Assessing structural performance of existing concrete structures damaged by ASR

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Abstract: Many concrete bridges and dam structures in Australia have been reported to be affected by various degrees of deleterious alkali-silica reaction (ASR). The development of ASR in concrete causes expansion, cracking, and significant losses in its mechanical properties, which consequently results in compromised capacity and serviceability of the structures. On investigating these structures, two crucial questions need to be answered for an efficient rehabilitation and management solution, i.e. (i) the current damage condition and its effects on structural behaviour (in terms of structural capacity and serviceability); and (ii) the prediction of damage progression and impact to the structure in the coming months or years. To answer these questions, many challenges are yet to be addressed due to inherent complexities of both ASR characteristics and the field structures. This research proposed a new integrated modelling approach to address those questions based upon measurement data from laboratory testings. The approach consists of a semi-empirical model for forecasting ASR-induced expansion of concrete in the field and a finite element model used for assessing condition of the affected structures. With the promising outcomes, the proposed modelling approach is capable of providing an effective tool for the assessments of ASR effects on the concrete structures along with the traditional field inspections and appraisal. In addition, the approach reveals the importance of construction records such as type of aggregates, concrete mix proportion, alkali content, as well as structural design information for the condition assessment of the existing structures suffering from ASR.

Keywords: alkali-silica reaction, expansion, condition assessment, finite element modelling.

1. Introduction

Alkali-silica reaction (ASR), one of the most harmful distress mechanisms affecting concrete material and structures, which causes deleterious expansion, crack formation followed by reductions in concrete mechanical properties and long-term performance (i.e., durability and serviceability) of concrete structures [1, 2]. Many concrete bridges and dam structures in Australia have been reported to be affected by various degrees of deleterious alkali-silica reaction (ASR). These affected structures require comprehensive diagnosis and prognosis protocols for evaluating the current damage degree and forecasting the potential of further deterioration. Such information is essential to specify efficient method(s) for remedial/rehabilitation strategies and management procedures for the affected structures. In this regard, several techniques for diagnosis and prognosis have been developed and improved over the last decades. Nowadays, several state-of-the-art diagnosis techniques have been achieved to successfully identify and assess the current cause and extent of ASR-induced damage; however, there are still limited numbers of effective techniques for the prognosis of the physicochemical mechanism to forecast how ASR will progress in the coming months or years. To accomplish this requirement, several mathematical models (i.e., empirical, semi-empirical, analytical and numerical) have been developed to provide insightful information on the potential of future deterioration. All these models, however, are either oversimplified, and thus are inaccurate for assessing the distress mechanism properly, being mostly applied to laboratory-made specimens [3, 4], or very overcomplicated, being most of the times impractical, and requiring heavy computer processing [5]. In this context, it is necessary to develop a practical, yet effective empirical/analytical model for forecasting the field expansion based on laboratory testing results.

The ultimate aim of this study is to provide a robust and engineering-friendly tool to estimate ASR-induced expansion and assess the performance of concrete members/structures in the field from experimental observations and laboratory testing data. To accomplish this goal, first, a semi-empirical model was proposed to model the free expansion of unrestrained concrete in the field. Then, a finite element model was developed to account for the effects of the multiaxial reinforcement and stress confinement to ASR-induced expansion progression in concrete structures.

2. Modelling for expansion of field concrete from the expansion of CPT

2.1 A semi-empirical model for the ASR induced expansion of unconfined concrete

2.1.1 Model development

A number of empirical and analytical models has been developed to estimate ASR kinetics and induced expansion in the laboratory [3, 4], which combined with numerical analyses, were intended to predict the structural implications (i.e., deformation, stability) of structures, structural members [5, 6]. Among these models, the semi-empirical model proposed by Larive [4] is one of the most accepted and widely used by the ASR community (see Figure 1) [5-8]. The model for the stress-free expansion evolution was developed based on an extensive experimental database of more than 600 concrete specimens incorporating various reactive aggregates and exposed to different laboratory conditions. In this model, ASR kinetics and induced expansion were constructed as a function of three main model parameters: ultimate expansion (ε^{∞}), latency (τ_L) and characteristic (τ_C) times [4], given by

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

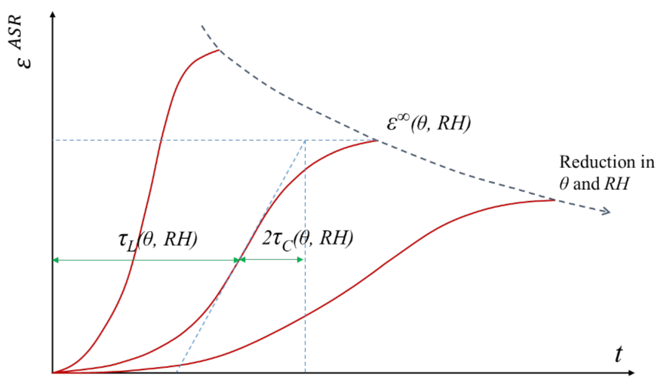


Figure 1. ASR-induced expansion curves obtained from Larive's model with considering temperature and relative humidity effects after Saouma and Perotti [5].

In order to account for the effect of temperature, relative humidity, and concrete alkali content and leaching, a semi-empirical model was proposed based on Larive's model by incorporating those effects into the three model parameters, ε^{∞}, τ_c, and τ_L. The value of the ultimate expansion ε^{∞} depends on the reactive aggregate used, relative humidity in concrete and alkali content, while characteristic time and latency time (τ_c, and τ_L) are dependent on the reactive aggregate, temperature, relative humidity. In addition, the amount of alkalis leaching (i.e., from laboratory tests, depending on the reactive aggregate, specimen size, and exposed condition) could change the characteristic time and latency time of the expansion. As such, the three model parameters could be defined as:

$$\varepsilon^{\infty} = \varepsilon^{\infty}(AG, RH, A) = \varepsilon^{\infty,o}(T_0, RH_0, A_0) \times k_{\varepsilon,\ RH} \times k_{\varepsilon,\ A} \tag{2}$$

$$\tau_c = \tau_c(AG, T, RH, LA) = \tau_c^{o}(T_0, RH_0, A_0) \times k_{c,\ T} \times k_{c,\ RH} \times k_{c,\ LA} \tag{3}$$

$$\tau_L = \tau_L(AG, T, RH, LA) = \tau_l^{o}(T_0, RH_0, A_0) \times k_{L,\ T} \times k_{L,\ RH} \times k_{L,\ LA} \tag{4}$$

where, *AG, RH, T, A* and *LA* denote the reactive aggregate type/nature, relative humidity (%), temperature (°C), concrete alkali content (kg/m^3), and alkali leaching at 1-year (%), respectively. Dependent coefficients are introduced to account for the effects of these factors, as mentioned above. The model parameters and dependent coefficients are explained in detail as follows:

- $\varepsilon^{\infty,0}(AG, RH_0, A_0)$, $\tau_c^0(AG, T_0, RH_0, A_0)$ *and* $\tau_l^0(AG, T_0, RH_0)$ are ultimate expansion and ASR time constants at a reference boundary condition, i.e., *T = 38°C*, *100% RH* and alkali loading $A = A_o$;
- $k_{\varepsilon,\ RH}$: *RH*-dependent coefficient of the ultimate expansion, where $k_{\varepsilon,\ RH}$ = 1 at *R.H* = 100%;
- $k_{\varepsilon,\ A}$ and $k_{\varepsilon,\ Ao}$: alkali content-dependent coefficient of the ultimate expansion, where $k_{\varepsilon,\ A}$ = 1 at *A = 5.25* kg/m^3;
- $k_{c,\ T}$ and $k_{L,\ T}$: temperature-dependent coefficient of the time constants (τ_c and τ_L), where $k_{c,\ LA}$ & $k_{L,\ LA} = 1$ at *T = 38°C*;
- $k_{c,\ LA}$ and $k_{L,\ LA}$: alkali leaching-dependent coefficient of the time constants (τ_c and τ_L) ($k_{c,\ LA}$ & $k_{L,\ LA} = 1$ if no leaching occurs, *LA = 0%).*

The temperature-dependent coefficients were developed based on physicochemical parameters and were thoroughly calibrated using a significant experimental database from Larive (1997) [4]:

$$k_{C,\ T} = \exp\left[U_C\left(\frac{1}{\theta} - \frac{1}{\theta_0}\right)\right] \tag{5}$$

$$k_{L,\ T} = \exp\left[U_L\left(\frac{1}{\theta} - \frac{1}{\theta_0}\right)\right] \tag{6}$$

where, θ_0 is reference absolute temperature (*θ K = 273 + T °C,* $T_0 = 38^0C$); $U_C = 5400 \pm 500K$ and $U_L = 9400 \pm 500K$ are thermal activation constants. This temperature dependence model of the τ_C and τ_L has been widely accepted and successfully implemented in forecasting the induced expansion of not only samples manufactured in the laboratory but also field structures such as dams and bridges [5].

In terms of the modelling, the relative humidity-dependent model proposed by Capra and Bournazel (1998) [3] as aforementioned is adopted in this study. This internal RH dependency is written in the form of the dependent coefficient $k_{\varepsilon,\ RH}$:

$$k_{\varepsilon,\ RH} = RH^8 \tag{7}$$

where, *RH* herein is the internal relative humidity or relative humidity in the material pores. The model was utilised for developing a constitutive model for ASR in Saouma and Perotti (2006) and is widely accepted and used in modelling ASR-induced expansion [5].

For the alkali content-dependent coefficient $k_{\varepsilon,A}$, experimental data from the literature [9-11] are collected for a comparison of alkali content from 1.5 kg/m^3 to 12.4 kg/m^3, as shown in Figure 1, in which 5.25 kg/m³ is assumed to be the control alkali content ($k_{\varepsilon,A}$ = *1.00*). In this study, $k_{\varepsilon,A}$ is obtained by averaging these available experimental data to take into account the impact of alkali content on the ultimate expansion, as shown in Figure 2.

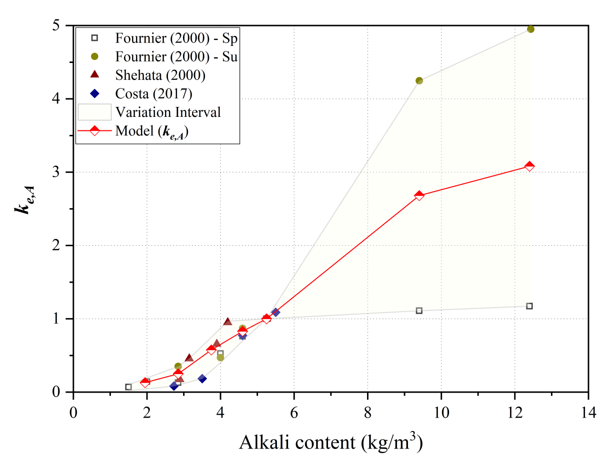


Figure 2. Dependency of the ultimate expansion (ε^∞) to the alkali content.

2.1.2 Consideration of alkali leaching and environmental condition

In general, forecasting expansion of concrete in the field requires: (1) observations from laboratory testing (i.e., ASR-induced expansion and alkali leaching over time) and, (2) environmental conditions in the field (i.e., ambient temperature and humidity, precipitation, snow and solar radiation). A two-step calculation procedure shown in Figure 3 was proposed to account for these two input groups for the calculation of field-exposed blocks expansion. The expansion curve and 1-year alkali leaching are utilised for the calculation of the model parameters of the semi-empirical model for the ideal "*no leaching*" scenario in the controlled environmental conditions, while environmental conditions are taken into consideration of the differences between laboratory and field conditions as well as possible changes of field conditions over time.

In the first step, by assuming that no leaching of alkalis occurs from the field blocks, an ideal expansion curve for this "*no-leaching*" scenario has to be simulated based on laboratory measurements. In this context, the ultimate expansion and time constants (ε^{∞} and τ_C, τ_L) of the ideal "*no-leaching*" scenario are calculated from the expansion over time and the alkali leaching amount at 1 year measured from laboratory samples. The inputs obtained from the laboratory tests include expansion over time, initial concrete alkali content and leaching of alkalis at 1 year.

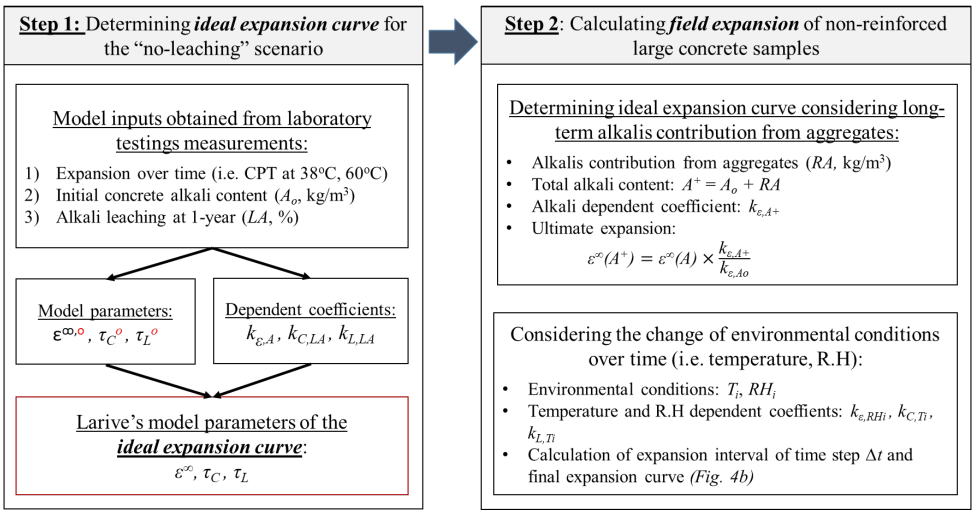


Figure 3. Overall procedure for modelling expansion of concrete in the field.

Considering a concrete mixture containing reactive aggregate fabricated in the laboratory containing an initial alkali content of A_o (kg/m^3), due to the leaching over time, a higher alkali loading (namely updated alkali content, A, *kg/m^3*) should be required to compensate for the leaching amount in order to simulate the ideal "*no leaching*" scenario of the original A_o alkali loading. As such, the updated alkali loading A could be calculated from the original alkalis A_o and the leaching amount measured at 1-year (*LA, %*):

$$A = \frac{A_o}{1 - LA} \tag{8}$$

or, $$A_o = A \times (1 - LA) \tag{9}$$

The alkali content-dependent coefficients $k_{\varepsilon,A}$ and $k_{\varepsilon,Ao}$ are then derived from the alkali loading of A and A_o, respectively, based on the proposed relationship illustrated in Figure 4.4. The fractional difference between $k_{\varepsilon,A}$ and $k_{\varepsilon,Ao}$ is utilised to increase the induced expansion measured in the laboratory on small samples to represent its ideal expansion curve without leaching.

After finalising the ideal expansion curve at the reference laboratory exposure conditions (i.e., 38°C and 100% RH), the effect of environmental conditions in the field is considered through the temperature- and RH-dependent coefficients presented in Section 2.1.1. The calculation procedure to capture the change of temperature and RH was adopted from [8]. As the temperature and RH in the field and thus in concrete changes over time, their effects on ASR-induced expansion have to be continuously considered. Each each set of temperature and RH produces an expansion curve of the concrete, namely a master curve. Expansion calculation is implemented through the determination of the incremental expansion of every single time step Δt. The incremental expansion at the time t_i is calculated based on the master curve of the corresponding environmental conditions (i.e., T_i, RH_i). The monthly average ambient temperature was utilised for the expansion calculation of the concrete blocks; thus, the time step of 1 month was adopted in this work.

The validation of the proposed semi-empirical model has been then conducted using three important experimental campaigns: : (1) Kingston exposure site, ON, Canada [12]; (2) CANMET exposure site, ON, Canada [13, 14]; and (3) The University of Texas at Austin, USA (UT) [15].

2.2. FE modelling for ASR induced expansion of field concrete under confinements

ASR-induced expansion in concrete under restraints/confinements is significantly different and far more complicated in comparison to the free expansion of unrestrained concrete. As such, a constitutive model is required to simulate the restrained ASR expansion. A constitutive model is required for considerations of (i) reaction kinetics (or, reaction advancement) in relation to affecting factors such as temperature and relative humidity in concrete; and (ii) effects of multiaxial stresses and restraints to the ASR-induced expansion. The former is normally referred to as the expansion of un-restrained concrete, namely free expansion of concrete, while the latter is required to simulate the relationship between the free expansion and restrained expansion of concrete. The former was covered by the thermodynamically-based semi-empirical model proposed in the previous section. The latter is addressed herein to accomplish the constitutive model for the ASR expansion and be implemented in the numerical model, i.e., finite element analyses.

A general form of the incremental ASR strain tensor to be implemented in the FE analysis could be expressed as:

$$\dot{\varepsilon}^{\mathrm{ASR}} = \mathrm{EWE^T} f(\sigma)\dot{\varepsilon}_{\mathrm{V}}^{\mathrm{ASR,\,free}} \tag{11}$$

where $\dot{\varepsilon}_{\mathrm{V}}^{\mathrm{ASR,free}}$ is the free volumetric expansion of concrete which calculated per the semi-empirical model presented previously, $f(\sigma)$ is expansion-stress dependent function accounting for the impact of stress state on ASR expansion, E is the eigenvectors derived from the stress tensor, and ***W*** is the weight tensor that distributes the volumetric expansion to each of three principal directions, given by:

$$\mathrm{W} = \begin{bmatrix} \mathrm{W}_1 & 0 & 0 \\ 0 & \mathrm{W}_2 & 0 \\ 0 & 0 & \mathrm{W}_3 \end{bmatrix} \tag{12}$$

Several models have been proposed for the expansion-stress dependence, yet, not all of these models are derived from multiaxial testing schemes and able to determine the expansion distribution weights. As discussed previously, two empirical models were devised based on the tri-axial stress testing data and widely used in the numerical modelling at the structural level, and these were derived from Gautam, Panesar [16].

In the test set up by Gautam et al. (2018), only normal stresses were applied in three primary directions, which could be considered as three principal directions. Therefore, the weights calculated above are equivalent to the weights in three principal directions, so that incremental ASR strain tensor is as same as in Eq. 11 to capture the ASR anisotropic behaviour. In addition, the experimental observations revealed an insignificant effect of stress confinement on the reaction kinetic and thus decoupled the stress effect in the reaction kinetic in this proposed model.

In addition, ASR cause losses of mechanical properties over time (i.e., modulus of elasticity, compressive strength and tensile strength) at various degrees. In this regard, the finite element model is able to account for these losses as the volumetric expansion increases.

3. Case study: results and discussions

3.1. Test overview

Concrete blocks exposed in CANMET and Texas (UT) sites

The CANMET and UT exposure sites were established as a part of a comparative study on the laboratory versus field performance using a wide variety of reactive aggregate types and natures across North America to study the efficiency of laboratory testing in representing field performance in different climatic conditions as well as to investigate the effectiveness of numerous preventive measures [13, 15]. Several identical concrete mixtures incorporating several reactive aggregates and different concrete alkali contents were tested for expansion in both the laboratory (i.e., CPT) and in the field (i.e., 0.40 × 0.40 × 0.70 m non-reinforced blocks manufactured in Ottawa - CANMET and Texas -UT). The field data of the concrete blocks were reported in [13, 17] up to 20-year and 3-year exposure from CANMET and UT site, respectively. Due to the use of identical mixtures, the results are preferable to evaluate the effect of environmental conditions, which is "*warmer*" in Texas and "*colder*" in Ottawa. The semi-empirical model presented in section 2.1 was adopted to simulate the free expansion of both concrete with and without alkali boosting (i.e., 5.25 kg/m^3 and 3.78 kg/m^3) using a single set of test results from standard CPT (i.e., 5.25 kg/m^3 alkalis). More information on these two exposure sites can be found in Fournier, Ideker [13] and Ideker, Bentivegna [15].

Concrete beams exposed in Kingston site

This outdoor exposure site was established by the Ontario Ministry of Transportation (MTO) in Kingston, Ontario, Canada in 1991, which aimed at providing correlation between short-term laboratory tests and long-term performance, as well as evaluating the efficiency of SCMs in mitigating ASR development (Figure 5) [12]. Different concrete mixtures incorporating the Spratt reactive aggregate, both high- and low-alkali content cement, and several types and proportions of SCM have been used in this experimental campaign. The low- and high-alkali cement (LAPC and HAPC) contained 0.79% and 0.46% Na2O equivalent per cement mass, respectively, which consists of 3.33 kg/m3 and 1.91 kg/m3 of alkalis in the concrete, respectively. The field study was conducted on both non-reinforced and reinforced concrete beam (i.e., dimension of 0.6 x 0.6 x 2 m, 1.41% reinforcement ratio), while three prisms (75 x 75 x 400 mm) were manufactured from the same concrete mixtures for laboratory testing. A recent report from the MTO in 2018 reported the updated 27-year data of this field exposure site [12]. In this study, only the data from the CPT samples and field beam elements (both non-reinforced and reinforced beams) with high- cement content was utilised for the purpose of validation of the proposed model. It is noted herein that the environmental conditions in Kingston are roughly similar to the conditions in Ottawa.

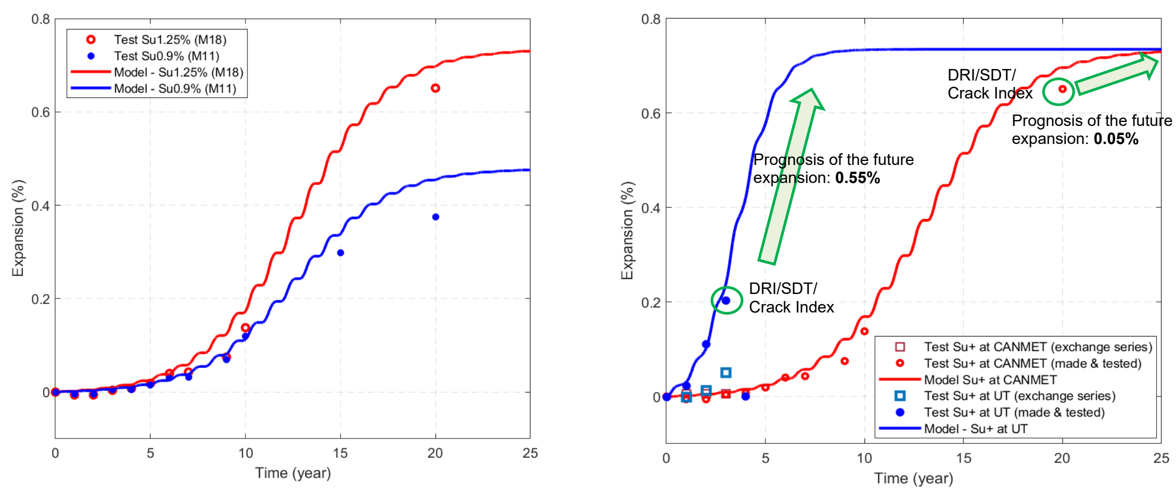
Figure 5. Kingston exposure site [12]

3.2. Results and discussions

Concrete blocks kept at CANMET and Texas sites

The proposed semi-empirical model was used to simulate the induced expansion of non-reinforced concrete blocks kept at CANMET and Texas sites. Figure 6(a) illustrates the model outcomes for the mixtures made of Sudbury aggregates varying in concrete alkali level in comparison to the measured data. By accounting for the alkali leaching and alkali contribution by the aggregate, the model also provides excellent results for the concrete made of cement with 0.9% and 1.25% of alkalis (i.e., 3.78 kg/m^3 and 5.25 kg/m^3, respectively). This result indicates the importance of considering the alkali leaching and alkali contribution by aggregate along with the applicability of the alkali content – expansion relationship proposed in Section 2. It is worth noting herein that the expansion of un-boosted concrete block (i.e., 3.78 kg/m^3 alkali content) is very well modelled using test results from the standard CPT method in the laboratory. This is an important advantage of the model to utilise CPT results and model ASR induced expansion of concrete structures in the field, where the alkalis in concrete are not boosted and mainly from cement.

The same model was applied for simulating the induced expansion of concrete blocks at the UT site using the same set of model parameters for the concrete mixture made of Sudbury reactive aggregate, yet changed to the temperature measured at the UT exposure site. Figure 6(b) shows the model outcomes in comparison to the field observations. Similar to the experimental observations of [13], the ASR-induced expansion calculated for blocks kept at the UT was obviously faster than CANMET's, i.e., about 4-5 times. This is due to higher ambient temperature in Texas, i.e. yearly average temperature of about 20°C in Texas compared to about 5°C in Ottawa. In general, the proposed model provides a reasonably good estimation of ASR-induced expansion from the two sites with different environmental conditions using only a single set of laboratory testing data. With this capability of the model, a single set of CPT test data can be used to simulate the expansion of concrete structures at different location varying in environmental conditions. In addition, another important advantage of the proposed model is for the prognosis of the potential future expansion. Nowadays, several state-of-the-art diagnosis techniques have been proposed to access and quantify the current expansion/or damage level of ASR affected concrete, such as Damage Rating Index (DRI), Stiffness Damage Test (SDT) or Crack Index (CI) [1]; however, there are still limited numbers of effective techniques for the prognosis of the physicochemical mechanism to forecast how ASR will progress in the coming months or years. After having reliable quantification of the current damage level using these diagnosis techniques, the proposed model is extremely helpful to forecast the potential future expansion of the affected structures. For instance, the concrete block at UT, after 3-year exposure, the concrete could expand further up to 0.55% in the next 5 years, and then stabilise afterwards, while the concrete block at CANMET after 20-year exposure could induce a further expansion of only about 0.05% in the next five years.



(a) Blocks at CANMET with different alkali levels

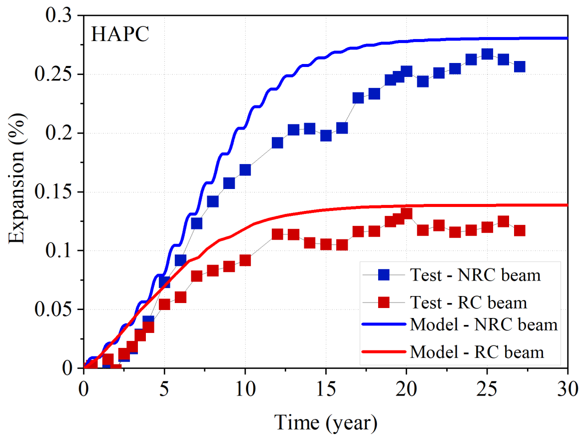
(b) Blocks exposed to CANMET and Texas sites

Figure 6: Model outcomes in comparison to the experimental data of specimens incorporating different alkali contents in CANMET.

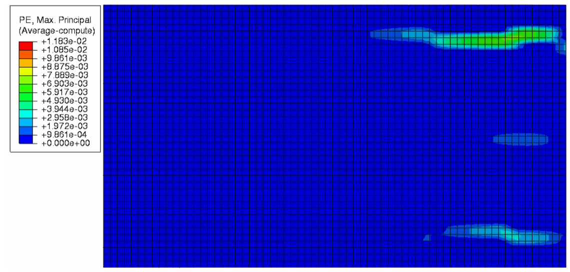
Concrete beams exposed in Kingston site

In this case study, the proposed semi-empirical model was used to model the free expansion of the non-reinforced concrete beam (NRC beam), while the FE model was applied for modelling expansion of the reinforced concrete beam (RC beam). The free expansion curve obtained from the semi-empirical model was used as an input to the FE model with additional considerations of confinements. Model outcomes for the non-reinforced and reinforced concrete beams from the semi-empirical model and FE model, respectively, are shown in Figure 7(a). It is clearly seen that the semi-empirical model accurately forecast the expansion of the non-reinforced concrete beams made of Spratt limestone. Furthermore, the proposed FE model is able to quantify the effect of reinforcement confinement and provides a very good estimation for the expansion of the reinforced concrete beam. Under 1.41% reinforcement confinement, the expansion reduced by about 50%, from 0.25% in the non-reinforced concrete beam to 0.125% in the reinforced concrete.

In addition, while the non-reinforced concrete beam kept expanding at a high rate after 12 years of exposure, the expansion of the reinforced concrete beam tended to be stable since that time. Finally, the model is able to capture crack development along the main reinforcement due to ASR induced expansion, as shown in Figure 7(b), which is commonly observed in real structures. With this very good outcome, the proposed integrated modelling approach consisting of the semi-empirical model and the FE model is promising for the prognosis of the ASR affected concrete structure and further evaluate implications of the expansion/damage to structural behaviour.



(a) Expansion of NRC and RC beams from the semi-empirical model



(c) Crack development in reinforced concrete

Figure 7: Model outcomes in comparison to the experimental data of concrete beams from Kingston site.

4. Conclusions

In this study, the integrated modelling approach consisting of the semi-empirical model and FE model was proposed for forecasting ASR induced expansion in concrete structures. The model is capable of account for effects of alkali content, alkali leaching, exposure conditions (i.e., temperature and relative humidity) and confinements to simulate ASR induced expansion of concrete in the field from measurements from laboratory accelerated test methods such as CPT. Test data from three important exposure sites (i.e., CANMET - Canada, Texas – the US, and Kingston – Canada exposure sites) were collected to validate the model. The following conclusions can be drawn from this work:

- The semi-empirical model is able to consider this leaching phenomenon and environmental conditions in the field to correlate expansion of concrete in the laboratory to the field. The free expansion curve obtained from the semi-empirical model is an important input to the FE model for modelling expansion of actual concrete structures under confinements. It is worth highlighting the importance of measuring alkali leaching from laboratory accelerated test methods such as CPT in order to correlate to the field performance.
- Confinements, such as from reinforcement, restraints and compressive stresses, reduce expansion significantly in the confined direction, yet, may increasingly expand in other less confined directions. The FE model was able to account for this confinement and expansion transfer behaviour to simulate the expansion of reinforced concrete members.
- The outcomes of the integrated model could be used for prognosis of ASR in the existing affected concrete structures, in which potential future expansion under free expansion and confined conditions can be estimated from the proposed model. The model, therefore, can be used effectively with other state-of-the-art diagnosis techniques such as DRI, SDT and CI.
- The success of the proposed model also highlights the importance of having construction records, such as type of aggregates, cement type (alkali content), reinforcement configuration to support the prognosis of the existing structures affected by ASR, which enable specifying efficient method(s) for remedial/rehabilitation strategies and management procedures for the structures.

Additional considerations of creep and ASR effects on the steel-concrete bond are helpful to improve the model to apply for condition assessment of field structures.

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