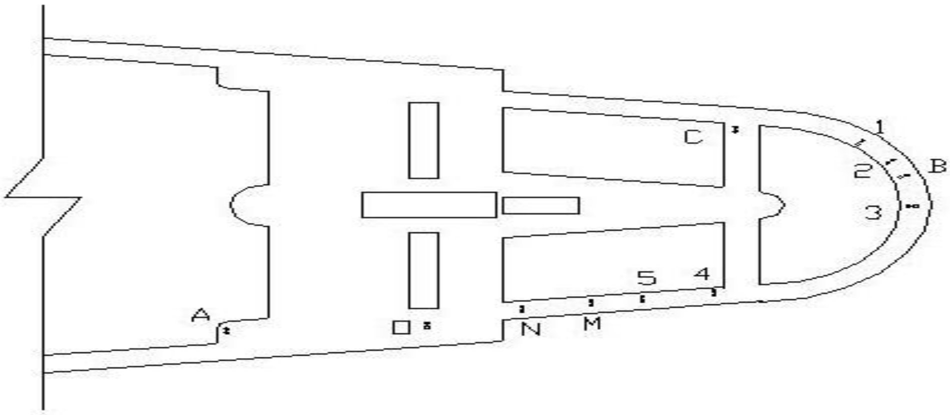

Figure 2 – Plan showing schematic location of pins at the Paiva Castro dam spillway (not on scale).

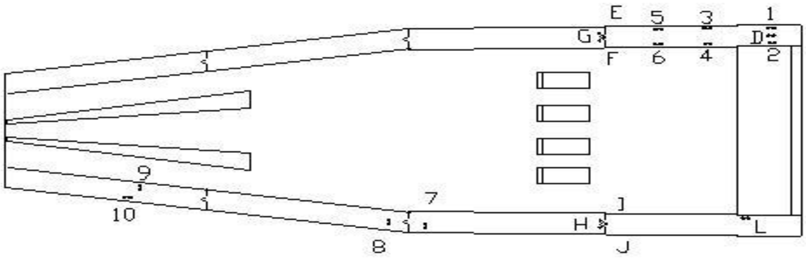

Figure 3 - Plan showing schematic location of pins at the dissipation basin walls of Paiva Castro dam (not on scale).

Figure 4 – Paiva Castro dam spillway showing the gate (a) and a detail of the triortogonal meter (b).

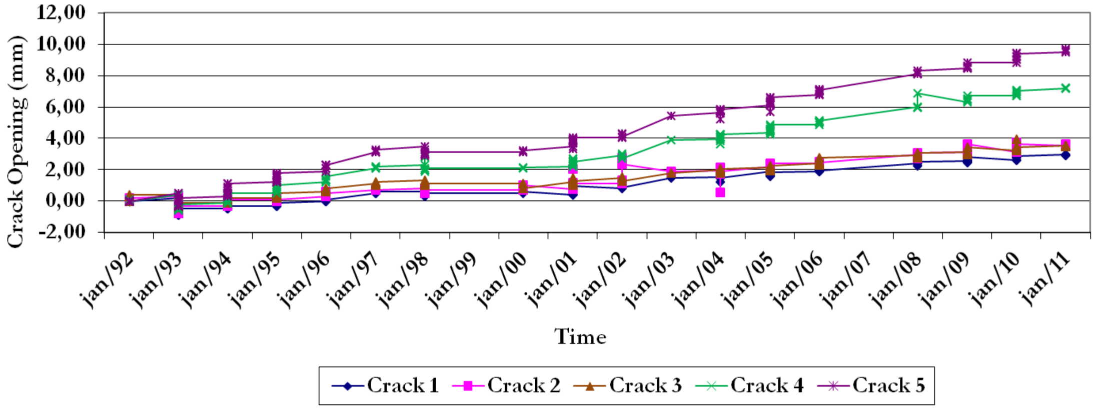

Figure 5 – Evolution of cracks openings at Paiva Castro dam spillway.

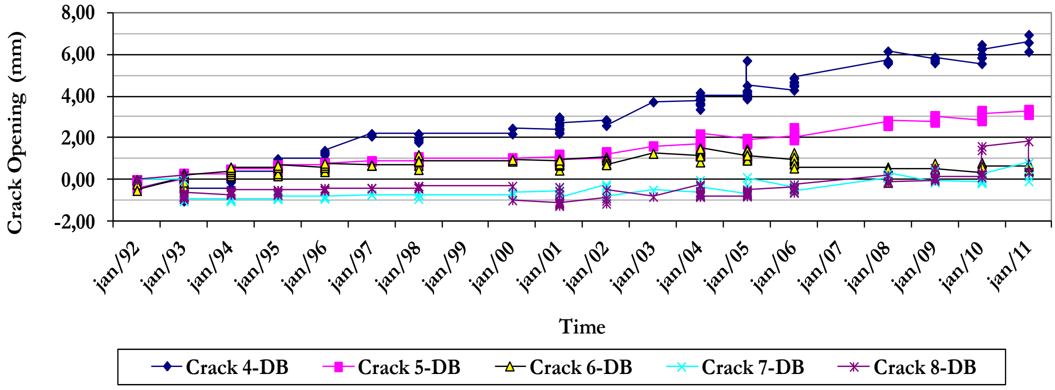

Figure 6 – Evolution of cracks openings at Paiva Castro dam dissipation basin walls.

Figure 7 – Detail of pin number 5 placed at the spillway of Paiva Castro dam.