Characterization of alkali-silica reaction damage in concrete by X-ray tomography

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Summary: The alkali-silica reaction (ASR) is a chemical reaction between the alkaline pore solution in concrete and its aggregates, mainly those rich in silicates. The ASR products can lead to a significant amount of cracking upon swelling due to pore solution uptake. The aggregate swelling leads first to aggregate cracking, then to crack propagation through the mortar matrix. We present an overview of how X-ray tomography and respective 3D image analysis allow investigating the ASR damage temporal evolution.

1. INTRODUCTION

The alkali-silica reaction (ASR) is one of the most frequent and deleterious durability issues in concrete structures older than a few decades in many countries [1]. It is a chemical reaction happening between the aggregates and the alkaline pore solution. The respective reaction products are hygroscopic, i.e., they adsorb the pore solution and swell, leading to aggregate expansion and, consequently, aggregate cracking. The cracking starts always inside the aggregates and then propagates through the mortar matrix. It eventually manifests itself as large cracks associated with macroscopic deformations (several cm/year) which compromise the properties of structures [2]. Despite being known since the 1940's, the knowledge about ASR's exact mechanisms is still too limited to support the development of control or even stopping approaches [3]. In order to arrive at making a prognosis for ASR damage evolution in old structures and to mitigate it in future ones, it is crucial to improve its understanding. Studies that can be performed at the laboratory scale typically require applying reaction acceleration protocols, due to its inherently slow kinetics in the field (years/decades) [4]. Based on laboratory testing results, an investigated concrete mix design can be approved or rejected for construction usage. Nevertheless, there is always a question of extent of reliability and applicability of such results to real concrete structures, since the test boundary conditions may differ considerably from the ones in the field [5]. Comparisons between expansion/damage progression in the field and in the lab are usually done only in regard to length changes, neglecting the microstructural differences. New techniques, such as non-destructive, time-lapse damage evolution monitoring, are required to achieve a more comprehensive and reliable understanding of the ASR chemo-poromechanics. In this study, we report some examples of the X-ray tomography and respective 3D image processing applications for analysis of concrete specimens exposed to both accelerated and real world conditions.

2. EXPERIMENTAL METHOD

The concrete (B1 (C+F)) was produced in 2004 within the framework of the "PARTNER" project [4] using cement of type CEM I 42,5 R (1.26 mass-% Na_2O-equivalent) with a 440 kg/m^3 cement content and water-to-cement ratio (by mass, w/c) of 0.5. The aggregate type was a siliceous limestone from Belgium. A prism with size 300×300×300 mm^3 was cast for storage outdoor. Three prisms of size 75×75×280 mm^3 were instead cast to be exposed to the accelerated testing in the laboratory. We selected one particular sample exposed unsheltered in Valencia/Spain for 13 years as an example to represent the application of X-ray tomography to investigating the ASR damage extent. The accelerated tests used are the RILEM AAR-4.1 [6] standard (60°C and a 100% RH). To perform X-ray tomography, smaller sub-samples from each sample type, with cross-section of 10×10 mm^2, were carefully cut out after impregnating the samples with resin in order to avoid microstructural changes due to the cutting itself. X-ray tomography was carried out using an EasyTom-XL tomograph (RX Solutions, France) at 105 keV maximum photon energy. The tomograms were reconstructed with a cone-beam filtered back-projection algorithm implemented in the XAct software by RX Solutions. The spatial resolution was approximately 20 μm. The Avizo software (Thermo Fisher Scientific™) was utilized to perform image pre-processing (filtering) and crack segmentation.

3. RESULTS

The accelerated sample demonstrated a fastest expansion during the first four weeks and later, with a continuously decreasing expansion rate. After 20 weeks it reached a final expansion of 0.15%. The field-exposed block continuously expanded with the same rate and achieved a 0.36% relative expansion after 11 years. A 3D render of the tomogram of the field exposed sample is represented in Figure 1A. To analyze the cracks, the “black top-hats transform” was used along with a binary mask for excluding the air voids and the sample exterior (Figure 1C). The aggregates were segmented using a manual voxel value thresholding method (Figure 1D). The 3D renderings, comparing the crack patterns in the lab-tested samples (Figure 1F) with those in the field-exposed samples (Figure 1D and 1E), clearly illustrate a larger amount of crack volume in the field-exposed sample. Nevertheless, an additional crack analysis was performed to quantify the crack volumetric density within the volume of the samples. The crack density (or volume fraction) was calculated as the total crack volume divided by the total volume of the concrete sample. The crack density of the field-exposed sample (2.0%) is about 1.5 times more than that of the lab-tested sample (1.3%). To quantify the crack density referring only to the aggregate volume, the aggregate binary mask (Figure 1B) was exploited to segment the crack volume only inside the aggregates. The aggregate crack density could then be computed as the volume of cracks inside the aggregates per unit volume of aggregates. The field-exposed sample exhibited about 1.5 times higher aggregate crack density (2.6%) than the lab-tested sample (1.8%).

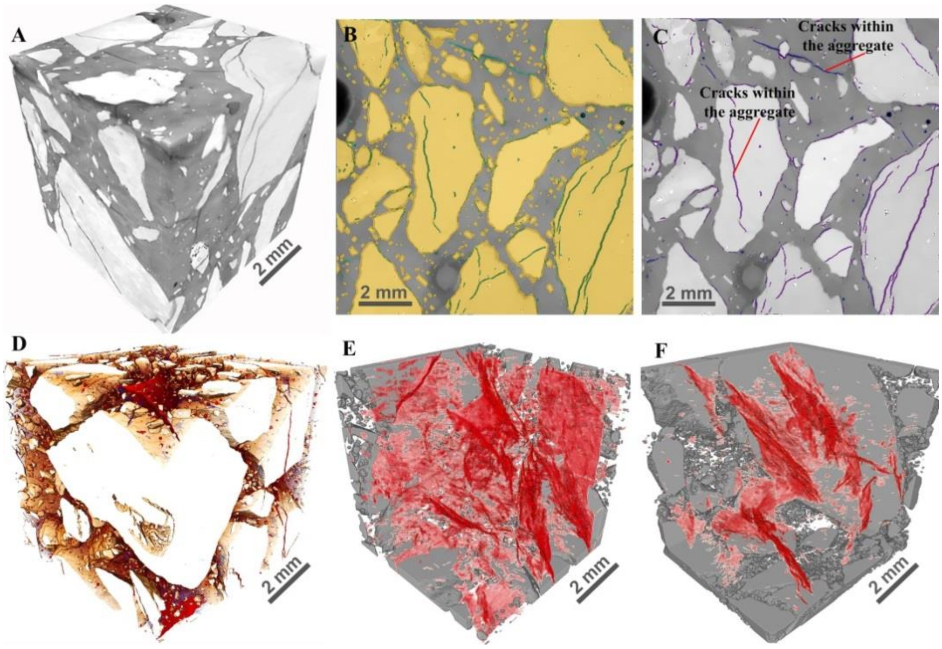

Figure 1: (A) 3D render of a volume from the field-exposed sample; (B) a selected 2D slice from the tomogram of the fieldexposed sample, illustrating the segmentation of the cracks and of the aggregates; (C) same slice as in (B) but highlighting only the cracks, distinguishing by colors between those within the aggregates (purple) and the ones within the mortar matrix (blue); 3D rendering of all the cracks within the irradiated volume of the (D,E) field-exposed sample and (F) of the lab-tested sample. Parts of the segmented aggregates are also visualized in the background of the cracks in both (C) and (D).

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