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AAR –Dams Affected in Brazil -
Report on the Current Situation

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AAR –Dams Affected in Brazil - Report on the Current Situation

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ABSTRACT

The main purpose of this paper is to gather the Brazilian experience regarding observations, studies, research, cases registered and constructions affected by **AAR: Alkali-Aggregate Reactions** in Brazil.

Keywords: AAR; aggregate; cracks; granitic; pozzolanic material; rock flour; stressed-deformed quartz;

PRESENTATION

There are approximately 830 major dams in Brazil, that is, dams more than 30-m high. To put together this group of dams, almost 62,700,000m^3 of concrete were used since the end of the XIX century.

The occurrence of alkali- aggregate reactions was first observed in Brazil, in the beginning of the 60's during studies at the Jupiá Dam with 1,600,000m^3 of concrete. The studies on the aggregates (agate, quartzite) showed expansions caused by AAR, which made it imperative to use pozzolanic material in the concrete. At the time, the owner of the hydroelectric complex implemented a system to mill clinker to produce cement associated with a pozzolan production system from the caolinitic clay. The investigation carried on and the safety and advantages they revealed then led to the addition of pozzolanic material in all the concrete structures built by this company. Likewise, constructions built before the 60s also did not use pozzolanic materials. From the need to understand, investigate, inform and prevent the occurrence from happening, as well as evaluate the possibility of enduring it, the professionals and companies mentioned in the Acknowledgements have helped realize a summary of dam constructions affected by AAR.

INTRODUCTION

To establish a scenario of AAR in Brazil, government agencies and private enterprises, Research Institutes, Schools and Universities freelance professionals and currently employed professionals were contacted.

The number of cases, known or that are "made" known, (and here we must distinguish between what is unknown because it has not occurred and what has not been observed for lack of a statistical census or monitoring) has increased every year. By comparing data collected to reality, especially considering statistics of less developed countries, it is possible to conclude that the number of constructions affected by AAR is growing. Among the cases registered in Brazil, what comes to our attention is the occurrence of the phenomenon in structures not only of dams, where the implications are substantial, but also in structures where hydrodynamics and electrical equipment has been installed, like sluice gates, generators and turbines, where the consequences are greater. This is the case at Moxotó Hydroelectric Power Plant.

BRAZILIAN PANORAMA

In Brazil, the "granitic" aggregates, widely used in concrete works, comprehend feldspar-quartz rocks, like granite, gneiss, etc., found in a great extension of the country. Quartzites are essentially quartz rocks with restricted use as concrete aggregate. Tectonic forces of various intensities, through different geological eras, affected a great part of these "granitics" and are responsible for the development of some texture features capable of making the aggregate potentially reactive to other cement alkalis. Examples of deteriorated concrete structures at Moxotó, Joanes, Paulo Afonso, Rasgão, Billings, Pedro Beicht and other Dams are cases where these reactive "granitics" were used. The orientation of the cracks depends on internal and external constraints. The speed of development and magnitude of the deformations depend on a great number of factors; in the first place, the nature and amount of reactive aggregates available, the levels of alkalis in the cement, local temperature, moisture available and eventual restrictions. The main symptoms caused by AAR, may be noticed by a collection of information available regarding statistics and occurrence of the AAR phenomenon in Brazilian dams as follows (Table 1- up to 1999):

TABLE 1- Dams Affected by AAR

General Data				*AAR Symptom*		
Project/Dam	/End of Construction	Owner	Rock-Aggregate	Structure	Observation Period	Symptom
Paulo Afonso I	1954	CHESF	Granite-Gneiss	Water Intake; Power House	1978	a;c
Paulo Afonso II	1960	CHESF	Granite-Gneiss	Water Intake, Power House	1978	a;c
Paulo Afonso III	1973	CHESF	Granite-Gneiss	Water Intake, Power House	1978	a;c;d;f
Paulo Afonso IV	1979	CHESF	Granite-Gneiss	Water Intake, Power House	1985	a;b;c;d;e;f
Moxotó	1977	CHESF	Granite-Gneiss	Spillway, Power House	1978	a;b;c;d;e;f
Pedras	1970	CHESF	Quartzites	Dam	1990	a;c
Traição	1940	EL.PAULO	Milonyte	Water Intake; Power House	1990	B
Bilings Pedra	1926	EL.PAULO	Granite	Water Intake	1995	B
Jaguara	1971	CEMIG	Quartzite	Water Intake, Power House, Spillway	1996	b;e;f;g
Peti	1946	CEMIG	Gneiss	Water Intake; Spillway	1990	B
Furnas	1964	FURNAS	Quartzite	Spillway	1976	B
Cantareira	1974	SABESP	Granite-Gneiss	Water Intake	1989	a;b;c;f
Ilha dos Pombos	1930	LIGHT	Gneiss	Dam; Spillway	1990	b;c
Jurupará	1970	CBA	Gneiss	Dam	1995	C
Sá Carvalho	1975	ACESITA	Gneiss	Power House	1995	C
Pedro Bight	1932		Granite-Gneiss	Dam; Spillway	1995	B
Santa Branca	1960		Gneiss	Dam; Spillway	1995	B
Rio das Pedras	1970	CHESF	Gneiss	Dam; Spillway	1996	B
Joanes II	1971	COELBA	Gneiss	Dam	1994	B
(a): stressed quartz; (b): cracks; (c): opened construction joint; (d):displacements between blocks; (e): crest movement; (f): turbine movement; (g): turbine base deformation						

BRAZILIAN KNOWLEDGE

Relevant Current Research

Most current research is directed to two aspects:

- A greater understanding of the mechanisms of the reaction, and;
- Detecting the phenomenon, in the fastest and safest way.

It is important to give emphasis to the research done on “Rock Flour” and its eventual ability to reduce the expansive effects of AAR. It is reasonable to mention also all the research developed to minimize problems after the phenomenon has been detected. This would be the “therapeutic” action (**CBGB 1997**: Proceedings of the *Symposium on Alkali-Aggregate Reactivity in Concrete Structures* - Portuguese Edition-1997).

Tests on Pozzolanic Materials

The procedures described have been adopted since the 60s when these materials were first employed in concrete in mixtures containing Portland cement.

Pozzolanic Materials -- The NBR 12653/92 (Brazilian Standard), as does the ASTM, classifies pozzolanic materials in natural pozzolan and artificial pozzolan. Among the artificial types are the calcinated clays and fly ashes – main focus of the present chapter.

Development in Brazil -- The use of pozzolanic material in large concrete jobs in Brazil was implemented in studies developed during the construction of Jupiá Dam. Investigating the most abundant and economic aggregate - gravel, with a predominance of agate and quartzite – revealed a highly alkali reactive material and indicated the consequences the AAR would have to the concrete’s stability and durability. Originally, the use of Portland cement low in alkalis, around 0.2 %, was adopted. The definite solution although was to adopt the use of common cement with artificial pozzolan. Fly ash from Thermoelectric Plants in Rio Grande do Sul State were used temporarily until the installation and operation of the pozzolan plant at Jupiá Dam was completed. Research on variable sizes and indexes on resulting activity, with calcinated clay, indicated its capacity and potential.

Systematic to Evaluate Materials --

- *Clays for Pozzolan:* The proper clay for producing pozzolans, after calcinated and powdered, results in quality artificial pozzolan. Only a certain temperature interval of the calcinated clay allows for the pozzolanic qualities to take place. Pozzolanic activity varies according to the final product’s fineness. The Differential Thermal Analysis determines the endothermic and exothermic peaks of the material and can therefore obtain the best temperature interval for calcination, where clay achieves pozzolanic properties;
- *Pozzolan Testing:* Chemical analysis is performed on samples of raw clay and after calcination has taken place, for a certain temperature and fineness;
- *Fly Ash:* Fly ash produced at thermoelectric plants in the south of Brazil is high quality material, but its fineness– Blaine of 2635 cm^2/g and 52% of retained material in sieve nº 325 (typical values of annual supply) – generates low pozzolanic activity having to be powdered in order to become more active.

Tests on "Rock Flour"

Introduction -- The powdered rock also known as Rock Flour has only recently been used in concrete, more specifically in RCC (Roller Compacted Concrete), at the beginning of the Capanda RCC Dam (Angola) construction **(CBGB 1997)**. The powdered rock-aggregate passing through sieve 200 (< 75µm) is normally used mixed with artificial sand, representing the fines content after the crushing. Workability increases and permeability is reduced through the filling of the voids. Another advantage of using powdered aggregate is the reduction of alkali-aggregate expansion of the concrete. Studies on the subject were carried out, and in Brazil, publications related to this material have been referred to since the 90's **(CBGB 1997)**.

An evaluation of pozzolanic activity and efficiency in the fight against the AAR was established. Results show that the pozzolanic activity with cement varies as a function of the replacement ratio used but the general behavior was satisfactory. At Capanda Dam, the fine content present in the crushed (metasandstone rock) sand maintained a standard 10%. In Brazil, among the many dams where Rock Flour was used from crushed sand, it is important to mention:

- At the Jordão River Dam (PR), where 100% of crushed (basalt) sand was used in the RCC, the fines content was still present; the powdered material represented an 8% to 10% of the aggregate's mass;
- At Bertarello and Salto Caxias Dams 100% of crushed (basalt) sand was also used;
- At Val de Serra Dam, both natural and crushed sand were used the last with a 10% to 15% of powdered material.

Pozzolanic Activity -- The fines from some powdered sand can work similarly to a pozzolan. When using powdered aggregate as pozzolanic material the understanding of its pozzolanic activity is fundamental to establish an ideal concrete replacement rate.

Influence on the Alkali-Aggregate Reaction -- The use of powdered rock has always been a great alternative for conventional pozzolanic material especially when the last is not available as was the case at Capanda RCC Dam. The reason for the beneficial function of Rock Flour in fighting AAR is: basically, the simple replacement of cement for powdered material results in the decrease of the concentration of alkalis released during cement hydration. Besides this, a chemical mechanism occurs with the reaction between the alkalis available in the solution and the fine particles of the aggregate, in non-confined spaces, leading to a reduction of the concentration of alkalis near the aggregate's surface. During this, Rock Flour, together with the other products formed fill in the pores promoting a densification of the matrix, making it harder for alkaline species to migrate.

MONITORING OF THE STRUCTURE

Introduction- Brazilian Experience

An intensive instrumentation plan was installed, in Brazil, at Moxotó, Billings Pedras, Paulo Afonso IV, Peti (being installed) dams and hydroelectric powerplants after detecting AAR. The instruments that have turned out to be most appropriate to observe concrete deformations in dams affected by AAR are multiple rod extensometers, the no-stress extensometer and the pendulum (direct or inverted), considering it is equipped with plumb lines to show vertical movements. Inverted pendulums have recently been substituted for other instruments installed alongside vertical holes, allowing for the observation of shear sliding alongside the joints between concrete layers. The installation of jointmeters is extremely useful to observe differential sliding between blocks, to observe the closing movements after cutting joints between blocks. The installation of superficial marks along the crest is also very important to observe crest elevation of the dam and to follow the upstream deflection of the structures. The Table 2 presents the main characteristics of two dams affected by AAR and the annual concrete expansion rates observed by instrumentation usually along the vertical plane.

TABLE 2- Expansion Rates of dams affected by AAR

Dam	Construction Finished	Structure Type	Annual Expansion Rate (x 10^{-6})
Moxotó	1977	Gravity	90
Furnas	1963	Gravity	13

Although the Peti arch Dam, owned by CEMIG and built in the 40s, is the first Brazilian dam to confirm the existence of concrete expansion caused by AAR, and has superficial marks on the dam’s crest installed during construction, it was the Moxotó dam, and more accurately the Water Intake and Powerhouse, the first structures to be monitored specially for AAR in Brazil. The instrumentation plan at Moxotó was conceived in 1982 and implemented in 1984. Besides the information regarding the Moxotó Dam, there are also details from the instrumentation plan for the Paulo Afonso IV and Jaguara Hydroelectric Powerplants and the Billings-Pedras Dam.

Moxotó Project -- The Moxotó Hydroelectric Powerplant is part of the Paulo Afonso Hydroelectric Project, owned by CHESF, and having been built between 1972 and 1977. The problems caused by concrete expansion affected the dam since its construction period, causing turbine Nº 3 to have its blades touch the cover of the case in 1981, only 4 years after the equipment had been commissioned. In the months that followed the other three units revealed similar problems among others, such as axle inclination of the generating units, all caused by AAR.

During construction only some piezometers had been installed at the foundation of the Water Intake and Powerhouse, near the concrete-rock contact. In 1982, an additional instrumentation plan was set up (8 multiple extensometers; 5 direct pendulums; 4 inverted pendulums; 15 triortogonal jointmeter; 8 convergence marks; 17 superficial sliding marks), with the intention of discovering the causes to the problems with the generators considering that, at the time, AAR was unknown. The data provided by the multiple extensometers were of great value in order to identify and confirm AAR.

During the first years of observation the yearly expansion rates were quite regular, with values around 90 micro-deformations/year, upstream, and around 50 micro-deformations/year, downstream. At the end of the 80s, the cutting of the contraction joints between blocks was performed, and in the following years, expansion rates of 40 to 50 micro-deformations/year, upstream, and around 50 micro-deformations/year, downstream. In 1993, after nearly 10 years of observation of the concrete expansion rates, the multiple extensometers indicated an accumulated expansion between 500 and 650 micro-deformations. The triortogonal meters installed on the upper floors at the contraction joints between blocks, indicated differential sliding between blocks with values around:

- Opening/Closing: 0,37 mm/year
- Differential settlement: 0,46 mm/year
- Horizontal Shear displacement: 0,26 mm/year

Paulo Afonso IV Project -- The Paulo Afonso IV Dam, part of the CHESF energy generating complex is located on the São Francisco River, near the Paulo Afonso waterfalls, at the border of the States of Bahia and Alagoas. Its underground Powerhouse is 210m long and 24m wide, with a height of 54 m, and has 6 generating units with Francis type turbines and a nominal capacity of 403 MW each. The Project was built from 1975-79, the filling of the reservoir took place in Aug/79 and the six machines started operating between Dec/79 and May/83.

The first evidence of AAR at the Powerhouse of PA-IV, date from 1986, in the form of cracking of concrete structures (mostly in the area of the generators) and also as problems observed with the generating equipment, based on experience obtained by CHESF at the Moxotó Project and an geologically identical aggregate to the PA-IV. The problems observed with the equipment were basically the following:

- Inclination of the turbine-generator axle;
- Tilting of the turbine top;
- Variations in the tolerance spaces between the paddles;
- Deformation of the turbine case;

The petrography test confirmed the AAR at the concrete of PA-IV. The results found the deformed quartz (“strained quartz”) to be a reactive aggregate, but with reactivity still at an initial level, at least in the sample taken.

Further confirmation of AAR surfaced with the readings from the triortogonal jointmeters installed at the contraction joints between units, in 1988. Between Oct/88 and Jun/94 differential settlements varying from 0.25 to 0.70 mm and horizontal sliding between 0 and 0.25 mm appeared that could only be explained by a differential deformation between the concrete of the different units. These instruments indicate a tendency of the openings growing in time, independent of the thermal variations between summer and winter, another symptom of AAR.

The instrumentation plan of the concrete structures at the underground Powerhouse of PA-IV had, as main object, the determination of the concrete expansion rates (now and in the future) and the observation of structural distortions of the concrete structures near the generating equipment. Efforts were concentrated on the concrete deformation according to the vertical, longitudinal and transversal directions through the readings of basically extensometers and multiple rod extensometers. The joints between blocks were than equipped with 12 triortogonal jointmeters, besides the previously installed ones, and superficial marks installed from the floor of the generator room, to control vertical sliding of the six generating units.

Billings-Pedras Project -- Although the Billings-Pedras dam has been operating for more than 63 years and affected by AAR, the compressive strength is 25.7 MPa and indirect tension (splitting test) is 3.1 MPa, with a traction/compression ratio of 0.12. This means that it may be classified as a normal construction, without the need of repairs to improve the safety features of the structure.

As soon as AAR was detected in the concrete structures of the Billings-Pedras Dam, the monitoring plan of the concrete structures began. It was focused mainly on observing the deformations in order to characterize the concrete expansion rate and verifying how they vary with time besides eventually performing necessary repair jobs, etc.

Studies on tridimensional mathematical models were also carried out to predict the deformations that should be measured by the instruments installed in the dam. The main instruments used to monitoring the concrete expansion deformations were the multiple rods extensometers installed at the drilled holes in the concrete.

To observe concrete expansion along the longitudinal direction of the dam, the last position to be monitored in terms of deformability, four bases were installed to measure convergence. It must be kept in mind however, that the converging meters are not as precise as the multiple rod extensometers, because of the use of cable in the measuring system, the need of constant calibration and the attachments necessary at each measurement, etc. _Next to the converging bases, five superficial marks have been installed to measure vertical and horizontal sliding of the dam. Vertical sliding directly affected by concrete expansion can be this way compared to sliding measured by the multiple extensometers placed vertically.

In order to monitor eventual sliding at cracks at the joints of the dam, eight triortogonal jointmeters were installed allowing for the measurement of differential sliding between blocks, considering possible displacements, horizontal sliding and the movement of the joints. Although measuring moderate pressures is not directly associated to concrete expansion caused by AAR, it was decided to complement the instrumentation plan with the installation of 10 piezometer tubes.

Vertical concrete expansion rates at Billings-Pedras present variations from 10 to 30 μ.ε/year, with an average of 20μ.ε/year. Based on the classification suggested by **(**Silveira in **CBGB 1997)**, dams with a concrete expansion rate below 20 μ.ε/year are submitted to structural problems of little importance, or even none, which is consistent with the behavior of the Billings-Pedras Dam.

Jaguara Project -- The Jaguara Project is located on the River Grande, at the limits of the states of São Paulo and Minas Gerais. It began operating commercially in 1971 with four generators and a total capacity of 456 MW.

Concrete structures were monitored during construction with superficial marks installed at the crest of the dam, with vertical sliding being observed by periodic operations of topographic surveying. During the period from 1971 to 1996 these marks allowed for the monitoring of the elevation of the dam's crest, resulting in an average concrete expansion rate of 11 micro-deformations/year. This rate is very low if compared to other deformations of gravity type dams affected by AAR, may be because of the low rate of alkalis in the cement used at the job. During 1981, a total number of 16 mechanical extensometers were installed in the construction joints between blocks of the Water Intake, alongside the drainage galleries of the foundation. After confirming in 1996 the occurrence of AAR in the concrete structures of the powerhouse, a more detailed monitoring plan was elaborated including the installation of multiple extensometers, triortogonal joinmeters and flowmeters, and is now being implemented.

SUGGESTIONS OF THE BRAZILIAN COMMITTEE

When selecting and locating instruments it is very important to have a previous knowledge of the magnitude of the results expected so as to choose instruments with precision and sensibility. Their location must attempt to determine the deformability of the concrete in areas with different types of confinement, related to the strong influence of internal tensions, on the concrete expansion rates. Definition of the monitoring plan must be always closely related to mathematical modeling and should be according to the following stages:

- Installation of the monitoring instruments should provide, among other things, values to control the mathematical models used;
- Creation of the first mathematical model should be based on average values of concrete deformability and adjusted gradually, through an interactive process, using data produced by the instruments installed in the many blocks or by measurements taken from the electromechanical equipment of the power plant;
- After implementation of the repair work, return to calibration of the mathematical model based on data from the instrumentation, produced in this stage to evaluate the behavior of the structure in the future.

The use of instruments of adequate precision in the monitoring of concrete expansion in structures affected by AAR is very important for the success of the auscultation plan of the structure. For example, if the crest of the dam presents a 1 to 5mm variation in its vertical sliding, the measurements must have, at least, a 0.2mm precision. Measurements taken with an electronic surveying equipment, for example, may assure a precision of ± 1.5 mm for horizontal sliding and ± 0.2 mm for vertical ones, while the multiple rods extensometers will present a ± 0.05 mm precision. The precision of the direct and inverted pendulums that use optical devices, is usually ± 0.3 mm, although there are also mechanical devices, that assure a ± 0.03 mm precision of horizontal sliding. In the case of hydroelectric powerplants, where the concrete expansion interferes with the generating equipment, the instrumentation plan must contemplate the installation of instruments to measure the space between the turbine paddles and the case. These measurements can be presently made with a ± 1.0 mm/m precision.

MATHEMATICAL MODELING AND SIMULATIONS

Mathematical models of concrete structures affected by expansion from alkali-aggregate reactions are created as a way to predict tendencies of the expansion, in order to program rehabilitation actions that will eventually be necessary, as well as to provide for the evaluation of the actions taken. The first models used simulated expansions as imposed deformations. This procedure was used, at Moxotó dam, in the tridimensional study by **(**Silveira **in CBGB 1997)** of a typical block of the complex formed by the Water Intake and the Powerhouse.

The modeling technique with equivalent thermal dilatations was improved with the use of structural analysis programs that consider the thermal dilatation of each different direction, allowing for the representation of the anisotropy of expansion. Representation of heterogeneity is still a problem however, because of the uneven distribution of the reactive substances in the body of the structure and the action of compressive stresses, that reduce expansion and, depending on the intensity, may even inhibit expansion completely.

Models may be calibrated with the help of optimization techniques used in the identification problems of systems, like the retroanalysis technique, as demonstrated by **(**Bernardes in **CBGB 1997)**.

THERAPEUTIC MEASURE APPLIED IN BRAZIL

The Brazilian condition on this respect is still very precarious not having an established systematic. It must be mentioned the works developed at CHESF, at Moxotó Dam, on the lines of deformation release.

COMMENTS

The main comment is that the experience related to AAR need be disseminated to mitigate its risks.

REFERENCES

CBGB 1997- Brazilian Committee on Large Dams – Furnas Centrais Elétricas SA- *Proceedings of the Symposium on Alcali-Aggregate Reactivity in Concrete Structures*, Goiânia- GO- Brazil; 1997- Portuguese Edition;

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