Alkali-Aggregate Reaction at Moxotó Dam, Brazil

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ABSTRACT

A severe cracking in the concrete structures was observed at Moxotõ Dam and it was also noticed that the turbines had moved as much as 2 mm. The drilled cores showed that alkli-silica reaction was present throughout, although the extent of the reaction and the deleterious effects produced are widely variable. The paper deals on the extent of distress and describes the present condition of the dam's concrete structures and the investigation works being conducted

INTRODUCTION

Moxotõ Dam is located in Northeastern Brazil and is a part of the Paulo Afonso hydro generating complex operated by Companhia Hidroelétrica do São Francisco - CHESF.

The Hydro Power Plant consists of an earthfill and rockfill dam and concrete structures: a spillway and a combined intake - power house (36-55 m high). The concrete blocks have a 30.5 m crest length and the power house features 4 generating units rated 110 MW each, driven by Kaplan turbines.

The construction of the concrete structures began in 1972 and was completed in 1977.

DISTRESS HISTORY

After 1980 it was observed that many cracks had developed in the concrete, mostly on the thin parts of the structure, such as the turbine and generator floors and generator walls. Some of these cracks on the generator walls were coincident with the construction joints, and some were vertical to the floor. Thereafter, severe cracking has been observed in the concrete supporting the water-power equipment, as well as inside and outside of the turbine-shaft chambers. Some of the cracks were more than 1 mm wide in many locations and were oriented in various directions. It was observed that the cracks were slowly increasing in width with time. By 1980, the turbines had moved as much as 2 mm in a north-easternly direction (or the casings had moved this distance in the opposite direction). During 1983 the turbine blades touched the northeast side of the draft tube and were found to be 3 to 7 mm off center. All the units have been submitted to new centralization. The number 3 unit, that was recentralized in 1983, will require another this year (1986).

The concrete structures, mainly the generator and turbine floors and the generator wall, are showing progressive opening of the cracks. The contraction joints between blocks are opening above the generator level and are closed at the levels below. This could be explained by different concrete expansion due to different moisture ratios on concrete.

CONCRETE REACTION

The petrographic examination of the coarse aggregate shows that the "predominant constituent is a series of biotite-hornblende granites that are hard to moderately hard, massive, and medium to coarse grained in texture. Biotite mica is the predominant characterizing accessory mineral. The biotite and hornblende occupy intergranular spaces among the interlocking crystals of quartz, microcline and oligoclase. The microcline is characteristically pale to dark pink whereas the plagioclase is white. The quartz is clear and colorless to white varying from unstrained to moderately strained. The biotite is commonly partially altered to chlorite. Microcrystaline calcite and epidote-group minerals are common secondary products of hydro-thermal alteration".

Some core samples were drilled from different parts of the structure and submitted to petrographic examination. It was observed that the alkali-silica reaction was present throughout the specimens although the extent of the reaction and the deleterious effects produced were widely variable. Some of the cores presented an advanced degree of distress including major tensile cracking, while some did not have any cracking, and some displayed minor cracking of affected aggregate particles at depth. Although the core samples displayed a wide range of the alkali-silica reaction development, it was evident in all the samples, most notably in the occurrence of darkened reactions rims and the presence of variable quantities of alkali silica gel.

It is likely that the variation in development of the reaction from place to place is the result of the difference in access of moisture and ambient temperature.

CONCRETE AND CONSTRUCTION CHARACTERISTICS

All the mixes used for the construction of the power house of the Moxotō Dam were found to have a large amount of cement, in the range of 350 kg/m^3, to meet a specified strength of 210 kgf/cm^2 (28 days). For some of the structures, concrete was placed through pump, due to the impossibility of using conventional methods of placing. The water/cement ratio was 0.45 to 0.50, the slump was 6 to 8 cm, and the maximum size of aggregate was 38 mm. Because of the high environmental temperatures, retarders were used for all mixes. Although precooling is largely used for mass concrete in Brazil, it was not applied in this construction.

As for cementitious material, Portland cement type I ASTM was used, and the use of four different brands was recorded, some having alkali content superior to 1.0%. No pozzolanic material was used to substitute part of the cement.

INVESTIGATION PROGRAM

Some investigations are being held with the aim of estimating the potential expansion produced by alkali-aggregate reaction, and to verify what can be done to minimize the damaging effects on the concrete structures.

Instrumentation

The concrete structures of Moxotō were not instrumented. So, a program of permanent monitoring was elaborated, comprised of multiple rod extensometers, direct and inverted pendulae, triorthogonal joint meters and geoldectic survey points. (See Fig. 1.)

Since July 1984 the multiple rod extensometers have shown an average annual specific strain of 0.082 mm/m at the upstream portion and 0.040 mm/m at the downstream portion. The specific strain at the upstream zone coincides with the value obtained on the mathematical model, for a rate of volumetric expansion of 10^{-4} on the zones most subject to expansive reaction (concrete in contact with water).

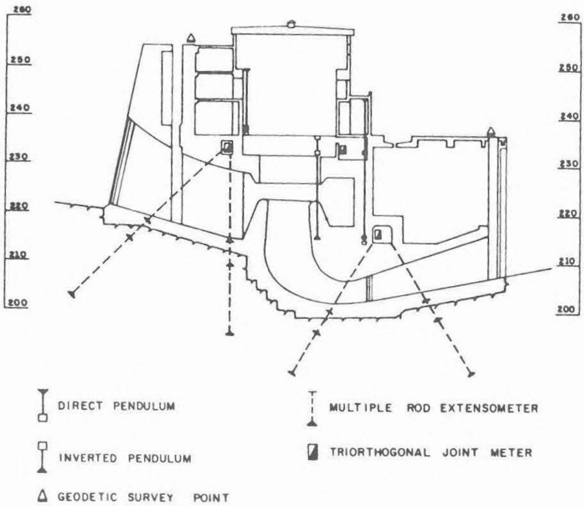

FIGURE 1: INSTRUMENTATION SCHEME

Mathematical Model Studies

A tridimensional simulation using a finite element model was performed in order to study the resulting effects of expansion in a typical concrete block. The model has 2,430 hexagonal elements and 48 linear elements, in a total of 3,803 nodal points, and the SAP IV program was used.

Some simulations were made with an expansion rate of 10^{-4} on concrete in contact with water, in two different situations: with open and closed contraction joints. The results with closed joints have shown total agreement with the observations made at the structures and the behavior of the mechanical equipment.

Influence of Temperature

In order to estimate the expansion rate, some tests were made with aggregates from Moxotó, according to ASTM C-227 (Mortar Bar Test). A modification was introduced to include a test condition with a temperature of 60°C. The partial results are in Table 1, the expansion was less than 0.1% after 6 months, but it is clear that the temperature of 60°C has accelerated the reaction.

The influence of temperature is also being estimated by tests on cores drilled from the structure and submitted to temperature conditions of 60°C.

TABLE 1

MORTAR BAR EXPANSION OF MOXOTÓ AGGREGATES
(Na_2O + 0,658 k_2O of cement = 1.04%)

Petrographic type	QUARTZ %	QUARTZ Undulatory extinction angle	EXPANSION (%) 37.8°C ± 1.2°C 3 Months	37.8°C ± 1.2°C 6 Months	60.0°C ± 2.0°C 3 Months	60.0°C ± 2.0°C 6 Months
Granite	30	20°	0.023	0.024	0.046	0.049
Granite	25-30	18°	0.025	0.024	0.044	0.044
Cataclastic granite	20-25	24°	0.027	0.027	0.036	0.035
Biotite granite	20-25	18°	0.023	0.027	0.037	0.039
Diorite gneiss	-	13°	0.026	0.029	0.038	0.040
Biotite granodiorite	20-25	17°	0.024	0.025	0.035	0.039
Biotite granodiorite	15	10°	0.020	0.026	0.039	0.049
Anorthosite microcline	-	-	0.021	0.021	0.026	0.032
Mixture	-	-	0.021	0.021	0.037	0.042
Sand	-	-	0.018	0.025	0.037	0.048

Influence of Moisture

The effect of moisture on the development of alkali-silica reaction is being studied in cores drilled from the structures, saturated in water and sealed. The results of these tests will indicate the effects of sealing of saturated concrete, a condition that will reflect upon the possible effect of waterproofing portions of the structure subject to immersion. It must be known if such seal will allow reductions of internal humidity sufficient to impede or prevent progressive expansion of the concrete.

Influence of CO_2 on the Reaction

The effectiveness of the technique of maintaining concrete in an atmosphere of water-saturated carbon dioxide is being studied, in order to control further expansion. The study consists of tests in specimens drilled from the structure and in a molded concrete block.

A small diameter bore hole will be drilled on the drilled cores, followed by injection of water saturated carbon dioxide under a pressure of 2 kgf/cm^2, for 30 days. The depth of penetration of carbon dioxide from the surface can be determined by examination of sawed cross sections of the core, during which the extent of carbonation of the matrix is determined microscopically and chemically.

For a practical verification of this process, a concrete block of 1 m^3 was molded with the same materials and mixture of the ones used for the concrete structures of Moxotó, but with a substitution of 20% (in weight) of aggregate by pyrex glass. When the expansion will be characterized, the injections of CO_2 will be executed for 1 month, with pressure of 2.0 kgf/cm^2 through a central hole.

Depending on the results obtained with the cores and the block, "in situ" tests will be performed on the structures. A part of the structure showing expansion was chosen and some holes will be drilled to allow the injections of CO_2 at a depth of 1.5 m. Cores drilled midpoint between injection holes will show to what extent the reaction had been mitigated.

Opening of Transversal Joints Between Blocks

At the present, there is no practical way of stopping the reactive process. For this reason, the operation of the power plant has been possible through interventions on the mechanical equipment. Nevertheless, if the present rate of concrete expansion continues, there will be no possibility of turbine recentering after 1997. Taking into account this situation, the results of the opening of contraction joints between the concrete blocks were studied by mathematical model. The effects of this solution on the mechanical equipment were: tensile stress relief on the stay vanes and supporting concrete cone, lesser ovalization of turbine discharge ring and generator stator. This will allow the power house operation for a much longer period.

It seems that the most suitable technique for cutting the joints is with helicoidal wire and silicon carbide (carborundum) as abrasive. This technique was used in Brazil for cutting two vertical joints at Itaipu Dam, in a concrete block 19 m wide and 30 m deep. The work lasted for three months, which makes 190 m^2/month.

The cutting of transversal joints at the Moxotó power house is planned to start during the next months.

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