Assessing and forecasting ASR-induced expansion in the laboratory and in the field

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Abstract

Currently, there is a need to forecast the future behaviour of ASR-affected concrete in the field. Therefore, mathematical (i.e. analytical, numerical and or empirical) models have been established over the years. Larive developed an analytical/empirical model that describes the swelling behaviour of ASR-affected specimens in the laboratory. This approach has been widely used, even to predict the behaviour of concrete structures in the field. Yet, there is currently a lack of understanding on the variation of Larive's model parameters as a function of the material's properties (i.e. aggregates, alkalis, etc.) and environmental conditions (i.e. temperature, relative humidity, exposure degree, etc.). This work aims to discuss the potential use of Larive's model to predict affected concrete in the field. First, a comprehensive laboratory testing campaign using a variety of concrete strengths and aggregate types is conducted. Second, Larive's model is used to match laboratory data and a discussion on its main parameters is performed. Then, the same procedure is conducted to appraise the expansive behaviour of concrete blocks containing the same mix-design and reactive aggregates and exposed outdoors in Ottawa, Canada. Incompatibilities between laboratory data and predictions are discussed, and a proposal is made for improving the Larive's model performance to describe the behaviour of affected concrete in the field.

***Keywords**: analytical modelling; forecasting ASR-induced expansion; ASR prognosis*

1. INTRODUCTION

Alkali-silica reaction (ASR) is a chemical reaction between the alkali hydroxides (Na^+, K^+, and OH^-) from the concrete pore solution and some unstable silica mineral forms from the fine and coarse aggregates used to make concrete [1]. ASR generates a secondary product (i.e. ASR gel) that swells upon moisture uptake, leading to volumetric expansion and damage. This reaction is one of the most harmful distress mechanisms affecting the performance and long-term behaviour (i.e. durability and serviceability) of concrete infrastructure around the world [2].

Various factors may affect ASR-induced expansion and damage such as alkali loading, the type (i.e. coarse vs fine) and reactivity (mineralogy) of the aggregates, environmental conditions such as temperature, humidity, exposure degree, etc. [3]. Forecasting ASR-induced expansion and damage along with its consequences is extremely challenging. A number of empirical, analytical and numerical models have been developed over the years and amongst those, Larive's model [4] is a widely accepted approach by ASR community [4-7]. It was developed to describe the swelling behaviour of concrete specimens in the laboratory but has been even used to forecast the performance of concrete structures in the field.

2. LARIVE'S MODEL

Larive [4] developed an analytical/empirical model to describe the reactive behaviour of ASR affected concrete specimens in the laboratory. Larive has worked with over 600 specimens that were subjected to a wide range of environmental and mechanical conditions. In Larive's model, ASR-induced expansion is described as a function of three main parameters: ultimate expansion ($\varepsilon\infty$), latency (τ_l) and characteristic (τ_c) times (Equation (1)). Each set of parameters is only valid for a given temperature (θ). Figure 2.1 illustrates a typical expansion curve resulting from Larive's analytical model [4]. It is worth noting that both characteristic and latency times do not have a clear physical meaning, being mostly mathematical parameters.

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

Where θ is the absolute temperature, τ_c, τ_l are the characteristic and latency times, respectively and ε^{∞} is the maximum (or ultimate) expansion at infinity [5].

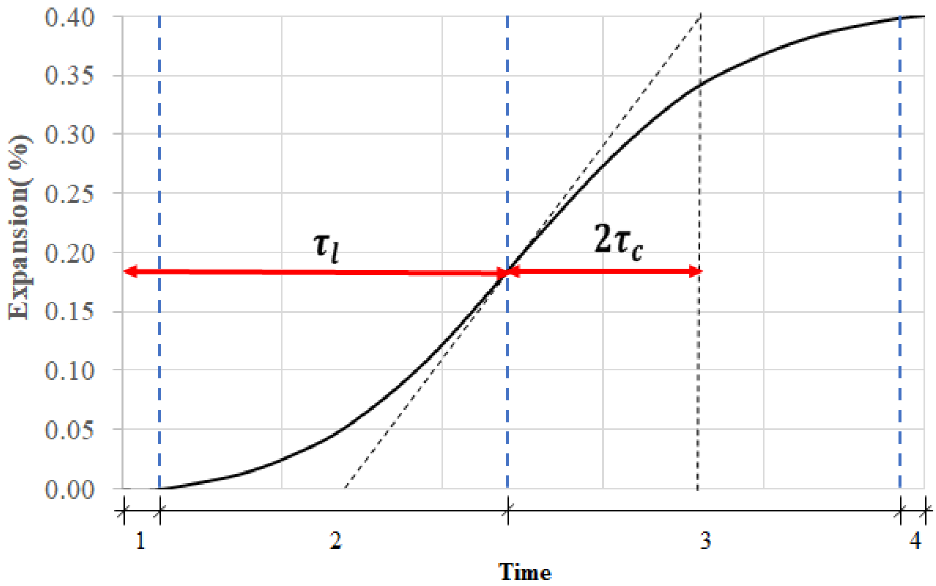

Figure 2.1: S-shape ASR-induced expansion plot [4].

Larive's model often displays an S-shape expansion curve that may be divided into four phases. The first phase represents ASR secondary products (i.e. ASR-gel) formation and accommodation within the reactive aggregate particles and adjacent cement paste with little to no expansion as per [3]. The second phase (i.e. ascending curve period) represents a sharp ASR-induced expansion period due to moisture uptake from the reaction products. In this phase, expansion with limited cracking is expected, explaining the initial "convex" shape of the curve. Phase two ends at the inflection point of the S-shape curve, above and beyond which major deterioration (i.e. cracks) is expected to take place within the aggregate particles and surrounding cement paste as per [3]. In phase 3, the curve shape changes from "convex" to "concave" since the reaction products that keep forming over the induced physicochemical process have supplementary space (i.e. cracks, flaws, etc.) at this stage to accommodate, lessening ASR-induced expansion rate. Finally, the fourth and last phase of the curve shows a reaction levelling off trend due to the total alkalis and/or silica consumption from the system. It is important to note that the expansion levels provided in Figure 2.1 are merely qualitative and were simply selected to properly illustrate ASR physicochemical process. They are not intended whatsoever to precisely represent the expansion levels where ASR-induced cracks are thought to be generated and propagated as per [3].

3. ASR-INDUCED DEVELOPMENT: LABORATORY VERSUS FIELD PERFORMANCE

A wide range of research has been conducted in the past decades trying to correlate laboratory test outcomes mostly under accelerated conditions with the performance of affected structures or structural components made of similar mixtures (i.e. alkalis loading, amount and type of aggregates, etc.) in the field [8-11]. These works have clearly demonstrated that although one may think laboratory and accelerated conditions are quite severe, the outcomes of expansion and deterioration obtained in the laboratory are often lessened when compared to the field.

Amongst all the existing accelerated test procedures aiming to appraise the reactivity of aggregates and or the efficiency of preventive measures in the laboratory, the concrete prism test (CPT) as per ASTM C 1293 or CSA.A23.14A is likely the most reliable test procedure. It consists of manufacturing concrete prisms (i.e. 75 mm side and 285 mm long) with a fixed water-to-cement ratio range (i.e. 0.42-0.45) and incorporating reactive coarse or fine aggregates; non-reactive coarse or fine aggregates (depending on the reactive aggregate's selection) need to be used in combination with the reactive materials for concrete manufacturing. A conventional Portland cement (GU type or ASTM type I) should be used, and the alkalis in the mix raised to display 1.25% of Na_2O_e. Once manufactured, the specimens are stored under conditions enabling ASR-induced development (i.e. 38 °C and 100% R.H.) and monitored over one year. The test may take up to two years in the case of using preventive measures to mitigate ASR such as supplementary cementing materials (SCMs). The expansion of 0.04% at one year is the threshold established to classify reactive and non-reactive behaviour of aggregates in the laboratory. The same limit, yet to be evaluated at two years, should be adopted to assess the efficiency of preventive measures to mitigate potential ASR-induced expansion.

Although quite reliable to distinguish reactive and non-reactive behaviour along with determining the reactivity degree of aggregates (i.e. marginal, moderate, high and very high) in the laboratory, the CPT procedure presents important limitations. First, there is currently no correlation between the correspondent "time period" in the field that represents the one-year test outcome evaluated at 38 °C and 100% R.H. The time period (i.e. one year) and threshold (0.04%) of the CPT test were established in such a way that the material tested in the laboratory would display its "potential reactivity" in the field. In other words, the laboratory outcomes might represent the behaviour of "similar concrete mixtures" or concrete mixtures made of "similar aggregates" in the field over their proposed service life. Yet, the prior statement is too qualitative and no further discussion is made on current standards. Second, some potential issues such as alkali leaching may take place while the CPT test, which may reduce ASR-induced development and ultimate expansion in the laboratory. According to Lindgård et al [12], concrete specimens tested over the CPT are expected to lose between 3 and 20% of alkalis in the first 4 weeks and between 10 and 50% after one year. All the above brings some concerns regarding the actual reliability of accelerated laboratory tests to assess performance in the field.

With the above scenario, CANMET initiated in 1991 a comparative field and laboratory research program to develop an engineering database on the long-term performance of ASR-affected blocks incorporating reactive aggregates along with the efficiency of SCMs and lithium-based products in controlling ASR-induced expansion [8]. Further information and results on the CANMET study can be found in [9,10]. A comprehensive testing matrix was developed including reactive aggregates and cementitious materials from different parts of the world. From each of the mixtures manufactured over this research program, concrete prisms and exposure blocks were fabricated and subjected to accelerated test conditions in the laboratory or to natural environmental conditions at CANMET outdoor exposure site in Ottawa, Canada. Expansion and cracking due to ASR were (laboratory testing) and are still (exposure blocks – Figure 3.1) being monitored [12]. Preliminary data from CANMET analyses suggest an important incompatibility between laboratory and field outcomes. Yet, there is a very limited discussion in the literature on the "quantitative" scattering between laboratory and field, and on whether the scattering remains similar for concrete incorporating distinct aggregate types (fine vs coarse) and reactivity degrees (≠ lithotypes). The latter is imperative to implement successful models, such as Larive's, to describe and predict ASR-induced expansion and deterioration in the laboratory or in the field.

Figure 3.1: CANMET outdoor exposure site.

4. SCOPE OF THE WORK

As previously mentioned, there is currently an important need to forecast critical infrastructure affected by ASR. Therefore, empirical, analytical, and numerical models such as Larive's have been developed in this regard. However, most of the proposed models are based upon laboratory data and yet, research works suggest a clear incompatibility between the reactivity of affected concrete in the laboratory when compared to the field. Although preliminary data from the literature addresses those differences as per [8-12], very few quantitative evaluations have been conducted so far for concrete mixtures incorporating a wide range of reactive aggregates (i.e. presenting distinct reactivity degrees), which prevents a deep understanding on the matter.

In this context, Larive's equation was primarily developed to describe the behaviour of reactive concrete in the laboratory. Although very interesting and widely accepted by ASR community, it is a somewhat limited approach because its coefficients (τ_l and τ_c) have no clear physical meaning, which means that Larive's equation is not able, in its current state, to predict ASR-induced development in the laboratory accounting for the most important physicochemical parameters that influence on the chemical reaction such as aggregates type (fine vs coarse), reactivity (low, moderate, high and very high), alkali loading, temperature and relative humidity without extensive laboratory tests and calibration. Furthermore, the range of values of the two Larive's parameters (τ_l and τ_c) as a function of the above-mentioned parameters as well as whether this range of values applies to field conditions is mostly unknown.

This paper presents a two-fold objective. First, one aims to assess, discuss and quantify the incompatibility in performance of affected concrete appraised in the laboratory and in the field. Second, one intends to use Larive's equation (in its current state) to describe ASR-induced expansion and development in the laboratory for concrete presenting distinct aggregate reactivities. The range values of τ_l and τ_c according to the different material features will then be established and used to evaluate concrete blocks manufactured with materials but stored under environmental conditions for over 20 years in Ottawa, Canada. Finally, a proposal for improving the performance of Larive's model to better describe the behaviour of affected concrete in the field is performed.

5. MATERIALS AND METHODS

5.1 Materials, storage and mixture proportioning: laboratory research program

A number of concrete mixtures incorporating five reactive aggregates and presenting distinct mix-proportions and mechanical properties (i.e. 25, 35, and 45 MPa) were selected for this research as per [13] and illustrated in Table 5.1. The size of coarse aggregates used ranged from 5 to 20 mm. A non-reactive fine aggregate (i.e. Control) was used in combination with the reactive materials for concrete manufacturing. A conventional Portland cement (CSA Type GU equivalent to ASTM type 1) containing high alkali content (0.88% Na_2O_e) was used in the mixture. Reagent grade NaOH was used to raise the total alkali content of the mixtures to 1.25% Na_2O_e by cement mass, for accelerating ASR expansion process.

Table 5.1: Aggregates used in this research [13].

Aggregate		Reactivity	Location	Rock type	AMBT* 14-day exp. (%)
Coarse	Su	R	Sudbury (Canada)	Sandstone, quartzwacke, arkose, greywacke and argillite	0.450
	Sp	R	Ottawa (Canada)	Siliceous limestone	0.310
	Conr	R	Halifax (Canada)	Metagraywacke, shale, siltstone	0.365
	Pots	R	Montreal (Canada)	Siliceous sandstone (orthoquartzite)	0.093
	NM	R	New Mexico (USA)	Polymictic Gravel (Mixed Volcanic, quartzite, chert)	1.056
Fines	Control	NR	Quebec (Canada)	Natural derived from Granite	0.068

*AMBT: Accelerated Mortar Bar Test [13].

Third-five concrete cylinders (100 by 200 mm cylinders) from each of the concrete mixtures (i.e. each concrete mixture incorporates one reactive aggregate and the non-reactive control sand as per Table 1) were fabricated, demoulded after 24 hours, and moist cured over 24 hours. Small holes, 5 mm in diameter by 15 mm long, were then drilled in both ends of each test specimen and stainless steel gauge studs were glued in place, with a fast setting cement slurry for longitudinal expansion measurements. After the completion of the first 72 hours (i.e. three days from casting), the zero reading was taken and the specimens were stored at 38°C and 100% R.H. All the specimens were regularly monitored over one year (i.e. 365 days). They were then classified in terms of reactivity according to [14] and illustrated in Table 5.2.

Three mix-design sets were selected to proportion the different laboratory concrete mixtures studied in this work so that comparisons might be conducted. First, the absolute volume method (ACI method) was selected to proportion 25, 35 and 45 MPa mixtures incorporating the NM reactive coarse aggregate. The amount of alkalis used in these mixtures were 2.51, 4.62 and 5.30 kg/m^3 respectively, for the 25, 35 and 45 MPa mixes. Second, 35 MPa mixes incorporating both Pots and Conr aggregates were also proportioned as per the absolute volume method displaying 4.62 kg/m3 of alkalis. Finally, concrete mixtures designed as per the CPT mix-design (i.e. ASTM C 1293 or CSA.A23-14A) were proportioned incorporating the NM, Sp and Su aggregates and presenting 5.25 kg/m^3. All mix-designs proportioned are illustrated in Table 5.3.

Table 5.2: Classification of ASR-induced damage degree as per [14].

ASR damage degree	Reference expansion level (%)
Negligible	≥ 0.00 and ≤ 0.03
Marginal	≥ 0.04 ± 0.01 and < 0.10
Moderate	≥ 0.11 ± 0.01 and < 0.19
High	≥ 0.20 ± 0.01 and < 0.29
Very high	≥ 0.30 ± 0.01 and < 0.49
Ultra-high	≥ 0.50

Table 5.3: Mix-proportions used in the research.

Type of concrete	Concrete Mix designs: Ingredients and strengths		25 MPa		35 MPa		45 MPa	
			kg/m³	L/m³	kg/m³	L/m³	kg/m³	L/m³
25, 35 and 45 MPa mixtures ACI mix-proportioned	Common to all mixtures	Cement	314	101	370	118	424	151
		Water	192	192	174	174	157	142
		Air	-	20	-	20	-	20
	NM + control	Sand	714	264	714	264	714	264
		Coarse aggregate	1073	424	1073	424	1073	424
	Pots + Control	Sand			737	272		
		Coarse aggregate			1068	416		
	Conr + Control	Sand			807	298		
		Coarse aggregate			1060	390		
35 MPa mixtures CPT mix-designs	Common to all mixtures	Cement			420	134		
		Water			176	176		
		Air			-	20		
	NM + Control	Sand						
		Coarse aggregate						
	Sp + Control	Sand			762	285		
		Coarse aggregate			1038	384		
	Su + Control	Sand			784	294		
		Coarse aggregate			1012	375		

Following the experimental tests and expansion results, Larive's model has been implemented to describe all expansion curves gathered in the laboratory. Therefore, the range of τ_l and τ_c values could have been obtained for the different aggregates and mix-proportions tested, displaying quite distinct reactivity degrees.

5.2 Materials storage and mixture proportioning: CANMET research program

Concrete blocks (40 mm by 40 mm by 70 mm) incorporating the same aggregates used in the laboratory (Table 5.1), and mix-proportioned as per the concrete prism test (CPT, ASTM C 1294 or CSA.A23.14A – Table 5.3 – 5.25 kg/m^3 of alkalis) were fabricated. The size of coarse aggregates ranged from 5 to 20 mm. A non-reactive fine aggregate was used in combination with the five reactive materials for concrete manufacturing. A conventional Portland cement (CSA Type GU, ASTM type 1) containing high alkali content (0.90% Na_2O_e) was used in the mixture. Reagent grade NaOH was used to raise the total alkali content of the mixtures to 1.25% Na_2O_e by cement mass, for accelerating ASR expansion process.

Eight stainless steel threaded studs (9 mm in diameter by 75 mm in length) were partially embedded in the sides and on the top of the concrete blocks for length change monitoring. The blocks were placed on an outdoor exposure site, which consisted of a well-compacted layer of 0-19-mm crushed limestone material. Length-change was taken on the longitudinal axis on the top and sides of the blocks, generally once a year under similar conditions (cloudy day; temperature of 23 ± 2°C). Although CANMET exposure site blocks have been monitored for over 20 years, only the measurements taken up to 15 years will be presented in this work. Following the expansion results, Larive's model was used to describe the measurements conducted in the field. Therefore, the range of τ_l and τ_c values was obtained for field conditions.

6. RESULTS

6.1 ASR-induced expansion and Larive's model calibration in the laboratory

Figure 6.1 illustrates the expansion vs time for the concrete mixtures proportioned in the laboratory (Figure 6.1a) along with the use of Larive's model to describe the behaviours obtained (Figure 6.1b).

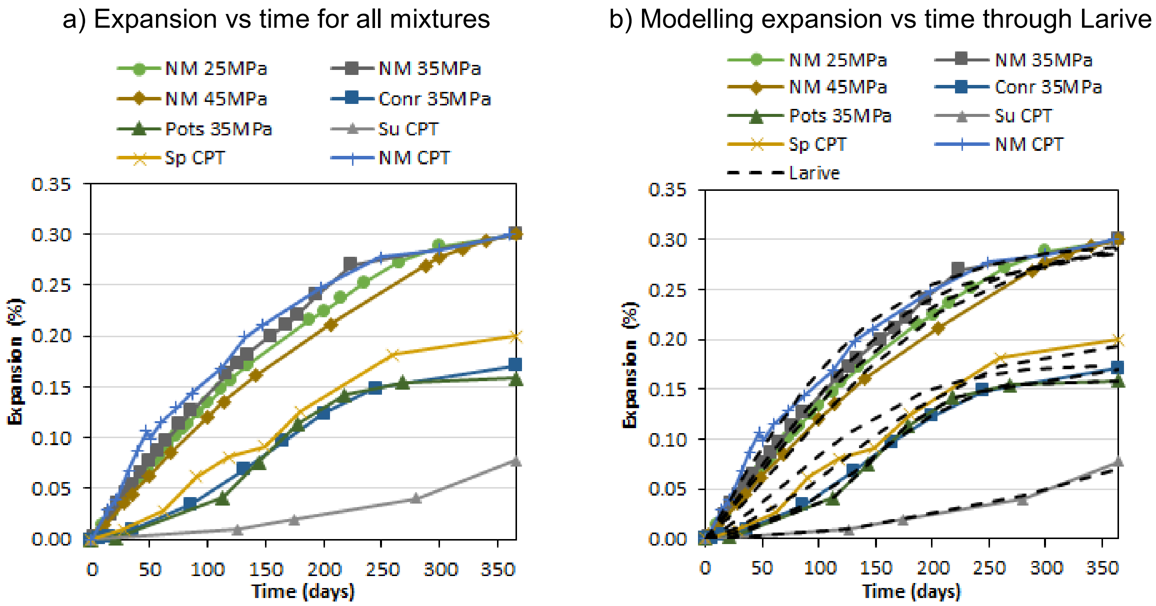

Figure 6.1: Evolution of ASR-induced expansion of the mixtures proportioned in the laboratory. A) Expansion vs time and, B) Expansion vs time modelled using Larive's approach.

Analyzing Figure 6.1a, one verifies that interesting results were gathered. First, all NM concrete mixtures (i.e. 25, 35 and 45 MPa along with CPT) displayed quite similar ASR-induced development over time (i.e. kinetics and ultimate expansion), regardless of their strength (i.e. 25, 35 and 45 MPa) and alkali loading (i.e. 2.51, 4.62, 5.25, and 5.30 kg/m^3). Very high expansion levels (i.e. about 0.30%) were reached for all NM mixtures at 365 days.

Concrete mixtures made of Sp, Conr, Pots and Su displayed a much slower ASR-induced development than NM mixes. SP mix reached a high expansion level (i.e. 0.20%) at one year, while Conr and Spot achieved 0.17% and 0.16%, respectively. Otherwise, Su mix reached a moderate expansion level (0.08%) at 365 days.

Larive's equation has been implemented to describe ASR-induced development (kinetics and ultimate expansion) of all mixtures developed in the laboratory. The least-square method (LSM) was adopted to find the best fitting for the model and thus τ_l and τ_c parameters were obtained for the distinct mixes (Table 6.1). Observing the results obtained, it is possible to notice that τ_l values ranged from 0 to 367 while τ_c values varied from 34 to 114. The faster ASR-induced development, the lower the τ_l; conversely τ_c does not seem to have a direct correlation with the ultimate expansion but rather with the shape of the curve from the inflection point till the end of the monitoring period.

Overall, concrete mixtures incorporating very high, high and moderate/low reactive aggregates (see Table 5.2) seem to display quite low, moderate and high latency times (τ_l) times, respectively. Conversely, there is no pattern for the characteristic time (τ_c) parameter, since as aforementioned, it mainly depends on the existence of a levelling of trend at the end of the 1-year test. If at one-year a given concrete is reaching its plateau, moderate to low characteristic times (τ_c) are expected. Otherwise, moderate to high characteristic times will be displayed.

Table 6.1: Larive model (i.e. τ_l and τ_c) parameters obtained through the best fitting using the LSM for affected concrete specimens in the laboratory.

Concrete Mixture	τ_c	τ_l	ε^{∞}	Reactivity Degree
NM 25MPa	88	39	0.30	Very high reactivity (VHR)
NM 35MPa	82	35	0.30	Very high reactivity (VHR)
NM 45MPa	84	75	0.30	Very high reactivity (VHR)
NM CPT	80	0	0.30	Very high reactivity (VHR)
Conr 35MPa	53	146	0.17	Moderate reactivity (MR)
Pots 35MPa	34	146	0.16	Moderate reactivity (MR)
Su CPT	114	367	0.15	Moderate reactivity (MR)
Sp CPT	56	132	0.20	High reactivity (HR)

7. ASR-INDUCED EXPANSION AND LARIVE'S MODEL CALIBRATION IN THE FIELD

Figure 7.1 illustrates ASR-induced expansion of concrete blocks fabricated with the same aggregates as presented in the laboratory studies but stored at the CANMET exposure site (Ottawa, Canada) for over 15 years. It is worth noting that the plots displayed in Figure 7.1 were obtained through the use of Larive's model coupled with the LSM to better fit three field measurements taken over 15 years of exposure (i.e. initial reading, and readings after 10 and 15 years). Furthermore, predictions through Larive's model were performed until 50 years of service so that this might represent the expected induced expansion over the service life of concrete structures made of these mixtures.

Analyzing Figure 7.1, one verifies that NM concrete blocks display an ultra-high expansion level (i.e. 0.68%) over time, whereas Conr and Su blocks show very high expansion levels (i.e. 0.36% and 0.32%), respectively; moreover, Sp and Pots present high expansion levels (0.24% and 0.23%, respectively). Comparing the block expansions with the results obtained through the concrete prism test in the laboratory, one verifies that the induced expansion obtained in the field is higher or even much higher than the data gathered in the laboratory.

The blocks manufactured with Su and NM aggregates displayed expansion levels of 300% and 126% greater than the values obtained in the laboratory, respectively. Conr blocks showed expansion levels 112% higher than laboratory specimens while Pots and Sp specimens presented respectively 43% and 20% higher expansions in the field when compared to laboratory. Although a direct pattern may not be found herein, the above results suggest that some moderately aggregates that do not present levelling off trends within the 1-year concrete prism test such as Su and Conr may display significantly higher performance in the field.

Table 7.1 illustrates Larive's parameters (τ_l and τ_c) obtained to describe ASR-induced development in the field. Latency times (τ_l) for all blocks ranged from 0 to 77, being much lower than the values obtained in the laboratory; the latter demonstrates that latency is a phenomenon that does not take place in the same fashion in the field. Otherwise, characteristic times (τ_c) seem to be also much lower when compared to laboratory parameters, ranging from 33 to 52 for all aggregates. These results seem to indicate a more pronounced levelling off trend for the blocks exposed to environmental conditions when compared to CPT specimens at one year.

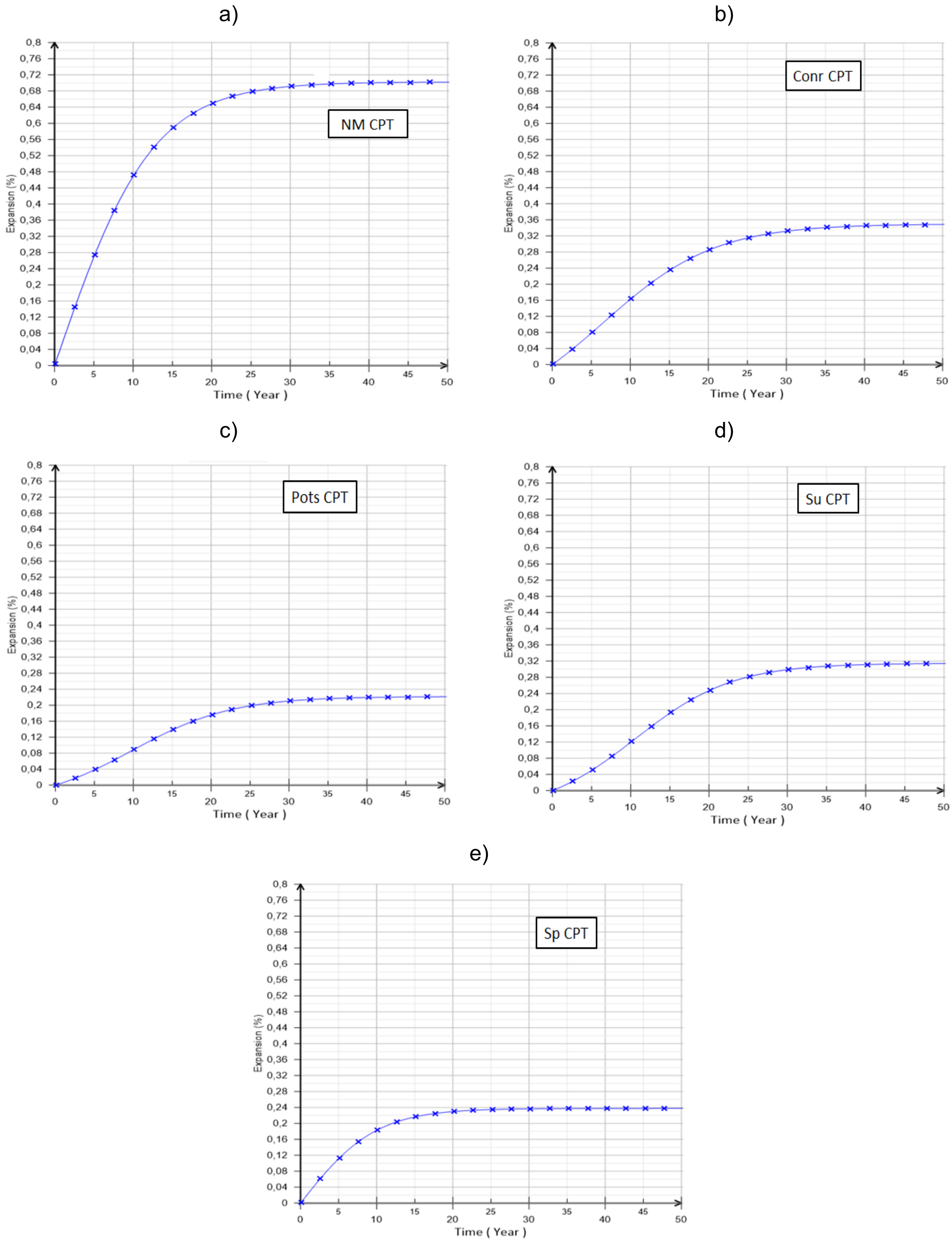

Figure 7.1: ASR-induced development of concrete blocks stored at CANMET exposure site in Ottawa, Canada and manufactured with the CPT mix-design incorporating the following aggregates a) NM, b) Conr, c) Pots, d) Su and, e) Sp.

Table 7.1: Larive model (i.e. τ_l and τ_c) parameters obtained through the best fitting using the LSM for affected blocks stored at the Ottawa exposure site.

Concrete Mixture	τ_c	τ_l	ε^{∞}	Reactivity Degree
NM CPT	45	0	0.70	Ultra-high reactivity (UHR)
Conr CPT	52	47	0.35	Very high reactivity (VHR)
Pots CPT	47	72	0.22	Moderate reactivity (MR)
Su CPT	45	77	0.31	High reactivity (HR)
Sp CPT	33	0	0.21	High reactivity (HR)

8. DISCUSSION

8.1 Insights for improving Larive's model to forecast affected blocks in the field

The results presented in the previous section raised important doubts on the reliability of the concrete prism test (CPT) to appraise the "reactivity degree" that aggregates may generate in field concrete. As aforementioned, the CPT is likely the most reliable tool used to assess the "potential reactivity" of aggregates in the laboratory. Yet, being reliable to measure the "potential reactivity" does not mean the CPT is efficient to evaluate the "reactivity degree" of reactive concrete mixtures in the field.

Comparing the laboratory vs field results gathered in this work, it is evident that the field expansions are much higher than the laboratory results. One of the likely key reasons for that is the alkalis loading. It has been found by many authors that leaching may be quite an important issue in the CPT procedure (being less important in the field). Values as high as 50% of alkalis leaching have been reported by Lindgård et al. [12]. Therefore, it seems that whether leaching is incorporated in the laboratory data and modelling (i.e. Larive's equation), the lab outcomes might be closer to (or more representative of) field performance. Fournier & Bérubé [15] studied the 1-year CPT outcomes of concrete mixtures incorporating two reactive aggregates used in this work (i.e. Su and Sp) as a function of the alkalis loading of the mix (Figure 8.1). The authors noticed that first, the higher the alkali loading the higher the 1-year CPT expansion. Second, the increase of expansion was deemed to vary as a function of the aggregate nature and reactivity (i.e. Su > Sp). In this work, 5.25 kg/m^3 alkali systems were selected to accelerate ASR-induced development in the laboratory and field. Yet, if one accounts for the 50% alkalis leaching in the laboratory as per [12], mixtures with alkali loadings as high as 8 kg/m^3 would be required to match field mixtures. As per Figure 8.1, whether leaching is accounted for, CPT final expansion levels of about 12.5% and 125% higher might have been expected from concrete mixtures incorporating Sp and Su aggregates, respectively.

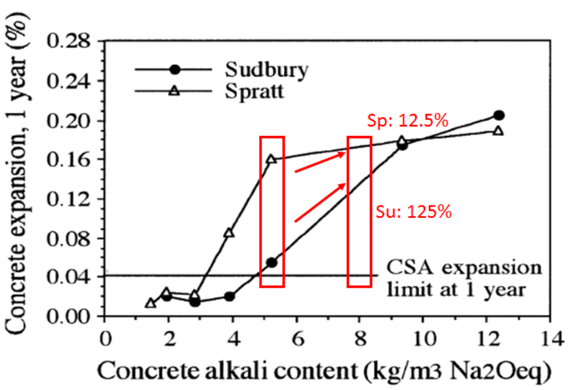

Figure 8.1: ASR 1-year CPT expansion as a function of the concrete alkali loading. Adapted from [15].

In this context, Figure 8.2 gives a plot of induced expansion results obtained in the laboratory (i.e. CPT test – solid red), in the field (Blocks – solid blue) and also illustrates a rise in expansion (CPT – alkali-correction – solid green) due to 50% of leaching. Although still not precisely capturing the field behaviour, the previous scattering from 300% and 20% for concrete blocks made of Su and Sp would have been lessened to 60% and 9% respectively.

Finally, it is worth noting that all blocks curves were obtained through the use of Larive's equation fitting three expansion readings only (i.e. 0, 10 and 15 years). Thus, higher number of readings are required to improve Larive's field prediction and the accuracy of the current discussion. Nonetheless, it has been noticed that from 10 to 15 years, the expansion readings conducted on Su blocks raised of about 150%, which is deemed too high and might have been a measurement error. Hence, adopting an expansion increase from 10 to 15 years of 70% (which is the average increase over 5 years for all blocks studied), a new curve could be plotted (CPT – measurement correction – solid black). This curve would represent only a 10% scattering from the CPT- alkali correction curve and indicates a potential to include leaching on Larive's equation to better predict induced expansion in the field. Yet, a non-negligible scattering is observed at the beginning of the expansion process, likely due to the difference in latency time found in the laboratory when compared to the field.

a) Blocks made of Sp | b) Blocks made of Su

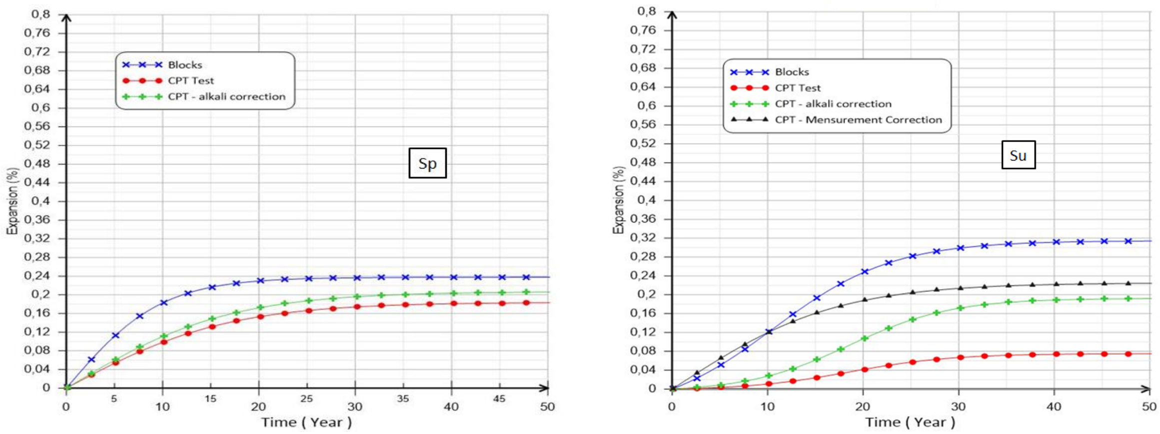

Figure 8.2: ASR-induced development of concrete blocks stored at CANMET exposure site in Ottawa, Canada and manufactured with the CPT mix-design incorporating a) Sp and, b) Su aggregates.

9. CONCLUSION

This work aimed to evaluate the laboratory vs field performance of concrete mixtures incorporating distinct reactive aggregates. Furthermore, Larive's model, a quite accepted analytical/empirical approach has been used to describe the induced expansion obtained in both conditions. After evaluating the test and model outcomes, it is evident that the reactive behaviour of aggregates is much more pronounced in the field when compared to the laboratory. The latter means that:

1) the test procedures one currently uses in the laboratory are not necessarily reliable to measure the field performance of reactive aggregates, and;
2) models aiming to properly describe field performance need to incorporate these differences. As per the authors, field behaviour could have been better described whether models such as Larive's incorporate the most important factors that affect ASR-induced expansion such as alkali loading, type (i.e. coarse vs fine) and reactivity (mineralogy) of the aggregates, and environmental conditions. In this context, trials were conducted to incorporate the alkalis leaching in laboratory performance and modelling and to compare the outcomes with field behaviour. Although still not perfect, the outcomes obtained were much closer to field performance and thus represent a promising approach to improve the prediction of affected field concrete. Further analyses and developments are still required to improve the accuracy and reliability of current models by implementing the other aforementioned variables which were not addressed in the present work.

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