INVESTIGATION AND ASSESSMENT OF ALKALI AGGREGATE REACTION (AAR) IN THE PIRAPORA DAM

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Abstract

The increase in understanding of the mechanisms and effects of alkali aggregate reaction (AAR) in concrete since the 1990s has allowed for a correlation between visual symptoms existing in the Pirapora Dam and AAR monitored over the years. Due to the significant evolution of the surface map cracking and subparallel cracks presented, a study was developed to characterize the concrete of the Dam and the expansive reactions resulting from AAR sulphate contribution that affect the Dam. This study includes the mapping of the anomalies and testing, as the evaluation of the physical and mechanical properties of concrete, petrographic analysis, and determination of the alkali content and residual expansion of samples.

It was possible to assess the evolution of the expansive reactions in concrete and the Dam durability conditions, taking into account the environmental conditions and factors that are important for the determination of the most appropriate mitigation and recovery measures for the structure.

Keywords: alkali aggregate reaction, petrography, gravity dam

1 INTRODUCTION

The occurrence of expansive reactions in the Pirapora Dam was first observed in the 1990s after the expansion of the dissemination of this phenomenon in technical media.

Visual symptoms of the occurrence of expansive concrete reactions in the Pirapora Dam are mainly concentrated in the spillways and buttress in the trunnion beams area (downstream side). Concern regarding the possibility of pathological picture advancement impairing the operation of the floodgates guided this study.

This article aims to present a characterization of the dam's concrete and the expansive reactions that affect it, stemming from AAR and sulphate attack.

To this end, the visual inspection and tests performed include an assessment of exposed – concrete using ultrasound; determination of the water absorption, void ratio and specific mass (density); determination of the residual mechanical properties; petrographic analysis complemented by electronic scanning microscopy; and determination of the alkali content and residual expansion.

These techniques have effectively been applied to real structures, and the results obtained and their interpretation are of great value in determining the course of action in similar situations. In this article, the aim is to expose how some of the tests, which have been extensively studied from an academic perspective, can be used in other civil engineering applications involving diagnosing structures with infrequent expansive reactions.

2 INVESTIGATION OF ALKALI AGGREGATE REACTION (AAR) IN THE PIRAPORA DAM

2.1 General

The Pirapora Dam, located in Pirapora de Bom Jesus, SP, Brazil, was built in 1956 to retain the flow of the Juqueri River and to harness it for power generation in the Henry Borden Power Plant, in Cubatão, SP. It is a gravity dam built from reinforced concrete, containing of buttresses and a wide base wall that incorporates a spillway with two openings. The dam is approximately 85 m long in the crest and 25 m in height. Figure 1 illustrates the Pirapora Dam.

The investigation of the Pirapora Dam's pathological scene began in 2013 and was structured in 11 steps:

1. Collection and analysis of data from the project, construction, operation, and instrumentation;

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2. **Visual inspection, registration of anomalies in structures, and implementation of non-destructive testing;**
3. Dynamic tests to determine the mechanical properties of the structures;
4. Mathematical models and calibration with experimental results;
5. Structural safety evaluation;
6. **Characterization of the AAR parameters and constituent materials;**
7. Development of a three-dimensional mathematical model and dam behaviour simulation;
8. Evaluation of alternatives for mitigation;
9. Simulation using mathematical models calibrated for possible interventions in structures;
10. Basic project for implementation of the adopted solution;
11. Preparation of a long-term monitoring project.

This article addresses steps 2 and 6.

2.2 Methods for assessment and analysis

It was indicated by Founier and Bérubé [1] that the advanced AAR investigation in structures involves detailed visual site inspection, mechanical testing, petrography, alkali measurements, core expansion testing, and structural investigations. The developed activities were structured similarly as follows:

Visual Inspection

Visual inspection conducted at the Pirapora Dam aimed at mapping the anomalies presented by the concrete structures as well as their classification and quantification.

To this end, the structures were accessed by industrial climbing techniques by trained professionals who recorded, among other information, the type, size, precise location and criticality of each abnormality according to a predetermined pattern.

The collected data were recorded through spreadsheets and drawings.

Concrete Assessment by the Ultrasonic Pulse Velocity (UPV) Test

Before carrying out the laboratory tests, the concrete cores was assessed in terms of homogeneity and compactness using ultrasound, following the requirements of the Brazilian National Standards Organization (ABNT) NBR 8802:2013 [2] and ASTM C597-09 [3].

Samples were tested using the direct method at a frequency of 54 Hz.

The test consists, in a simplified manner, of the emission of ultrasound waves by a generator-and-receiver circuit, which transmits waves to the samples through a transmitting transducer and receives waves through a receiving transducer, recording the time required for the waves to traverse a known length of the material and calculating the speed thereof. The wave propagation speed is related to concrete quality in regard to its compactness and homogeneity and is strongly reduced by the presence of voids and cracks within the samples.

Determination of Water Absorption, Void Ratio and Density

The test procedure specified by standard ABNT NBR 9778: 2009 [4] consists of drying and weighing of the concrete samples or specimens, which are then saturated with water, boiled and reweighed. With the amounts obtained, the absorption, void ratio and density of the samples are estimated. The results indicate the quality of concrete regarding the absorption and void ratio, that is, properties that influence its durability.

Residual mechanical properties of concrete

As noted by Mehta and Monteiro [5], the expansion and cracking of concrete due to expansive reactions can lead to a loss of resistance and a decrease in the deformation modulus. Founier and Bérubé [1] further argued that studies report a loss of concrete tensile strength on the order of 40-80%. Accordingly, the axial tensile load resistance, elastic (Young's) modulus and tensile strength of concrete were measured.

The compressive strength may be related to the concrete durability, as shown in standard ABNT NBR 6118:2014 [6]. Marzouk and Langdon [7] affirmed that many authors indicate that the loss of compressive strength due to AARs affects concrete, yielding values of 40-60%, and that the aggregate type (highly or moderately reactive aggregate), among other parameters, greatly influences the loss of mechanical properties of concrete. They also note that normal strength concrete had a worse performance than high strength concrete related to the loss of mechanical properties by AAR.

Thus, specimens were extracted to conduct this test using a diamond hole saw. The reference standard used was ABNT NBR 5739:2007 [8].

The concrete elastic modulus, obtained by tests according to ABNT NBR 8522:2008 [9] specifications, can also be reduced over time from eventual hairline cracks, which may result from expansive reactions.

Thus, specimens were also extracted to conduct this test with the use of a diamond hole saw.

As with the concrete's compressive strength and modulus of elasticity, its tensile strength can be affected by hairline cracks, which may result from expansive reactions.

To assess this property, specimens were extracted to conduct this test in accordance with standard ABNT NBR 7222:2008 [10] using a diamond hole saw.

Petrographic analysis, stereoscopic and optical microscopy and scanning electron microscopy (SEM)

To identify the expansive reactions in concrete, it is essential to carry out a petrographic analysis of concrete combined with techniques such as scanning electron microscopy. In this way, one can not only determine the potential reactivity of aggregates but also the presence of any products of reactions, among others. The tests follow standards ABNT NBR 7389:1992 [11], ABNT NBR 15577-3:2008 [12] and ASTM C856-83:1983 [13] and were conducted by ABCP (*Associação Brasileira de Cimento Portland* – Brazilian Portland Cement Association).

Determination of the alkali content

Using this assay, the soluble and total alkali contents are obtained as well as the alkaline equivalent in Na_2O, whose value is limited in new concrete to 0.6% based on the standard ASTM C-150 [14].

Because the alkali-aggregate reaction consumes the developing concrete alkalis, the amount of alkaline equivalent may also be used to assess the progress of the reaction: the less remaining alkali in the material, the smaller the greater the degradation potentially caused by the alkali-aggregate reaction over time.

Determining the residual expansion in concrete specimens

The test, conducted over one year, is intended to assess the potential for residual expansion of concrete specimens and to estimate the trends for material behaviour with respect to the expansive reactions presented. It was performed according to Standards NBR 15577-1 [15] and NBR 15577-6 [16].

The amounts of samples were defined following three principles:

1. Standard requirements;
2. Minimizing damage to the Dam caused by concrete core extraction;
3. Availability of results from the tests performed after the disclosure of AARs in the structure, obtained from step 1 of the pathological scene investigation.

3 RESULTS

Visual Inspection

Among the anomalies possibly caused by the expansive reactions in concrete, the exudation of whitish-efflorescence materials and/or products of the reactions were observed. The mapped cracks showed a maximum opening between 0.3 and 2.0 mm, and spalling of concrete was observed, arising from the development of cracks, as illustrated by Figures 2, 3 and 4.

Moreover, spots and areas affected by other abnormalities were mapped, such as concrete surface erosive wear.

When necessary, the visual inspection was complemented by the prospecting of elements, demonstrating the suitable condition of conservation of embedded armours.

Concrete Assessment from the Ultrasonic Pulse Velocity (UPV) Test

The results are presented in Table 1.

Determination of Water Absorption, Void Ratio and Density

The results are presented in Table 2.

Residual mechanical properties of concrete

The results are presented in Table 3.

Petrographic analysis, stereoscopic and optical microscopy and scanning electron microscopy (SEM)

From the conducted tests of two samples, as illustrated in Figures 5 and 6, the following results were obtained:

- An absence of fracturing or hairline cracks, but poor adhesion between mortar and coarse aggregate;
- Rare presence of reaction edges in the vicinity of the aggregates;
- Presence of potentially reactive coarse granite aggregate with locally recrystallized microgranular quartz and deformed quartz with undulating extinction;
- Potentially reactive small aggregate with quartz fragments composed of microgranular quartz;
- Needle-like fibro-radiated crystals of ettringite deposited in pores in the shape of clumps or large masses in the paste-aggregate interface;
- High porosity;
- Presence of AAR-typical minerals in the aggregate-mortar interface;
- Large amount of AAR gel in the pores and around the coarse aggregates;
- Evidence of the occurrence of an alkali-silicate reaction;
- Heterogeneous distribution of expansive reactions in the samples.

Determination of alkali contents

The alkaline equivalent in average Na_2O, calculated from the contents of soluble alkalis in the two samples, is 0.075±0.015%, a low amount that renders the application of high intensity mitigation measures unnecessary at the moment.

The alkali equivalent in average Na_2O, calculated from the total alkali contents of the two samples, however, is 2.66±0.55%, which his notably higher than the threshold amount of 0.6%.

Determining the residual expansion in concrete specimens

It was found that the residual expansion was very low, reaching 0.1% in the two tested samples after a 1-year period of testing.

The limit for expansion during this period was 0.4%. As the results are below 0.4%, it can be stated that the residual expansion of the samples is presented within the permissible limit.

4 DISCUSSION

Analysis of the results allowed us to attest that the concrete of the analysed samples showed good performance when subjected to UPV testing, which indicates the absence of cracks and concrete failure within the witnesses, as well as good to high compactness. According to the standard indicated by Cánovas [17], the concrete samples analysed are classified as high quality to durable based on their homogeneity and compactness.

In analysing the results according to the parameters proposed by CEB 192 [18], the samples exhibit poor to average quality with respect to absorption – i.e., medium to high absorption – and moderate to good quality with respect to the void ratio, a property that may be related to compactness.

It is worth mentioning that the Brazilian standard ABNT NBR 6118 for concrete structure design, 2003, incorporates criteria that consider both the bearing capacity of the structure and its durability against the environment, reflecting changes noted by the technical community.

Because the Pirapora Dam was inaugurated in the 1950s, the above rule was not enforced at the time of its construction and therefore was not considered in this project. However, these new concepts are of great importance and must be applied to the analysis of the structure.

Applying the correction coefficients to the results obtained in the laboratory, it was found that the average resistance to compression of the samples was 33.7±6.2 MPa, lower than the 40 MPa currently required by ABNT NBR 6118: 2014 [6] for concrete exposed to environments with Aggressiveness Class IV.

Because the experimental elastic modulus amount of the concrete at the time of construction has not been achieved, a comparison of the results achieved with the calculated theoretical amounts was performed according to ABNT NBR 6118:2014 [6].

It was found that the experimental secant modulus of elasticity and the tangent modulus of elasticity of the concrete were higher than those of the theoretical module, appearing close to the amounts indicated in Table 8.1 of the standard for concrete classes C30 and C35 (E_{ci} = 32±3 GPa e E_{cs} = 29±3 GPa).

The tensile strength of the concrete experimentally obtained by diametrical compression showed a value of 3.2±0.3 MPa, that is, 5% higher than the theoretical average value calculated according to ABNT NBR 6118:2014 [6] based on the compressive strength results obtained in the tests previously described.

It was also noted that the tensile strength and elastic modulus were not reduced relative to their theoretical values, as could occur from the AAR and DEF, indicating that the expansive reactions did not significantly affect these concrete properties.

It is noteworthy that performing UPV tests on the samples is particularly recommended because it allows proof of their integrity before the determination of their resistance to axial compression. As the value of this property was used to calculate the theoretical values of the tensile strength and elastic modulus, it is noted that impairment in the evaluation of the concrete's strength against compression affects the analysis of all analysed mechanical properties.

Through petrographic analysis, it was verified that, in addition to AAR, the concrete shows DEF. The low content of soluble alkalis, however, indicates that there are few alkalis available for the continuation of the AAR at the moment. Indeed, the samples were approved in the assessment for residual expansion, indicating that the pathological condition resulting from the expansive reactions should not evolve significantly in the future, unless the total alkalis are released to the environment.

5 CONCLUSIONS

It is concluded that the Pirapora Dam exhibits significant cracking conditions, with areas of lesser extent than other abnormalities identified upon visual inspection. It is further concluded that Pirapora Dam's concrete shows expansion through AAR and DEF, but its mechanical properties are not compromised, and a significant evolution of the expansive reactions is not expected as long as the total alkalis are not released into the environment.

As for the other features related to the durability of the material analysed, it was found that the concrete, despite having a compressive strength lower than that currently recommended by NBR 6118:2014 for concrete in Aggressiveness Class IV environments, that is, the classification applicable to the Pirapora Dam, and medium to high absorption, it presents satisfactory homogeneity and compactness.

Thus, it is understood that interventions to mitigate widespread or highly complex expansive reactions will not be necessary for the Pirapora Dam because they could be limited to the most affected areas – the buttress. Furthermore, logically, it is necessary to apply protection systems with chemical and high abrasion resistance given the exposure conditions and steam permeability, allowing the evaporation of the water present inside the elements, but preventing liquid water from entering the elements. This measure is important given that both AAR and DEF depend on the presence of water for their development.

The results also suggest the prioritization of activities and provide essential data to conduct the next steps for the structure's assessment, including the development of numerical models.

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TABLE 1: Results - Concrete Assessment from the Ultrasonic Pulse Velocity (UPV) Test.

Test	***Sample size***	**Mean**	**Coefficient of variation**
Ultrasonic Pulse Velocity (m/s)	16	4262	8.0%

TABLE 2: Results - Determination of Water Absorption, Void Ratio and Density.

Test	***Sample size***	**Mean**	**Coefficient of variation**
Water Absorption (%)	2	4.95	30.0%
Void Ratio (%)	2	11.75	25.9%
Density (g/cm³)	2	2.68	0.2%

TABLE 3: Results - Residual mechanical properties of concrete.

Test	***Sample size***	**Mean**	**Coefficient of variation**
Compressive strength (MPa)	6	33.7	18.4%
Elastic modulus – E_{ci} (GPa)	3	26	27.0%
Elastic modulus – E_{cs} (GPa)	3	25	27.0%
Tensile strength – fct,sp (MPa)	2	3.2	9.5%
Tensile strength – fct (MPa)	2	2.6	27.3%

FIGURE 1: Downstream side (a) and upstream side (b) of Pirapora Dam.

FIGURE 2: Map cracking and efflorescence of the buttress side (a) and trunnion beam area (b).

FIGURE 3: Map cracking chalk lined on the buttress top - (a) and (b).

FIGURE 4: Cracks on the dam spillways – (a) and (b)

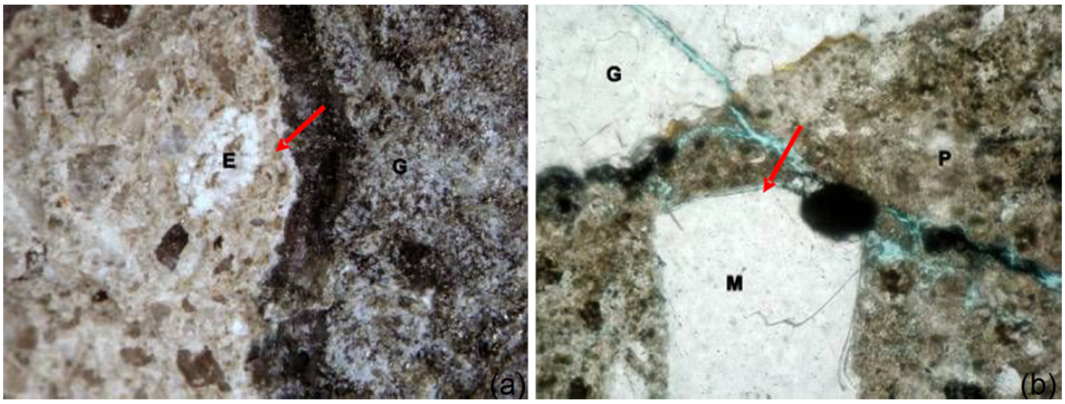

FIGURE 5: Ettringite (E) in the pores of the concrete magnified by 12x (a), and crack between the aggregate and mortar filled with the reaction gel, magnified by 100x (b) (ABCP).

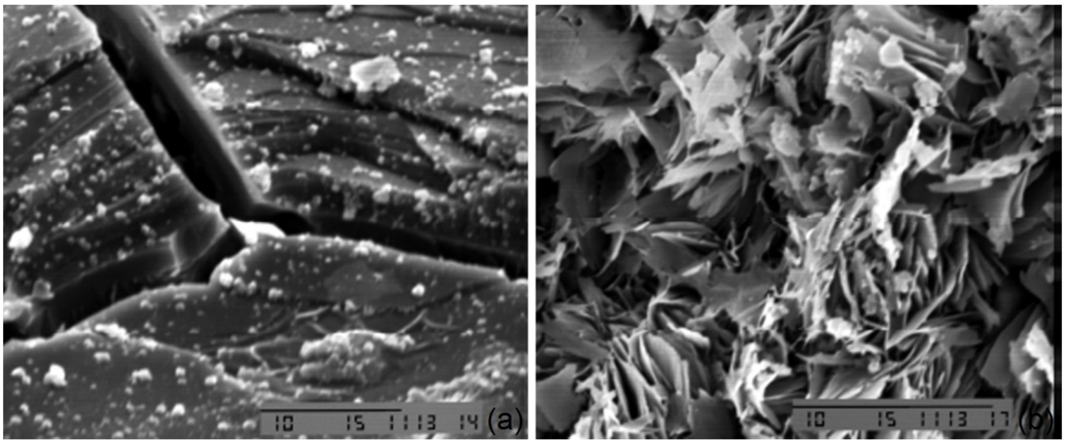

FIGURE 6: SEM images magnified 2500x (a) and 3000x (b) of the gel reaction and AAR crystals, respectively (ABCP).