Correlation between damage parameters and mechanical properties of concrete affected by ASR

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Abstract. To investigate the potential correlation between damage parameters used to assess the level of alkali silica reaction (ASR) in concrete and the mechanical properties of the material is a promising approach. Currently, ASR damage evaluation of concrete is done following FHWA protocol [1]. The actual level of damage (diagnosis) is evaluated using the Stiffness Damage Test (SDT) and the Damage Rating Index (DRI). Both methods provide parameters correlated to the concrete's expansion level. In addition, future potential of damage (prognosis) is assessed using residual expansion tests in specific climatic conditions (R.H. >95 % and T = 38+/-°C) and alkaline solution (NaOH 1N, 38+/-°C). Expansion is thus currently used to assess the damage and predict future deterioration. However, only expansion measurements are insufficient for infrastructure managers who need to understand the structural impact of ASR on concrete structures. Therefore, this research aims to identify new correlations between the actual test results and structural parameters of the concrete, providing more relevant information for infrastructure management. In this project, cores from ASR-affected bridges were extracted, cut into samples and subjected to both prognosis and diagnosis tests, as well as compressive tests, directly after extraction and after expansion tests, respectively. A linear trend was identified for compressive strength, correlating with DRI values in cores tested after extraction, indirectly linking to the concrete's expansion level. Young's modulus also decreased with additional expansion during the tests, but no significant trendline was identified.

Keywords: ASR, diagnosis, prognosis, mechanical parameters

1 Introduction

Alkali-silica reaction (ASR) is one of the most detrimental reactions affecting the durability of concrete. This destructive phenomenon compromises the durability of concrete structures by causing internal expansion, leading to cracking (in the aggregates and cement paste), thereby threatening their structural integrity. It is imperative to assess the current level of damage caused to the concrete. This assessment, known

as "diagnosis," relies on two specific tests: the Damage Rating Index (DRI) and the Stiffness Damage Test (SDT).
These methods provide parameters related to the level of concrete expansion. Simultaneously, it is crucial to anticipate the potential future damage to the structure, a process referred to as "prognosis." This step is based on residual expansion tests in humid air (R.H. > 95% and T = 38+/-2°C) and in alkaline solution (NaOH 1N, 38+/-2°C). Expansion is thus the output parameter currently used. However, this parameter is not ideal for structure managers, as they would prefer to have parameters focused on the structural capacity of the construction. Such an indicator would allow them to perform remaining capacity calculations and determine the urgency of intervention in case of structural danger. The goal is therefore to identify correlations between the concrete's mechanical parameters (compressive strength and Young's modulus), the results of diagnosis tests and expansion measurements. This aim to provide a more comprehensive perspective on the concrete's mechanical properties and their potential evolution.

2 Materials and methods

In this project, cores extracted from the *Champlain Bridge* and its *Estacade*, two bridges located side by side spanning the Saint Lawrence River in the Montreal area, were cut into samples and subjected to prognosis and diagnosis tests. Both bridges' samples contained the same reactive limestone aggregate and granitic sand. Diagnosis tests (DRI, SDT) and compressive tests were then conducted on cores (9 for DRI and 19 for SDT) that had not undergone expansion tests to evaluate the current level of damage. The DRI is a petrographic method involving examining polished concrete plates under a stereomicroscope at 15X magnification to count various ASR symptoms, primarily cracks in aggregates and cement paste, which are weighted and normalized for a 100 cm² surface area to represent the extent of damage and cracking patterns. The SDT is a mechanical test involving five cycles of loading and unloading concrete at a fixed level, providing mechanical parameters such as Young modulus. Expansion tests realized were humid air (R.H. > 95%) and alkaline solution (NaOH 1N) at 38+/-2°C. The cores were kept under these conditions for a year and a half in total, but expansion measurements related to ASR were measured frequently for 66 weeks after re-humification. Finally, cores subjected to expansion tests were also evaluated with these diagnosis and compressive tests at the end of those tests.

By comparing the results of the diagnostic and compressive tests on cores that did not undergo expansion with those that did, the additional damage caused by the expansion tests can be assessed and correlated with the extent of the expansion. This comparison is made between different but comparable cores, which share similar locations, depths, and presumably similar initial levels of damage. This approach enables the analysis of the loss of mechanical properties in relation to increased expansion and evolution in diagnosis outputs (DRI and SDT).

Diagnosis tests results (DRI and SDT) were sourced from previous studies: Fournier et al. (2024) [1] provided the data for the Champlain Bridge, while Thériaux et al. (2022) [2] provided the data for the *Estacade* of the *Champlain Bridge*.

The final expansion reached by the cores was measured in this work, but the expansion curves were calculated by Fournier et al. (2024) [1]. The work done in this study thus primarily focuses on post-expansion residual tests (SDT, DRI, fc). Additionally, an equal number of samples from the Champlain Bridge tested for DRI after expansion, was tested on DRI for cores pre-expansion, despite the availability of pre-expansion DRI results [1]. This approach was used to enable a comparison of DRI values generated by the same petrograph and minimize additional variability.

Cores tested in humid air had diameters of 140, 100, 95, and 93 mm, while those tested in alkaline solution had diameters of 93, 95 and 100 mm, respectively. The larger diameter cores were used in humid air to minimize alkali leaching and thus prevent the premature plateauing of expansion. SDT and fc results were compared using cores of similar diameters.

3 Results and discussion

Only compression strength tests after expansion tests in humid air were conducted. Figure 1 shows the evolution of compressive strength as a function of the DRI number for samples that did not undergo expansion tests and after expansion in humid air. Each DRI sample was compared to two adjacent borehole samples for which compression strength tests were performed. Finally, the compression strengths were determined on specimens of the same diameter, allowing the results to be compared on the same graph.

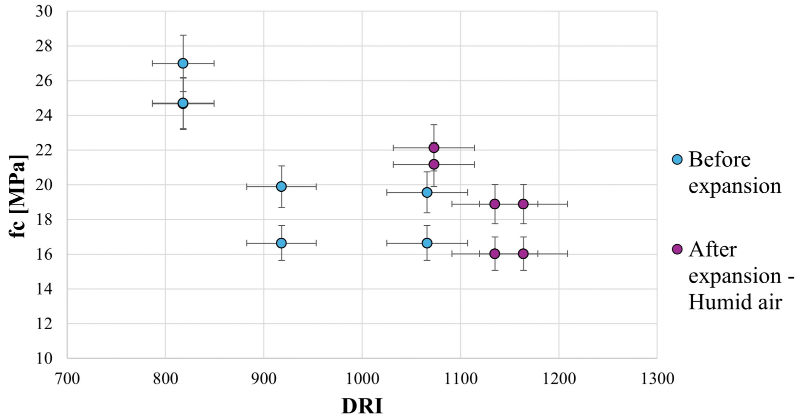

Fig. 1. Compressive strength as a function of DRI indices measured on cores as extracted and on cores subjected to residual expansion testing in humid air.

Before expansion, the samples show a noticeable decrease in compressive strength as the DRI increases. After expansion, this decrease remains, raising the question of whether the data can be compared on the same graph. To do this, it would be necessary to assume that the damage in humid air follows the same trend as on-site.
However, a difference is observed between the samples before and after expansion. For similar DRI values, the post-expansion samples show higher compressive strengths, suggesting an additional mechanism at play. Two hypotheses are proposed:

1. **Concrete Hydration**: the exposure conditions in humid air favor concrete hydration, increasing compressive strength. However, this increase seems too high to be solely due to hydration, especially for a 50-year-old bridge.
2. **Leaching and Crack Stop**: this phenomenon could stop cracking in the aggregates, stabilizing compressive strength despite the continued increase in DRI.

Ultimately, it is challenging to compare points before and after expansion, so that the post-expansion data is removed from the analysis. An additional point representing the initial state of undamaged concrete is added for compensating the lack of data, although this is based on uncertain assumptions, and Figure 2 is obtained.

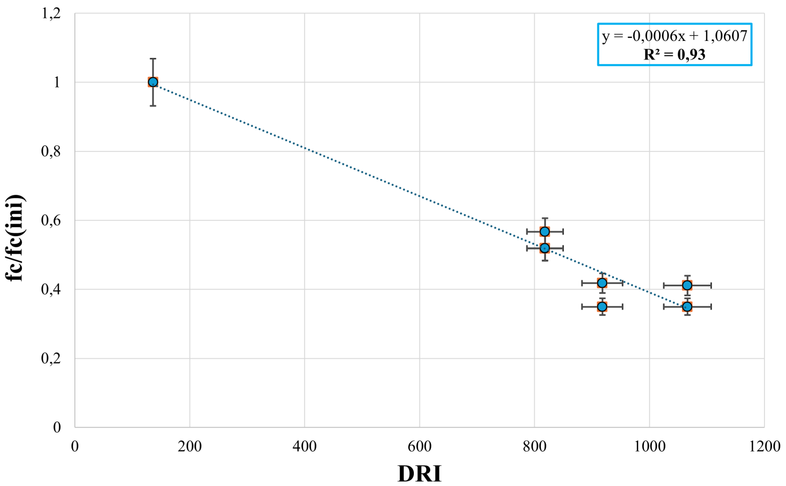

Fig. 2. Decrease in compressive strength fc as a function of the DRI number.

A linear relationship can be established between the decrease in compressive strength and the DRI number, with a high coefficient of determination. However, the relevance of this trend should be considered cautiously due to the limited number of data points available.

Figure 3 illustrates the decrease in Young's modulus in relation to the additional expansion generated in humid air.

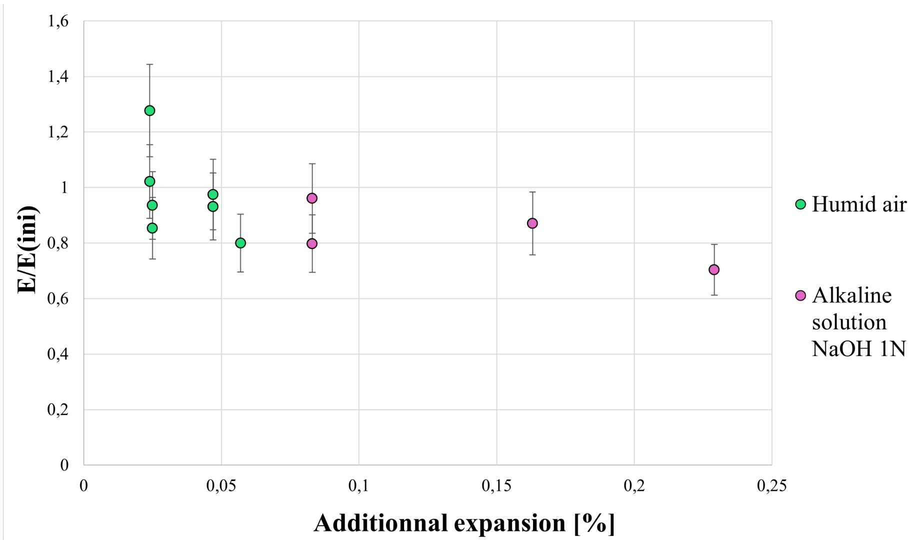

Fig. 3 : Relationship between the increase in parameter E and the residual expansion of concrete at 66 weeks after re-humidification, measured in NaOH solution.

As it can be observed (Fig.3), a decrease in Young modulus is observed with increasing expansion. The decrease in the Young's modulus continues for relatively high levels of expansion and does not seem to reach a plateau around 0.2%, as proposed by Sanchez et al. (2017) [4].

4 Conclusions

The following conclusions were made.

- An approximately linear trend (requiring further verification and consideration of additional data) was identified between compressive strength and the damage values of the concrete obtained through DRI in cores tested after extraction. The analyzed data also demonstrated a decrease of Young's modulus with increasing expansion and damage generated during residual expansion tests, but a statistically significant trendline was not identified.

- It is relevant to suggest conducting compressive strength tests during diagnosis and thus obtain information on the mechanical properties of the affected concrete.

- However, it should be noted that compressive strength is typically not the concrete property which is the most negatively affected by the expansion (and damage) associated with ASR.

- Compressive strength tests cannot replace the DRI test, as they are variable and do not reliably indicate the extent of cracking in the concrete, which is essential for accurately interpreting results and ensuring the durability of the material. Understanding the state of cracking is essential as it affects other issues like freeze-thaw cycles and corrosion.

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