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Combining nonlinear acoustics and physico-chemical analysis of aggregates to improve alkali–silica reaction monitoring

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ABSTRACT

Very few chemical, physical and mechanical parameters appear suitable to monitor progressive damage caused by alkali–silica reaction (ASR) in concrete with the proper level of sensitivity and/or specificity. The purpose of the experimental work presented in this paper is to handle this limitation by proposing a non-conventional approach based on the combined use of nonlinear acoustics and physico-chemical analysis to assess the damage caused by ASR.

The study was first carried out on laboratory concrete specimens kept in conditions promoting ASR (100% R.H. and 38 °C), as well as on laboratory concrete specimens submitted to thermal damage (thermal shock). For both types of damage, nonlinear acoustics allowed detecting and tracking the early evolution of microcracking in concrete with a higher sensitivity than other non-destructive parameters (i.e. dynamic Young's modulus or ultrasonic pulse velocity). The physico-chemical approach allowed distinctions to be made between types of damage by assessing granular swelling in the case of ASR, while no physical change in aggregates was detected regarding thermal damage.

The procedure was then applied to concrete cores extracted from a large concrete field structure affected by ASR and submitted to residual expansion tests. Results confirmed the sensitivity of the nonlinear parameter to track residual damage in concrete and confirmed (with physico-chemical analysis) that ASR specifically contributed to the residual expansion and damage observed.

1. Introduction

The abundance of literature concerning alkali–silica reaction (ASR) can be mainly attributed to the multiplicity of ASR impacts on concrete, which are dependent on the nature and stoichiometry of reactants (reactive silica, alkalis and humidity), temperature [1], concrete stiffness [2], confining conditions [3] or aggregate size [4]. The incidence of ASR, depending on concrete mix and conditioning, has been widely documented, yet our capacity to understand, predict and characterize the development of ASR in concrete properties remains limited.

From the author's point of view, the lack of suitable tools and parameters to monitor ASR in concrete plays a significant role in these limitations.

Regarding the multi-scale aspect of ASR, the use of a combination of monitoring parameters seems necessary. The expansion of concrete is the usual and "natural" reference parameter since it is, with the associated cracking, the most direct and visible prejudicial consequence of ASR on structures. The main limitation of expansion monitoring (on concrete cores or directly on structures) is its non-specificity to ASR since other phenomena, such as delayed ettringite formation, can contribute to concrete expansion [5].

Petrographic observation is the primary technique used to identify the presence of ASR in concrete. Several petrographic features allow detecting ASR damage in concrete (e.g. cracking inside the aggregates, reaction products within the cracks or reaction rims around the aggregates [6]). Petrographic observations can be combined with an evaluation and a grading criteria, such as the "damage rating index" [7,8] or the "crack index" [9], in order to quantify damage and to correlate it with the concrete expansion. However, the effectiveness of quantitative petrographic methods is limited by the subjectivity of the operator. Scanning electron microscopy (SEM) is one of the most reliable tools used to detect ASR in concrete. SEM allows the identification and characterization of ASR products and microcracks [10,11]; however its use remains limited due to its cost and lack of spatial representativeness.

Apart from concrete expansion monitoring and petrographic examination, which are usually used as reference parameters, ASR can be monitored with a wide range of "secondary" parameters. Regarding mechanical properties, many authors have demonstrated that ASR can affect the tensile strength and the Young's modulus, while the impact on compressive strength is lower [12]. Although the mechanical properties of the concrete decrease with evolving ASR, these changes cannot solely be associated with the concrete expansion since they are affected

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by the mineralogy of rocks, the aggregate size, and the kinetics of reaction (rate of expansion) [2]. In some cases, no significant differences in compressive strength can be observed between reference concrete and reactive concrete (stored at 38 °C, 100% R.H.), even when reactive concrete expansion exceeds 0.1% [2,13].

Regarding the non-destructive methods, indicators derived from the analysis of the propagation of ultrasonic waves (ultrasonic pulse velocity, attenuation, maximal amplitude, etc.) generally show significant changes only for high levels of expansion. The dynamic Young's modulus seems to provide a better sensitivity to cracking [14,15].

The slow development of ASR compels authors to conduct a majority of studies on laboratory concretes/mortars submitted to environmental conditions promoting ASR and leading to high levels of expansion (in general > 0.1% for concrete) compared with the field observations (expansion rate between 0.005%/year and 0.01%/year [16,17]). Consequently, the range of expansion for which “secondary” parameters (i.e. mechanical properties, non-destructive testing) are used to assess concrete damage caused by ASR generally exceeds 0.1%. Experimental data focused on lower expansion levels are scarce and therefore the sensitivity of assessment parameters to ASR damage is consequently limited [12].

One of the purposes of non-destructive testing is to detect concrete damage at an early stage of ASR, when surface cracking is hardly visible. Another objective is to be able to track damage progress in concrete with an adequate sensitivity, considering the low ASR development in field conditions. An alternative monitoring method to conventional ultrasonic wave propagation consists of analyzing the behavior of concrete through nonlinear acoustics. The potential of these methods to assess damage in concrete (especially at low-damage levels) has been highlighted by several studies [18–21]. It was shown that “porous” materials, such as concrete, exhibit a nonlinear behavior, which is enhanced by the presence of microcracks. Chen et al. recently applied this technique to quantify microcracking caused by ASR in mortar samples conditioned in 1 M NaOH and 80 °C, concluding that the nonlinear technique used is sensitive to the material's nonlinearities introduced by ASR [22], such as cracking and aggregate/paste debonding. Yet the possibilities to detect damage specifically caused by ASR in concrete are limited with a non-destructive approach. A method was developed over the last decade in order to deal with the specificity of ASR damage which focuses on the physico-chemical deterioration of reactive aggregates caused by ASR [23]. The physical variations observed at the mesoscopic scale (swelling of the aggregate particles) were associated with the amorphization of silica at the microscopic scale [24]. This phenomenon can be considered as a direct consequence of ASR. A consecutive swelling model based on expansion of the aggregate particles was developed [25].

The aim of this paper is to highlight how the combined use of nonlinear acoustics and physico-chemical analysis of the aggregates can contribute to improving the effectiveness and accuracy of ASR monitoring. The information brought by both techniques could be relevant in order to study low levels of expansion (for early detection of ASR) and/or low variations of expansion (to approach field conditions). In a first step, monitoring was performed on two different batches of laboratory concrete, respectively damaged by ASR and thermal shocks. This phase enhances the possibility to detect microcracking in concrete with a high level of sensitivity and to specify whether this micro cracking can be attributed to ASR or not. In a second step, the same monitoring technique was applied on reactive concrete cores submitted to residual expansion tests in order to assess further internal damage of the concrete and the potential contribution of ASR to the observed residual expansion.

2. Materials and methods

2.1. Materials, mix designs and conditioning

2.1.1. Laboratory concrete for ASR

One concrete mixture was made incorporating Spratt limestone as coarse aggregate with equal mass quantities of size fractions 20–14, 14–10 and 10–5 mm. This aggregate, well known for its reactivity, is a crushed fine-grained clayey limestone with chalcedony inclusions. A crushed non-reactive aggregate from the Marbleton quarry (Québec, Canada), was selected for its low-silica content (<2%) and was used as fine aggregate. Concrete mix was prepared with a W/C ratio of 0.5, and a ratio of coarse aggregate/fine aggregate/cement = 1.89:1.38:1 by mass (cement content: 450 kg/m^3).

To promote ASR, reagent grade NaOH pellets were added to the mixing water to increase the total alkali content to 5.62 kg/m^3 Na_2O_{eq}. Thirty-three reactive concrete samples were cast for ASR deterioration. Four prisms (75 × 75 × 300 mm) were cast with stainless reference studs fixed at both ends for length measurements. Three cylinders (100 × 200 mm) were used for non-destructive testing (linear and nonlinear acoustics). Twenty-four cylinders (100 × 200 mm) were used to determine mechanical properties and physico-chemical properties of aggregates. Each sample used for mechanical characterization was then crushed in order to perform physico-chemical analysis. Two cylinders (100 × 200 mm) were used for petrographic examinations.

After 28 days in a curing room at 21 °C, samples were placed over water in hermetic plastic pails to provide the humidity conditions required for ASR development. The pails were stored at 38 °C to accelerate the reaction. All initial measurements were taken after the curing period.

Concrete expansion was used as a reference parameter to assess ASR development. Four levels of concrete expansion were defined for extensive characterization of concrete damage: 0% (initial measurement), 0.03%, 0.06% and 0.09%.

2.1.2. Laboratory concrete for thermal shock

Ten cylinders (100 × 200 mm) were cast for the thermal damage experiment. The mix design was the same as defined in Section 2.2.1 except that no alkalis were added to the mixing water. Six samples were used to determine the mechanical properties at 28 days, and the remaining four samples were used for thermal damage and non-destructive testing. The thermal damage process consisted of heating the specimens at 150 °C for 3 h. Then, samples were taken out from the oven and soaked in water at room temperature for a period of 15 min.

Three levels of thermal damage were defined for extensive characterization of concrete damage: T0 (initial measurement after 28 days of curing), T1 (after one thermal shock), and T2 (after two thermal shocks).

2.1.3. Concrete cores

Ten concrete cores were drilled from a lock located on the St. Lawrence Seaway in eastern Canada. The structure was built in the late 1950s and ASR had been detected about 20 years after its construction. The present ASR in this structure is associated with the use of a reactive crushed clayey limestone, similar to Spratt limestone, as coarse aggregate in the concrete.

Concrete cores of 80 mm in diameter and about 170 mm in length were tested: stainless reference studs were fixed at both ends of each of the three samples used for length measurements, as well as the three samples used for the initial characterization of physico-chemical properties and the four samples used for the residual expansion tests. Residual expansions tests were performed in alkaline solution (NaOH 1 M) kept at a constant 60 °C. Initial expansion measurements were recorded after a 24 h curing period in NaOH.

Three levels of residual concrete expansion were defined for extensive characterization of concrete damage: 0% (initial measurement), 0.017% (after 15 days of immersion in NaOH) and 0.054% (after 35 days of immersion in NaOH).

2.2. Methods for assessment and analysis

2.2.1. Length change and mass variation

Length change and mass variation of prisms (laboratory concrete) and cylinders (cores) were measured periodically following the