FEM Approach to Appraise Bridges Affected by Alkali Silica Reaction (ASR)

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1.0 Abstract

Alkali silica reaction (ASR) is one of the most harmful distress mechanisms affecting the performance of aging concrete structures worldwide [1]. One of the biggest challenges present in civil engineering nowadays is to detect the current damage degree of ASR-affected structure/structural members (i.e. diagnosis), to establish an accurate correlation between ASR development and the losses in mechanical properties/durability of the affected material, as well as to understand its potential to produce further damage (i.e. prognosis) [2-3]. Such information is essential in selecting efficient remedial/rehabilitation actions for existing structures in the field. This project aims to develop a practical, yet accurate engineering-based finite element model (FEM) for assessing ASR damage and predicting the future behaviour of affected infrastructure. Data gathered from the assessment of a highly distressed overpass (the Robert-Bourassa/Charest overpass) with nearly 50 years in service and demolished in 2010/2011 will be used for the purposes of evaluating and validating the proposed model.

2.0 Introduction

Alkali aggregate reaction (AAR) is a chemical reaction between the alkalis from the concrete pore solution and some mineral reactive phases from the aggregates used to make concrete [1]. AAR is normally divided into two different mechanisms, so-called alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). ASR being by far the most common issue found around the world [1].

To develop ASR, three components are considered necessary: 1) aggregate containing reactive mineral phases, 2) high moisture content (normally assumed $\geq$ 85%) and, 3) high alkalis content [1]. ASR mechanism is considered to be fairly well understood (at least in its major steps) and, roughly, its development can be described in four major stages as by Saouma et al. [4]. The first stage is defined as “nucleation” where the reaction products start forming and filling surrounding aggregates, matrix voids and flaws. It is followed by a second step (“development”) where significant expansion occurs with minor crack formation

[4]. Then, a third stage (“acceleration”) takes place with the presence of important crack formation. Finally, the fourth and last stage is defined as “deterioration” (which could also be called deceleration phase), during which severe damage is found as well as a levelling off trend of ASR expansion, which might likely be caused by leaching (often found in laboratory testing procedures) or theoretical completion of the reactive mineral forms within the aggregates.

Moreover, it is well established that ASR damage in real concrete structures/structural members is influenced by a number of different parameters such as location, exposure conditions, etc. [1, 5]. Generally, greater damage is found in exposed sites compared to non-exposed sites as well as in locations closer to the member’s surface, compared to the member’s core [5].

Modeling the resulting expansions and damage generated by ASR is quite complex, yet necessary to obtain accurate predictions of the structural responses of distressed concrete members. To be efficient and reliable, models should take into account both the chemical and physical aspects of the reaction. Several ASR models were developed over the past decades to predict expansion and damage at the material (microscopic models) or the structural scales (macroscopic models). However, these either neglect or overemphasize the critical physicochemical parameters of the reaction. Respectively, this leads the models either to become incapable of assessing the distress mechanism properly or to become too complex, requiring heavy computer programing/ processing and, more importantly, the need to “fit” some of the variables with literature data or non-technical guesses. This, unfortunately, tends to make the models less useful and attractive for the engineering community. Therefore, a new simple yet reliable engineering based approach using FEM is developed and validated to assess ASR affected bridges.

The ASR macro-model was developed using a FEM software. This method was selected because it is a very well-established approach, able to evaluate structures/structural members presenting complex geometry types, material properties and loading conditions, especially in cases where analytical solutions don’t exist or are too time consuming.

However, before modeling it was necessary to develop an equation capable of representing the overall estimated expansion caused by ASR. Several parameters are known to affect the chemical reaction and those considered the most important were used in the development of the input equation. This equation proposes adjustment coefficient for Larive`s equation [5] in order to simulate the non-linear ASR free expansion and the consequent mechanical properties losses (compressive strength, tensile strength and modulus of elasticity). The five parameters considered as input on the current proposed model are: a) concrete expansion potential and characteristics (i.e. aggregate nature (i.e. lithotype), aggregate type (i.e. coarse, fine or coarse and fine); b) alkali content of the mix; c) moisture, d) temperature and e) exposure level. Both moisture and temperature values are allowed to vary over time, which allows the user to estimate what the regional behaviour of the structure would be and consequently improve the simulation. All these parameters were taken into consideration by applying and modifying Larive's equation [5] as an imposed expansion level (i.e. strain) to the structure. The equation is presented below, where τ_c is the characteristic time, τ_l is the latency time and ε^{∞} is the maximum expansion (final strain).

$$\varepsilon(t,\theta) = \frac{1 - e^{-\frac{t}{\tau_c}}}{1 + e^{-\frac{(t-\tau_l)}{\tau_c}}} \times \varepsilon^{\infty}$$

This equation was selected since it represents a time-dependent ASR behaviour as a function of the final expansion level (i.e. expansion expected to happen at t=∞). As illustrated above, it is possible to account for the four main stages of the reaction described in 2.0.

Three different validations are proposed to establish the accuracy of the approach. First of all, the selected material model (i.e. concrete damaged plasticity) was used to analyze 6 beams [6] with different longitudinal reinforcement ratios, transverse reinforcement ratios and spans. Based on these analyses it was possible to prove that the proposed model is able to accurately capture the non-linear behaviour of reinforced concrete members.

Next, the ASR expansion was validated by modeling ASR affected push-off specimens tested by Sanchez et al. (2017) [7] while investigating the influence of ASR in the shear capacity of concrete members. Different transverse reinforcement ratios were used, which validated the proposed ASR input expansion curve and the anisotropic stress-state dependency of the reaction, as proposed by Gautam et al. (2017) [8]. Figure 01 shows the surface cracking pattern found for one of the specimens containing 2 stirrups.

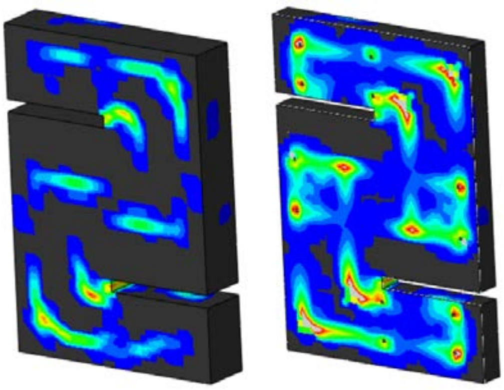

Figure 01 – Push-off Specimen – 2 Stirrups Case – Surface Cracking Pattern on the Left and Core Cracking Pattern on the Right

Lastly, a highly ASR distressed reinforced concrete structure (Robert-Bourassa/Charest overpass – RBC, Figure 03), presenting severe damage signs over nearly 50 years in service, was used as the main validation for the proposed model. It was selected because a number of detailed evaluations (i.e. visual inspection, mechanical, microscopic and residual expansion assessment, displacement measurements, etc.) were performed over the years before its demolition in 2010/2011. Thus, data gathered from the prior mentioned analyses was used to test and validate the proposed ASR macro-model.

Additionally, the model is currently being modified to be able to assess massive (dam) structures affected by ASR as the main topic of a research OCE-NSERC/Engage grant with the private sector company GHD. The most important additional aspects influencing the ASR expansion are the effect of reduced leaching due to the size of the structure on the reaction rate and the residual thermal stresses (as well as the temperature gradients over time) generated by the heat of hydration of cement.

Figure 02 – RBC Overpass (Picture on the Left and FE Model on the Right)

3.0 References

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