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Effects of an internal sulfate attack and an alkali-aggregate reaction in a concrete dam

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HIGHLIGHTS

- Case study of a concrete dam with cracks and non-recoverable displacements.
- Damage due to an initial internal sulfate attack followed by alkali-silica reaction.
- 3D and 2D FEM models used as a tool for the diagnosis.
- Contribution of damage and cracks in the displacement considered in model.

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ABSTRACT

The alkali-aggregate reaction and the internal sulfate attack are two chemical reactions that lead to expansions in concrete structures. The former is one of the main causes of expansions in concrete dams and has been extensively reported in the literature, whereas the latter is less common and, thus, less studied. The confluence of both reactions in one structure is highly unlikely but still possible as shown by the case of the dam studied in this paper. This gravity dam exhibits significantly high non-recoverable displacements that may only be justified by the superposition of both phenomena. This paper focuses on the study of a concrete dam whose diagnosis hypotheses have changed throughout the years according to evolution of the behavior observed. The hypotheses proposed in the study are validated by conducting numerical analyses through 3D and 2D finite element models. The results confirmed the diagnosis proposed and the capability of the model to reproduce the behavior of the dam.

1. Introduction

Hydraulic infrastructures have a major economic influence in the environment and the society given their ability to transform the territory. Concrete dams are the greatest example of the repercussion in the territory of large infrastructures. Despite concrete dams are built to endure high external loads and be durable, pathologies may arise during their service life. In some cases, the pathology may compromise the safety of the structure, but often it only affects the daily operations of the dam.

Expansive reactions are a common phenomenon in concrete dams. The expansions usually generate internal stresses, cracking and non-recoverable displacement that may alter the normal functioning. Identifying the causes and determining the extent of the damage is essential to conduct rehabilitation tasks and avoid further degradation of the dam. The most common expansive reactions in concrete dams are alkali-aggregate (AAR) and, in particular, the alkali-silica reaction (ASR) that has been extensively studied and reported in the literature. The internal sulfate attack (ISA) is another type of expansive reaction that is less frequent.

The ASR has been studied for 70 years [1–4] and occurs in the presence of aggregates that contain amorphous and cryptocrystalline silica. Examples of such aggregates are glassy volcanic rocks and tuff, rocks containing opal and other rocks with high silica content. The reaction generates a gel that absorbs humidity and expands. The expansive mechanism of the ASR may be described, in simplified way, as a two-stage reaction between the alkalis (sodium and potassium) of the cement and the reactive silica of the aggregates.

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A certain type of ISA may be caused by the use of aggregates containing iron sulfides (pyrrhotite and pyrite) that oxidize inside the concrete releasing sulfates [5–7]. The sulfates, in turn, react with the cement paste components (portlandite and tricalcium aluminate) generating potentially expansive secondary ettringite [8].

The evolution of the ISA in concrete dams depends on the oxygen concentration and humidity, which varies from the upstream to the downstream faces. As a result, a clear difference takes place between the areas close to the oxidant agent (the oxygen in the atmosphere) and the rest of the dam, thus leading to differential deformations and internal stresses that are higher in the downstream face due to the higher concentration of oxygen.

References of concrete dams experiencing separately ISA or AAR may be found in the literature; however, cases where both reactions occurred in the same dam are unusual (some cases have been diagnosed in the Spanish Pyrenees) and scarcely documented.

In fact, in most cases the report the combination of AAR with a certain type of ISA known as delayed ettringite formation (DEF). DEF is associated to the decomposition of primary ettringite, which is not stable at high temperatures (generally over 70 Celsius degrees), into monosulfate and gypsum. After the hardening, the temperature in concrete decreases and the secondary ettringite is formed resulting in expansions [9,10]. Usually, the studies about these combined phenomena deal with the microstructure and experimental data [11,12], without considering the influence in the structural damage.

In this context, evaluating the rare confluence of AAR and ISA gains special relevance since it may yield further information on the degradation processes. Additionally, if numerical tools are used to validate the diagnosis hypotheses and justify the structural behavior observed in the dam, the study may serve as an example for future diagnosis.

Modelling expansive reactions in concrete dams may help to estimate the long-term behavior of the structure and define the rehabilitation strategy. The studies in the literature mostly correspond to the modelling of AAR, to a lesser extent to the external sulfate attack (ESA) and those related to modelling ISA are almost non-existent. Generally, AAR models may be grouped in three categories according to their level of approximation [13]: micro, meso and macro scale.

The models at a micro-scale [14–17] and a meso-scale [18–21] represent explicitly the heterogeneity of concrete and their goal is to elucidate the underlying mechanisms of the expansions. Therefore, these levels of approximations are less relevant in a structural analysis such as in the case of the present study.

The models at a macro-scale are generally implemented in finite elements (FEM) and consider concrete as a homogeneous material combining chemical aspects and their mechanical effects. According to Saouma [13] can be distinguished:

- *Empirical models* where ASR expansions are estimated through kinetic laws (depending on chemical reactions, stresses, temperature and relative humidity (RH)) that are imposed in each point of the mesh (analogously to thermal expansions) [22–25]
- *Coupled chemo-mechanical models* that account for the time-depending nature (kinetics) of chemical reactions (due to the diffusion processes) in the mechanical response [26–32]

Generally, modelling chemical reactions requires considering the transport processes involved, thus leading to reaction-diffusion systems. These systems allow evaluating how the concentration of one or more substances distributed in the space change under the influence of the chemical reactions (locally transforming substances in others) and the diffusion (transporting substances in the space). Fick's law is usually used to describe the diffusion processes of the chemical components in pervious materials. In the case of ISA due to oxidation of the iron sulfides in the aggregate, the reaction depends on the transport of oxygen from the outside to the inside of the concrete matrix.

Fig. 1. View of the dam from downstream.

The paper presents the real case of a concrete dam monitored for more than 25 years with cracking and significant non-recoverable displacements (in some blocks up to 200 mm). The early diagnosis suggested an ISA; however, long-term monitoring has revealed that the ISA alone could not justify the displacements registered. The aim of the study is to define a conclusive diagnosis.

For that, the diagnosis hypotheses are reformulated assuming the confluence of an ISA and AAR developed at different stages of the service life. Subsequently, the structural behavior is simulated through 3D and 2D finite element models. The present study applies the kinetic model proposed by Ulm et al. [26] to simulate the expansions due to AAR (in AAR, the transport models used in the literature are mainly at a micro-scale). The ISA is considered by means of a reaction-diffusion model proposed by the authors for concrete dams in [33]. The 2D non-linear model includes joints to represent the cracks observed in the structure, applying the formulation proposed by Carol et al. [34]. This approach allows assessing the contribution of the damage and cracking on the displacements registered. Finally, the new hypotheses are numerically and experimentally validated.

2. Description of the dam

2.1. General characteristics

The concrete dam studied is a gravity dam located in Pyrenees in the northeast of Spain and built between 1968 and 1971. The dam presents a straight form in the ground plant with a crest length of 102.4 m and a height of 28.9 m (the lowest level of the foundation is at 1327.7 m and the crest is at 1356.6 m above sea level, respectively). The dam is divided into seven blocks as shown in Fig. 1, which are 15.0 m wide with the exception of block 1 that is 12.4 m wide. The dam presents one gallery at level 1335.3 m. The reservoir, which exhibits a capacity of 0.33 hm^3, was filled for the first time in November 1971.

Regarding the geological characteristics of the region, the dam is located in an area where the predominant rocks are slate and phyllites. The use of this type of aggregate in the concrete for dam construction was confirmed by the historical records on the construction procedure and by the microstructural analyses performed.