
This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Expansions in a concrete dam with bridge over spillway in South America

PLEASE CITE THE PUBLISHED VERSION

<https://www.wiley.com/en-us/Swelling+Concrete+in+Dams+and+Hydraulic+Structures:+DSC+2017-p-9781786302137>

PUBLISHER

Wiley-ISTE

VERSION

AM (Accepted Manuscript)

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Blanco, Ana, Sergio H. Cavalaro, Ignacio Segura, Luis Segura-Castillo, and Antonio Aguado. 2019.
"Expansions in a Concrete Dam with Bridge over Spillway in South America". figshare.
<https://hdl.handle.net/2134/32324>.

Expansions in a concrete dam with bridge over spillway in South America

Case study with expansions of different origin

A. Blanco*, **S. Cavalaro***, **I. Segura****, **L. Segura-Castillo*****, **A. Aguado***

**Universitat Politècnica de Catalunya
Jordi Girona 1-3,
Barcelona 08034
Spain*

*ana.blanco@upc.edu
sergio.pialarissi@upc.edu
antonio.aguado@upc.edu*

***Smart Engineering SL
Jordi Girona 1-3, ParcUPC K2M,
Barcelona 08034
Spain
ignacio.segura@smartengineeringbcn.com*

****Universidad de la República
Julio Herrera y Reissig 565,
Montevideo 11300
Uruguay
lsegura@fing.edu.uy*

ABSTRACT. A gravity concrete dam built 61 years ago in South America is diagnosed due to the cracking and signs of deterioration detected in the spillway and other elements. Besides the interest to identify the causes, the authorities are concerned by the structural effects on the concrete slab road bridge that is supported on the spillway. This road is one of the main routes for transportation of the country. A comprehensive diagnosis on the state of the dam is presented, including research of the historical documentation, visual inspection of the dam, performance of tests and numerical simulations. The case study is particularly interesting since several phenomena occur, including expansive reactions of different origin.

KEYWORDS: gravity dam, expansions, alkali-silica reaction, DEF, finite element method

1. Introduction

Expansions in concrete dams may be generated by different causes such as chemical reactions or physical phenomena. The most frequent cause is the alkali-aggregate reaction (AAR) (Stanton 1942; Hobbs 1988; Mehta *et al.*, 2006). Therefore, most of the expansive reactions in dams reported in the literature correspond to AAR (Shayan 1988; Regamey *et al.*, 1995; Ulm *et al.*, 2000, Saouma *et al.*, 2007), even though several cases were reported on internal sulfate attack (ISA) (Chinchón *et al.*, 1995; Ayora *et al.*, 1998; Oliveira *et al.*, 2013a; Oliveira *et al.*, 2013b; Oliveira *et al.*, 2014; Chinchón-Payá *et al.*, 2015) and alkali-carbonate reaction (ACR) (Neville 2004; Blanco *et al.*, 2015). Nevertheless, sometimes the structural response of the dam and the signs of deterioration may not be explained by a single source. In such cases, the diagnosis and evaluation gains special interest due to the scarcity of cases reported in the literature and because they may serve as a valuable example for future diagnosis.

The objective of this paper is to present the comprehensive diagnosis of a concrete dam build 60 years ago in South America with significant cracking and other signs of deterioration that might be attributed to an expansive phenomenon. The outcome of the study reveals that the expansions generated in the dam are caused by a delayed ettringite formation (DEF) and a subsequent ASR.

2. Description of the dam

The dam is located in South America, less than 100 km of coast and was built in 1955 as an infrastructure for the water supply for the capital of the country. The dam consists of a plain concrete Creager spillway of 100 m of length. The slopes of the spillway are 1:20 in the upstream face and 1:0.63 in the downstream face, being its maximum height from the foundations is 14.0 m. The spillway is divided in concrete blocks of 15.0 m of width, with the exception of the central block that is 7.1 m wide.

The concrete spillway provides support to the piles of a reinforced concrete slab road bridge that crosses a river (see Figure 1a). The thickness of the slab is 0.39 m and it is divided in three parts: a central part of 7.10 m of length and two continuous parts that are supported every 5.0 m. The piles are 0.35 m thick with the exception of the ones supporting the central part which are 0.40 m. The piles were built in two stages with a vertical joint in their axis. The control valves are accessible from the road by means of a concrete stairway located at the central span of the bridge.

Consolidated soil dikes with lengths of 451 m on the left side and 231 m on the right side provide access to the bridge. The width of the dikes is 61.3 m at the base and 9.8 m at the crest. Unreinforced concrete retaining walls contain the dikes.

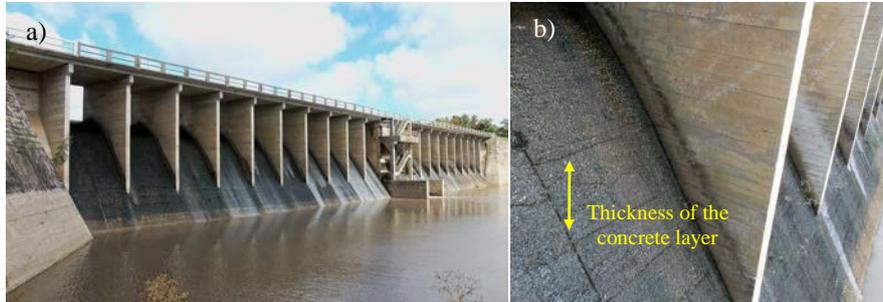


Figure 1. View of the downstream face of the dam and the bridge over the spillway.

3. Current state of the dam

The spillway exhibits horizontal cracks both in the downstream and in the upstream faces that correspond to construction or filling joints (see Figure 1b). This cracking was also reported in previous studies dating from 1989 and 1996, and was described as non-continuous and with no signs of infiltrations. The structure of the stairway is one of the elements of the dam that presents more signs of degradation of the concrete, including loss of concrete cover, deformation of the reinforcement and corrosion. These phenomena are observed in reinforced concrete elements such as columns or walls of the structure.

The piles of the bridge that are supported on the spillway also present signs of degradation of different sort, including erosion of the surface, corrosion of the reinforcement and three types of cracking. The first type are cracks that develop perpendicularly from the contact area with the spillway (see Figure 2a). The second type are vertical cracks along the axis of the pile that correspond to a construction joint since the piles were constructed in two stages (see Figure 3b). The third type of crack is induced by the corrosion of the reinforcement and develop vertically according to the position of the rebars in the pile.

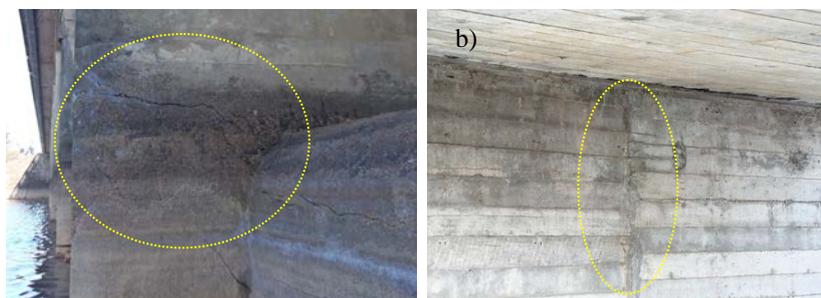


Figure 2. Cracks in piles: a) in the contact with the spillway and b) in construction joints.

The deck of the bridge does not exhibit significant signs of deterioration. The retaining walls of the dikes exhibit map cracking in the upstream face and both horizontal cracks and map cracking in the downstream face.

4. Historical documentation

The study of the historical documentation available on the construction and the service life of concrete structure is paramount to provide a diagnosis of their current state. In this particular case, the documentation of the dam is scarce. A descriptive report of the original project and the construction plans dating from 1950-1952 were available. However, no record is available from the construction procedure nor incidents that may have occurred at the time. The information regarding the concrete mix and its components is not accurate.

Regarding the operation and management period, the historical documents and reports reveal that the horizontal cracking in the spillway appeared shortly after the construction since repair and maintenance operations were already conducted in the decade of the 60's. Furthermore, the dam is not instrumented and thus no records are available of the evolution of displacements through the years.

5. Microstructural analysis

The evaluation of the concrete microstructure was performed by using different techniques on samples (mortar and aggregate) obtained from the dam in 2015, including X-Ray Diffraction (XRD), scanning electron microscope with energy dispersive spectroscopy mode (SEM-EDS) and petrography. The tests were conducted in facilities of the University of Barcelona (Serveis d'Anàlisi del CCiT) and the University of Alicante (Servicios de Análisis) in Spain.

The aggregates samples analyzed correspond to metamorphic rocks, mainly quartzite, quartzitic schists and chalcedonies, which are potentially reactive aggregates and may induce ASR. Even though no signs of amorphous silica were detected, other characteristics were observed in the optical microscope that, according to the literature, suggest their reactivity such as small size of the grain, low crystallinity and presence of undulatory extinctions. The XRD and SEM-EDS analyses of the concrete samples have confirmed the presence of an ASR. Amorphous gel was detected in the samples as shown in Figure 3. The EDS analysis showed it was a product of the ASR in an advanced stage of the reaction due to the ratio between the calcium and potassium peaks.

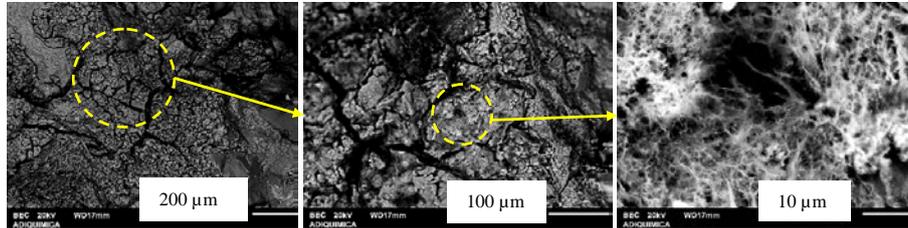


Figure 3. Alkali-silica gel.

Likewise, massive presence of a sulfoaluminate phase at an incipient stage (monosulfoaluminates phases) and an advance stage (ettringite). In some samples, the ettringite needles were particularly long (see Figure 4a and 4b), which suggest a slow formation process over time. Furthermore, in several samples the sulfoaluminate phases are covered by products of the ASR (see Figure 4c and 4d), which is confirmed by the EDS analysis.

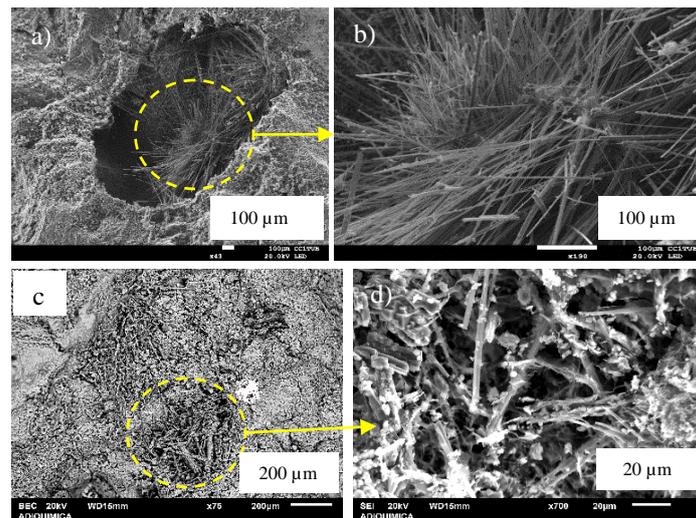


Figure 4. a) Ettringite needles, b) detail of ettringite needles, c) sulfoaluminate phases covered by product of reaction and d) detail of the ettringite needles covered by the gel.

The presence of ettringite in concrete samples that are more than 60 years old is an evidence of a sulfate attack, either internal or external. Given that the minerals in the aggregates are not susceptible of causing an internal sulfate attack (such as phyrte or pyrrhotite) and the lack of an external source of sulfates in the environment, its presence must be associated with a DEF (Taylor *et al.*, 2001; Glasser 2002; Brunetaud *et al.*, 2008). Such phenomenon may be justified if the temperature during the hydration and curing of the concrete exceeded the temperature of 70°C. Notice that there are no historical documentation regarding the

cement used or the construction of the dam that could have helped to confirm this hypothesis.

The first time that an unusual ettringite content associated to DEF is reported in the literature is in the case of Roxburgh dam built between 1951 and 1956 in New Zealand (Kennerly 1965). Recently, another case was reported in the Vrané nad Vltavou dam in Czech Republic (Šachlová *et al.*, 2014).

6. Thermal modelling of the dam

In order to evaluate the hypothesis of a DEF, the possibility of the concrete temperature exceeding 70 °C should be verified. For that, a finite difference model that simulates the construction the dam and the different processes of thermal interchange and the heat generation was developed. The result of the simulations allows to predict the historical record of the internal temperature of the concrete and the temperature at the surface.

6.1. Basic considerations

Several phenomena need to be considered to reproduce the thermal behavior of the dam besides the heat due to the cement hydration, namely the heat transfer due to convection, radiation and thermal diffusion. The two former occur in the interface between the concrete and the environment, whereas the latter is internal. The heat transfer due to convection occurs when the atmospheric air warms up due to the higher temperature of the surface of the dam. The warm air reduces its density and its driven away by new air volumes at lower temperatures that contact the concrete surface. This phenomenon takes place successively until thermal equilibrium with the environment is reached. The difference of temperature between the concrete surface and the environment generates a second heat transfer (radiation), which consists in the emission of thermal radiation that contributes to cool the concrete.

Given that the temperature is not uniform inside the dam, other heat transfers must occur among different points in the concrete mass. Due to the heat release from the cement hydration and the heat transfer with the environment, the early age concrete exhibits a non-stationary temperature profile. Assuming such non-stationary condition, the heat transfer in each point is governed by Fick's second law. The total heat variation (dQ) with time in a certain point located at the surface of the dam and the point located inside the dam may be calculated with [1].

$$\begin{cases} \frac{\partial Q}{\partial t} = \frac{\partial Q_D}{\partial t} + \frac{\partial Q_H}{\partial t} & \text{for internal point} \\ \frac{\partial Q}{\partial t} = \frac{\partial Q_D}{\partial t} + \frac{\partial Q_H}{\partial t} - \frac{\partial Q_C}{\partial t} - \frac{\partial Q_R}{\partial t} & \text{for superficial point} \end{cases} \quad [1]$$

The temperature variation in each point of the dam is calculated by considering the heat content for a certain time in that point. The temperature variation is estimated with equation [2] and depends of the concrete specific heat (C) and the concrete mass (m_H).

$$\partial T = \frac{\partial Q}{m_H \cdot C} \quad [2]$$

6.2. Description of the model

The modelling of dams is usually simplified and performed at a sectional level per length unit (in this case, linear meter). This is possible given that one of its dimensions is significantly larger than the other two. The cross-section of the dam is discretized in square elements of 10 cm. The calculation of the temperature is always conducted taking as a reference the center of gravity of each element.

The heat variation in each element is obtained with the equations described in the previous section. The calculations are performed with finite differences, assuming time intervals sufficiently small to be representative of the real situation. Based on preliminary evaluations, the maximum time interval is set to 5 minutes. Therefore, the simulation of each year in the life of the structure requires approximately 105000 time steps. Table 1 presents the properties of the concrete, defined according the literature, and the input data for the simulations. These values remain constant during the analysis.

Parameter	Value
Cement content ($\text{kg}\cdot\text{m}^{-3}$)	285
Specific weight ($\text{kg}\cdot\text{m}^{-3}$)	2300
Specific heat C ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	880
Diffusion coefficient D ($\text{m}^2\cdot\text{s}^{-1}$)	7.39E-06
Emissivity ϵ (-)	0.9
Convection coefficient h ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)	5

Table 1. Concrete properties and input data for the model.

The model considers the construction procedure of the dam based on casting by layers. For this reason, from the bottom level to the top of the dam, the elements of the same row are activated as the concrete is cast. Such assumption implies a change in the equations used to calculate the temperature in each time step. Before casting a new concrete layer, the horizontal surface of the last layer is unprotected and exchanges with atmospheric air may occur, besides the diffusion with the bottom and lateral layers. When the new concrete layer is cast, transfers with the environment stops, remaining only the diffusion with the other concrete layers.

6.3. Parametric study

Given that the details of the type of cement and the construction rate of each block are unknown, a parametric study is conducted, where several types of cements and construction rates are considered (see Table 2). Based on the available information, the model assumes that concrete layers are built in layers up to 1.5 m high. Afterwards, the formworks are moved to another block to continue casting. This way, there is a certain time t_{layer} between the finishing of a layer and the casting of the following layer in the same block. Given the dimensions of the mixer used in the construction of the dam, the layer could not be completed with one mixing. In fact, it is assumed that the layer is the sum of several thinner layers of 0.1 m executed in a time t_{cast} . The values considered in the model are presented in Table 2 and correspond to two speeds: fast (V1) and slow (V2).

Parameter	Value
Time between layers t_{layer} (days)	20 (V1) and 30 (V2)
Time to cast a layer of 0,1 m t_{cast} (h)	2.4 (V1) and 3.6 (V2)
Maximum energy released Q_{max} (kJ/kg)	150 (E1), 200 (E2), 250 (E3) and 300 (E4)
Kinetic coefficient (-)	0.5×10^{-5} (C1), 1.0×10^{-5} (C2), 1.5×10^{-5} (C3) and 2.0×10^{-5} (C4)

Table 2. Variables of the parametric study.

Regarding the cement hydration, both the maximum energy released (Q_{max}) and the kinetics of the energy release (a) are variables. The first one depends mainly on the composition and the clinker content of the cement and the second is related with the fineness and composition of the clinker. The values assumed for both variables were defined according to heat release curves in the literature for several types of cement. The ambient temperature (T_a) and the initial temperature of the concrete before the casting ($T_{Hinitial}$) remain constant along the simulation with a value of 20 °C (T_a is always equal to $T_{Hinitial}$).

6.4. Results and discussion

Figure 5 shows the maximum temperatures reached in different point of the dam assuming a construction rates V1 (the graphic results for V2 are not presented but are commented subsequently). The results for both rates reveal that the highest temperatures occur in the center of the different layers. This is reasonable given that the regions closer to the perimeter are exposed to the heat transfer with adjacent layers or the environment. The results also indicate that the increase of maximum energy released during the hydration and of the hydration kinetics coefficient leads to a temperature rise in the center of each layer. In certain cases, the temperatures reached are consistent with the DEF, even in points close to the surface of the dam.

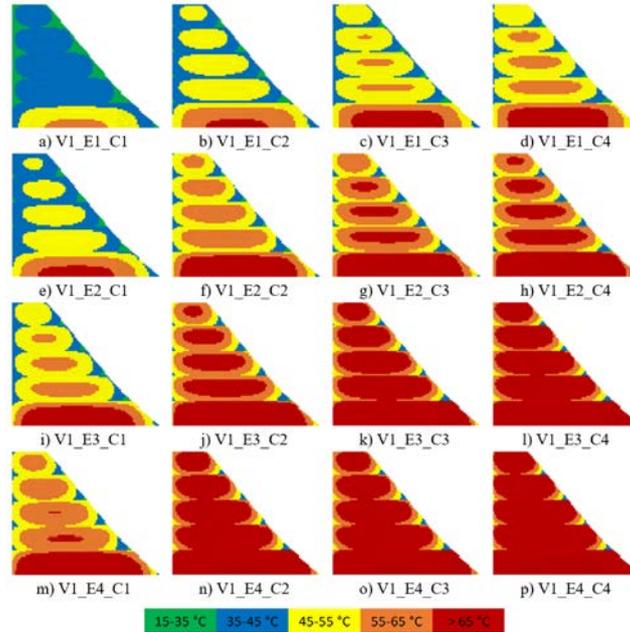


Figure 5. Maximum temperature reached in each point for construction rate V1.

In the scenarios affected by high temperatures, an expansion in the central area of the layers is expected, which generates compression in the center of each layer and tension in the upstream and downstream faces. If the tension in such locations reaches the tensile strength of concrete, horizontal cracks should appear both upstream and downstream. By comparing equivalent scenarios for the two construction rates, a similar distribution is detected. However, V2 leads to temperatures that are between 1°C and 3°C lower than for V1; nevertheless, the center of the layer still reaches temperatures higher than 65°C.

Figure 6 shows the influence of the maximum hydration energy of the cement in the maximum temperature of points located in the center of the layers, for V1 and different hydration kinetics (C1, C2, C3 and C4) at different heights of the dam (2.25 m, 3.75 m, 5.25 m and 6.75 m) for points located at the center (C). The results reveal an approximately linear relation between the maximum energy released in the hydration and the maximum temperature reached. Likewise, the hydration kinetics C2, C3 and C4, with maximum values of energy between 200 kJ/kg and 250 kJ/kg, lead to temperatures above 70 °C inside all layers. It should be remarked that the cements currently classified as low heat cement present values of energy release between that range. At the time of construction of the dam, cements with a hydration heat lower than 200 kJ/kg were not common. Considering the above, the DEF may be the cause of the horizontal cracks observed few years after the construction of the dam.

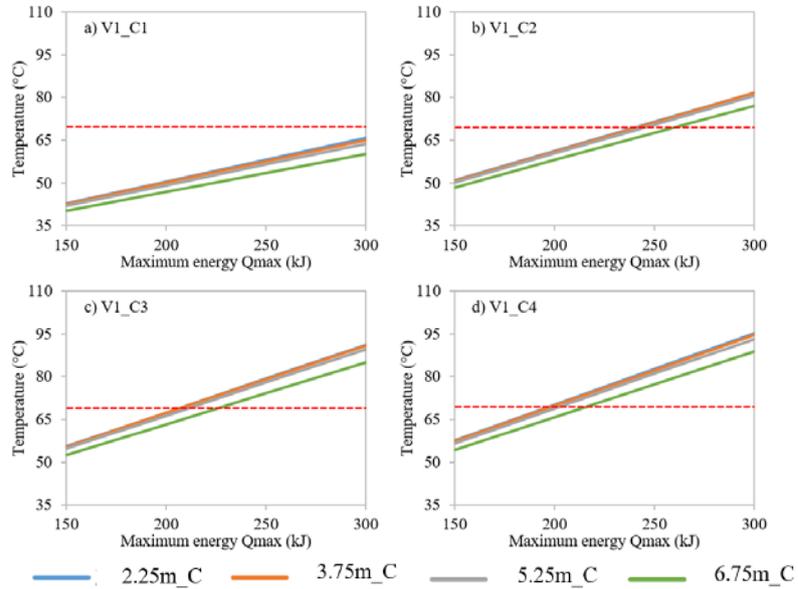


Figure 6. Influence of the maximum energy released in the hydration in the maximum temperature reached at the center of different layers (at different heights).

7. Expansion in the spillway

The ASR and a DEF diagnosed in previous sections may affect the piles of the bridge supported on the spillway. In fact, the expansion generates tension stresses in the piles and, if the tensile strength of the concrete is reached, cracks may appear perpendicularly to the direction of the tension (see Figure 7).

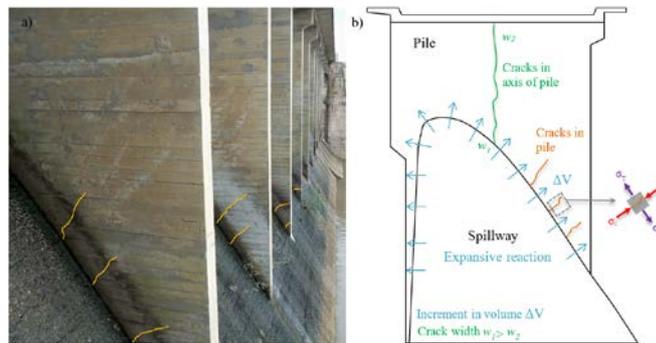


Figure 7. a) Diagonal cracks in the piles and b) phenomenon causing the cracks.

The vertical crack observed in several piles of the bridge is also due to the expansive reaction, however its development is governed by the presence of a construction joint that is a weak plane and is also more susceptible to cracking.

8. Conclusions

The study presents the comprehensive diagnosis of a concrete dam with significant cracking and other signs of deterioration in different elements, including horizontal cracking in the spillway and map cracking in some of the elements that suggest the presence of expansive phenomena in the concrete.

The DRX and SEM-EDS analyses confirm the presence of an alkali-silica reaction in an advanced stage in the concrete spillway. Massive presence of sulfoaluminate phases both at an incipient stage and at an advanced stage are also detected. Having dismissed the possibility of an internal or external sulfate attack and considering the shape of the ettringite needles and how they developed over time, its presence is associated with a delayed ettringite formation (DEF).

This hypothesis is validated through the thermal modelling of the construction procedure of the dam. For that, a specific model based on finite differences and that considers the equations governing the different heat transfer phenomena involved was developed. The outcome of the model reveals that concrete temperatures over 70 °C were reached during the construction, which is the cause for the DEF. This phenomenon explains the horizontal cracking in the spillway of the dam. The expansions in the spillway due to the DEF and the alkali-silica reaction generate tension stresses in the piles of the bridge which may lead to the cracking observed.

Acknowledgements

The authors acknowledge the economic support provided by the Spanish Ministry of Science and Innovation through the project BIA2013-49106-C2-1-R and the collaboration project with Universidad de la República. The authors thank Professor Servando Chinchón and Dr. Servando Chinchón-Payá for their kindness and willingness to collaborate in the microstructural analyses of this study.

9. Bibliography/References

- Ayora, C., Chinchón, J.S., Aguado, A., Guirado, F., "Weathering of Iron Sulfides and Concrete Alteration: Thermodynamic Model and Observation in Dams From Central Pyrenees, Spain". *Cement Concrete Res.*, vol. 8, no. 4, 1998, p. 591-603.

- Blanco, A., de la Fuente, A., Cavalaro, S.H.P., Aguado, A., “A century of sand-cement: durability of the concrete in the Camarasa dam”. *J. Perform. Constr. Fac.*, vol. 30, no. 4, 2016, p. 04015083-1 - 04015083-10.
- Brunetaud, X., Divet, L., Damidot, D., “Impact of Unrestrained Delayed Ettringite Formation-induced expansion on concrete mechanical properties”. *Cement and Concrete Res.*, vol. 38, 2008, p. 1343-1348.
- Cervenka, V., “Simulating a response”. *Concr. Eng. Int.*, vol. 4, no. 4, 2000; p. 45-49.
- Chinchó, J.S., Ayora, C., Aguado, A., Guirado, F., “Influence of Weathering of Iron Sulphides Contained in Aggregates on Concrete Durability”. *Cement Concrete Res.*, vol. 25, no. 5, 1995, p. 1264-1272.
- Chinchón-Payá, S., Aguado, A., Coloma F., Chinchón, J.S., “Study of aggregate samples with iron sulphides trough micro X-Ray Fluorescence (μ XRF) and X-ray Photoelectron Spectroscopy (XPS)”. *Mater. Struct.*, vol. 48, no. 5, 2015, p. 1285-1290.
- Glasser, F. P., “The stability of ettringite”. *International RILEM TC 186-ISA Workshop on Internal Sulfate Attack and Delayed Ettringite Formation*, 4-6 September 2002, Villars, Switzerland, p. 43-64.
- Hobbs, D. W., *Alkali-silica reaction in concrete*, Michigan, Telford, 1988.
- Kennerly, R. A., “Ettringite Formation in Dam Gallery”. *ACI Journal*, vol. 62, 1965, p. 559-576.
- Mehta, P. K., Monteiro, P. J., *Concrete Microstructure, properties, and materials*, New York, McGraw-Hill, 2006.
- Neville, A., “The confused world of sulfate attack on concrete”. *Cement Concrete Res.*, vol. 34, no. 8, 2004, p. 1275-1296.
- Oliveira, I., Cavalaro, S.H.P., Aguado, A., “New kinetic model to quantify the internal sulfate attack in concrete. *Cement Concrete Res.*, vol. 43, no. 1, 2013a, p. 95-106.
- Oliveira, I., Cavalaro, S.H.P., Aguado, A. “New unreacted-core model to predict pyrrhotite oxidation in concrete dams”. *J. Mater. Civil Eng.*, vol. 25, no. 3, 2013b, 372-381.
- Oliveira, I., Cavalaro, S.H.P., Aguado, A., “Evolution of pyrrhotite oxidation in aggregates for concrete”. *Mater. Construcc.*, vol. 64, no. 316, 2014.
- Regamey, J.M., Hammerschlag, J.G. “Barrage d’Illsee—assaintment”. *Proc., Research and development in the field of dams*, Crans-Montana, Switzerland, 1995.
- Šachlová, S., Pertold, Z., Šťastná, A., Míčka, T. “Factors affecting DEF and ASR in the concrete dam at Vrané nad Vltavou”. *International Journal of Research in Engineering and Technology*, vol. 3, no. 13, 2014, p. 57-62.
- Saouma, V., Perotti, L., Shimpo, T., “Stress Analysis of concrete Structures Subjected to Alkali-Aggregate Reactions”. *ACI Struct. J.*, vol. 104, no. 5, 2007, p. 532-541.
- Shayan, A., “Alkali aggregate reaction in a 60-year-old dam in Australia”. *International Journal of Cement Composites and Lightweight Concrete*, vol. 10, no. 4, 1988, p. 259-266.
- Stanton, T. E., “Expansion of concrete through reaction between cement and aggregate”. *Transactions of the American Society of Civil Engineers*, 107(1), 1942, p. 57-84.
- Taylor, H. F. W., Famy, C., Scrivener, K. L., “Delayed ettringite formation”, *Cement and Concrete Res.*, vol. 31, no. 5, 2001, p. 683-693.
- Ulm, F.-J., Coussy, O., Kefei, L., and Larive, C. “Thermo-Chemo-Mechanics of ASR Expansion in Concrete Structures”. *J. Eng. Mech.-ASCE*, vol. 126, no. 3, 2000, p. 233-242.