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Expansions with different origins in a concrete dam with bridge over spillway

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HIGHLIGHTS

- Comprehensive diagnosis of concrete dam reveals two different expansive reactions.
- High temperatures during construction led to delayed ettringite formation.
- Model based on finite differences to simulate heat transfer phenomena is developed.
- Thermal modelling of construction process confirms concrete temperatures over 70 °C.
- Microstructural analysis reveals presence of products of alkali silica reaction.

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ABSTRACT

Concrete dams with expansions from different origins are rare and scarcely documented in the literature, therefore their study gains special interest. This study presents the case of a 62-year-old concrete dam with signs of deterioration due to expansive reactions. Several tests performed on the samples extracted from the dam such as X-ray diffraction, scanning electron microscope with energy dispersive spectroscopy mode and petrography suggest that the expansions are due to a delayed ettringite formation and a subsequent alkali-silica reaction. Thermal and mechanical models developed in the study support this diagnosis.

1. Introduction

Concrete dams are massive structures that may be subjected to different processes of deterioration, including expansions, that affect its structural behavior. Often, the source of the damage cannot be explained by a single phenomenon. The diagnosis and evaluation of the concrete dam in such scenario gains special relevance given the scarce number of cases reported in the literature.

In terms of expansive reactions, the most common is the alkali-silica reaction (ASR), which has been extensively studied [35,18,40,27,22]. Less common are the internal sulfate attack (ISA), despite several studies conducted in the past years [10,2,33,23,24,25,11,28,29] and the alkali-carbonate reaction (ACR) [17,36,6,31].

Beside the above reactions, another type of internal sulfate attack may occur that it is not caused by the presence of sulfates in the aggregates, known as delayed ettringite formation (DEF). It occurs when the temperature during construction and curing exceeds 70 °C. DEF may be defined as the formation of ettringite (secondary ettringite) in a hardened material stored in wet conditions and without any external sulfate source, resulting in swelling [34,14,37].

Roxburgh dam in New Zealand is the first case reported in the literature with an unusual ettringite content associated to DEF [19]. Recently, another case was reported in Vrané nad Vltavou dam constructed between 1930 and 1936 in Czech Republic [30].

This paper aims at presenting a conclusive diagnosis for a gravity dam with evident signs of degradation due to expansive reactions. The hypothesis, formulated after analyzing the state of the dam and reviewing the scarce historical documents available, consists in the combined effect of a DEF occurring short after the

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construction and a subsequent ASR. In order to validate such hypothesis, microstructural analyses on mortar and aggregate samples were performed as well as models to assess the evolution of temperature during the construction of the dam and the expansion in the spillway.

The relevance of this paper lies in the singularity of the case study, where two expansions of different origins occurred in the same concrete dam. Additional interest may come from the lack of monitoring and limited historical documentation, which hinders the diagnosis. In this context, the study may serve as a valuable example for future diagnosis of concrete dams.

2. Description of the dam

2.1. General characteristics

This gravity dam was built in 1955 for water supply. It consists in a plain concrete Creager spillway of 100 m of length and a maximum height from the foundations of 14.0 m. The spillway is divided into 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 diaphragms of a reinforced concrete slab road bridge that crosses the river (see Fig. 1).

The slab is 0.39 m thick and it is divided in three parts: a central part 7.10 m long and two continuous parts supported every 5.0 m. The diaphragms are 0.35 m thick with the exception of the ones supporting the central part which are 0.40 m. 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.

2.2. Construction and materials

The documents related to the design and construction of the dam include descriptive report of the original project and the construction plans dating from the early 1950 s. The information regarding the construction procedure is not extensive, however specifications are given for the pouring of the concrete, the joints and the curing.

Specifically, it is mentioned that the concrete will not be poured at a temperature lower than 5 °C or higher than 28 °C. Likewise, the concrete layers between contraction joints will not exceed 30 cm with a maximum progress of 1.5 m. The exposed surface, which will maintain a rough texture to ensure bond with the subsequent layer, will be protected from the sunlight at least during 3 days after the pouring. In addition, the concrete will be wetted during the following 3 weeks. The document also includes recommendations regarding the joints between two layers of concrete and between concrete and rock.

Fig. 1. General view of the concrete dam and the bridge over the spillway.

In terms of concrete mix and its components, the information is not sufficiently accurate. The only reference to the type of cement is in the tender specifications of the project, where it is stated: "*the Portland cement will be of slow setting. Cement that was previously stored will not be employed*". Despite the above, there is no certainty that this type of cement was used in the construction of the dam since no records from the construction period are available. Furthermore, it is known that slow setting cements were first introduced in the country for the construction of another concrete dam in 1974. These uncertainties regarding the origin and type of cement represent a drawback in the diagnosis given that the amount of gypsum, alumina phases (C_3A) and alkali in the cement is unknown.

In terms of the operation and management period, the historical documents indicate that horizontal cracking in the spillway appeared shortly after the construction since repair and maintenance operations were already conducted in the decade of the 1960 s. In addition, the dam is not monitored and thus no records are available of the evolution of displacements through the years.

3. Current state of the dam

The current state of the dam will be described according to the main elements of the structure: the spillway (including the structure of the stairway), the bridge and the dikes. Table 1 presents a summary of the main evidences of damage found in the visual inspection of the dam.

The spillway presents horizontal cracks in the upstream and downstream faces that develop along the planes of the construction or filling joints. These cracks were reported in studies dating from 1989 and 1996 and were described as non-continuous (the downstream face was dry and were no signs of infiltrations).

Fig. 2 shows the horizontal cracks in the downstream face. Some of the gate mechanisms, hanging from the central blocks of the spillway are detached from the concrete due to a certain rotation between the upper and bottom part of the blocks. This rotation is consistent with the presence of horizontal cracks in the construction joints.

The structure of the stairway exhibits several signs of degradation of the concrete in the columns and the walls of the structure, such as loss of concrete cover in certain areas and corrosion of the reinforcement (Fig. 3).

The deck of the bridge is not severely damaged, some cracks were detected in the lower surface of the deck, perpendicular to its axis, that may correspond to cold joints. In the central block of the spillway, the deck is supported on two rocker bearing beams, one of which exhibits a certain rotation. The connection with the diaphragms consists in 20 rebars per pile with a diameter of 19 mm. The diaphragms of the bridge present signs of degradation

Table 1
Evidences of damage in the main elements of the dam.

Element	Location	Description of damage
Spillway	Downstream face	Horizontal cracks without signs of infiltration
	Upstream face	Horizontal cracks
	Structure of stairway	Loss of concrete cover, corrosion and deformation of the reinforcement
Bridge	Deck	No signs of severe damage
	Diaphragms	Surface erosion, corrosion of reinforcement and cracking
Dikes	Retaining walls	Map cracking