

Contribution to the development of analytical models to forecast alkali-aggregate reaction (AAR) kinetics and induced expansion

Niloufar Goshayeshi

A thesis submitted to the Faculty of Graduate and Postdoctoral Studies in partial fulfillment of the requirements for the degree of

MASTER OF APPLIED SCIENCE

in Civil Engineering

Department of Civil Engineering

Faculty of Engineering

University of Ottawa

© Niloufar Goshayeshi, Ottawa, Canada, 2019

Abstract

Alkali-aggregate reaction (AAR) is one of the most harmful distress mechanisms affecting the durability and serviceability of concrete infrastructure worldwide. Currently, there is a need to forecast future behaviour of AAR-affected concrete, and thus analytical and numerical models have been developed over the years. Larive developed a model in 1998 that is able to describe the behaviour of concrete samples in the laboratory. This model has been widely accepted and used by AAR community, even to predict the behaviour of concrete structures in the field. Larive's model is based upon three main parameters and although they are normally set according to the concrete type under analysis, these parameters do not have a clear physicochemical meaning to describe AAR-induced expansion and development. Furthermore, it is widely known that AAR is influenced by several measurable variables such as the type and reactivity degree of the aggregates, temperature, moisture, and alkali content; those are currently not accounted for in Larive's equation. This work aims to incorporate the previously mentioned parameters to Larive's equation so that AAR kinetics and final expansion might be precisely described in the lab and/or field. Results indicate that the proposed modified Larive's equation can predict AAR kinetics and final expansion in the laboratory although some modifications seem still necessary to assess field structures.

Keywords: Alkali-aggregate reaction (AAR), Type and nature of the aggregate, Humidity, Temperature, and Alkali content.

Acknowledgement

First of all, I am thankful for the opportunity God provided me with to fulfill my dream and conclude a Master of Applied Science (M.Sc.) in Civil engineering at the University of Ottawa.

I want to acknowledge and express my deepest gratitude to my supervisor Dr. Leandro Sanchez, who helped and guided me not only throughout this research but also teaching me how to become a better researcher. Moreover, Dr. Sanchez has become a friend who believed in my potential, and with his effort and availability, he showed me that it is always possible to work smarter along with good mood especially when we do what we love.

My deepest thanks to my husband, Hamed Mozaffari, for all his support from the beginning until the end of this project. I appreciate all his support, and I am extremely grateful for the opportunity he gave me to study in Canada.

I would also like to emphasize and thank all the support of my parents, Maryam and Abbas along with my sister Shaghayegh, throughout my life. I will be forever grateful for their love and hard work that enabled me to study and follow my dreams.

I would like to express my deepest appreciation to my friends and colleagues, for their support and friendship throughout my graduate studies, making it an engaging experience.

Last but not least, I would like to thank all the financial support I received over my project from the University of Ottawa, Professor Leandro Sanchez and GHD.

Table of Content

Chapter 1	Introduction.....	1
1.1	General	1
1.2	Research Objectives	2
1.3	Overview of the thesis.....	3
1.4	References	3
Chapter 2	Literature Review and Background	12
2.1	Alkali-Aggregate Reaction (AAR).....	12
2.2	Factors Influencing on AAR	14
2.2.1	<i>Aggregates type and nature/reactivity</i>	14
2.2.2	<i>Temperature</i>	16
2.2.3	<i>Moisture</i>	17
2.2.4	<i>Alkali content</i>	19
2.3	Forecasting AAR-kinetics and induced expansion	20
2.4	References	26
Chapter 3	Analytical modelling to describe Alkali aggregate reaction (AAR)-kinetics and induced expansion in the laboratory	34
3.1	Introduction	35
3.2	Forecasting AAR-kinetics and induced expansion	36
3.3	Scope of the work.....	41

3.4	Materials and methods	42
3.4.1	Materials.....	42
3.4.2	Methods.....	48
3.5	Results	49
3.5.1	Aggregate’s type and nature/reactivity	49
3.5.2	Temperature.....	51
3.5.3	Relative humidity.....	52
3.5.4	Alkali content.....	53
3.6	Discussion	54
3.6.1	Aggregate’s type and nature/reactivity	54
3.6.2	Temperature.....	57
3.6.3	Relative humidity.....	59
3.6.4	Alkali content.....	60
3.6.5	Modified Larive’s equation for predicting AAR-kinetics in the laboratory and its use for field assessments	61
3.6.6	Calibrating time periods of test procedures in the laboratory.....	63
3.7	Conclusions	67
3.8	Acknowledgments.....	68
3.9	References	69

Chapter 4	Analytical Modelling to Describe Alkali-Aggregate Reaction Induced Expansion in the Field	77
4.1	Introduction	78
4.2	Literature review	79
4.3	Scope of the work.....	80
4.4	Materials and methods	81
4.5	Results	83
4.6	Discussion	85
4.6.1	AAR kinetics and development	85
4.6.2	Comparison with blocks exposed outdoors.....	86
4.7	Conclusion.....	88
4.8	References	88
Chapter 5	Chapter Five: Summary and Conclusions.....	97
Chapter 6	Chapter Six: Recommendations for Future Research.....	99

List of Figures

Figure 2.1 AAR kinetics (expansion vs. time - A, B, C) for the 25 (A), 35 (B) and 45 (C) MPa concrete mixtures (Sanchez et al. 2017).....	15
Figure 2.2 Accelerated concrete prism expansions as a function of time.....	17
Figure 2.3 Accelerated concrete prism expansions as a function of time.....	18
Figure 2.4 One-year expansions of concrete prisms made with highly-reactive Spratt limestone and moderately-reactive Sudbury gravel and different concrete alkali contents (Fournier and Bérubé 2000).....	19
Figure 2.5. AAR-induced expansion curve obtained from Larive’s model (Larive 1997a).	22
Figure 2.6. Long-term swelling behaviour of concrete affected by internal swelling reactions (ISR) (Brunetaud 2005).	23
Figure 2.7. AAR induced expansion proposed by Capra & Boumazel (Capra and Bournazel 1998).	24
Figure 3.1. AAR-induced expansion curve obtained from Larive’s model (Larive 1997)	38
Figure 3.2. Long-term swelling behaviour of concrete affected by internal swelling reaction (Brunetaud 2005).	39
Figure 3.3. AAR induced expansion proposed by (Capra and Bournazel 1998)	41
Figure 3.4. AAR kinetics (expansion vs. time - A, B, C) for the 25 (A), 35 (B) and 45 (C) MPa concrete mixtures (Sanchez 2014).	51
Figure 3.5. Accelerated concrete prism expansions as a function of time (Sanchez 2008).....	52

Figure 3.6. ASR swelling over time for different and constant external relative humidity (Poyet et al. 2006).....	53
Figure 3.7. One-year CPT test as per ASTM C 1293 for concrete mixtures incorporating two reactive aggregates (Spratt limestone and Sudbury gravel) and different alkali contents (Fournier and Bérubé 2000).....	54
Figure 3.8. Expansion vs time for various concrete mixtures and aggregate types and natures.	55
Figure 3.9. Reference curves based on the coefficients presented in	57
Figure 3.10. Calibration of the proposed Larive's modified model as a function of the temperature.	58
Figure 3.11. Expansion vs time for different R.H. conditions as per Poyet et al. (Poyet et al. 2006) calibrated by Larive's proposed model.	60
Figure 3.12. Expansion plots obtained from concrete incorporating the same aggregate (i.e. Rec 1) for distinct exposure conditions: A, B and C are the initial plateau points for the curves; D, E and F are the 0.04% expansion points and; G and H are the time required for concrete specimens at 60 °C and 80 °C to reach the same ultimate expansion obtained at 38°C.	65
Figure 4.1 S-shape AAR-induced expansion plot (Larive 1997).....	81
Figure 4.2 Expansion vs time for various concrete mixtures and aggregate types and natures. .	84
Figure 4.3 Comparison amongst blocks exposed outdoors (blue curve), CPT performed in the laboratory (pink curve) and calibrated Larive's model (green curve) for a) Pots and, b) Sp. Figure 4c illustrates the blocks to Larive's equation expansion ratio over time.....	87

List of Tables

Table 3.1. Characteristics of coarse and fine aggregates used in the concrete mixtures manufactured for the development of the model coefficients related to the aggregate's type, nature and alkali content of the concrete (Sanchez 2014).....	43
Table 3.2. Characteristics of coarse and fine aggregates used in the concrete mixtures fabricated for the calibration of the model coefficients related to temperature (Sanchez 2014).	45
Table 3.3. Concrete mixtures fabricated with ten different reactive aggregates and presenting distinct mechanical properties (Sanchez 2014).	46
Table 3.4. Concrete mixtures fabricated with the CPT mix-design as per ASTM C 1293 and incorporating three distinct coarse reactive aggregates (ASTM 2018).	48
Table 3.5. AAR-expansion levels classification (Sanchez et al. 2017).	49
Table 3.6. Aggregate's type and nature/reactivity coefficients.....	56
Table 3.7. Temperature coefficients.	58
Table 3.8. R.H. coefficients.	59
Table 3.9. Alkali content coefficients obtained for marginal/moderate and high/very high reactive aggregates.....	61
Table 3.10. Time periods required from similar concrete mixtures made of aggregates with distinct reactivities and evaluated at distinct exposure conditions (38°C, 60°C and 80°C) to present the same expansion level.	67
Table 4.1 Aggregates used in this research. U = USA, C = CANADA, B = Brazil.....	82

Table 4.2 Classification of the AAR-induced damage degree as per (Sanchez 2014).....	83
Table 4.3 Aggregates used to fabricate the concrete blocks as per (Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier 2004).....	83
Table 4.4 Latency and characteristic times for the different categories of expansion.	84

List of Symbols/Acronyms

- AAR = alkali aggregate reaction
- ASR = alkali silica reaction
- ACR = alkali carbonate reaction
- CPT = concrete prism test
- CSA = Canadian standard association
- RH = relative humidity
- C-S-H = calcium silicate hydrates
- τ_c = characteristic time (as a function of aggregate type and nature/reactivity)
- τ_l = latency time (as a function of aggregate type and nature/reactivity)
- ε = expansion at a given elapsed time
- ε^∞ = maximum expansion at infinity (or ultimate expansion)
- θ = temperature
- $K_{C,T}, K_{C,RH}, K_{C,E}$ = Temperature, humidity, and exposure coefficients impacting on the characteristic time
- $K_{L,T}, K_{L,RH}, K_{L,E}$ = temperature, humidity, and exposure coefficients impacting on the latency time
- $K_{Inf,T}, K_{Inf,RH}, K_{Inf,E}, K_{Inf,\%A}$ = temperature, humidity, exposure, and alkali content coefficients influencing on the maximum expansion

Chapter 1 Introduction

1.1 General

Alkali-Aggregate Reaction (AAR) is one of the most harmful damage mechanisms affecting the durability and serviceability of concrete infrastructure worldwide. AAR is normally divided into two categories: Alkali-Carbonate Reaction (ACR) and Alkali-Silica Reaction (ASR). ASR is by far the main mechanism affecting concrete structures around the world (Fournier and Bérubé 2000).

ASR consists of a chemical reaction between the alkalis (i.e. Na^+ , K^+ , and OH^-) from the concrete pore solution and some mineral phases from the aggregates used in concrete. This reaction generates a product (i.e. ASR gel) that swells while moisture uptake, leading to concrete expansion and damage (Fournier and Bérubé 2000; Owsiak et al. 2015). On the other hand, ACR is a mechanism still not fully understood. It is believed ACR takes place due to the dedolomitization of the dolomite rocks, which is an expansive reaction and may lead to induced expansion and damage. Yet, there is still an important debate on the topic (Fournier and Bérubé 2000; Katayama 2010; Katayama and Grattan-Bellew 2012).

A number of factors may affect AAR-induced expansion and development such as the amount of alkalis in the concrete, climate conditions such as temperature and humidity, the type (i.e. fine and/or coarse) and reactivity (low, moderate, high and very high) of aggregates, and exposure degree of the affected concrete. AAR-induced development is extremely variable, yet affected structures are often observed to present damage signs within 5 to 25 years, depending on the aforementioned conditions (Sanchez et al. 2015b).

One of the biggest challenges in civil engineering nowadays when dealing with AAR-affected infrastructure is to establish a correlation between AAR-induced damage and: a) the expansion

level reached by the affected concrete; b) the reductions of mechanical properties and durability of the deteriorated material and; c) the potential for further damage of the concrete. In this context, various mathematical (analytical and/or numerical) models have been developed over the past decades to forecast AAR-induced expansion and development in the laboratory and/or field. Among those, Larive's (Larive 1997) model is probably the most accepted approach by the AAR community, since it showed to be able to forecast the unrestrained expansion behaviour of affected samples in the laboratory. This model has been even implemented in finite element (FE) software to predict the performance of affected reinforced concrete structures in the field. Yet, Larive's model is based on two main parameters (characteristic time- τ_c and latency time- τ_L) that do not have a clear physicochemical meaning which prevents its use for a wide range of concrete materials (e.g. \neq types of cement and aggregates) and climate conditions (i.e. temperature, humidity, exposure conditions, etc.) without extensive laboratory tests and calibration.

1.2 Research Objectives

As aforementioned, there is a need to predict the future behaviour of AAR-affected infrastructure. Yet, there is a lack of analytical models able to describe AAR-induced development through a physicochemical point of view. This project aims to develop a new analytical approach (modified Larive's equation) to forecast AAR-induced development that accounts for the most important (and measurable) parameters influencing the chemical reaction, such as temperature, moisture, alkali content of the concrete and type and nature/reactivity of the aggregates. The development of the new model is based on a comprehensive experimental campaign performed by Sanchez et al. (Sanchez 2014; Sanchez et al. 2017) that studied AAR kinetics and final expansion of affected concrete presenting distinct mechanical properties (i.e. 25, 35, 40 and 45 MPa), test temperatures

and alkali contents and incorporating a wide range of reactive aggregate types (i.e. fine vs coarse aggregates) and natures (\neq lithotypes).

1.3 Overview of the thesis

The thesis is divided into five chapters. Chapter 1 presents the problem and the scope of the work. This chapter includes the introduction, objectives and overview of the thesis. Chapter two illustrates the state-of-the-art on analytical modelling to forecast AAR-induced expansion and damage. Chapter three consists of a scientific paper which proposes a new analytical model to forecast AAR-induced expansion in the laboratory. Chapter four comprises a second scientific paper where the new analytical model proposed in Chapter 3 is used to forecast the behaviour of unreinforced concrete blocks exposed to field conditions. Chapter five summarizes the most important results gathered throughout this research and concludes the thesis. Finally, Chapter six suggests future research needed in the area.

1.4 References

- ASTM. (2018). "C1293 - Standard Test Method for Determination of Length Change of Concrete Due to AlkaliSilica Reaction."
- ASTM C1260. (2016). "Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)." *American Society for Testing and Materials*, 1–5.
- Bangert, F., Kuhl, D., and Meschke, G. (2004). "Chemo-hygro-mechanical modelling and numerical simulation of concrete deterioration caused by alkali-silica reaction." *International Journal for Numerical and Analytical Methods in Geomechanics*, 28(7–8), 689–714.
- Bazant, Z. P., and Steffens, A. (2000). "Mathematical model for kinetics of alkali-silica reaction in concrete." *Cement and Concrete Research*, 30(3), 419–428.

- Benoit Fourniera et al. (2004). “the Accelerated Concrete Prism Test (60 ° C): Variability.” *12th International Conference on Alkali–Aggregate Reaction in Concrete, International Academic Publishers—World Publishing Corporation, Beijing, China*, (December 2014).
- Bérubé, M.-A., Durand, B., Vézina, D., and Fournier, B. (2011). “Alkali-aggregate reactivity in Québec (Canada).” *Canadian Journal of Civil Engineering*, 27(2), 226–245.
- Brunetaud, X. (2005). “Étude de l’influence de différents paramètres et de leurs interactions sur la cinétique de l’amplitude de la réaction sulfatique interne au béton.” Châtenay-Malabry, Ecole centrale de Paris.
- Capra, B., and Bournazel, J.-P. (1998). “Modeling of induced mechanical effects of alkali-aggregate reactions.” *Cement and Concrete Research*, Elsevier, 28(2), 251–260.
- Charpin, L., and Ehrlacher, A. (2012). “A computational linear elastic fracture mechanics-based model for alkali – silica reaction.” *Cement and Concrete Research*, Elsevier Ltd, 42(4), 613–625.
- Comby-peyrot, I., Bernard, F., Bouchard, P., Bay, F., and Garcia-diaz, E. (2009). “Development and validation of a 3D computational tool to describe concrete behaviour at mesoscale . Application to the alkali-silica reaction.” *Computational Materials Science*, Elsevier B.V., 46(4), 1163–1177.
- Comi, C., Fedele, R., and Perego, U. (2009). “A chemo-thermo-damage model for the analysis of concrete dams affected by alkali-silica reaction.” *Mechanics of Materials*, Elsevier Ltd, 41(3), 210–230.
- Comi, C., Kirchmayr, B., and Pignatelli, R. (2012). “Two-phase damage modeling of concrete

- affected by alkali-silica reaction under variable temperature and humidity conditions.” *International Journal of Solids and Structures*, Elsevier Ltd, 49(23–24), 3367–3380.
- CSA. (2014). *Concrete materials and methods of concrete construction/methods of test and standard practices for concrete*. Toronto (Ontario, Canada). Csa a23.1/23.2.
- Cwirzen, A., and Penttala, V. (2005). “Aggregate–cement paste transition zone properties affecting the salt–frost damage of high-performance concretes.” *Cement and Concrete Research*, 35(4), 671–679.
- Dunant, C. F., and Scrivener, K. L. (2010). “Micro-mechanical modelling of alkali-silica-reaction-induced degradation using the AMIE framework.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 517–525.
- Esposito, R., and Hendriks, M. A. N. (2017). “Literature review of modelling approaches for ASR in concrete : a new perspective.” *European Journal of Environmental and Civil Engineering*, Taylor & Francis, 8189(December), 1–21.
- Farage, M. C. R., Alves, J. L. D., and Fairbairn, E. M. R. (2004). “Macroscopic model of concrete subjected to alkali-aggregate reaction.” *Cement and Concrete Research*, 34(3), 495–505.
- Fecteau, P. L., Fournier, B., Choquette, M., and Duchesne, J. (2012). “Contribution to the understanding of the so-called alkali--carbonate reaction (ACR), 14th ICAAR International Conference on Alkali--Aggregate Reaction in Concrete.” May.
- Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier, R. (2004). “Comparative Field and Laboratory Investigations on the Use of Supplementary Cementing Materials to Control Alkali-Silica Reaction in Concrete.” *Proceedings of the 12th International Conference on*

Alkali-Aggregate Reaction (ICAAR), 1, 528--537.

Fournier, B., and Bérubé, M.-A. (2000). "Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications." *Canadian Journal of Civil Engineering*, 27(2), 167–191.

Franz-Josef Ulm et al. (2000). "THERMO-CHEMO-MECHANICS OF ASR EXPANSION IN CONCRETE STRUCTURES." *Journal of Engineering Mechanics*, (March), 233–242.

Gorga, R. V., Sanchez, L. F. M., and Martín-Pérez, B. (2018). "FE approach to perform the condition assessment of a concrete overpass damaged by ASR after 50 years in service." *Engineering Structures*, Elsevier, 177(June), 133–146.

Grimai, E., Sellier, A., Pape, Y. Le, and Bourdarot, E. (2008). "Creep, shrinkage, and anisotropic damage in alkali-aggregate reaction swelling Mechanism-Part II: Identification of model parameters and application." *ACI Materials Journal*, v 105, n 3(105), p 236-242.

Grimal, E., Sellier, A., Multon, S., Le Pape, Y., and Bourdarot, E. (2010). "Concrete modelling for expertise of structures affected by alkali aggregate reaction." *Cement and Concrete Research*, Elsevier Ltd, 40(4), 502–507.

Katayama, T. (2010). "The so-called alkali-carbonate reaction (ACR) - Its mineralogical and geochemical details, with special reference to ASR." *Cement and Concrete Research*, Elsevier Ltd, 40(4), 643–675.

Katayama, T., and Grattan-Bellew, P. E. (2012). "Petrography of the Kingston experimental sidewalk at age 22 years--ASR as the cause of deleteriously expansive, so-called alkali-carbonate reaction." *Proceedings of the 14th international conference on alkali-aggregate*

reaction in concrete. Austin, Texas, USA, 10.

Kawabata, Y., Martin, R.-P., Seignol, J.-F., and Toutlemonde, F. (2016). “Modelling of Evolution of Transfer Properties Due To Expansion of Concrete Induced By Internal Swelling Reaction.” *ICAAR 2016 - 15th international conference on alkali aggregate reaction.*

Kurihara & Katawaki. (1989). “Effects of moisture control and inhibition on alkali silica reaction.” *kyoto, Japan, 629–634.*

Larive, C. (1997). “Combined contribution of experiments and modelling to the understanding of alkali-aggregate reaction and its mechanical consequences (PhD thesis; in: French).”

Li, K., and Coussy, O. (2002). “Concrete ASR degradation : from material modeling to structure assessment.” *Concrete Science and Engineering, 4(March), 35–46.*

Lindgård, J., Andiç-Çakir, Ö., Fernandes, I., Rønning, T. F., and Thomas, M. D. A. (2012). “Alkali-silica reactions (ASR): Literature review on parameters influencing laboratory performance testing.” *Cement and Concrete Research, 42(2), 223–243.*

Lothenbach, B., Winnefeld, F., Alder, C., Wieland, E., and Lunk, P. (2007). “Effect of temperature on the pore solution, microstructure and hydration products of Portland cement pastes.” *Cement and Concrete Research, 37(4), 483–491.*

Multon, S., Sellier, A., and Cyr, M. (2009). “Chemo – mechanical modeling for prediction of alkali silica reaction (ASR) expansion.” *Cement and Concrete Research, Elsevier Ltd, 39(6), 490–500.*

Multon, S., and Toutlemonde, F. (2004). “Water distribution in concrete beams.” *Materials" and Structures, 37(July), 378–386.*

- Multon, S., and Toutlemonde, F. (2006). "Effect of applied stresses on alkali-silica reaction-induced expansions." *Cement and Concrete Research*, 36(5), 912–920.
- Nielsen, A. e. al. (1993). "Development of stresses in concrete structures with alkali-silica reactions." *Materials and Structures*, 152–158.
- Olafsson, H. (1986). "The effect of relative humidity and temperature on alkali expansion of mortar bars." *7th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 461–465.
- Owsiak, Z., Zapała-Sławeta, J., and Czapik, P. (2015). "Diagnosis of concrete structures distress due to alkali-aggregate reaction." *Bulletin of the Polish Academy of Sciences Technical Sciences*, 63(1), 23–29.
- Pesavento, F., Gawin, D., Wyrzykowski, M., Schrefler, B. A., and Simoni, L. (2012). "Modeling alkali-silica reaction in non-isothermal, partially saturated cement based materials." *Computer Methods in Applied Mechanics and Engineering*, Elsevier B.V., 225–228, 95–115.
- Poyet et al. (2007). "Chemical modelling of Alkali Silica reaction : Influence of the reactive aggregate size distribution." 229–239.
- Poyet, S., Sellier, A., Capra, B., Thèvenin-Foray, G., Torrenti, J. M., Tournier-Cognon, H., and Bourdarot, E. (2006). "Influence of Water on Alkali-Silica Reaction: Experimental Study and Numerical Simulations." *Journal of Materials in Civil Engineering*, 18(August), 588–596.
- Prinčič, T., Štukovnik, P., Pejovnik, S., De Schutter, G., and Bosiljkov, V. B. (2013). "Observations on dedolomitization of carbonate concrete aggregates, implications for ACR and expansion." *Cement and Concrete Research*, 54, 151–160.
- Rashidi, M., Kim, J. Y., Jacobs, L. J., and Kurtis, K. E. (2016). "Insights into alkali-silica reaction

- damage in mortar through acoustic nonlinearity.” *AIP Conference Proceedings*, 1706(2016).
- Sanchez, L. (2014). “Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction.” UNIVERSITE LAVAL.
- Sanchez, L. F. M. (2008). “Contribuição ao estudo dos métodos de ensaio na avaliação das reações álcali-agregado em concretos.” Universidade de São Paulo.
- Sanchez, L. F. M., Drimalas, T., Fournier, B., Mitchell, D., and Bastien, J. (2018). “Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms.” *Cement and Concrete Research*, 107(September 2017), 284–303.
- Sanchez, L. F. M., Fournier, B., Jolin, M., and Bastien, J. (2015a). “Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses.” *Construction and Building Materials*, Elsevier Ltd, 77, 20–32.
- Sanchez, L. F. M., Fournier, B., Jolin, M., and Duchesne, J. (2015b). “Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI).” *Cement and Concrete Research*, Elsevier Ltd, 67, 74–92.
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., and Bastien, J. (2017). “Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures.” *Cement and Concrete Research*, Elsevier Ltd, 93, 17–31.
- Sanchez, L. F. M., Multon, S., Sellier, A., Cyr, M., Fournier, B., and Jolin, M. (2014). “Comparative study of a chemo-mechanical modeling for alkali silica reaction (ASR) with

- experimental evidences.” *Construction and Building Materials*, Elsevier Ltd, 72, 301–315.
- Sanchez, L., Kuperman, S. C., and Helene, P. (2011). “Using the accelerated Brazilian concrete prism test (ABCPT) to evaluate alkali aggregate reaction (AAR).” *Ibracon Structures and Materials Journal*, 4, 575–581.
- Sanchez, L., Kuperman, S., and Helene, P. (2008). “Trials To Correlate the Accelerated Mortar Bar Test , the Standard and the Accelerated Concrete.” *13th International Conference on Alkali Aggregate Reaction (ICAAR)*, Trondheim, Norway.
- Saouma, V. E., Martin, R. A., Hariri-Ardebili, M. A., and Katayama, T. (2015). “A mathematical model for the kinetics of the alkali-silica chemical reaction.” *Cement and Concrete Research*, Elsevier Ltd, 68, 184–195.
- Saouma, V., and Perotti, L. (2006). “Constitutive model for alkali-aggregate reactions.” *ACI Materials Journal*, 103(3), 194–202.
- Schmidt et al. (2009). “AKR-Performance-Prüfung von flugaschehaltigen Betonen – Einfluss der Temperatur auf die Porenlösung und Möglichkeiten zur zielsicheren Bewertung.” *17. Internationale Baustofftagung, ibausil, F. A. Finger-Institut für Baustoffkunde, Bauhaus Universität Weimar, 23.-26. September 2009. In: Tagungsbericht, S. 2 0267 2 0276.*
- Suwito, A., Jin, W., Xi, Y., and Meyer, C. (2002). “A Mathematical Model for the Pessimum Size Effect of ASR in Concrete.” *Concrete Science and Engineering*, 1–31.
- Urhan, S. (1987). “Alkali silica and pozzolanic reactions in concrete. Part 1: Interpretation of published results and an hypothesis concerning the mechanism.” *Cement and Concrete Research*, 17(c), 141–152.

Vivian, H. E. (1981). "The effect of drying on reactive aggregate and mortar expansions." *Proc., 5th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 228–252.

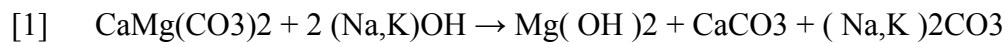
Winnicki, A., and Pietruszczak, S. (2008). "On Mechanical Degradation of Reinforced Concrete Affected by Alkali-Silica Reaction." *Journal of Engineering Mechanics*, 134(8), 611–627.

Chapter 2 Literature Review and Background

2.1 Alkali-Aggregate Reaction (AAR)

Alkali-aggregate reaction (AAR), a chemical reaction between certain mineral phases from the aggregates and the alkali hydroxides (Na, K, OH⁻) from the concrete pore solution, is one of the most important deterioration processes affecting the durability and serviceability of concrete structures around the world (Fournier and Bérubé 2000). Overall, AAR can be divided into alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).

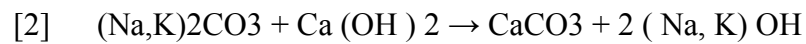
ASR is by far the most common reaction type found around the globe. It consists of a chemical reaction between unstable silica mineral forms within the fine and or coarse aggregates used to make concrete and alkali hydroxide ions dissolved in the concrete pore solution. The result of this reaction is a secondary product (ASR gel) that swells while moisture uptake, leading to major cracking (Sanchez et al. 2015a). Conversely, ACR typically occurs while the use of argillaceous dolomitic limestones. Although there is still an important debate on the topic on whether ACR exists or not (some experts believe ACR may be part of ASR), the majority of experts believe ACR is triggered by the alkali hydroxides attack to the dolomite crystals of the aggregate, which causes the so-called “dedolomitization” process (Fournier and Bérubé 2000) presented hereafter:



Dolomite Alkali Hydroxide Brucite Calcite Alkali Carbonate

Expansion and cracking due to ACR is deemed to take place through one or a combination of the following processes (Fournier and Bérubé 2000), very often not generating significant amount of gel: a) hydraulic pressures caused by the migration of water molecules and alkali ions into the restricted spaces of the calcite/clay matrix around the dolomite grains, b) adsorption of the alkali ions and water molecules on the surfaces of the “active” clay minerals scattered around the

dolomite grains, and c) growth and rearrangement of the products of dedolomitization. Furthermore, the alkali carbonates may eventually react with the Portlandite from the cement paste thus regenerating alkali hydroxides in the pore solution, as per [2]. The latter suggests that ACR might proceed almost indefinitely.



Alkali Carbonate Portlandite Calcite Alkali Hydroxide

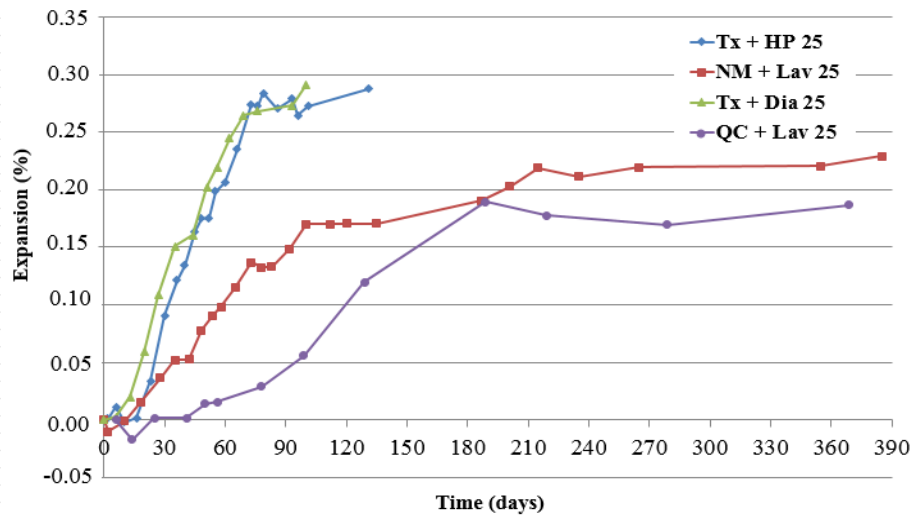
AAR kinetics, induced expansion and damage at both microscopic or macroscopic scales depend upon the type (i.e. fine or coarse aggregate) and nature (i.e. mineralogy, reactivity, etc.) of the aggregates, the amount of alkalis of the concrete, the temperature and relative humidity of the environment along with the exposure degree and confinement conditions (e.g. reinforcement ratio, etc.) of a given structure/structural member under analysis (Lindgård et al. 2012; Multon and Toutlemonde 2006; Poyet et al. 2006; Rashidi et al. 2016; Sanchez et al. 2014). Several analytical, empirical and numerical models were developed on both microscopic (Bazant and Steffens 2000; Charpin and Ehlacher 2012; Comby-peyrot et al. 2009; Dunant and Scrivener 2010; Multon et al. 2009; Nielsen 1993; Poyet et al. 2007; Suwito et al. 2002) and macroscopic (Comi et al. 2009; Franz-Josef Ulm et al. 2000; Grimai et al. 2008; Li and Coussy 2002; Saouma and Perotti 2006) scales to describe AAR development; however, predicting AAR-kinetics and induced expansion is quite challenging since AAR is a very complex non-linear physicochemical phenomenon. Yet, to accurately describe AAR-development, mathematical models able to account for all the parameters influencing on the reaction should be considered (Gorga et al. 2018).

2.2 Factors Influencing on AAR

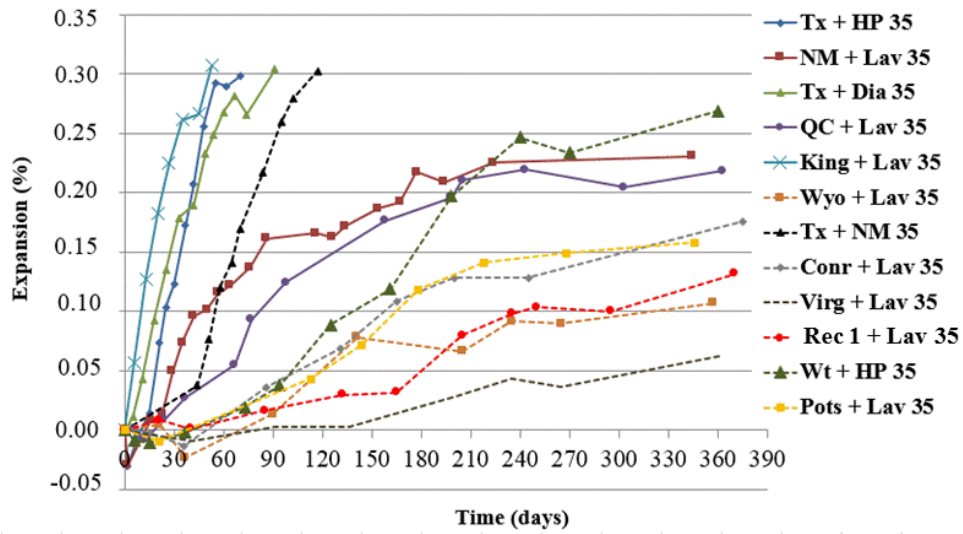
2.2.1 Aggregates type and nature/reactivity

It is widely known in the literature as per ACI Committee 201 (ACI 1992) and (Fournier and Bérubé 2000; Sanchez et al. 2017), that AAR kinetics and induced expansion vary as a function of the type (i.e. fine vs coarse aggregate) and nature (i.e. mineralogy) of the aggregates.

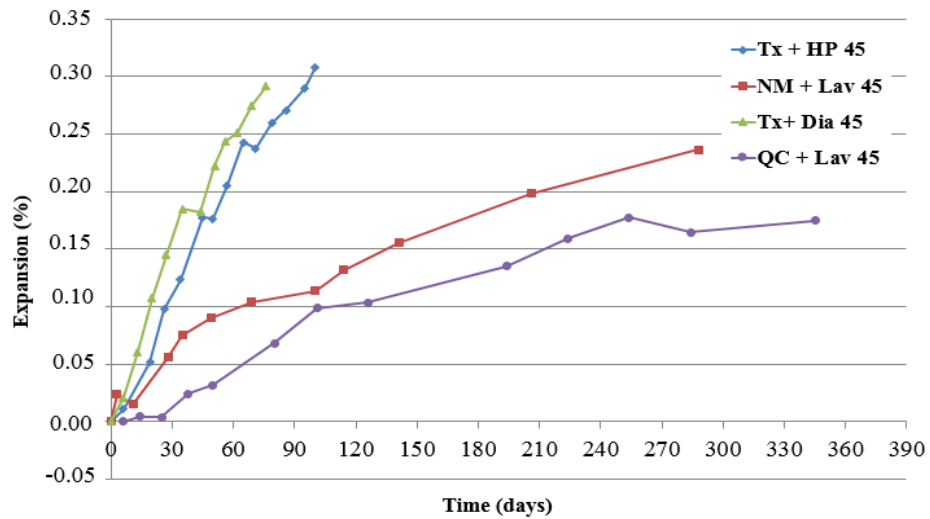
Sanchez et al. (Sanchez et al. 2017) conducted a series of laboratory tests on concrete mixtures incorporating a wide range of aggregate types/natures and presenting distinct mechanical properties (i.e. 25, 35 and 45 MPa). After one year of testing at 38°C and 100% R.H. as per ASTM C1293 requirements, distinct AAR behaviours were obtained (Figure 2.1).



(A)



(B)



(C)

Figure 2.1 AAR kinetics (expansion vs. time – A, B, C) for the 25 (A), 35 (B) and 45 (C) MPa concrete mixtures (Sanchez et al. 2017).

From Figure 2.1, the authors verified that the aggregate's type and nature impacted both AAR-kinetics and final expansion. In general, two kinetic behaviours were observed: 1) a very fast ascending curve with little to no accommodation time (i.e. period without expansion) and no

levelling off trend up until the ultimate expansion is reached and, 2) a slower ascending curve, presenting some accommodation time and a significant levelling off trend close to the ultimate expansion level obtained over the test. Concrete mixtures containing reactive fine aggregates (e.g. Tx sand) showed a faster development and thus a kinetics similar to type 1 above, whereas mixes incorporating reactive coarse aggregates showed a reaction kinetics similar to type 2. The only exception observed was King + Lav 35MPa mix (Figure 2.1.B), since King coarse aggregate is supposed to be susceptible to ACR, presenting a quite fast and unique reaction trend. Conversely, the authors did not find that AAR-kinetics changed as a function of the inner quality (i.e. mechanical properties) of the concrete since the 25, 35 and 45 MPa mixtures presented very similar trends as per Figure 2.1.

2.2.2 Temperature

A number of research projects have reported that the temperature is one of the main parameters influencing AAR-induced development (Benoit Fourniera et al. 2004; Franz-Josef Ulm et al. 2000; Larive 1997; Lothenbach et al. 2007; Pesavento et al. 2012; Schmidt et al. 2009; Urhan 1987). It has been found that the higher the temperature, the higher the concentration of sulfate ions in the concrete pore solution, which also raises the concentration of hydroxyl ions (OH^-) ions in the pores; the latter increases SiO_2 instability (and solubility) and thus increases AAR reactivity (Fournier and Bérubé 2000; Larive 1997).

Sanchez et al. (Sanchez et al. 2008) performed an experimental test campaign with concrete specimens incorporating three reactive aggregates and tested at different temperatures (i.e. 38°C, 60°C and 80°C, Figure 2.2).

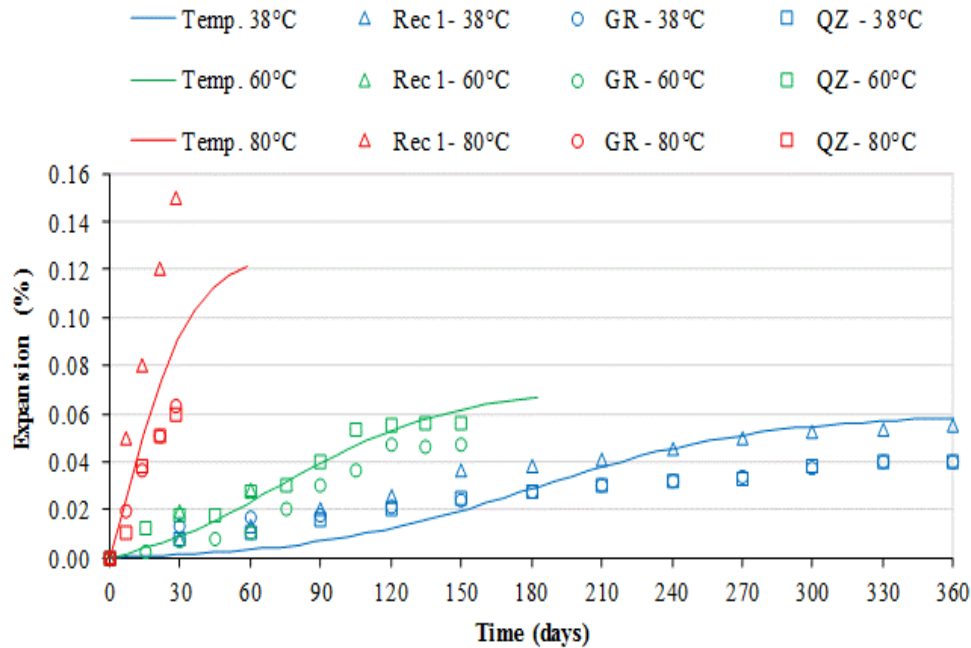


Figure 2.2 Accelerated concrete prism expansions as a function of time.

The authors verified that the exposure temperature completely changes AAR development. The higher the temperature, the faster the AAR-kinetics and development for all aggregates tested. Furthermore, raising the temperature also showed to increase the final expansion at infinity. Ultimate expansions of about 33% and 166% higher were found at 60°C (5 months) and 80°C (1 month), respectively when compared to tests performed at 38°C (1 year).

2.2.3 Moisture

Water plays an essential role on AAR-induced expansion and development due to three main reasons: 1) first, water constitutes the transport medium for the diffusion of alkali and hydroxyl ions through the concrete pore solution, 2) second, water is required for AAR gel formation through the dissolution of reactive silica and, 3) third, the AAR gel swelling process is directly related to the water uptake from the surroundings (Bazant and Steffens 2000).

According to Fournier and Bérubé, a minimum of moisture is needed to trigger AAR-induced development. Although still under debate, it is fairly accepted by the AAR community that a minimum of 80% of relative humidity (R.H.) is required to develop the chemical reaction in the field (Fournier and Bérubé 2000; Kurihara & Katawaki 1989; Olafsson 1986; Vivian 1981).

Poyet et al. (Poyet et al. 2006) conducted a large experimental program studying the expansion behaviour of concrete under a wide range of R.H. conditions (i.e. from 59% to 100%, Figure 2.3).

The authors verified an important impact of the relative humidity on AAR-kinetics and ultimate expansion, since the higher the relative humidity, the faster the AAR-kinetics and the higher the ultimate expansion over time. Surprisingly, the authors obtained results for 96% humidity that were slightly higher than the ones gathered at 100%; yet this could have been only an imprecision and/or deviation while the samples are monitored. The final expansion obtained on samples exposed to 96% R.H. when compared to 59% R.H. is about 4.12 times higher. Finally, Poyet et al. verified that no further AAR-induced expansion takes place whenever R.H. values are below 50% (Poyet et al. 2006).

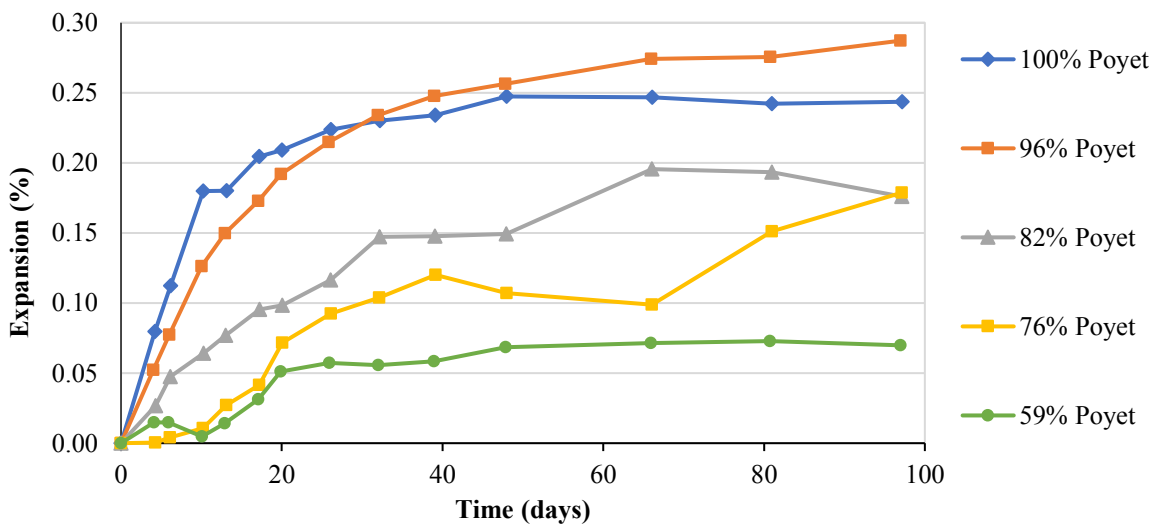


Figure 2.3 Accelerated concrete prism expansions as a function of time.

2.2.4 Alkali content

Portland cement (PC) is the main source of alkalis (sodium Na^+ and potassium K^+) in concrete. It is widely known that the pH of concrete is very high, of about 12.5-13.0; this alkalinity contributes to C-S-H stability, protecting it from decalcification and enhancing the durability of reinforced concrete structures against steel corrosion. However, it may also trigger AAR since numerous aggregates used in concrete present mineral phases that are unstable at high pH environments (Bérubé et al. 2011; Fournier and Bérubé 2000; Sanchez 2014).

Fournier and Bérubé (Fournier and Bérubé 2000) conducted an important experimental campaign where concrete specimens were tested in the laboratory (38°C and 100% R.H.) presenting a large variety of alkali contents (i.e. 1.5 kg/m^3 to 12.5 kg/m^3). The authors used two types of aggregates: a moderately-reactive gravel (i.e. Sudbury aggregate) and a highly reactive limestone (i.e. Spratt aggregate). Figure 2.4 illustrates the results gathered in this research.

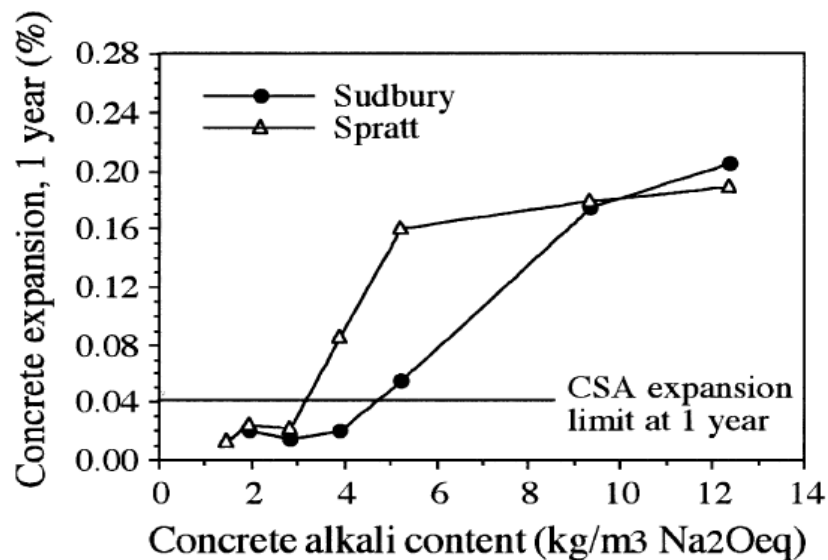


Figure 2.4 One-year expansions of concrete prisms made with highly-reactive Spratt limestone and moderately-reactive Sudbury gravel and different concrete alkali contents (Fournier and Bérubé 2000).

From Figure 2.4, it is clear that the higher the alkali content of the concrete, the higher the final expansion generated. Moreover, the authors also found that the nature of the aggregate might interfere with the ultimate expansion of concrete made of distinct amounts of alkalis. Comparing the results obtained to 5.25 kg/m³ of alkalis (which is the standard value normally used as per ASTM C 1293 (ASTM 2018)), concrete prisms incorporating the Sudbury gravel with 1.5 kg/m³ and 12.5 kg/m³ of alkalis reached 500% lower and 235% higher expansion results, respectively. Otherwise, concrete prisms made of Spratt aggregate and the same alkali levels reached 1500% lower and 25% higher expansion results, respectively.

2.3 Forecasting AAR-kinetics and induced expansion

A number of analytical, numerical and empirical models have been proposed over the past decades to predict AAR-kinetics and induced expansion in the laboratory (i.e. materials level) and its impact on the mechanical properties and performance of affected structures/structural components in the field (i.e. structures level) (Bangert et al. 2004; Comi et al. 2009, 2012; Farage et al. 2004; Grimal et al. 2010; Larive 1997; Li and Coussy 2002; Multon and Toutlemonde 2004, 2006; Poyet et al. 2006; Saouma et al. 2015; Saouma and Perotti 2006). Amongst those, Larive's analytical model is probably one of the most accepted approaches by the AAR community (Prinčič et al. 2013; Rashidi et al. 2016; Sanchez et al. 2015b, 2018).

Larive's proposed a theoretical model to understand AAR-induced development that was based upon a comprehensive experimental campaign. Larive's model was initially developed to describe the induced expansion behaviour of unrestrained concrete specimens in the laboratory but has also been used to predict the expansion rate of concrete structures in the field. It consists of a semi-empirical approach base on the mechanics of reactive porous media that was established and calibrated with about 600 specimens evaluated in the laboratory according to a wide range of test

conditions such as temperature, moisture, mixture types and loading scenarios (Larive 1997; Winnicki and Pietruszczak 2008). In this model, AAR-kinetics and induced expansion are described as a function of three main parameters: ultimate expansion (ε^∞), latency (τ_l) and characteristic (τ_c) times (Eq.2.1). Latency time (τ_l) corresponds to the period from the origin of the chemical reaction to its inflection point whereas characteristic time (τ_c) corresponds to the phase from the tangent at the inflection point to the asymptotic unit volume of ε . Each set of parameters is only valid for a given temperature (θ). Figure 2.5 illustrates an expansion curve resulting from Larive’s analytical model (Larive 1997).

$$\varepsilon(t, \theta) = \frac{1 - e^{-\frac{t}{\tau_c(\theta)}}}{1 + e^{-\frac{(t-\tau_l(\theta))}{\tau_c(\theta)}}} \times \varepsilon^\infty \quad \text{Eq. 2.1}$$

Larive’s induced expansion plot often displays an *S-shape* curve that may be divided and explained into four phases. The first phase represents AAR secondary product formation and its accommodation likely within the reactive aggregates and adjacent cement paste with little to no expansion as per Sanchez et al. (Sanchez et al. 2015b). The second phase (i.e. ascending curve period) represents AAR-induced expansion process due to moisture uptake from the reaction product. In this phase, expansion with little to 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 Sanchez et al. (Sanchez et al. 2015b). In phase 3, the curve shape changes from “convex” to “concave” since the reaction product that keeps forming over the physicochemical process has supplementary space (i.e. cracks, flaws, etc.) at this stage to

accommodate, which decreases the AAR-expansion rate. Finally, the fourth and last phase shows a reaction levelling off trend due to the total alkalis and/or silica consumption from the system.

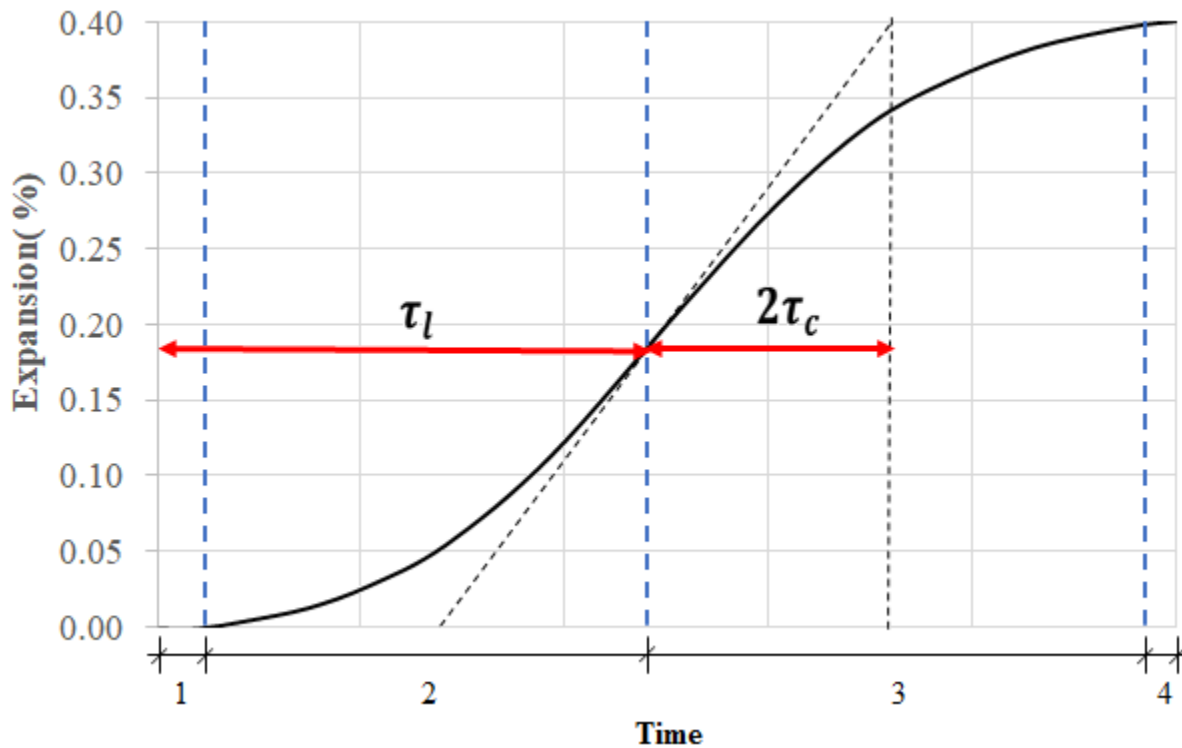


Figure 2.5. AAR-induced expansion curve obtained from Larive's model (Larive 1997a).

Building upon Larive's works, Brunetaud (Brunetaud 2005) proposed a modification (Eq. 2.2 and Eq. 2.3) to the initial Larive's approach to better represent the long-term swelling behaviour of concrete affected by internal swelling reactions (ISR, which comprises AAR and delayed ettringite formation- DEF), by adding a time-dependent coefficient to the proposed equation $\beta(t)$, where Φ and δ are corrective parameters and t is the elapsed time; (Figure 2.6). The latter has showed to better represent the long-term performance of massive structures in the field (Kawabata et al. 2016).

$$\varepsilon(t) = \varepsilon_{\infty} \frac{1 - e^{(-t/\tau_c)}}{1 + e^{(-t/\tau_c + \tau_l/\tau_c)}} \times \beta(t) \quad \text{Eq. 2.2}$$

$$\beta(t) = 1 - \frac{\varphi}{\delta + t} \quad \text{Eq. 2.3}$$

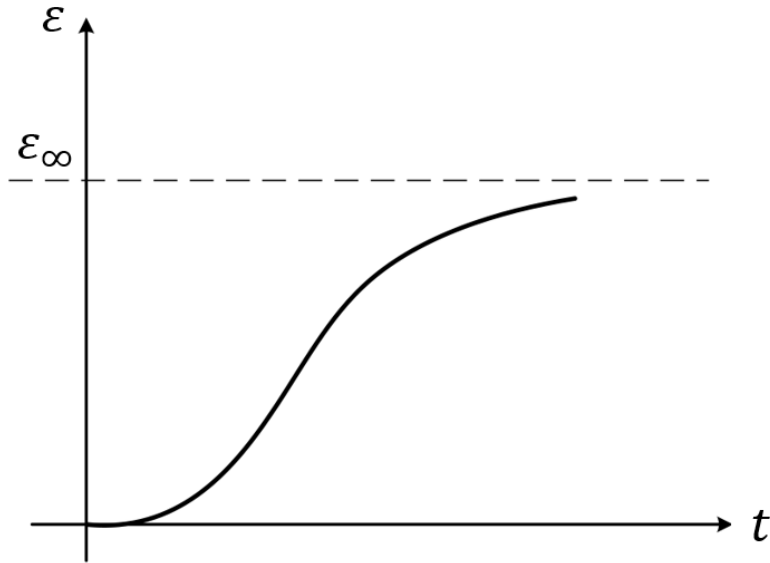


Figure 2.6. Long-term swelling behaviour of concrete affected by internal swelling reactions (ISR) (Brunetaud 2005).

Although interesting, the approaches proposed by Larive (Larive 1997) and Brunetaud (Brunetaud 2005) are only valid under constant conditions (i.e. temperature, moisture, exposure, etc.). Furthermore, the main parameters from Larive and Brunetaud equations such as latency (τ_l) and characteristic (τ_c) times along with expansion at infinity (ε_{∞}) are set and adapted in practice according to the concrete mixture and/or structure under analysis; yet there is currently a lack of understanding on the range of these parameters as a function of the reactivity potential of the concrete (i.e. aggregate type and nature, alkalis content, etc.) as well as exposure conditions (i.e. temperature, humidity, and their variations over time).

Capra & Boumazel (Capra and Bournazel 1998) proposed an approach that accounts for variations on exposure conditions, especially temperature. In this model, the alkalis consumption is first computed (Eq. 2.4), followed by the expansion level (Eq. 2.5). AAR is then assumed to be linearly proportional to the ratio of the alkalis reacted (A). The authors have also introduced a parameter (A_0) to account for the initial accommodation period with little to no expansion (Figure 2.7). Where K is the kinetics constant and ε_0 is the first point of expansion which depends on the material properties such as porosity. This model showed to be more complete than Larive's (Larive 1997) and Brunetaud's (Brunetaud 2005) equations, but further "case by case" calibration and fitting from experimental test procedures and/or in-situ measurements are also needed to implement such a model in practice.

$$\frac{dA}{dt} = K \times (1 - A) \quad \text{Eq. 2.4}$$

$$\varepsilon(t) = \begin{cases} 0 & \text{for } A < A_0 \\ \frac{\varepsilon_0}{A_0} \times (A - A_0) & \text{for } A \geq A_0 \end{cases} \quad \text{Eq. 2.5}$$

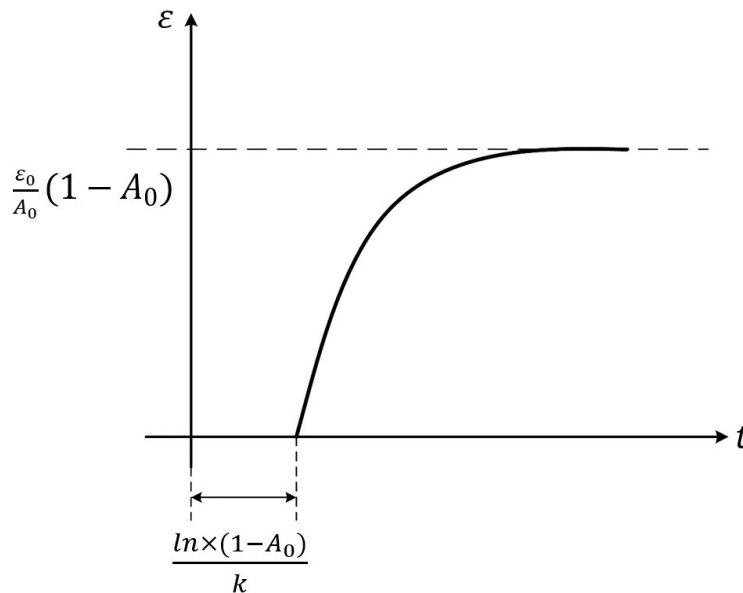


Figure 2.7. AAR induced expansion proposed by Capra & Boumazel (Capra and Bournazel 1998).

Nielsen et al (Nielsen 1993) developed a model with the aim of determining ASR-induced expansion in concrete. The model accounts for numerous parameters such as the material's quality, geometry of the element considered, silica content, and climate conditions. The attained expansion ε_0 is determined as per Eq. 2.6. Where P_i is the internal pressure, E is the modulus of elasticity and A and B are parameters that account for how close the particles are from one to another. The results showed to be promising in determining ASR-induced expansion in the concrete for distinct materials and conditions. Yet, no range of values according to distinct conditions were proposed.

$$\varepsilon_{0,i} = \frac{6}{5} \left(\frac{P_i}{E_m} \right) \frac{A}{B^3 - A^3} \quad \text{Eq. 2.6}$$

Multon et al. (Multon et al. 2009) developed a microscopic physio-chemical model at LMDC (Toulouse, France) to forecast AAR-induced expansion and damage in affected concrete. The model accounts for a wide variety of parameters such as alkali and reactive silica contents, aggregates grading and materials features (i.e. water-to-cement ratio, porosity, etc.). All of the above is defined based on a representative elemental volume (REV) of concrete, contacting aggregates and cement paste in the proportions implemented by the user. To use this model for concrete, Sanchez et al. (Sanchez et al. 2014) analyzed the LMDC chemo- mechanical model based on experimental tests for three different strengths (i.e. 25,35, and 45 MPa) and two different highly reactive aggregates. The outcome results showed that the LMDC model is reliable and effective for expansion in concrete.

All of the aforementioned clearly demonstrates the need to have a new analytical approach that is built upon the most important (and measurable) factors influencing AAR. Such a model would then be able to describe the physicochemical process for a wide range of materials and exposure conditions without further experimental calibration and/or fitting.

2.4 References

- ACI Committee 201. (1992). Guide to durable concrete, American Concrete Institute, Report of ACI Committee 201.
- ASTM. (2018). “C1293 - Standard Test Method for Determination of Length Change of Concrete Due to AlkaliSilica Reaction.”
- ASTM C1260. (2016). “Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method).” *American Society for Testing and Materials*, 1–5.
- Bangert, F., Kuhl, D., and Meschke, G. (2004). “Chemo-hygro-mechanical modelling and numerical simulation of concrete deterioration caused by alkali-silica reaction.” *International Journal for Numerical and Analytical Methods in Geomechanics*, 28(7–8), 689–714.
- Bazant, Z. P., and Steffens, A. (2000). “Mathematical model for kinetics of alkali-silica reaction in concrete.” *Cement and Concrete Research*, 30(3), 419–428.
- Benoit Fourniera et al. (2004). “the Accelerated Concrete Prism Test (60 ° C): Variability.” *12th International Conference on Alkali–Aggregate Reaction in Concrete, International Academic Publishers—World Publishing Corporation, Beijing, China*, (December 2014).
- Bérubé, M.-A., Durand, B., Vézina, D., and Fournier, B. (2011). “Alkali-aggregate reactivity in Québec (Canada).” *Canadian Journal of Civil Engineering*, 27(2), 226–245.
- Brunetaud, X. (2005). “Étude de l’influence de différents paramètres et de leurs interactions sur la cinétique de l’amplitude de la réaction sulfatique interne au béton.” Châtenay-Malabry, Ecole centrale de Paris.
- Capra, B., and Bournazel, J.-P. (1998). “Modeling of induced mechanical effects of alkali-

- aggregate reactions.” *Cement and Concrete Research*, Elsevier, 28(2), 251–260.
- Charpin, L., and Ehrlacher, A. (2012). “A computational linear elastic fracture mechanics-based model for alkali – silica reaction.” *Cement and Concrete Research*, Elsevier Ltd, 42(4), 613–625.
- Comby-peyrot, I., Bernard, F., Bouchard, P., Bay, F., and Garcia-diaz, E. (2009). “Development and validation of a 3D computational tool to describe concrete behaviour at mesoscale . Application to the alkali-silica reaction.” *Computational Materials Science*, Elsevier B.V., 46(4), 1163–1177.
- Comi, C., Fedele, R., and Perego, U. (2009). “A chemo-thermo-damage model for the analysis of concrete dams affected by alkali-silica reaction.” *Mechanics of Materials*, Elsevier Ltd, 41(3), 210–230.
- Comi, C., Kirchmayr, B., and Pignatelli, R. (2012). “Two-phase damage modeling of concrete affected by alkali-silica reaction under variable temperature and humidity conditions.” *International Journal of Solids and Structures*, Elsevier Ltd, 49(23–24), 3367–3380.
- CSA. (2014). *Concrete materials and methods of concrete construction/methods of test and standard practices for concrete. Toronto (Ontario, Canada). Csa a23.1/23.2.*
- Cwirzen, A., and Penttala, V. (2005). “Aggregate–cement paste transition zone properties affecting the salt–frost damage of high-performance concretes.” *Cement and Concrete Research*, 35(4), 671–679.
- Dunant, C. F., and Scrivener, K. L. (2010). “Micro-mechanical modelling of alkali-silica-reaction-induced degradation using the AMIE framework.” *Cement and Concrete Research*, Elsevier

Ltd, 40(4), 517–525.

Esposito, R., and Hendriks, M. A. N. (2017). “Literature review of modelling approaches for ASR in concrete : a new perspective.” *European Journal of Environmental and Civil Engineering*, Taylor & Francis, 8189(December), 1–21.

Farage, M. C. R., Alves, J. L. D., and Fairbairn, E. M. R. (2004). “Macroscopic model of concrete subjected to alkali-aggregate reaction.” *Cement and Concrete Research*, 34(3), 495–505.

Fecteau, P. L., Fournier, B., Choquette, M., and Duchesne, J. (2012). “Contribution to the understanding of the so-called alkali--carbonate reaction (ACR), 14th ICAAR International Conference on Alkali--Aggregate Reaction in Concrete.” May.

Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier, R. (2004). “Comparative Field and Laboratory Investigations on the Use of Supplementary Cementing Materials to Control Alkali-Silica Reaction in Concrete.” *Proceedings of the 12th International Conference on Alkali-Aggregate Reaction (ICAAR)*, 1, 528--537.

Fournier, B., and Bérubé, M.-A. (2000). “Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications.” *Canadian Journal of Civil Engineering*, 27(2), 167–191.

Franz-Josef Ulm et al. (2000). “THERMO-CHEMO-MECHANICS OF ASR EXPANSION IN CONCRETE STRUCTURES.” *Journal of Engineering Mechanics*, (March), 233–242.

Gorga, R. V., Sanchez, L. F. M., and Martín-Pérez, B. (2018). “FE approach to perform the condition assessment of a concrete overpass damaged by ASR after 50 years in service.” *Engineering Structures*, Elsevier, 177(June), 133–146.

- Grimai, E., Sellier, A., Pape, Y. Le, and Bourdarot, E. (2008). “Creep, shrinkage, and anisotropic damage in alkali-aggregate reaction swelling Mechanism-Part II: Identification of model parameters and application.” *ACI Materials Journal*, v 105, n 3(105), p 236-242.
- Grimal, E., Sellier, A., Multon, S., Le Pape, Y., and Bourdarot, E. (2010). “Concrete modelling for expertise of structures affected by alkali aggregate reaction.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 502–507.
- Katayama, T. (2010). “The so-called alkali-carbonate reaction (ACR) - Its mineralogical and geochemical details, with special reference to ASR.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 643–675.
- Katayama, T., and Grattan-Bellew, P. E. (2012). “Petrography of the Kingston experimental sidewalk at age 22 years--ASR as the cause of deleteriously expansive, so-called alkali-carbonate reaction.” *Proceedings of the 14th international conference on alkali-aggregate reaction in concrete. Austin, Texas, USA*, 10.
- Kawabata, Y., Martin, R.-P., Seignol, J.-F., and Toutlemonde, F. (2016). “Modelling of Evolution of Transfer Properties Due To Expansion of Concrete Induced By Internal Swelling Reaction.” *ICAAR 2016 - 15th international conference on alkali aggregate reaction*.
- Kurihara & Katawaki. (1989). “Effects of moisture control and inhibition on alkali silica reaction.” *kyoto, Japan*, 629–634.
- Larive, C. (1997). “Combined contribution of experiments and modelling to the understanding of alkali-aggregate reaction and its mechanical consequences (PhD thesis; in: French).”
- Li, K., and Coussy, O. (2002). “Concrete ASR degradation : from material modeling to structure

- assessment.” *Concrete Science and Engineering*, 4(March), 35–46.
- Lindgård, J., Andiç-Çakir, Ö., Fernandes, I., Rønning, T. F., and Thomas, M. D. A. (2012). “Alkali-silica reactions (ASR): Literature review on parameters influencing laboratory performance testing.” *Cement and Concrete Research*, 42(2), 223–243.
- Lothenbach, B., Winnefeld, F., Alder, C., Wieland, E., and Lunk, P. (2007). “Effect of temperature on the pore solution, microstructure and hydration products of Portland cement pastes.” *Cement and Concrete Research*, 37(4), 483–491.
- Multon, S., Sellier, A., and Cyr, M. (2009). “Chemo – mechanical modeling for prediction of alkali silica reaction (ASR) expansion.” *Cement and Concrete Research*, Elsevier Ltd, 39(6), 490–500.
- Multon, S., and Toutlemonde, F. (2004). “Water distribution in concrete beams.” *Materials" and Structures*, 37(July), 378–386.
- Multon, S., and Toutlemonde, F. (2006). “Effect of applied stresses on alkali-silica reaction-induced expansions.” *Cement and Concrete Research*, 36(5), 912–920.
- Nielsen, A. e. al. (1993). “Development of stresses in concrete structures with alkali-silica reactions.” *Materials and Structures*, 152–158.
- Olafsson, H. (1986). “The effect of relative humidity and temperature on alkali expansion of mortar bars.” *7th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 461–465.
- Owsiak, Z., Zapała-Sławeta, J., and Czapik, P. (2015). “Diagnosis of concrete structures distress due to alkali-aggregate reaction.” *Bulletin of the Polish Academy of Sciences Technical Sciences*, 63(1), 23–29.

- Pesavento, F., Gawin, D., Wyrzykowski, M., Schrefler, B. A., and Simoni, L. (2012). “Modeling alkali-silica reaction in non-isothermal, partially saturated cement based materials.” *Computer Methods in Applied Mechanics and Engineering*, Elsevier B.V., 225–228, 95–115.
- Poyet et al. (2007). “Chemical modelling of Alkali Silica reaction : Influence of the reactive aggregate size distribution.” 229–239.
- Poyet, S., Sellier, A., Capra, B., Thèvenin-Foray, G., Torrenti, J. M., Tournier-Cognon, H., and Bourdarot, E. (2006). “Influence of Water on Alkali-Silica Reaction: Experimental Study and Numerical Simulations.” *Journal of Materials in Civil Engineering*, 18(August), 588–596.
- Prinčič, T., Štukovnik, P., Pejovnik, S., De Schutter, G., and Bosiljkov, V. B. (2013). “Observations on dedolomitization of carbonate concrete aggregates, implications for ACR and expansion.” *Cement and Concrete Research*, 54, 151–160.
- Rashidi, M., Kim, J. Y., Jacobs, L. J., and Kurtis, K. E. (2016). “Insights into alkali-silica reaction damage in mortar through acoustic nonlinearity.” *AIP Conference Proceedings*, 1706(2016).
- Sanchez, L. (2014). “Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction.” UNIVERSITE LAVAL.
- Sanchez, L. F. M. (2008). “Contribuição ao estudo dos métodos de ensaio na avaliação das reações álcali-agregado em concretos.” Universidade de São Paulo.
- Sanchez, L. F. M., Drimalas, T., Fournier, B., Mitchell, D., and Bastien, J. (2018). “Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms.” *Cement and Concrete Research*, 107(September 2017), 284–303.
- Sanchez, L. F. M., Fournier, B., Jolin, M., and Bastien, J. (2015a). “Evaluation of the Stiffness

- Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses.” *Construction and Building Materials*, Elsevier Ltd, 77, 20–32.
- Sanchez, L. F. M., Fournier, B., Jolin, M., and Duchesne, J. (2015b). “Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI).” *Cement and Concrete Research*, Elsevier Ltd, 67, 74–92.
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., and Bastien, J. (2017). “Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures.” *Cement and Concrete Research*, Elsevier Ltd, 93, 17–31.
- Sanchez, L. F. M., Multon, S., Sellier, A., Cyr, M., Fournier, B., and Jolin, M. (2014). “Comparative study of a chemo-mechanical modeling for alkali silica reaction (ASR) with experimental evidences.” *Construction and Building Materials*, Elsevier Ltd, 72, 301–315.
- Sanchez, L., Kuperman, S. C., and Helene, P. (2011). “Using the accelerated Brazilian concrete prism test (ABCPT) to evaluate alkali aggregate reaction (AAR).” *Ibracon Structures and Materials Journal*, 4, 575–581.
- Sanchez, L., Kuperman, S., and Helene, P. (2008). “Trials To Correlate the Accelerated Mortar Bar Test , the Standard and the Accelerated Concrete.” *13th International Conference on Alkali Aggregate Reaction (ICAAR)*, Trondheim, Norway.
- Saouma, V. E., Martin, R. A., Hariri-Ardebili, M. A., and Katayama, T. (2015). “A mathematical model for the kinetics of the alkali-silica chemical reaction.” *Cement and Concrete Research*, Elsevier Ltd, 68, 184–195.

- Saouma, V., and Perotti, L. (2006). "Constitutive model for alkali-aggregate reactions." *ACI Materials Journal*, 103(3), 194–202.
- Schmidt et al. (2009). "AKR-Performance-Prüfung von flugaschehaltigen Betonen – Einfluss der Temperatur auf die Porenlösung und Möglichkeiten zur zielsicheren Bewertung." *17. Internationale Baustofftagung, ibausil, F. A. Finger-Institut für Baustoffkunde, Bauhaus Universität Weimar, 23.-26. September 2009. In: Tagungsbericht, S. 2 0267 2 0276.*
- Suwito, A., Jin, W., Xi, Y., and Meyer, C. (2002). "A Mathematical Model for the Pessimism Size Effect of ASR in Concrete." *Concrete Science and Engineering*, 1–31.
- Urhan, S. (1987). "Alkali silica and pozzolanic reactions in concrete. Part 1: Interpretation of published results and an hypothesis concerning the mechanism." *Cement and Concrete Research*, 17(c), 141–152.
- Vivian, H. E. (1981). "The effect of drying on reactive aggregate and mortar expansions." *Proc., 5th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 228–252.
- Winnicki, A., and Pietruszczak, S. (2008). "On Mechanical Degradation of Reinforced Concrete Affected by Alkali-Silica Reaction." *Journal of Engineering Mechanics*, 134(8), 611–627.

Chapter 3 Analytical modelling to describe Alkali aggregate reaction (AAR)- kinetics and induced expansion in the laboratory

Goshayeshi, N.^a; Sanchez, L. F. M.^b; Gorga, R.^c; Santos, A. C.^d; Souza, D. J.^e; De Grazia, M.^f

(a) MSc Candidate – University of Ottawa

(b) Assistant Professor – University of Ottawa

(c) MSc – University of Ottawa

(d) Associate Professor – University of Uberlandia

(e) Ph.D. candidate – University of Ottawa

(f) Ph.D. candidate – University of Ottawa

Abstract

Predicting AAR-kinetics and induced expansion is a very complicated task, yet very useful to forecast the potential of further deterioration of concrete. Back in the 90s, Larive developed an analytical model to describe AAR-kinetics in the laboratory. Although relatively well accepted by the AAR community, Larive's equation is based on empirical mathematical parameters that do not have a clear physicochemical meaning and thus cannot directly describe AAR-development for a variety of materials and exposure conditions. This work proposes a modified Larive's equation based on five measurable parameters that directly affect AAR-induced development, such as aggregate's type and nature/reactivity, alkali content of the concrete, temperature and relative humidity. A comprehensive laboratory test campaign along with literature data are used to calibrate the proposed modified model. Coefficients from each of the above parameters are then established according to their influence on the chemical reaction. Results show that the proposed model may accurately describe AAR-kinetics and final expansion in the laboratory for a wide range of materials and exposure conditions without further calibration. Yet, an in-depth analysis

is still needed before using the current approach to assess AAR-affected concrete structures in the field.

Keywords: alkali-aggregate reaction (AAR), analytical model, reactivity, AAR-kinetics and induced expansion

3.1 Introduction

Alkali-Aggregate Reaction (AAR) is one of the most harmful distress mechanisms affecting the durability and serviceability of concrete infrastructure worldwide (Fournier and Bérubé 2000; Sanchez 2014). AAR is comprised of two main mechanisms: alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). ASR is by far the most common type of reaction found around the world, and its damage process is deemed to be fairly well understood (Fournier and Bérubé 2000). It consists of a chemical reaction between “unstable” silica mineral forms within fine and/or coarse aggregate materials and the alkali hydroxides (i.e. Na^+ , K^+ and OH^-) that are dissolved in the concrete pore solution. ASR generates a secondary product, the so-called alkali-silica gel, that induces expansive pressure within the reacting aggregate material(s) and the adjacent cement paste upon moisture uptake from its surrounding environment; thus leading to microcracking, loss of material integrity (mechanical properties and durability) and, in some cases, functionality of the affected structure/structural member. Conversely, ACR is a much less common reaction type whose distress mechanism is still mostly unknown, being considered as a form of ASR by some authors (Katayama 2010; Katayama and Grattan-Bellew 2012), whereas other researchers believe that ACR follows a “different” and unique mechanism (CSA 2014; Fecteau et al. 2012). Nevertheless, ACR is assumed to take place while the use of carbonate rocks in concrete through a process called “dedolomitization” with the formation of brucite and calcite (Fournier and Bérubé 2000; Prinčič et al. 2013). Moreover, it has been found that the alkali carbonates generated over

the dedolomitization process may further react with Portlandite from the cement paste, forming secondary calcite and regenerating alkali hydroxides. The latter indicates that ACR might have the potential to be an “endless” process (Fournier and Bérubé 2000; Prinčič et al. 2013).

AAR kinetics, induced expansion and damage both at the microscopic or macroscopic scales depend upon the type (i.e. fine or coarse aggregate) and nature (i.e. mineralogy, reactivity, etc.) of the aggregates, the amount of alkalis of the concrete, the temperature and relative humidity of the environment along with the exposure degree and confinement conditions (e.g. reinforcement ratio, etc.) of a given structure/structural member under analysis (Lindgård et al. 2012; Multon and Toutlemonde 2006; Poyet et al. 2006; Rashidi et al. 2016). Predicting AAR-kinetics and induced expansion is quite challenging, since AAR is a very complex non-linear physicochemical phenomenon. Yet, to accurately describe AAR-development in the laboratory or in the field, mathematical models able to account for both physical and chemical parameters of the reaction should be considered (Gorga et al. 2018).

3.2 Forecasting AAR-kinetics and induced expansion

One of the biggest challenges in the condition assessment of AAR-affected infrastructure is to establish the current expansion level reached by the structural member under analysis along with its potential for further distress. A number of analytical, numerical and empirical models have been proposed over the past decades to predict AAR-kinetics and induced expansion in the laboratory (i.e. materials level) and its impact on the mechanical properties and performance of affected structures/structural components in the field (i.e. structures level) (Comi et al. 2012; Larive 1997; Multon and Toutlemonde 2006; Poyet et al. 2006; Saouma et al. 2015; Saouma and Perotti 2006). Amongst those, Larive’s analytical model (Larive 1997) is probably one of the most accepted approaches by the AAR community (Prinčič et al. 2013; Rashidi et al. 2016; Sanchez et al. 2015b,

2018). Larive’s model was initially developed to describe the induced expansion behaviour of unrestrained concrete specimens in the laboratory but has also been used to predict the expansion rate of concrete structures in the field. It consists of a semi-empirical approach that was established based upon a large experimental campaign, where around 600 specimens were tested in the laboratory (Larive 1997; Winnicki and Pietruszczak 2008). In this model, the AAR-kinetics and induced expansion are described as a function of three main parameters: ultimate expansion (ε^∞), latency (τ_l) and characteristic (τ_c) times (Eq. 3.1). Each set of parameters is only valid for a given temperature (θ). Eq. 3.1 illustrates an expansion curve resulting from Larive’s analytical model (Larive 1997).

$$\varepsilon(t, \theta) = \frac{1 - e^{-\frac{t}{\tau_c(\theta)}}}{1 + e^{-\frac{(t-\tau_l(\theta))}{\tau_c(\theta)}}} \times \varepsilon^\infty \quad \text{Eq. 3.1}$$

Larive’s induced expansion plot often displays an *S-shape* curve that may be divided and explained into four phases. The first phase represents AAR secondary product formation and its accommodation likely within the reactive aggregates and adjacent cement paste with little to no expansion as per (Sanchez et al. 2015b). The second phase (i.e. ascending curve period) represents the AAR-induced expansion process due to moisture uptake from the reaction product. In this phase, expansion with little to 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 (Sanchez et al. 2015b). In phase 3, the curve shape changes from “convex” to “concave” since the reaction product that keeps forming over the physicochemical

process has supplementary space (i.e. cracks, flaws, etc.) at this stage to accommodate, which decreases the AAR-expansion rate. Finally, the fourth and last phase shows a reaction levelling off trend due to the total alkalis and/or silica consumption from the system. It is worth noting that the expansion levels provided in the plot below are merely qualitative and were selected to properly illustrate the physicochemical process. They are not intended whatsoever to represent precisely the expansion levels where AAR-induced cracks are generated and propagated as per (Sanchez et al. 2015b).

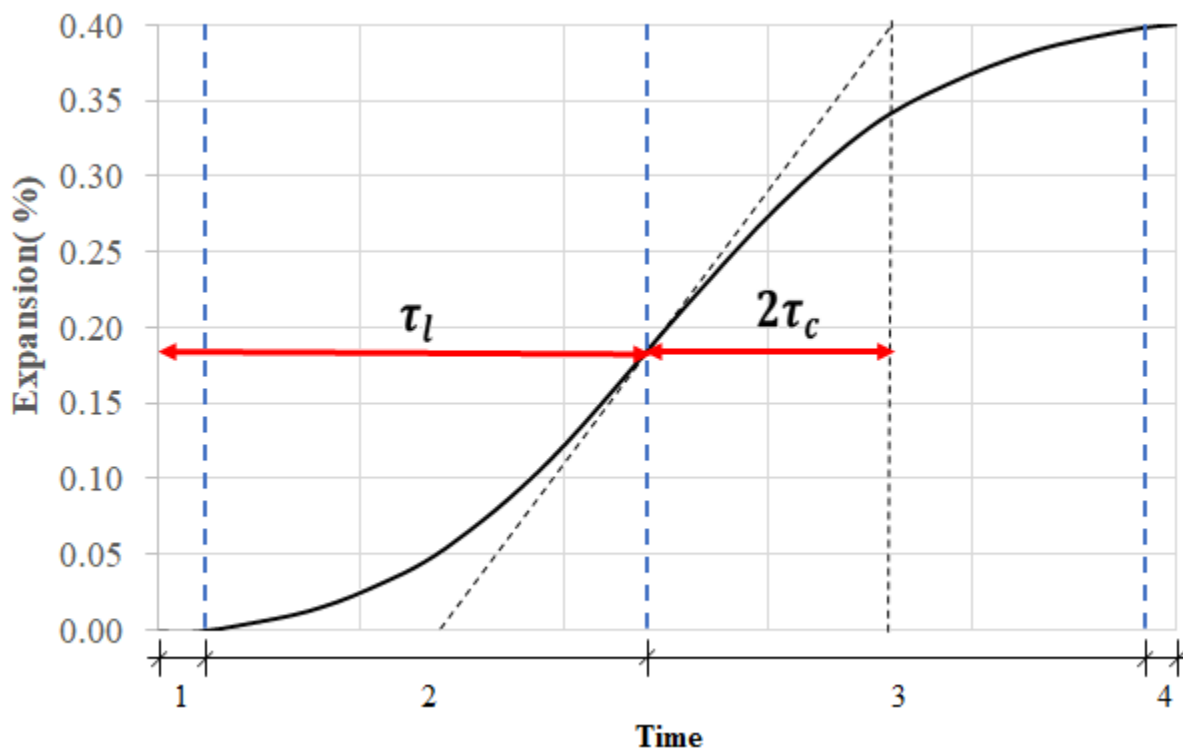


Figure 3.1. AAR-induced expansion curve obtained from Larive's model (Larive 1997)

Building upon Larive's works, (Brunetaud 2005) proposed a modification (Eq. 3.2 ,and Eq. 3.3) to the initial Larive's approach to better represent the long-term swelling behaviour of concrete affected by internal swelling reactions (ISR, which comprises AAR and delayed ettringite formation- DEF), by adding a time-dependent coefficient to the proposed equation (Figure 3.2).

The latter has showed to better represent the long-term performance of massive structures in the field (Kawabata et al. 2016).

$$\varepsilon(t) = \varepsilon_{\infty} \frac{1 - e^{(-t/\tau_c)}}{1 + e^{(-t/\tau_c + \tau_L/\tau_c)}} \times \beta(t) \quad \text{Eq. 3.2}$$

$$\beta(t) = 1 - \frac{\varphi}{\delta + t} \quad \text{Eq. 3.3}$$

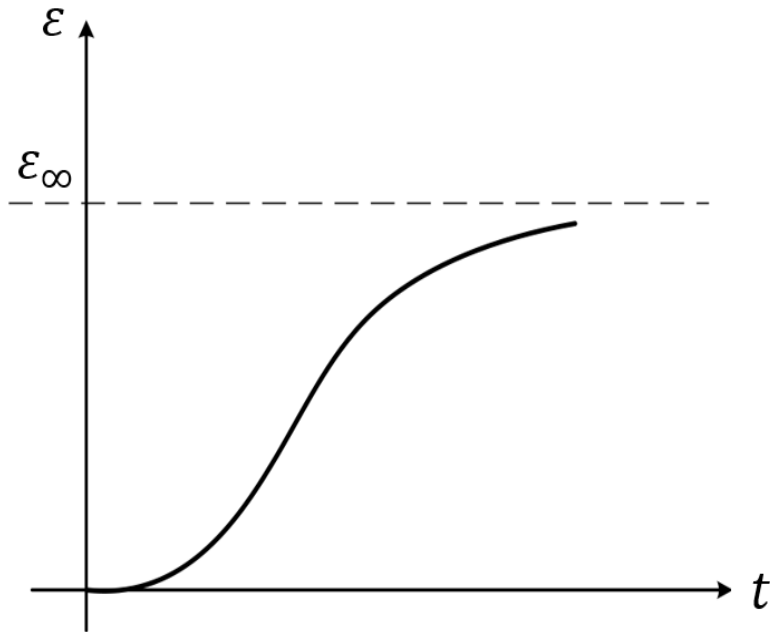


Figure 3.2. Long-term swelling behaviour of concrete affected by internal swelling reaction (Brunetaud 2005).

Although interesting, the approaches proposed by Larive and Brunetaud are only valid under constant conditions (i.e. temperature, moisture, exposure, etc.). Furthermore, the main parameters from Larive and Brunetaud equations such as latency (τ_l) and characteristic (τ_c) times along with expansion at infinity (ε^∞) are set and adapted in practice according to the concrete mixture and/or

structure under analysis; yet there is currently a lack of understanding on the range of these parameters as a function of the reactivity potential of the concrete (i.e. aggregate type and nature, alkalis content, etc.) as well as exposure conditions (i.e. temperature, humidity, and their variations over time).

(Capra and Bournazel 1998) proposed an approach that accounts for variations on exposure conditions, especially temperature. In this model, the alkalis consumption is first computed (Eq. 3.4), followed by the expansion level (Eq. 3.5). AAR is then assumed to be linearly proportional to the ratio of the alkalis reacted (A). The authors have also introduced a parameter (A_0) to account for the initial accommodation period with little to no expansion (Figure 3.3). This model showed to be more complete than Larive's and Brunetaud's equations, but further "case by case" calibration and fitting from experimental test procedures and/or in-situ measurements are also needed to implement such a model in practice.

$$\frac{dA}{dt} = K \times (1 - A) \quad \text{Eq. 3.4}$$

$$\varepsilon(t) = \begin{cases} 0 & \text{for } A < A_0 \\ \frac{\varepsilon_0}{A_0} \times (A - A_0) & \text{for } A \geq A_0 \end{cases} \quad \text{Eq. 3.5}$$

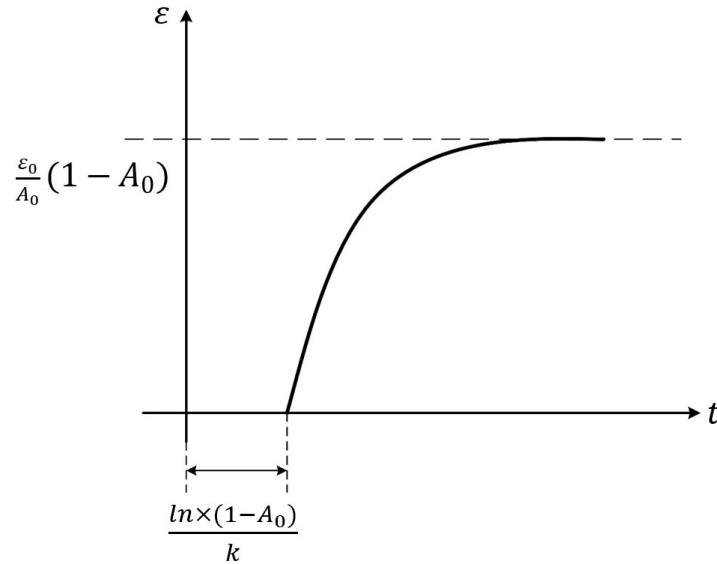


Figure 3.3. AAR induced expansion proposed by (Capra and Bournazel 1998)

3.3 Scope of the work

As previously mentioned, Larive's equation has been successfully used to describe the AAR-kinetics and induced expansion by many authors, especially in the laboratory at constant and unrestrained conditions. However, it is a somewhat limited approach because its coefficients (τ_i and τ_c) have no defined physical meaning, which means that Larive's equation is not able to predict AAR-development as a function of the properties of the materials and/or the environmental conditions without extensive laboratory tests and calibration. This paper aims to develop a modified Larive's model accounting for the most important (and measurable) parameters that affect the physicochemical reaction (i.e. aggregate's type and nature/reactivity, alkalis content, temperature, and relative humidity) and thus be able to fully describe AAR-kinetics and unrestrained induced expansion in the laboratory. First, a comprehensive experimental campaign (over 2000 samples) using a wide variety of reactive aggregate types and natures, distinct mix-designs and mechanical properties (25, 35, 40 and 45 MPa) is performed so that the influence of

the aforementioned parameters on AAR-induced development is established. Then, the proposed model is built and calibrated based upon coefficients defined for each of the five parameters influencing the physicochemical reaction. Finally, a discussion is made on the use of the proposed model to assess concrete structures in the field along with time periods required to evaluate the reactivity of aggregates in the laboratory at different temperatures.

3.4 Materials and methods

3.4.1 Materials

3.4.1.1 Aggregate's type, nature and alkali content

Twenty concrete mixtures with different strengths (i.e. 25, 35 and 45 MPa) and incorporating ten distinct reactive aggregate types and natures (R) were selected for the development and calibration of the model coefficients related to the aggregates type, nature and alkali content of the concrete. It is worth noting that nine out of the ten aggregates were ASR-reactive and only one aggregate (King) was ACR reactive material. The coarse aggregates ranged from 5 to 20 mm in size. Non-reactive (NR) fine (Lav) and coarse (HP or Dia) aggregates were used in combination with the reactive aggregate materials for concrete manufacturing. Table 3.1 provides information on the different aggregates used in this work. Supplementary data from the literature were also used regarding alkali content as per (Fournier and Bérubé 2000) to increase the alkali content's range evaluated.

Table 3.1. Characteristics of coarse and fine aggregates used in the concrete mixtures manufactured for the development of the model coefficients related to the aggregate's type, nature and alkali content of the concrete (Sanchez 2014).

Aggregate	Reactivity	Location	Rock type	Specific gravity	Absorption	AMBT ¹ 14-day exp (%)	
NM	R (ASR)	New Mexico (USO)	Polymictic Gravel (Mixed Volcanic, quartzite, chert)	2.53	1.59	1.056	
QC	R (ASR)	Quebec (CAN)	Siliceous and argillaceous limestone	2.50	1.16	0.302	
Wyo	R (ASR)	Wyoming	Granite, amphibolite, mixed volcanic	2.64	0.87	0.296	
Conr	R(ASR)	Halifax (CAN)	Metagreywacke, shale, siltstone	2.72	0.37	0.365	
Coarse	King ²	R (ACR)	Kingston (CAN)	Dolomite argillaceous limestone	2.69	0.55	0.11
	Virg	R (ASR)	Virginia (USA)	Metagranite	2.78	0.45	0.09
	Rec 1	R (ASR)	Recife (Brazil)	Granite-gneiss, mylonite	2.64	0.59	0.23
	Pots	R (ASR)	Montreal (CAN)	Siliceous sandstone (orthoquartzite)	2.57	1.15	0.093
	Dia	NR	Quebec (CAN)	Diabase (plutonic rock)	3.00	0.51	0.065
	HP	NR	Newfoundland (CAN)	High-purity fine-grained limestone	2.68	0.44	0.001
	Tx	R (ASR)	Corpus Christi (USA)	Polymictic sand (granitic, mixed volcanic, quartzite, chert, quartz)	2.60	0.55	0.755
Fine	Wt	R (ASR)	Texas (USA)	Polymictic sand (chert, quartz, feldspar)	2.60	0.40	0.335
	Lav	NR	Quebec (CAN)	Natural derived from Granite	2.71	0.54	0.068

¹ Typical results of accelerated mortar bar testing (ASTM C 1260) carried out on the aggregates as per (Sanchez et al. 2017).

² This aggregate is supposed to generate the so-called *Alkali Carbonate Reaction* (ACR), a different and less common type of Alkali-Aggregate Reaction (AAR) in which different distress patterns are found as by (Sanchez et al. 2015b).

Temperature and humidity

Three concrete mixtures with equivalent mix-designs (i.e. CPT mix as per ASTM C 1293 (ASTM 2018)) and incorporating three different reactive aggregate natures (R) were selected for the calibration of the model coefficients related to temperature. All three aggregates were ASR-reactive aggregates. The coarse aggregates ranged from 5 to 20 mm in size. A non-reactive (NR) fine aggregate (IPT) was used in combination with the reactive coarse materials for concrete manufacturing. Table 3.2 provides information on the different aggregates used in this research. Supplementary data from the literature were also used to complete the study dealing with relative humidity as per (Poyet et al. 2006). All the information on the materials and mix-designs used in Poyet's work may be found in (Poyet et al. 2006).

Table 3.2. Characteristics of coarse and fine aggregates used in the concrete mixtures fabricated for the calibration of the model coefficients related to temperature (Sanchez 2014).

Aggregate	Reactivity	Location	Rock type	Specific gravity	Absorption	AMBT ¹ 14-day exp (%)	
Coarse	Rec 1	R (ASR)	Recife (Brazil)	Granite-gneiss, mylonite	2.64	0.59	0.23
	QZ	R (ASR)	Tres Lagoas (Brazil)	Gravel (mixed rocks)	2.68	1.62	0.08
	GR	R (ASR)	Sao Paulo (Brazil)	Granite	2.72	0.55	0.05
Fine	IPT	NR	Sao Paulo (Brazil)	Natural derived from Granite	2.70	0.58	0.02

3.4.1.2 Mix-design and specimen production

Aggregate's type, nature and alkali content

All concrete mixtures investigated in this research section were mix-designed with a similar amount of cement paste and aggregates in volume so that one might compare similar systems (Table 3.3). Yet, distinct mixtures presenting different strengths (i.e. 25, 35 and 45 MPa) and amount of alkalis (i.e. 3.92, 4.62 and 5.25 kg/m³, respectively) were manufactured. About two hundred (i.e. 100 by 200 mm) specimens were fabricated from each concrete mixture (Sanchez et al. 2017). The specimens were demoulded after 24 hours, ground, and cured in the moist curing room for the next 24 hours. Small holes (with a diameter of 5 mm and 15 mm long) were drilled in both ends of each test cylinder. Stainless-steel studs were placed within the holes at the samples ends using a fast-setting cement slurry for axial expansion measurements. After 48 hours (hardening period), the zero-length reading was recorded. Then, four cylinders were placed in each sealed bucket, ensuring 100% relative humidity, and stored at 38°C. The samples were regularly monitored over time until they reached 0.30% expansion or an expansion plateau as per (Sanchez

et al. 2017). It is worth mentioning that before each expansion reading, the buckets were left at room temperature (23 °C) for 16 ± 4 hours as per ASTM C 1293 (ASTM 2018).

Table 3.3. Concrete mixtures fabricated with ten different reactive aggregates and presenting distinct mechanical properties (Sanchez 2014).

Type of concrete	Concrete mix design: ingredients and strength		25 MPa		35 MPa		45 MPa		
			kg/m ³	l/m ³	kg/m ³	l/m ³	kg/m ³	l/m ³	
Equivalent volumes: (paste and aggregates) (Base series)	Common to all mixtures of this series	Cement	314	101	370	118	424	151	
		Water	192	192	174	174	157	142	
		Air	-	20	-	20	-	20	
	Tx + HP	F.A.	790	304	790	304	790	304	
		C.A.	1029	384	1029	384	1029	384	
	Tx + Dia	F.A.	896	344	896	344	896	344	
		C.A.	1029	343	1029	343	1029	343	
	Lav + NM	F.A.	714	264	714	264	714	264	
		C.A.	1073	424	1073	424	1073	424	
	Lav + Qc	F.A.	705	260	705	260	705	260	
		C.A.	1068	427	1068	427	1068	427	
	Equivalent volumes (paste and aggregate) (Complementary series)	Common to all mixtures of this series	Cement			370	118		
			Water			174	174		
			Air			-	20		
Lav + Wyo		F.A.			770	283			
		C.A.			1065	403			
Lav + Pots		F.A.			737	272			
		C.A.			1068	416			
Lav + Conr		F.A.			807	298			
		C.A.			1060	390			
Lav + King		F.A.			794	293			
		C.A.			1062	395			
Lav + Virg		F.A.			829	306			
		C.A.			1061	382			
Lav + Rec 1		F.A.			773	285			
		C.A.			1062	402			
Wt + HP		F.A.			790	304			
		C.A.			1029	384			
Tx + NM		F.A.			719	276			
	C.A.			1040	411				

Note: F.A. = Fine Aggregate and C.A. = Coarse Aggregate.

Temperature and humidity

All concrete mixtures fabricated for the temperature calibration were mix-designed according to ASTM C 1293 (CPT mix, Table 3.4). Thirty concrete prisms (i.e. 75 x 75 x 285 mm) were manufactured from each concrete mixture (Sanchez et al. 2017). The specimens tested at 38°C and 60°C were demoulded after 24 hours and cured in the moist curing room for the next 24 hours. Otherwise, samples tested at 80°C were demoulded after 24 hours and cured in water at 80°C (to avoid any thermal gradient and thus non-AAR related expansion) for further 24 hours. Stainless-steel studs were embedded to the specimens mold ends prior to casting for axial expansion measurements. After 48 hours (hardening period), the zero-length reading was recorded in all samples. Then, four prisms were placed in sealed buckets (ensuring 100% relative humidity) in the cases of 38°C or 60°C storage, whereas the prisms were soaked into a 0.3125N NaOH solution to induce AAR-development without important diffusion and/or alkali leaching as per (Sanchez et al. 2011) and stored at 80°C. All the samples were regularly monitored over time for 2 months, 6 months and one year, respectively for 80°C, 60°C and 38°C tests. One may notice that before each expansion reading, the buckets from 38°C and 60°C tests were left at room temperature (23 °C) for 16 ± 4 hours as per ASTM C 1293 (ASTM 2018). Conversely, the 80°C test samples were measured hot, as per ASTM C 1260 procedure (ASTM C1260 2016) and described in (Sanchez et al. 2011).

Table 3.4. Concrete mixtures fabricated with the CPT mix-design as per ASTM C 1293 and incorporating three distinct coarse reactive aggregates (ASTM 2018).

Type of concrete	Concrete mix design: ingredients and strength		CPT mix (40 MPa)	
			kg/m ³	kg/m ³
CPT mix-design	Common to all mixtures of this series	Cement	420	135
		Water	189	189
		Air	-	20
	IPT + Rec 1	F.A.	773	285
		C.A.	1062	402
	IPT + QZ	F.A.	775	287
		C.A.	1050	392
	IPT + GR	F.A.	793	291
C.A.		1050	386	

For the relative humidity study, data from the literature were used as per Poyet et al. (Poyet et al. 2006). Mortar samples were fabricated and cured over 10 days at 20°C. The specimens were then wrapped in a plastic film, stored at 60°C and monitored over time at distinct relative humidity conditions (i.e. (i.e. 59%, 76%, 80%, 82%, 86%, and 100%). Further information on the mix-designs and procedures adopted in this work may be found in (Poyet et al. 2006).

3.4.2 Methods

All the samples fabricated in this research were stored in exposure conditions enabling AAR-induced development and monitored over time as described in 3.4.1. Five controlled parameters (i.e. aggregate's type and nature/reactivity, alkali content of the mixture, temperature and relative humidity) were selected to establish the modified Larive's model. These parameters were calibrated (through the use of the least square method) as a function of the results obtained in the laboratory; thus, coefficients related to each of them were generated. It is worth noting that the coefficients related to the aggregate's type and nature/reactivity were directly used to describe (i.e.

give values to) the latency (τ_l) and characteristic (τ_c) times in the proposed equation along with the ultimate expansion (i.e. ϵ_∞ , expansion at infinity), whereas the other coefficients (i.e. alkali content, temperature and relative humidity) created new variables in the model and thus were used to influence on the final τ_l , τ_c and ϵ_∞ results. Finally, AAR-reactivity (or expansion) levels were assumed in this work as the ones proposed by (Sanchez et al. 2017) and presented in Table 3.5.

Table 3.5. AAR-expansion levels classification (Sanchez et al. 2017).

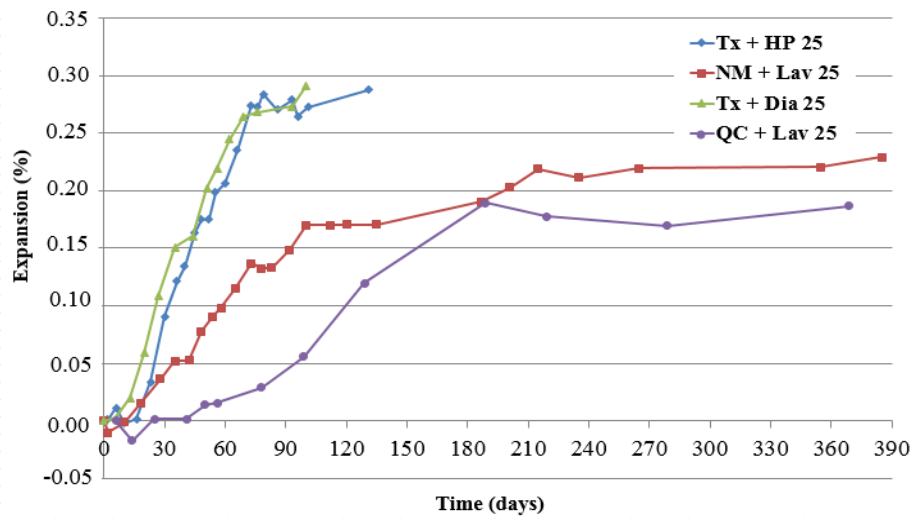
AAR-reactivity level	Reference expansion level (%)
Negligible	0.00 - 0.03
Marginal	0.04 ± 0.01
Moderate	0.11 ± 0.01
High	0.2 ± 0.01
Very high	$\leq 0.3 \pm 0.01$

3.5 Results

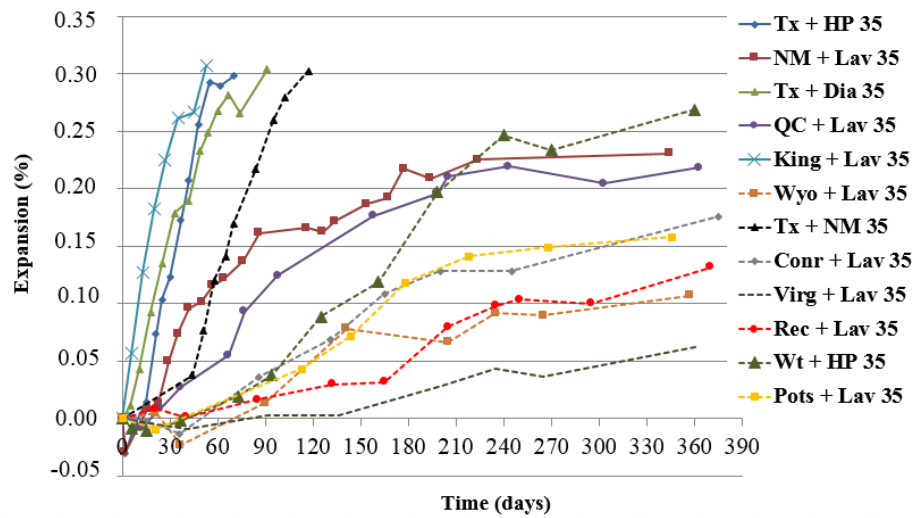
3.5.1 Aggregate's type and nature/reactivity

Figure 3.4 illustrates the influence of the type and nature/reactivity of aggregates on AAR-induced expansion obtained in the laboratory for mixtures presenting distinct mechanical properties (i.e. 25, 35 and 45 MPa). Analyzing the results, one observes that the aggregate's type and nature may impact both AAR-kinetics and final expansion. In general, two kinetic trends are observed: 1) a very fast ascending curve with little to no latency time and no levelling off trend up until the ultimate expansion is reached and, 2) a slower ascending curve, presenting some latency time and a significant levelling off trend close to the ultimate expansion level obtained over the test. Concrete mixtures containing reactive fine aggregates (e.g Tx sand) showed a faster development and thus a kinetics similar to type 1 above, whereas mixes incorporating reactive coarse aggregates

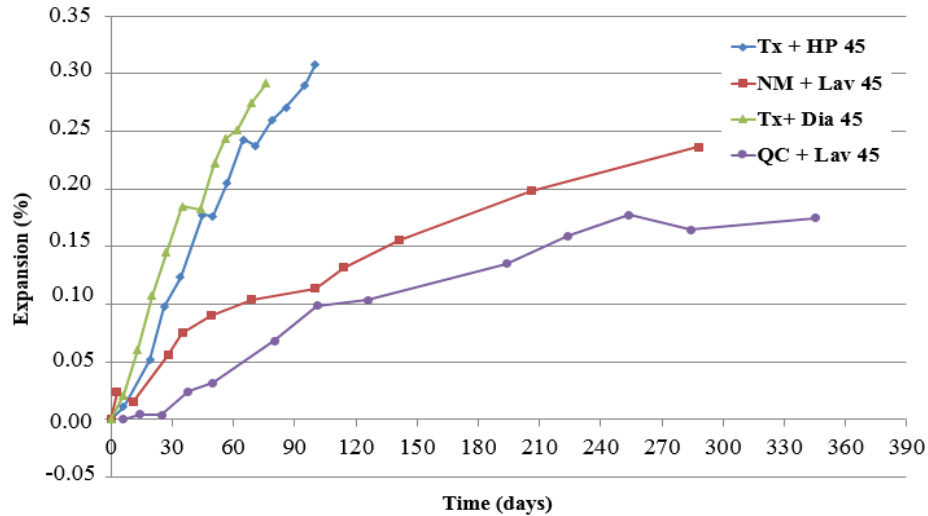
showed a reaction kinetics similar to type 2. The only exception is observed for King + Lav 35MPa mix (Figure 3.4.B), since King coarse aggregate is supposed to be susceptible to ACR, presenting a quite fast and unique reaction trend. Conversely, AAR-kinetics does not seem to change as a function of the inner quality (i.e. mechanical properties) and alkali content (i.e. 3.92, 4.62 and 5.25 kg/m³) of the concrete, since the 25, 35 and 45 MPa mixtures presented very similar trends as seen in Figure 3.4.A, 3.4.B and 3.4.C.



(A)



(B)



(C)

Figure 3.4. AAR kinetics (expansion vs. time – A, B, C) for the 25 (A), 35 (B) and 45 (C) MPa concrete mixtures (Sanchez 2014).

3.5.2 Temperature

Figure 3.5 shows the expansions recorded through the concrete prism tests performed at 38°C, 60°C and 80°C as per (Sanchez et al. 2008, 2011). As one observes, increasing the exposure temperature changes completely the AAR-kinetics, as expected, the higher the temperature, the faster the AAR-kinetics and development for all aggregates tested. Furthermore, raising the temperature also showed to increase the ultimate expansion over time. This was somewhat expected for the 80°C tests since the proposed test setup is supposed to prevent (at least partially) alkalis leaching from the samples which is often the main issue reducing AAR-final expansion in the laboratory. Yet, important expansion differences were also observed between 38°C and 60°C, although these tests presented exactly the same setup. Ultimate expansions of about 33% and 166% higher were found at 60°C (5 months) and 80°C (1 month), respectively when compared to tests performed at 38°C (1 year).

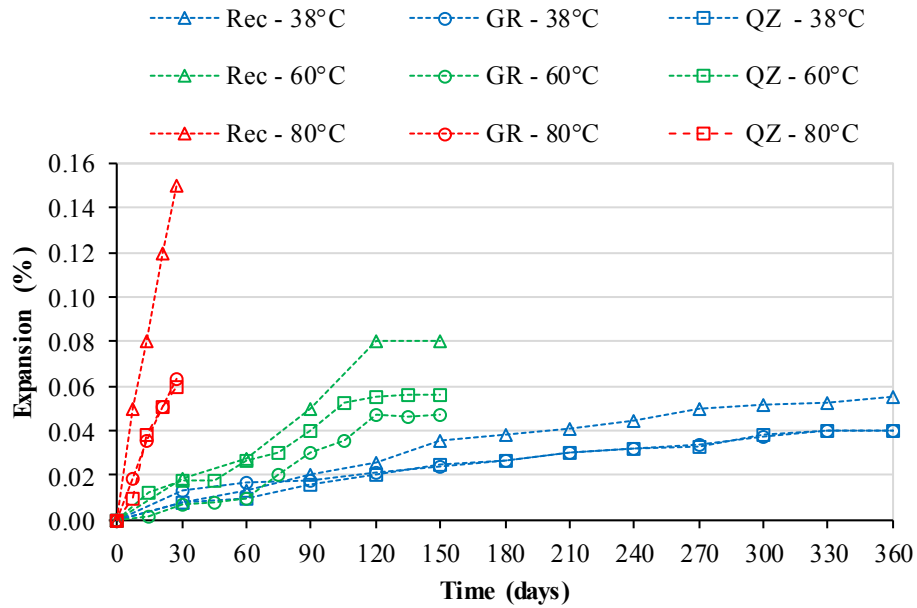


Figure 3.5. Accelerated concrete prism expansions as a function of time (Sanchez 2008).

3.5.3 Relative humidity

Figure 3.6 gives a plot for Poyet et al. (Poyet et al. 2006) results on the influence of the relative humidity on AAR-kinetics and induced expansion. From the plot, it is clear that the relative humidity impacts significantly the AAR-kinetics and ultimate expansion, as expected. Normally, the higher the relative humidity, the faster AAR-kinetics and the higher the ultimate expansion over time. Surprisingly, the results obtained at 96% humidity were slightly higher than the ones gathered at 100%; yet this could have been only an imprecision and/or deviation while the samples monitored. The final expansion obtained on samples exposed to 96% R.H. when compared to 59% R.H. is about 4.12 times higher.

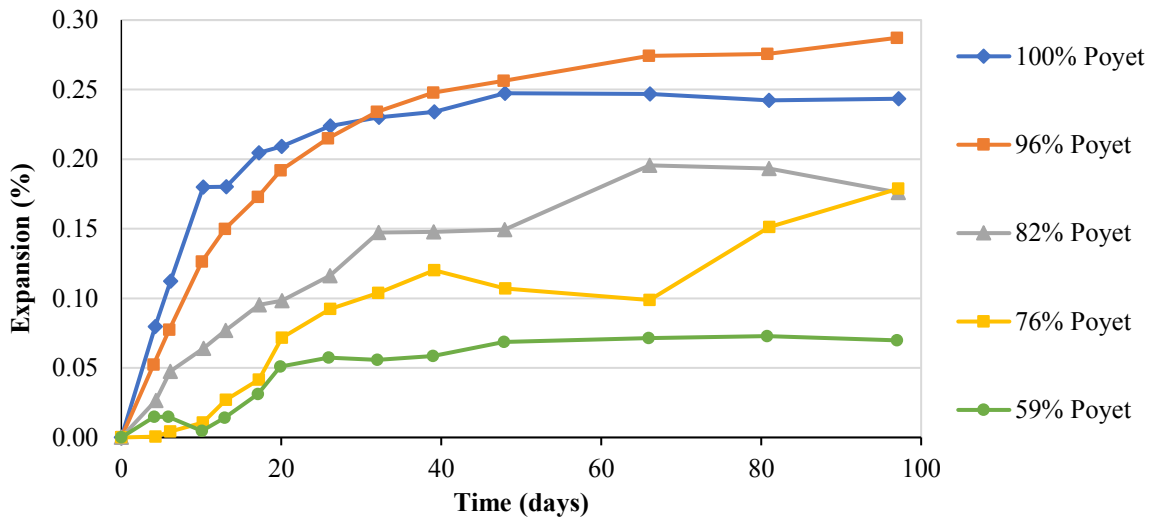


Figure 3.6. ASR swelling over time for different and constant external relative humidity (Poyet et al. 2006).

3.5.4 Alkali content

Due to the fact that AAR-kinetics and induced expansion were found to be quite similar on mixtures presenting distinct amounts of alkalis (i.e. from 3.92 to 5.25, section 3.5.1), further data from the literature with a much wider range of alkalis were also considered in this study. (Fournier and Bérubé 2000) tested reactive concrete prisms incorporating a large variety of alkali contents and two reactive coarse aggregates (Sudbury gravel and Spratt limestone). The alkali contents ranged from low (1.5 kg/m^3) to extremely high (12.5 kg/m^3) amounts and the concrete expansion levels obtained after one year of measurements at 38°C and 100% R.H. were quite different from each other (Figure 3.7). Observing the plot, it is clear that the higher the alkali content, the higher the final expansion generated. Moreover, it seems that the nature of the aggregate may also interfere with the ultimate expansion of concrete made of distinct amounts of alkalis. Comparing to 5.25 kg/m^3 of alkalis (which is the standard value normally used in the CPT test as per ASTM C 1293 (ASTM 2018)), concrete prisms incorporating the Sudbury gravel with 1.5 kg/m^3 and 12.5

kg/m³ of alkalis reached 500% lower and 235% higher expansion results, respectively. Otherwise, concrete prisms made of Spratt aggregate and the same alkali levels reached 1500% lower and 25% higher expansion results, respectively.

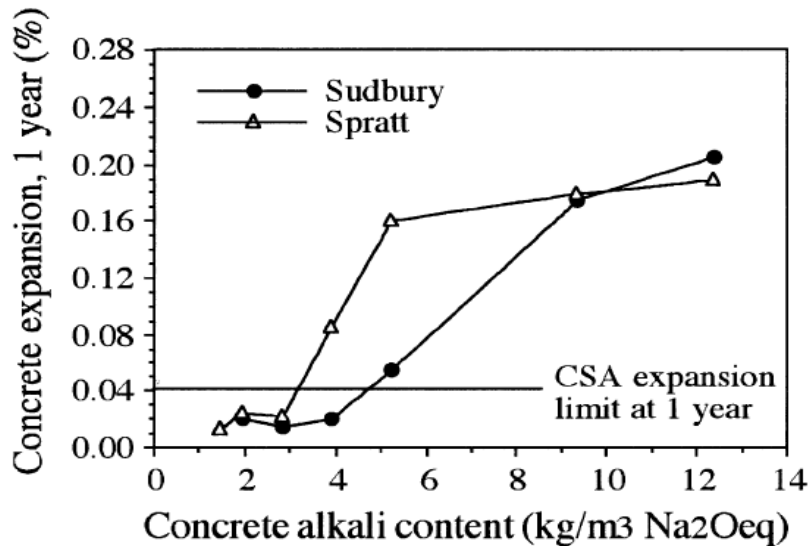


Figure 3.7. One-year CPT test as per ASTM C 1293 for concrete mixtures incorporating two reactive aggregates (Spratt limestone and Sudbury gravel) and different alkali contents (Fournier and Bérubé 2000)

3.6 Discussion

In this section, the results previously gathered from both experimental test campaigns and literature data are now used to establish and calibrate the proposed modified Larive’s equation. A detailed discussion on each of those is presented hereafter.

3.6.1 Aggregate’s type and nature/reactivity

Figure 3.8 shows the calibration of Larive’s model to match the results obtained in section 3.5.1 (Figure 3.4.A, 3.4.B and 3.4.C) through the use of the least square method. As previously discussed, the expansion behaviour of the distinct mixes presented two distinct trends (i.e. very

fast ascending curve with no latency time and slower ascending curve with some latency time) and thus three categories may be created according to the aggregates type and nature/reactivity: 1) ACR reactive aggregates presenting the fastest expansion kinetics and highest ultimate level; 2) ASR reactive fine aggregates showing a slightly lower reaction kinetics with the same ultimate expansion when compared to the ACR mechanism and; 3) ASR reactive coarse aggregates which present a much slower reaction kinetics and ultimate level when compared to the two previous mechanisms. For each AAR category, the ultimate expansion (ϵ_{∞} , or expansion and infinity), τ_l and τ_c coefficients are established and are illustrated in Table 3.6.. It is worth noting that the mixtures presenting 4.6 kg/m³ (or the 35 MPa mixes as per (Sanchez et al. 2017)) were selected as the “control mixtures” from which all the other mixes were compared to. Yet, no significant expansion differences from mixtures containing distinct alkalis amounts were found in this part of the work and thus the coefficients for alkali content were disregarded at this phase.

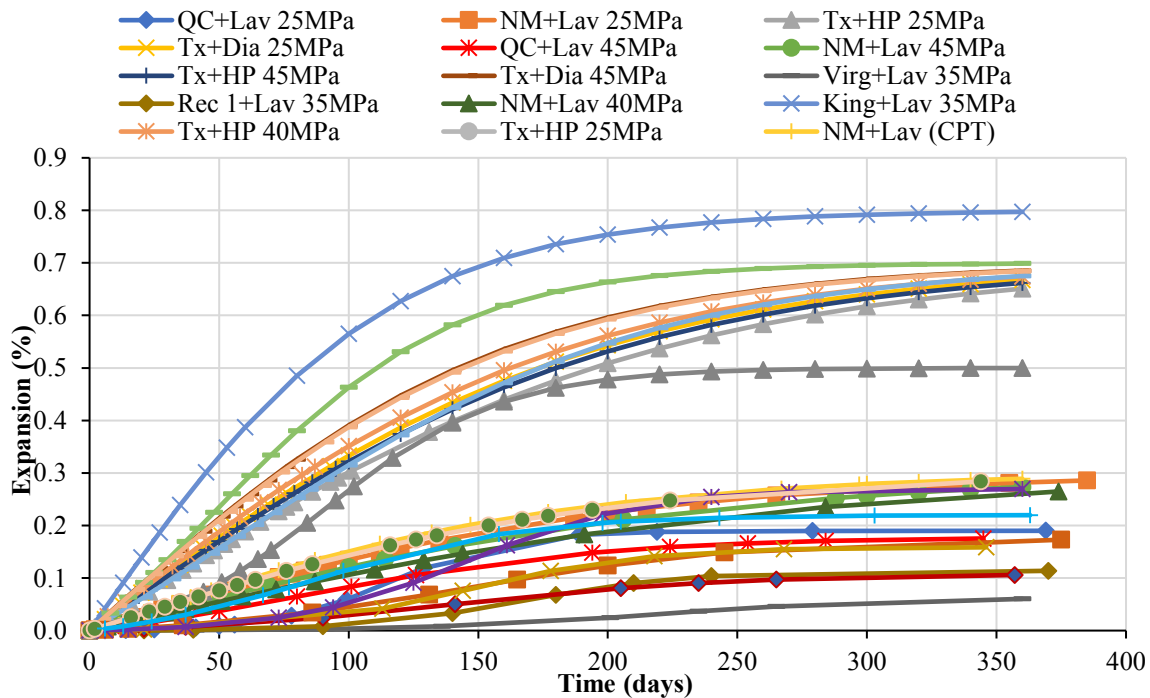


Figure 3.8. Expansion vs time for various concrete mixtures and aggregate types and natures.

Table 3.6. Aggregate's type and nature/reactivity coefficients.

	Damage Degree	Expansion	τ_c	τ_l	Epsilon Infinity (%)
ACR-All	Very High	≥ 0.30	57.0	0.0	0.80
ASR-Fine and Coarse	Very High	≥ 0.30	35.0	91.0	0.50
ASR-Fine	High	0.20	34.0	146.0	0.20
	Very High	≥ 0.30	93.0	0.0	0.70
ASR-Coarse	Marginal	0.04	49.0	181.0	0.04
	Moderate	0.11	39.0	143.0	0.11
	High	0.2	41.0	87.0	0.22
	Very High	≥ 0.30	108.0	0.0	0.3

Table 3.6, one may notice that increasing AAR-kinetics and induced expansion, latency time (τ_l) tends to decrease, being close to or even zero for extremely reactive aggregates (i.e. ACR mechanism, very high reactive fine or coarse aggregates). The latter means that the AAR-kinetics is so fast that there is almost no accommodation of the reaction products before important swelling takes place. Moreover, the values of τ_c for fast kinetics mechanisms are significantly higher than the slower reactive mechanisms, which means that they are not only faster but also present a higher ultimate expansion (i.e. expansion amplitude) at infinity. The τ_l values ranged from 0 to 181, whereas the τ_c results ranged from 34 to 108. Based on the suggested coefficients related to the aggregate's type and nature/reactivity, Figure 3.9 illustrates the approximated reference curves for each of the seven conditions displayed in Table 3.6. Finally, the variability between measured laboratory data and the proposed curves through the use of the least square method is less than 2% for all mixes.

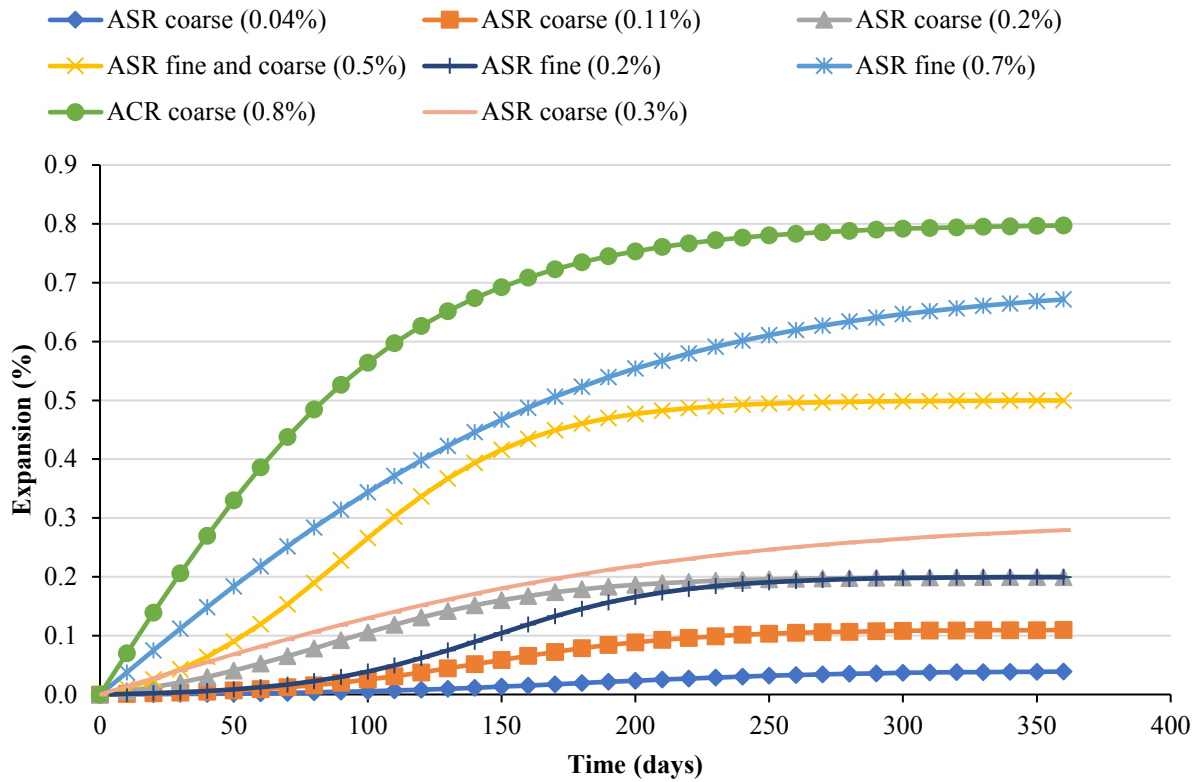


Figure 3.9. Reference curves based on the coefficients presented in

Table 3.6.

3.6.2 Temperature

Figure 3.10 displays the calibration of Larive's model to match the temperature results obtained in section 3.5.2 (Figure 3.5). As previously discussed, increasing the exposure temperature changes completely AAR-kinetics and ultimate expansion, since the higher the temperature, the faster and more linear the AAR-induced expansion development. For each temperature, coefficients impacting on the ultimate expansion (or expansion and infinity), τ_1 and τ_c were obtained (Table 3.7). It is important to mention that coefficients for different exposure temperatures that are not specified in Table 3.7 may be found by linear interpolation.

Table 3.7. Temperature coefficients.

Temperature	$Kt - \tau_c$	$Kt - \tau_l$	$Kt - \text{exp}$
38	1.00	1.00	1.00
60	0.73	0.41	1.17
80	0.30	0.03	2.13

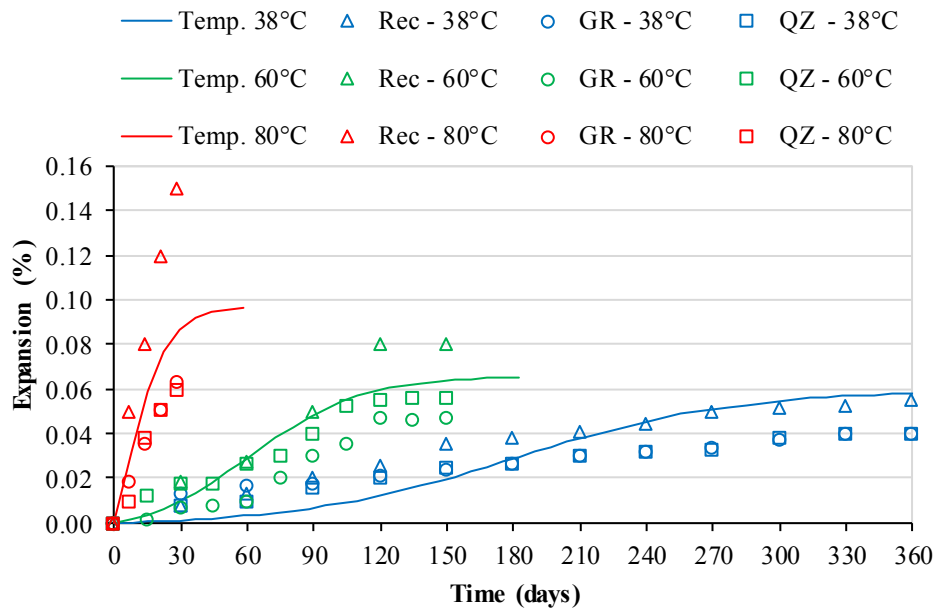


Figure 3.10. Calibration of the proposed Larive's modified model as a function of the temperature.

From Table 3.7 and Figure 3.10, one may notice that the higher the temperature (above and beyond 38°C), the lower the τ_1 and τ_c coefficients, since AAR-kinetics presents a more linear trend at higher temperatures. Conversely, the ultimate expansion increases significantly with the rise in temperature. The τ_1 coefficient values ranged from 1 to 0.03 whereas τ_c coefficient results ranged

from 1 to 0.30. Ultimate expansion coefficients ranged from 1 to 2.13. The variability of the laboratory gathered data and the calculated curves is 1.5%.

3.6.3 Relative humidity

Figure 3.11 displays the calibration of Larive’s model to describe the relative humidity data presented in section 3.5.3 (Figure 3.6). The scattering between measured and calculated data is less than 2% for all families studied. As discussed in (Poyet et al. 2006), the higher the R.H., the faster and the higher AAR-induced development. For each R.H., coefficients impacting on the ultimate expansion (or expansion and infinity), τ_l and τ_c were obtained (Table 3.8). As for the temperature, it is important to mention that coefficients for different R.H. that are within Table 3.8 range may be calculated by linear interpolation. Moreover, it is worth noting that since the results obtained at 100% and 96% R.H. were quite close and also difficult to fully understand (likely being an imprecision during the samples monitoring), all the coefficients (i.e. $K_{rh-\tau_c}$, $K_{rh-\tau_l}$ and K_{rh-exp}) for these two R.H. scenarios were kept as 1.00. Furthermore, analyzing Table 3.8 one sees that lowering R.H. results in decreasing $K_{rh-\tau_c}$ (1.00 down to 0.00) and $K_{rh-\tau_l}$ (1.00 down to 0.75) while raising K_{rh-exp} (1.00 up to 3.00). Finally, as per (Poyet et al. 2006) AAR-kinetics and induced expansion are assumed to be zero for R.H. values lower than 50%.

Table 3.8. R.H. coefficients.

Suggested value							
R.H.	100%	96%	82%	76%	59%	50%	0%
$K_{rh-\tau_c}$	1.00	1.00	0.68	0.62	0.25	0.00	0.00
$K_{rh-\tau_l}$	1.00	1.00	1.41	2.46	0.75	0.75	0.75
K_{rh-exp}	1.00	1.00	1.00	1.00	3.00	3.00	3.00

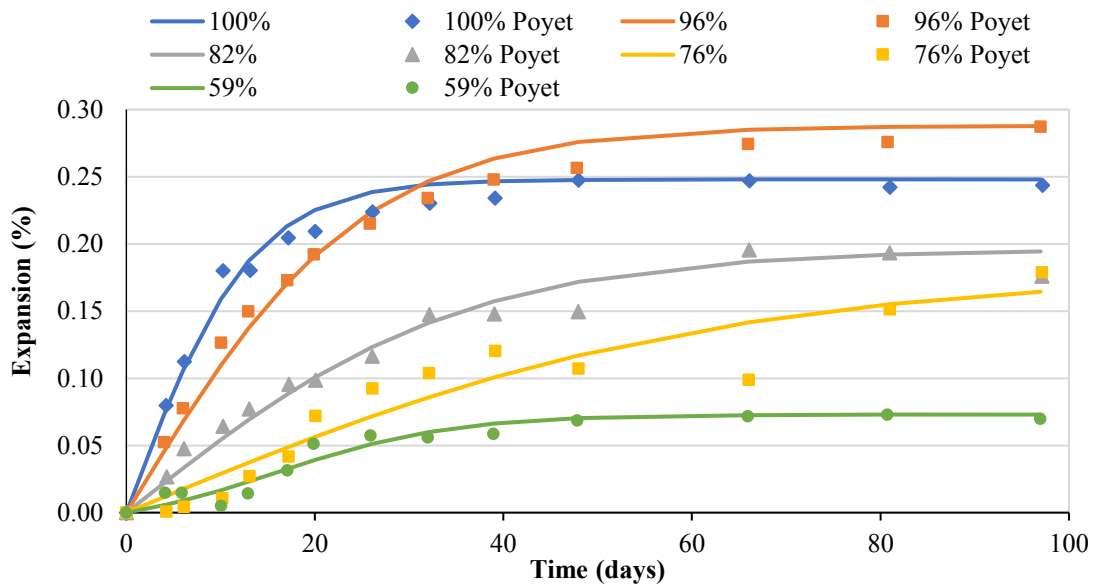


Figure 3.11. Expansion vs time for different R.H. conditions as per Poyet et al. (Poyet et al. 2006) calibrated by Larive's proposed model.

3.6.4 Alkali content

Table 3.9. Alkali content coefficients obtained for marginal/moderate and high/very high reactive aggregates. displays the calibration of Larive's model to describe the influence of the alkali content on AAR-development as presented in section 3.5.4 (Figure 3.7) according to Fournier & Berubé (Fournier and Bérubé 2000). Before discussing the coefficients obtained, it is important to highlight four important points: 1) the range of concrete alkali contents studied varied from 1.95 kg/m³ to 12.4 kg/m³, 2) 4.6 kg/m³ was assumed to be the control alkali content (coefficient equals to 1.00) according to Sanchez et al (Sanchez et al. 2017) and thus higher or lower amounts of alkali would result in higher or lower coefficients, respectively, 3) the concrete alkali content is believed to influence both AAR-kinetics and ultimate expansion. However, due to the lack of literature data, only its impact on the ultimate expansion is accounted for in the proposed model as per (Fournier

and Bérubé 2000) and, 4) according to (Fournier and Bérubé 2000), the impact of the alkalis on AAR-development is not similar for aggregates with different natures/reactivities. Thus, in this work, the alkali coefficients were adopted differently for marginal/moderate reactive aggregates and for high/very high reactive aggregates as per (Fournier and Bérubé 2000) findings. Analyzing Table 3.9 data, one verifies that the higher the alkali content of the mix, the higher the coefficients obtained, as expected. The ultimate expansion coefficients ranged from 0.65 to 4.18 and from 0.22 to 1.49 for marginal/moderate and high/very high reactive aggregates, respectively.

Table 3.9. Alkali content coefficients obtained for marginal/moderate and high/very high reactive aggregates.

Marginal/Moderate		High/Very high	
k (Inf,%A)	Category kg/m³	k (Inf,%A)	Category kg/m³
0.65	1.95	0.22	1.90
0.36	2.75	0.19	2.75
0.47	3.85	0.68	3.80
1.00	4.60	1.00	4.60
1.13	5.25	1.27	5.25
3.51	9.05	1.43	9.05
4.18	12.00	1.49	12.00

3.6.5 Modified Larive’s equation for predicting AAR-kinetics in the laboratory and its use for field assessments

After evaluating the impact of the five parameters studied in this research (i.e. aggregate’s type and nature/reactivity, temperature, alkali content and relative humidity) on AAR-kinetics and

induced expansion, one proposes the use of a modified Larive's model, as presented hereafter (Eq. 3.6).

$$\varepsilon(t, \theta) = \xi(t)\varepsilon^\infty = \frac{1 - e^{-\frac{t}{\tau_c k_{c,T} k_{c,RH} k_{c,E}}}}{1 + e^{-\frac{(t - \tau_l k_{L,T} k_{L,RH} k_{L,E})}{\tau_c k_{c,T} k_{c,RH} k_{c,E}}}} \times (k_{Inf,T} k_{Inf,RH} k_{Inf,E} k_{Inf,\%A}) \varepsilon^\infty \quad \text{Eq. 3.6}$$

Where:

- t is elapsed time;
- $\varepsilon(t)$ is the expansion at a given elapsed time;
- ε^∞ is the maximum expansion at infinity (or ultimate expansion);
- τ_c is the characteristic time (as a function of the aggregates type and nature/reactivity);
- τ_l is the latency time (as a function of the aggregates type and nature/reactivity);
- $k_{c,T}, k_{c,RH}, k_{c,E}$ is the temperature, humidity and exposure coefficients impacting on the characteristic time;
- $k_{L,T}, k_{L,RH}, k_{L,E}$ is the temperature, humidity and exposure coefficients impacting on the latency time;
- $k_{inf,T}, k_{inf,RH}, k_{inf,E}, k_{inf,\%A}$ is the temperature, humidity, exposure and alkali content coefficients influencing on the maximum expansion;

As one may see above, most of the coefficients obtained in this work are seen to influence on both AAR-kinetics and final expansion and thus they impact directly on the latency (τ_l) and characteristic (τ_c) times as well as on AAR-ultimate expansion (ε_∞ , or expansion at the infinity).

The only exception is the alkali content, which as previously stated only interferes on AAR-final expansion. The interest of using of Eq.3.6 instead of the conventional Larive's model is that the proposed approach makes possible the prediction of AAR-kinetics and unrestrained induced expansion in the laboratory for a wide range of materials and exposure conditions without the need of further laboratory tests, calibration or fitting. Therefore, knowing the aggregate type and

nature/reactivity (i.e. lithotype) to be evaluated and the conditions of the test (alkalis, temperature, R.H., etc.), the proposed model may predict the expansion behaviour over time quite accurately. Conversely, it is still premature (although promising) to think on using the proposed model “as is” to forecast the behaviour of AAR-affected concrete structures in the field; preliminary and interesting results were obtained by Gorga et al. (Gorga et al. 2018) while assessing slender reinforced concrete structures affected by AAR. Yet, an in-depth analysis on some of the most important parameters other than the ones accounted for in Eq. 3.6 such as alkalis leaching, exposure conditions and differences in temperature (laboratory vs field) should still be performed prior to its current use to assess field structures. The “exposure degree” for example, is deemed to be a very important parameter impacting on AAR-induced development (both kinetics and final expansion) in the field. A coefficient named $k_{C,E}$ and $k_{L,E}$, meaning “exposure degree” was already inserted in the above equation and for laboratory cases may be always kept as 1.00. However, according to Gorga et al (Gorga et al. 2018) a proper selection of this coefficient is a key parameter while assessing AAR-affected concrete structures in the field.

3.6.6 Calibrating time periods of test procedures in the laboratory

Another interesting point to be discussed while the development of the modified Larive’s model is the calibration of test periods for accelerated test procedures in the laboratory. Over the past decades, several approaches and recommendations, including a variety of accelerated laboratory procedures have been developed to assess the potential reactivity of aggregates in the laboratory. Amongst those, the concrete prism test (CPT as per ASTM C 1293 (ASTM 2018)) performed at 38°C and 100% R.H is considered nowadays the most important and reliable test method to assess the reactivity of aggregates in the laboratory. Yet, this test is considered to be quite time-consuming (one year), which always brings some criticism from the industry. In this context,

accelerated test procedures performed at 60°C and 80°C have been proposed worldwide; some of them have been standardized in numerous countries and technical communities (e.g. France, RILEM, etc.), especially the test procedure at 60°C, the so-called accelerated concrete prism test (ACPT). An important drawback from the ACPT is the amount of alkalis leaching over the test. Yet, the ACPT has been considered to be a reliable approach to distinguish reactive vs innocuous aggregates in the laboratory after 4 to 6 months (Sanchez et al. 2008; Sanchez 2008). Nonetheless, the ACPT time period is still a matter of some disagreement on the AAR community. Conversely, the 80°C procedure has been more criticized in the past decades. This test method is considered to be less realistic than 38°C and 60°C since a temperature of 80°C may destabilize ettringite and thus release sulphates to the system, which in turn may decrease the pH of the material. In any case, it has been found that this method might be able to detect the reactive behaviour of aggregates in the laboratory within 30 to 60 days. However, no standards nor time periods have been established so far.

All of the aforementioned discussion about temperature and time periods of accelerated procedures in the laboratory may be at least partially solved through the use of the proposed modified Larive's model. Using the new equation, one may understand what's the period required for each test procedure to provide similar specimens with the same reactivity level at distinct exposure conditions. To illustrate this discussion, Figure 3.12 gives a plot of concrete prism tests performed at 38°C, 60°C and 80°C with the same mix-design and reactive aggregate (Rec 1, Table 3.1). Looking at the plot, one observes interesting points as follows: 1) all curves obtained from the proposed modified Larive's model have shown very low scattering from the measured data gathered in the laboratory as per (Sanchez et al. 2017); i.e. 5.45%, 1.25% and 2% for tests at 38°C, 60°C and 80°C, respectively, which demonstrates the reliability of the proposed approach, 2) the

ultimate expansion reached by the concrete specimens incorporating Rec 1 aggregate at 38°C is 0.058% at 1 year (point C), whereas the same expansion level is reached at 88 days (point H) and 10 days (point G) at 60°C and 80°C procedures, respectively, 3) if one considers the CPT criterion to distinguish reactive vs innocuous aggregates as per ASTM C 1293 or CSA standards (i.e. 0.04%) at 38°C, this expansion was reached at 227 days (point F), 66 days (point E) and 8 days (point D), for testing at 38°C, 60°C and 80°C, respectively and, 4) in the three expansion scenarios, expansion plateaus were obtained at distinct periods (i.e. 360 days (point C), ≈150 days (point B) and ≈60 days (point A) for 38°C, 60°C and 80°C, respectively).

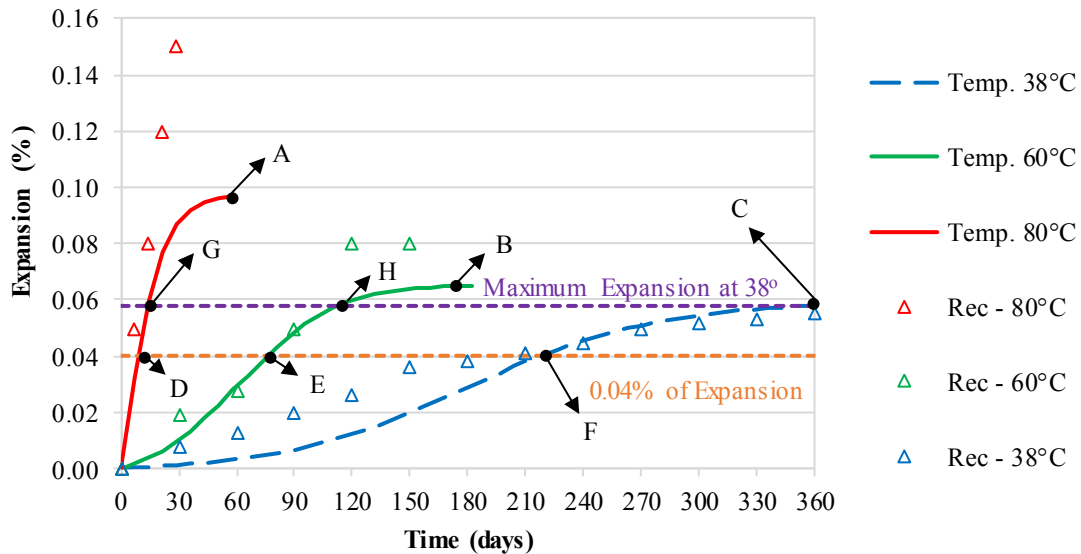


Figure 3.12. Expansion plots obtained from concrete incorporating the same aggregate (i.e. Rec 1) for distinct exposure conditions: A, B and C are the initial plateau points for the curves; D, E and F are the 0.04% expansion points and; G and H are the time required for concrete specimens at 60 °C and 80 °C to reach the same ultimate expansion obtained at 38°C.

With the preliminary discussion on Figure 3.12 for a single type of aggregate (Rec 1), Table 3.1 displays data obtained from the modified Larive’s model for all temperatures (i.e. 38°C, 60°C and

80°C) and aggregate reactivities (i.e. marginal, moderate, high and very high) evaluated in this work. Analyzing data from Table 3.10, one verifies that similar concrete mixtures have the potential to reach at approximately 4 months and 60°C (i.e. less than 135 days) and 1 month and 80°C (i.e. less than 27 days) similar expansions obtained at one year and 38°C for all the reactivity degrees studied in this research. Moreover, all the reactivity degrees showed to present levelling off trends (plateaus) within reasonable time periods (i.e. less than 365 days for 60°C and less than 240 days for 80°C), which seems to indicate reasonable trends for expansion curves captured at higher temperatures. Finally, whenever the ultimate expansion is not targeted and only the reactivity of the aggregate is searched (i.e. 0.04% threshold), the test period for higher temperatures may be even lessened (\approx 3 months and 2 weeks respectively at 60°C and 80°C procedures). The prior results highlight the potential of decreasing significantly the CPT time period whether higher temperatures are implemented and thus to faster classify the potential reactivity of aggregates in the laboratory.

Table 3.10. Time periods required from similar concrete mixtures made of aggregates with distinct reactivities and evaluated at distinct exposure conditions (38°C, 60°C and 80°C) to present the same expansion level.

		Time (days) exp = 0.04%		Time (days) to reach final exp. at 38°C		Time (days) Plateau		Final Exp Plateau	
		C.A.	F.A.	C.A.	F.A.	C.A.	F.A.	C.A.	F.A.
38° C	marginal	291	-	350	-	350	-	0.058	-
	moderat	95	-	328	-	328	-	0.163	-
	e	19	84	358	365	358	365	0.263	0.264
	high	-	8	-	365	-	365	-	0.888
60° C	very-high	91	-	135	-	175	-	0.066	-
	marginal	32	-	109	-	212	-	0.192	-
	moderat	12	24	109	107	321	226	0.310	0.310
	e	-	5	-	154	-	365	-	1.075
80° C	high	11	-	17	-	58	-	0.121	-
	very-high	3	-	13	-	88	-	0.349	-
	marginal	3	2	19	12	160	95	0.563	0.563
	moderat	-	1	-	27	-	240	-	1.969

3.7 Conclusions

In this research, a modified Larive's equation is proposed based on an extensive laboratory test campaign along with data gathered from the literature. The main findings of the current study are presented hereafter:

- The proposed approach relies on five of the most important parameters affecting AAR-kinetics and induced expansion such as the aggregates' type (coarse vs fine) and nature/reactivity, the alkali

content of the concrete, the temperature and relative humidity of the environment. First, the impact of each of the above parameters on AAR-kinetics and ultimate expansion is gathered; then, coefficients are attributed to each of them according to their influence on the physicochemical reaction;

- The new model showed to be quite accurate to describe AAR-kinetics and final expansion in the laboratory for a wide range of aggregates, concrete mixtures and exposure conditions. Scattering between the model and gathered data in the laboratory (or literature) as low as 5% was obtained, which proves its efficiency;
- The interest of using the proposed approach instead of the conventional Larive's equation is that the modified model makes possible the prediction of AAR-kinetics and induced expansion in the laboratory for a large variety of materials and exposure conditions without the need of further laboratory tests, calibration or fitting;
- The use of the proposed model may help to set time periods for accelerated test procedures performed in the laboratory at distinct exposure conditions to assess the potential reactivity of aggregates. It has been found that 60°C and 80°C procedures may lessen the required test periods in about 75% and 92%, respectively when compared to the conventional 38°C test;
- It is still premature (although promising results were found as per Gorga et al (Gorga et al. 2018)) to think on using the current version of the proposed modified model to appraise AAR-affected concrete structures in the field. Further analyses should still be performed in this regard.

3.8 Acknowledgments

The authors gratefully acknowledge the financial support received from the Ontario Centre of Excellence (OCE) in partnership with GHD.

3.9 References

- ASTM. (2018). “C1293 - Standard Test Method for Determination of Length Change of Concrete Due to AlkaliSilica Reaction.”
- ASTM C1260. (2016). “Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method).” *American Society for Testing and Materials*, 1–5.
- Bangert, F., Kuhl, D., and Meschke, G. (2004). “Chemo-hygro-mechanical modelling and numerical simulation of concrete deterioration caused by alkali-silica reaction.” *International Journal for Numerical and Analytical Methods in Geomechanics*, 28(7–8), 689–714.
- Bazant, Z. P., and Steffens, A. (2000). “Mathematical model for kinetics of alkali-silica reaction in concrete.” *Cement and Concrete Research*, 30(3), 419–428.
- Benoit Fourniera et al. (2004). “the Accelerated Concrete Prism Test (60 ° C): Variability.” *12th International Conference on Alkali–Aggregate Reaction in Concrete, International Academic Publishers—World Publishing Corporation, Beijing, China*, (December 2014).
- Bérubé, M.-A., Durand, B., Vézina, D., and Fournier, B. (2011). “Alkali-aggregate reactivity in Québec (Canada).” *Canadian Journal of Civil Engineering*, 27(2), 226–245.
- Brunetaud, X. (2005). “Étude de l’influence de différents paramètres et de leurs interactions sur la cinétique de l’amplitude de la réaction sulfatique interne au béton.” Châtenay-Malabry, Ecole centrale de Paris.
- Capra, B., and Bournazel, J.-P. (1998). “Modeling of induced mechanical effects of alkali-aggregate reactions.” *Cement and Concrete Research*, Elsevier, 28(2), 251–260.
- Charpin, L., and Ehrlacher, A. (2012). “A computational linear elastic fracture mechanics-based

- model for alkali – silica reaction.” *Cement and Concrete Research*, Elsevier Ltd, 42(4), 613–625.
- Comby-peyrot, I., Bernard, F., Bouchard, P., Bay, F., and Garcia-diaz, E. (2009). “Development and validation of a 3D computational tool to describe concrete behaviour at mesoscale . Application to the alkali-silica reaction.” *Computational Materials Science*, Elsevier B.V., 46(4), 1163–1177.
- Comi, C., Fedele, R., and Perego, U. (2009). “A chemo-thermo-damage model for the analysis of concrete dams affected by alkali-silica reaction.” *Mechanics of Materials*, Elsevier Ltd, 41(3), 210–230.
- Comi, C., Kirchmayr, B., and Pignatelli, R. (2012). “Two-phase damage modeling of concrete affected by alkali-silica reaction under variable temperature and humidity conditions.” *International Journal of Solids and Structures*, Elsevier Ltd, 49(23–24), 3367–3380.
- CSA. (2014). *Concrete materials and methods of concrete construction/methods of test and standard practices for concrete. Toronto (Ontario, Canada). Csa a23.1/23.2.*
- Cwirzen, A., and Penttala, V. (2005). “Aggregate–cement paste transition zone properties affecting the salt–frost damage of high-performance concretes.” *Cement and Concrete Research*, 35(4), 671–679.
- Dunant, C. F., and Scrivener, K. L. (2010). “Micro-mechanical modelling of alkali-silica-reaction-induced degradation using the AMIE framework.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 517–525.
- Esposito, R., and Hendriks, M. A. N. (2017). “Literature review of modelling approaches for ASR

- in concrete : a new perspective.” *European Journal of Environmental and Civil Engineering*, Taylor & Francis, 8189(December), 1–21.
- Farage, M. C. R., Alves, J. L. D., and Fairbairn, E. M. R. (2004). “Macroscopic model of concrete subjected to alkali-aggregate reaction.” *Cement and Concrete Research*, 34(3), 495–505.
- Fecteau, P. L., Fournier, B., Choquette, M., and Duchesne, J. (2012). “Contribution to the understanding of the so-called alkali--carbonate reaction (ACR), 14th ICAAR International Conference on Alkali--Aggregate Reaction in Concrete.” May.
- Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier, R. (2004). “Comparative Field and Laboratory Investigations on the Use of Supplementary Cementing Materials to Control Alkali-Silica Reaction in Concrete.” *Proceedings of the 12th International Conference on Alkali-Aggregate Reaction (ICAAR)*, 1, 528--537.
- Fournier, B., and Bérubé, M.-A. (2000). “Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications.” *Canadian Journal of Civil Engineering*, 27(2), 167–191.
- Franz-Josef Ulm et al. (2000). “THERMO-CHEMO-MECHANICS OF ASR EXPANSION IN CONCRETE STRUCTURES.” *Journal of Engineering Mechanics*, (March), 233–242.
- Gorga, R. V., Sanchez, L. F. M., and Martín-Pérez, B. (2018). “FE approach to perform the condition assessment of a concrete overpass damaged by ASR after 50 years in service.” *Engineering Structures*, Elsevier, 177(June), 133–146.
- Grimai, E., Sellier, A., Pape, Y. Le, and Bourdarot, E. (2008). “Creep, shrinkage, and anisotropic damage in alkali-aggregate reaction swelling Mechanism-Part II: Identification of model

parameters and application.” *ACI Materials Journal*, v 105, n 3(105), p 236-242.

Grimal, E., Sellier, A., Multon, S., Le Pape, Y., and Bourdarot, E. (2010). “Concrete modelling for expertise of structures affected by alkali aggregate reaction.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 502–507.

Katayama, T. (2010). “The so-called alkali-carbonate reaction (ACR) - Its mineralogical and geochemical details, with special reference to ASR.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 643–675.

Katayama, T., and Grattan-Bellew, P. E. (2012). “Petrography of the Kingston experimental sidewalk at age 22 years--ASR as the cause of deleteriously expansive, so-called alkali-carbonate reaction.” *Proceedings of the 14th international conference on alkali-aggregate reaction in concrete. Austin, Texas, USA*, 10.

Kawabata, Y., Martin, R.-P., Seignol, J.-F., and Toutlemonde, F. (2016). “Modelling of Evolution of Transfer Properties Due To Expansion of Concrete Induced By Internal Swelling Reaction.” *ICAAR 2016 - 15th international conference on alkali aggregate reaction*.

Kurihara & Katawaki. (1989). “Effects of moisture control and inhibition on alkali silica reaction.” *kyoto, Japan*, 629–634.

Larive, C. (1997). “Combined contribution of experiments and modelling to the understanding of alkali-aggregate reaction and its mechanical consequences (PhD thesis; in: French).”

Li, K., and Coussy, O. (2002). “Concrete ASR degradation : from material modeling to structure assessment.” *Concrete Science and Engineering*, 4(March), 35–46.

Lindgård, J., Andiç-Çakir, Ö., Fernandes, I., Rønning, T. F., and Thomas, M. D. A. (2012).

- “Alkali-silica reactions (ASR): Literature review on parameters influencing laboratory performance testing.” *Cement and Concrete Research*, 42(2), 223–243.
- Lothenbach, B., Winnefeld, F., Alder, C., Wieland, E., and Lunk, P. (2007). “Effect of temperature on the pore solution, microstructure and hydration products of Portland cement pastes.” *Cement and Concrete Research*, 37(4), 483–491.
- Multon, S., Sellier, A., and Cyr, M. (2009). “Chemo – mechanical modeling for prediction of alkali silica reaction (ASR) expansion.” *Cement and Concrete Research*, Elsevier Ltd, 39(6), 490–500.
- Multon, S., and Toutlemonde, F. (2004). “Water distribution in concrete beams.” *Materials" and Structures*, 37(July), 378–386.
- Multon, S., and Toutlemonde, F. (2006). “Effect of applied stresses on alkali-silica reaction-induced expansions.” *Cement and Concrete Research*, 36(5), 912–920.
- Nielsen, A. e. al. (1993). “Development of stresses in concrete structures with alkali-silica reactions.” *Materials and Structures*, 152–158.
- Olafsson, H. (1986). “The effect of relative humidity and temperature on alkali expansion of mortar bars.” *7th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 461–465.
- Owsiak, Z., Zapala-Slaweta, J., and Czapik, P. (2015). “Diagnosis of concrete structures distress due to alkali-aggregate reaction.” *Bulletin of the Polish Academy of Sciences Technical Sciences*, 63(1), 23–29.
- Pesavento, F., Gawin, D., Wyrzykowski, M., Schrefler, B. A., and Simoni, L. (2012). “Modeling alkali-silica reaction in non-isothermal, partially saturated cement based materials.”

- Computer Methods in Applied Mechanics and Engineering*, Elsevier B.V., 225–228, 95–115.
- Poyet et al. (2007). “Chemical modelling of Alkali Silica reaction : Influence of the reactive aggregate size distribution.” 229–239.
- Poyet, S., Sellier, A., Capra, B., Thèvenin-Foray, G., Torrenti, J. M., Tournier-Cognon, H., and Bourdarot, E. (2006). “Influence of Water on Alkali-Silica Reaction: Experimental Study and Numerical Simulations.” *Journal of Materials in Civil Engineering*, 18(August), 588–596.
- Prinčič, T., Štukovnik, P., Pejovnik, S., De Schutter, G., and Bosiljkov, V. B. (2013). “Observations on dedolomitization of carbonate concrete aggregates, implications for ACR and expansion.” *Cement and Concrete Research*, 54, 151–160.
- Rashidi, M., Kim, J. Y., Jacobs, L. J., and Kurtis, K. E. (2016). “Insights into alkali-silica reaction damage in mortar through acoustic nonlinearity.” *AIP Conference Proceedings*, 1706(2016).
- Sanchez, L. (2014). “Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction.” UNIVERSITE LAVAL.
- Sanchez, L. F. M. (2008). “Contribuição ao estudo dos métodos de ensaio na avaliação das reações álcali-agregado em concretos.” Universidade de São Paulo.
- Sanchez, L. F. M., Drimalas, T., Fournier, B., Mitchell, D., and Bastien, J. (2018). “Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms.” *Cement and Concrete Research*, 107(September 2017), 284–303.
- Sanchez, L. F. M., Fournier, B., Jolin, M., and Bastien, J. (2015a). “Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses.” *Construction and Building*

Materials, Elsevier Ltd, 77, 20–32.

Sanchez, L. F. M., Fournier, B., Jolin, M., and Duchesne, J. (2015b). “Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI).” *Cement and Concrete Research*, Elsevier Ltd, 67, 74–92.

Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., and Bastien, J. (2017). “Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures.” *Cement and Concrete Research*, Elsevier Ltd, 93, 17–31.

Sanchez, L. F. M., Multon, S., Sellier, A., Cyr, M., Fournier, B., and Jolin, M. (2014). “Comparative study of a chemo-mechanical modeling for alkali silica reaction (ASR) with experimental evidences.” *Construction and Building Materials*, Elsevier Ltd, 72, 301–315.

Sanchez, L., Kuperman, S. C., and Helene, P. (2011). “Using the accelerated Brazilian concrete prism test (ABCPT) to evaluate alkali aggregate reaction (AAR).” *Ibracon Structures and Materials Journal*, 4, 575–581.

Sanchez, L., Kuperman, S., and Helene, P. (2008). “Trials To Correlate the Accelerated Mortar Bar Test , the Standard and the Accelerated Concrete.” *13th International Conference on Alkali Aggregate Reaction (ICAAR)*, Trondheim, Norway.

Saouma, V. E., Martin, R. A., Hariri-Ardebili, M. A., and Katayama, T. (2015). “A mathematical model for the kinetics of the alkali-silica chemical reaction.” *Cement and Concrete Research*, Elsevier Ltd, 68, 184–195.

Saouma, V., and Perotti, L. (2006). “Constitutive model for alkali-aggregate reactions.” *ACI*

Materials Journal, 103(3), 194–202.

Schmidt et al. (2009). “AKR-Performance-Prüfung von flugaschehaltigen Betonen – Einfluss der Temperatur auf die Porenlösung und Möglichkeiten zur zielsicheren Bewertung.” 17. *Internationale Baustofftagung, ibausil, F. A. Finger-Institut für Baustoffkunde, Bauhaus Universität Weimar, 23.-26. September 2009*. In: *Tagungsbericht*, S. 2 0267 2 0276.

Suwito, A., Jin, W., Xi, Y., and Meyer, C. (2002). “A Mathematical Model for the Pessimism Size Effect of ASR in Concrete.” *Concrete Science and Engineering*, 1–31.

Urhan, S. (1987). “Alkali silica and pozzolanic reactions in concrete. Part 1: Interpretation of published results and an hypothesis concerning the mechanism.” *Cement and Concrete Research*, 17(c), 141–152.

Vivian, H. E. (1981). “The effect of drying on reactive aggregate and mortar expansions.” *Proc., 5th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 228–252.

Winnicki, A., and Pietruszczak, S. (2008). “On Mechanical Degradation of Reinforced Concrete Affected by Alkali-Silica Reaction.” *Journal of Engineering Mechanics*, 134(8), 611–627.

Chapter 4 Analytical Modelling to Describe Alkali-Aggregate Reaction

Induced Expansion in the Field

Goshayeshi, N.^a; Sanchez, L. F. M.^b; Santos, A. C.^c; Gorga, R.^d

(a) MSc Candidate – University of Ottawa

(b) Assistant Professor – University of Ottawa

(c) Associate Professor – University of Uberlandia

(d) MSc – University of Ottawa

Abstract

Alkali aggregate reaction (AAR) is one of the most harmful distress mechanisms affecting the durability of aging concrete structures worldwide. Currently, there is a need to forecast the future behaviour of AAR-affected concrete and thus analytical and numerical models have been developed over the years. Larive developed an analytical model able to describe the behaviour of concrete specimens in the laboratory. This model has been widely accepted and used by the AAR community, even to predict the behaviour of concrete structures in the field. Larive's model is based upon three main parameters, and although they are normally set according to the given concrete mixture/structure under analysis, there is currently a lack of understanding on the variation of those parameters as a function of the initial potential reactivity of the material. This work aims to calibrate Larive's equation according to the aggregates type and reactivity so that predictions may be performed based on the reactive potential of the mix. First, a comprehensive laboratory testing campaign using a variety of concrete strengths and aggregate types is conducted. Second, Larive's model is matched with laboratory data and a discussion on the main parameters of the equation is performed. Finally, the model is used to appraise the expansive behaviour of

blocks containing the same mix-design and reactive aggregates exposed outdoors in Ottawa, Canada.

Keywords: Alkali-aggregate reaction (AAR), Analytical model, Forecasting AAR-induced expansion, Aggregate type and reactivity.

4.1 Introduction

Alkali aggregate reaction (AAR) is a chemical reaction between some unstable silica mineral forms found within fine and coarse aggregates used to make concrete and the alkali hydroxides (Na, K – OH) from the concrete pore solution (Sanchez et al. 2015a). This reaction generates a gel that swells upon water uptake from the surroundings, leading to volumetric expansion and damage. AAR is one of the most harmful distress mechanisms affecting the performance (i.e. durability and serviceability) of aging concrete structures worldwide (Pesavento et al. 2012). AAR can be divided in two distinct mechanisms: alkali-silica reaction (ASR) and alkali-carbonate reaction; ASR being by far the most common mechanism found around the globe.

Various factors may affect AAR-induced expansion and damage such as the alkali loading, the reactivity of the aggregates, environmental conditions such as temperature, humidity, exposure, etc. (Sanchez et al. 2015b). Forecasting AAR-induced expansion and damage along with its consequences is extremely challenging. A number of analytical and numerical models have been developed over the years and amongst those, Larive's model (Larive 1997) is widely accepted by the AAR community (Cwirzen and Penttala 2005; Esposito and Hendriks 2017; Larive 1997; Saouma and Perotti 2006). It was developed to describe the behaviour of concrete specimens in the laboratory but has been used even to forecast the behaviour of concrete structures in the field. Larive's model is based upon three main parameters: latency and characteristic time and expansion at infinity, and although they have been set according to the given concrete mixture/structure under

analysis, there is currently a lack of understanding on the range of those parameters as a function of the reactive potential of a given concrete mix (Larive 1997).

4.2 Literature review

Larive (Larive 1997) developed an analytical model to describe the reactive behaviour of AAR affected concrete specimens in the laboratory. Larive worked with over 600 specimens that were subjected to a wide range of environmental and mechanical conditions. Larive's research program focused on the influence of temperature, relative humidity and stress-state on AAR reaction kinetics and development (Winnicki and Pietruszczak 2008). In Larive's model, AAR kinetics is assumed to be a function of the latency (τ_l) and characteristic (τ_c) times for a given time and an independent stress-state (Figure 4.1). This model describes a nonlinear time-dependent AAR swelling behavior (normally an S-shape curve) as a function of the final expansion level (i.e. expansion expected to happen at infinity; i.e. $t=\infty$), as presented hereafter (Larive 1997):

$$\varepsilon(t, \theta) = \frac{1 - e^{-\frac{t}{\tau_c(\theta)}}}{1 + e^{-\frac{(t-\tau_l(\theta))}{\tau_c(\theta)}}} \times \varepsilon^\infty \quad \text{Eq. 4.1}$$

Where θ is the absolute temperature, τ_c , τ_l are the characteristic and latency time, respectively, and ε^∞ is the maximum expansion at infinity (Saouma and Perotti 2006). The S-shape curve proposed by Larive's model may be divided into four categories. First, there is a period of AAR gel formation and accommodation within the aggregate particles where almost no expansion is generated. Second, AAR-gel uptakes water and the swelling process starts with almost no cracking formation (up to the inflexion point). Third, cracks are formed within the aggregate particles and surrounding cement paste which makes the expansion rate to decrease over time. Finally, either all

of the alkalis or silica (or both) is consumed (which normally happens due to the presence of leaching in laboratory test procedures) which causes a levelling off trend of AAR expansion.

4.3 Scope of the work

Larive's model was primarily developed to describe the behaviour of reactive concrete mixtures in the laboratory. Although very interesting and widely accepted by the AAR community, this model does not account for some of the most important physicochemical parameters that influence the chemical reaction such as aggregates type (fine vs coarse), reactivity (low, moderate, high and very high), alkali loading, temperature and relative humidity. This work aims to incorporate two of the prior mentioned parameters (i.e. aggregate type and reactivity) to Larive's initial equation. Therefore, the main parameters of Larive's model (τ_l and τ_c) will be calibrated according to the aggregate's type and reactivity of mixtures incorporating a wide range of reactive aggregates and presenting distinct mechanical properties, so that one may predict AAR expansive behaviour in the laboratory when the aggregate used in the mix is known. At the end, the model will be applied to forecast the behaviour of blocks exposed outdoors presenting the same aggregates and mix-design as the ones assessed in the laboratory.

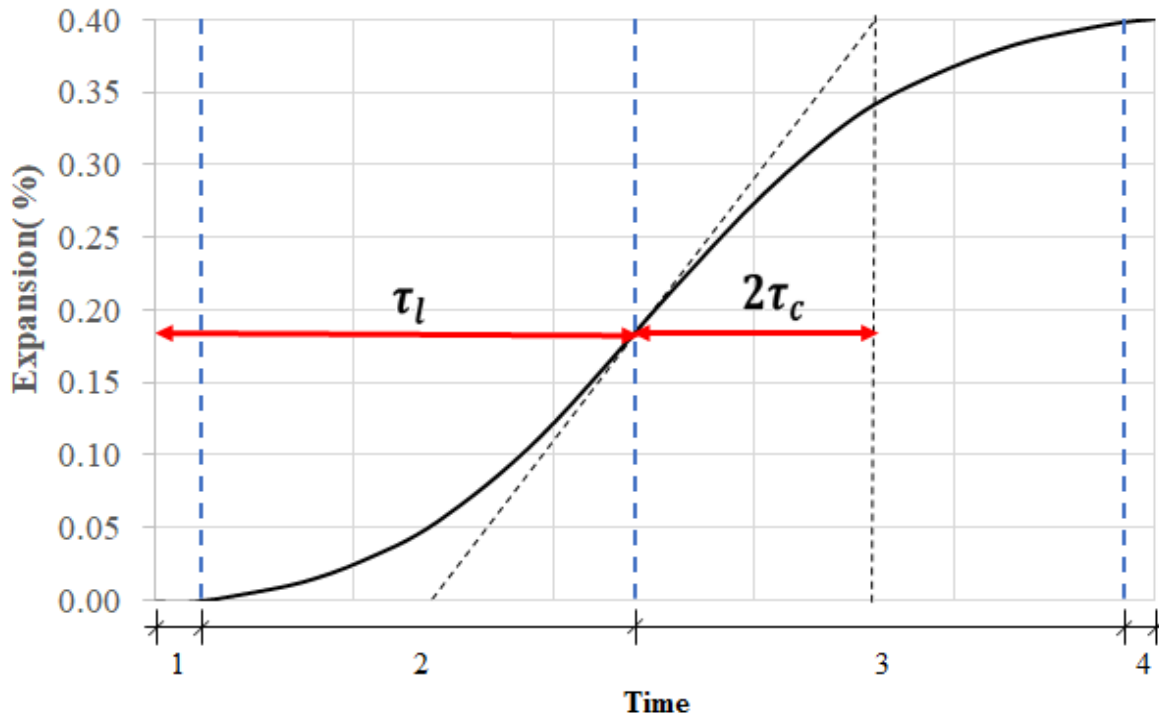


Figure 4.1 S-shape AAR-induced expansion plot (Larive 1997).

4.4 Materials and methods

A number of concrete mixtures incorporating a wide range of reactive aggregates and presenting distinct mechanical properties (i.e. 25, 35, and 45 MPa) were selected for this research as per (Sanchez et al. 2017) and illustrated in Table 4.1. The size of coarse aggregates used ranged from 5 to 20 mm. Non-reactive coarse and fine aggregates were used in combination with the reactive materials for concrete manufacturing. Third-five specimens from each of the concrete mixtures were fabricated and stored at the moist-curing room for 48 h. Afterwards, the zero-length reading was taken, and all the samples were then placed in sealed buckets (4 specimens per bucket) and stored at 38°C and 100% R.H. All the specimens were regularly monitored over time until they had their expansion levels stabilized (i.e. three consecutive measurements with no further

expansion). They were then classified in terms of reactivity according to (Sanchez et al. 2017) and highlighted in Table 4.2.

Following the experimental tests and results, all the data acquired in the laboratory was used to calibrate Larive’s model so that various latency and characteristic times for the different aggregate types and reactivity levels could be obtained. Finally, the latency and characteristic times gathered from the laboratory results were used to evaluate the behaviour of concrete blocks fabricated using similar aggregates and concrete mixtures and exposed outdoors in Ottawa, Canada (Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier 2004). Table 4.3 shows the two different blocks selected to be used in this research and their respective expansion levels after 10 and 15 years of exposure.

Table 4.1 Aggregates used in this research. U = USA, C = CANADA, B = Brazil

	Aggregate	Reactivity	Location	Rock type	Specific gravity	Absorptio n	AMBT* 14-day exp (%)
Coarse	K**	R	Kingston (C)	Dolomitic argillaceous limestone	2.69	0.55	0.110
	NM	R	New Mexico (U)	Polymictic Gravel (Mixed Volcanic, quartzite, chert)	2.53	1.59	1.056
	QC	R	Quebec (C)	Siliceous and argillaceous limestone	2.50	1.16	0.302
	Wyo	R	Wyoming	Granite, amphibolite, mixed volcanic	2.64	0.87	0.296
	Conor	R	Halifax (C)	Metagreywacke, shale, siltstone	2.72	0.37	0.365
	Virg	R	Virginia (U)	Metagranite	2.78	0.45	0.090
	Rec	R	Recife (B)	Granite, gneiss, mylonite	2.64	0.59	0.230
	Pots	R	Montreal (C)	Siliceous sandstone (orthoquartzite)	2.57	1.15	0.093
	Dia	NR	Quebec (C)	Diabase (plutonic rock)	3.00	0.51	0.065
	Hp	NR	Newfoundland (C)	High-purity fine-grained limestone	2.68	0.44	0.001
Fine	Tx	R	Corpus Christi (U)	Polymictic sand (granitic, mixed volcanic, quartzite, chert, quartz)	2.60	0.55	0.755
	Wt	R	Texas (U)	Polymictic sand (chert, quartz, feldspar)	2.60	0.4	0.335
	Lav	NR	Quebec (C)	Natural derived from Granite	2.71	0.54	0.068

*AMBT: Accelerated Mortar Bar Test

** Material susceptible to alkali-carbonate reaction (ACR)

Table 4.2 Classification of the AAR-induced damage degree as per (Sanchez 2014).

ASR damage degree	Reference expansion level (%)
Negligible	0.00 - 0.03
Marginal	0.04 ± 0.01
Moderate	0.11 ± 0.01
High	0.20 ± 0.01
Very high	0.30 ± 0.01

Table 4.3 Aggregates used to fabricate the concrete blocks as per (Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier 2004).

Type	ID	Reactivity level	Origin	Rock type
coarse	Sp	High	Canada	Siliceous Limestone
coarse	Pots	High	Canada	Siliceous Sandstone

4.5 Results

Figure 4.2 shows the calibration of Larive's expansion curves over time to match the results gathered through the concrete prism test (CPT – 38°C and 100% R.H) in the laboratory for all the mixtures studied in this research. As one may notice, the expansive behaviour of the distinct mixes may be classified into three categories: ACR reactive aggregate presenting the fastest expansion kinetics and level; ASR reactive fine aggregates showing a slightly lower reaction kinetics and expansion level when compared to the ACR reactive aggregate and; ASR reactive coarse aggregates which present a much slower reaction kinetics and level when compared to the previous discussed mixtures. Table 4.4 displays the latency and characteristic times obtained for these three categories.

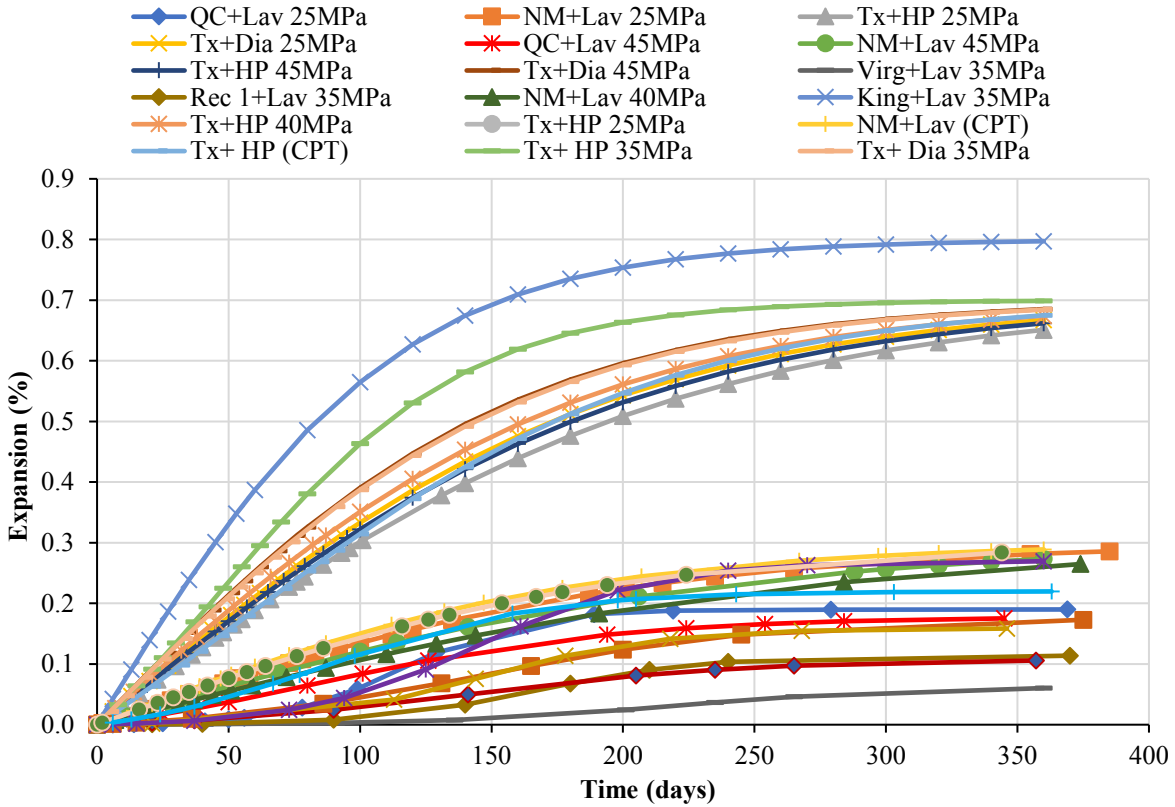


Figure 4.2 Expansion vs time for various concrete mixtures and aggregate types and natures.

Table 4.4 Latency and characteristic times for the different categories of expansion.

AAR mechanism	Damage degree	τ_c	τ_l	Ultimate expansion at infinity (%)
ACR-Reactive coarse	Very High	57	0.00	0.80
ASR-Reactive fine	High	34	146.00	0.20
	Vey High	93	0.00	0.70
ASR-Reactive coarse	Marginal	49	181	0.04
	Moderate	39	143	0.11
	High	41	87	0.22
	Vey High	108	0.00	0.3

4.6 Discussion

In this section, the results previously gathered in the calibration of Larive's model will be further discussed and an evaluation of their capacity to appraise blocks exposed to the environment over 15 years will be performed.

In order to assess concrete materials/structural members in service, AAR-accelerated laboratory test procedures need to “represent” the reactive behaviour of a given mix in the field throughout its service life. It is widely known that the latter is unfortunately not necessarily true and thus the correlation “laboratory vs field” is currently a very important topic for the AAR community. Otherwise, it has been found that the concrete prism test (CPT), performed at 38°C and 100% R.H., is the test procedure that most resembles field conditions and thus, although not perfect, might be used as benchmark for the reactive potential of a given mix in the field, especially when mitigation products such as supplementary cementing materials (SCMs) are not used in the concrete mixture. Therefore, in this work it is assumed for the sake of analysis that the 1-year CPT result represents the potential reactivity of a given concrete mixture in the field throughout its service life (i.e. ≈ 50 years). It is worth noting that potential reactivity does not directly mean expansion attained to date but rather the likelihood of the expansion level over time of a given mix whether proper conditions are provided to AAR development.

4.6.1 AAR kinetics and development

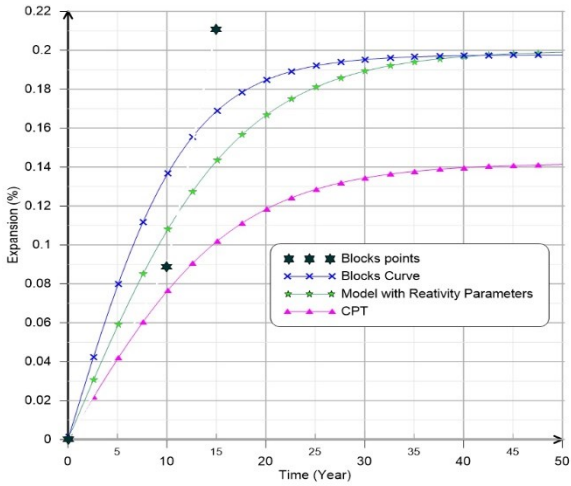
From Figure 4.2 and Table 4.4 one may notice that the faster AAR kinetics, the lower τ_l , which may be sometimes zero for fast kinetics mechanisms such as ACR along with ASR fine and coarse with very high damage degree. The latter physically means that there is almost no accommodation of the reaction products and thus the swelling process starts right away from the beginning. Moreover, the values of τ_c for fast kinetics mechanisms are significantly higher than the slower

reactive mechanisms and mixtures, which means that they are not only faster but also present a higher expansive behaviour (i.e. expansion amplitude) at infinity. The τ_l values ranged from 0 to 181 whereas the τ_c results ranged from 34 to 108.

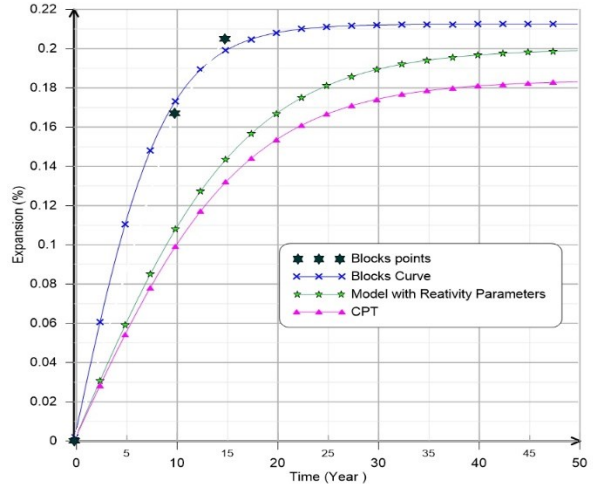
4.6.2 Comparison with blocks exposed outdoors

Fournier et al (Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier 2004) fabricated unreinforced concrete blocks (i.e. 400 by 400 by 700 mm), incorporating a wide range of reactive aggregates and mix-designed as per ASTM 1293 (concrete prism test mix – CPT). These blocks were then stored outdoors in Ottawa (Canada and have been exposed to Canadian climatic conditions and monitored over 15 years. In this work, two reactive aggregates (Sp, very similar lithotype and reactivity to QC and Pots – Table 4.1) with known behaviour in the laboratory and monitored in the field at 10 and 15 years were selected for further analysis and comparison. Figure 4.3 illustrates two expansion curves plotted for respectively Pots (Figure 4.3a) and Sp (Figure 4.3b) aggregates. First, Larive's equation was used to best fit the blocks measurements taken at 10 and 15 years (blue curve). Second, the concrete prism test (CPT) was performed in the laboratory presenting the same aggregates and mix-design as the ones used in the blocks (pink curve). Third, modified Larive's model in the previous chapter was used and the τ_l and τ_c parameters obtained in Table 4.4 were selected accounting for the aggregates type and reactivity to forecast the behaviour of the blocks made with similar aggregates in the field. The values adopted for τ_l and τ_c were 41 & 87 and 39 & 143 for Sp and Pots, respectively and assumed all alkali content, humidity and temperature coefficients as a reference number which is one.. Comparing the results in the plots, one verifies that the blocks expansive behaviour seems to be much higher than the results obtained in the CPT. The latter is very likely due to imperfections in the CPT test procedure such as leaching, which may take place due to the small size of the samples used in the test (i.e.

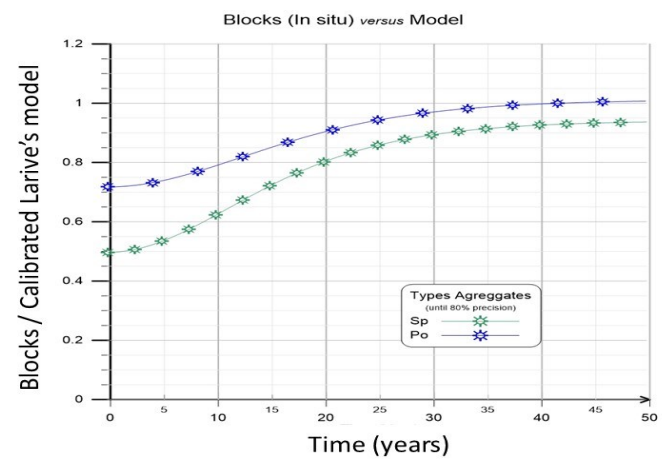
75 by 75 by 285 mm) and thus may inhibit the concrete mixture to achieve its reactive potential in the laboratory.



(A)



(B)



C

Figure 4.3 Comparison amongst blocks exposed outdoors (blue curve), CPT performed in the laboratory (pink curve) and calibrated Larive's model (green curve) for a) Pots and, b) Sp. Figure 4c illustrates the blocks to Larive's equation expansion ratio over time.

Conversely, forecasting the blocks through the use of Larive's model incorporating the calibrated τ_l and τ_c seems to yield much closer expansion values than the sole use of the CPT test. Figure 4.3c shows the blocks-to-Larive's model expansion ratio accounting for the aggregates type and reactivity. It is possible to see that the model forecasts the blocks expansion with a level of accuracy higher than 70% at 15 years which seems promising. Yet, it is worth noting that all the above is only true whether the initial assumption of Larive's model (i.e. 1-year CPT value obtained in the laboratory represents the reactive potential concrete mixtures throughout their life span in the field) is adopted.

4.7 Conclusion

In this research, the original Larive's model was calibrated using data gathered in the laboratory. The idea of the latter was to introduce a physicochemical meaning to Larive's model whether the aggregate's type and reactivity is known. The results obtained highlighted the capacity of the model to forecast both the behaviour of specimens in the laboratory and in the field. Yet, further assessment is still needed to evaluate the reliability of the proposed model with a wider range of exposed members under distinct climatic conditions. Moreover, there is an interest of adding further physicochemical parameters to the analytical model such as the alkali loading, temperature and relative humidity so that the analysis might be more comprehensive.

4.8 References

- ASTM. (2018). "C1293 - Standard Test Method for Determination of Length Change of Concrete Due to AlkaliSilica Reaction."
- ASTM C1260. (2016). "Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)." *American Society for Testing and Materials*, 1–5.

- Bangert, F., Kuhl, D., and Meschke, G. (2004). “Chemo-hygro-mechanical modelling and numerical simulation of concrete deterioration caused by alkali-silica reaction.” *International Journal for Numerical and Analytical Methods in Geomechanics*, 28(7–8), 689–714.
- Bazant, Z. P., and Steffens, A. (2000). “Mathematical model for kinetics of alkali-silica reaction in concrete.” *Cement and Concrete Research*, 30(3), 419–428.
- Benoit Fourniera et al. (2004). “the Accelerated Concrete Prism Test (60 ° C): Variability.” *12th International Conference on Alkali–Aggregate Reaction in Concrete, International Academic Publishers—World Publishing Corporation, Beijing, China*, (December 2014).
- Bérubé, M.-A., Durand, B., Vézina, D., and Fournier, B. (2011). “Alkali-aggregate reactivity in Québec (Canada).” *Canadian Journal of Civil Engineering*, 27(2), 226–245.
- Brunetaud, X. (2005). “Étude de l’influence de différents paramètres et de leurs interactions sur la cinétique de l’amplitude de la réaction sulfatique interne au béton.” Châtenay-Malabry, Ecole centrale de Paris.
- Capra, B., and Bournazel, J.-P. (1998). “Modeling of induced mechanical effects of alkali-aggregate reactions.” *Cement and Concrete Research*, Elsevier, 28(2), 251–260.
- Charpin, L., and Ehlacher, A. (2012). “A computational linear elastic fracture mechanics-based model for alkali – silica reaction.” *Cement and Concrete Research*, Elsevier Ltd, 42(4), 613–625.
- Comby-peyrot, I., Bernard, F., Bouchard, P., Bay, F., and Garcia-diaz, E. (2009). “Development and validation of a 3D computational tool to describe concrete behaviour at mesoscale . Application to the alkali-silica reaction.” *Computational Materials Science*, Elsevier B.V.,

46(4), 1163–1177.

Comi, C., Fedele, R., and Perego, U. (2009). “A chemo-thermo-damage model for the analysis of concrete dams affected by alkali-silica reaction.” *Mechanics of Materials*, Elsevier Ltd, 41(3), 210–230.

Comi, C., Kirchmayr, B., and Pignatelli, R. (2012). “Two-phase damage modeling of concrete affected by alkali-silica reaction under variable temperature and humidity conditions.” *International Journal of Solids and Structures*, Elsevier Ltd, 49(23–24), 3367–3380.

CSA. (2014). *Concrete materials and methods of concrete construction/methods of test and standard practices for concrete. Toronto (Ontario, Canada). Csa a23.1/23.2.*

Cwirzen, A., and Penttala, V. (2005). “Aggregate–cement paste transition zone properties affecting the salt–frost damage of high-performance concretes.” *Cement and Concrete Research*, 35(4), 671–679.

Dunant, C. F., and Scrivener, K. L. (2010). “Micro-mechanical modelling of alkali-silica-reaction-induced degradation using the AMIE framework.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 517–525.

Esposito, R., and Hendriks, M. A. N. (2017). “Literature review of modelling approaches for ASR in concrete : a new perspective.” *European Journal of Environmental and Civil Engineering*, Taylor & Francis, 8189(December), 1–21.

Farage, M. C. R., Alves, J. L. D., and Fairbairn, E. M. R. (2004). “Macroscopic model of concrete subjected to alkali-aggregate reaction.” *Cement and Concrete Research*, 34(3), 495–505.

Fecteau, P. L., Fournier, B., Choquette, M., and Duchesne, J. (2012). “Contribution to the

understanding of the so-called alkali--carbonate reaction (ACR), 14th ICAAR International Conference on Alkali--Aggregate Reaction in Concrete.” May.

Fournier, Benoit and Nkinamubanzi, Pierre-Claver and Chevrier, R. (2004). “Comparative Field and Laboratory Investigations on the Use of Supplementary Cementing Materials to Control Alkali-Silica Reaction in Concrete.” *Proceedings of the 12th International Conference on Alkali-Aggregate Reaction (ICAAR)*, 1, 528--537.

Fournier, B., and Bérubé, M.-A. (2000). “Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications.” *Canadian Journal of Civil Engineering*, 27(2), 167–191.

Franz-Josef Ulm et al. (2000). “THERMO-CHEMO-MECHANICS OF ASR EXPANSION IN CONCRETE STRUCTURES.” *Journal of Engineering Mechanics*, (March), 233–242.

Gorga, R. V., Sanchez, L. F. M., and Martín-Pérez, B. (2018). “FE approach to perform the condition assessment of a concrete overpass damaged by ASR after 50 years in service.” *Engineering Structures*, Elsevier, 177(June), 133–146.

Grimai, E., Sellier, A., Pape, Y. Le, and Bourdarot, E. (2008). “Creep, shrinkage, and anisotropic damage in alkali-aggregate reaction swelling Mechanism-Part II: Identification of model parameters and application.” *ACI Materials Journal*, v 105, n 3(105), p 236-242.

Grimal, E., Sellier, A., Multon, S., Le Pape, Y., and Bourdarot, E. (2010). “Concrete modelling for expertise of structures affected by alkali aggregate reaction.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 502–507.

Katayama, T. (2010). “The so-called alkali-carbonate reaction (ACR) - Its mineralogical and

geochemical details, with special reference to ASR.” *Cement and Concrete Research*, Elsevier Ltd, 40(4), 643–675.

Katayama, T., and Grattan-Bellew, P. E. (2012). “Petrography of the Kingston experimental sidewalk at age 22 years--ASR as the cause of deleteriously expansive, so-called alkali-carbonate reaction.” *Proceedings of the 14th international conference on alkali-aggregate reaction in concrete. Austin, Texas, USA*, 10.

Kawabata, Y., Martin, R.-P., Seignol, J.-F., and Toutlemonde, F. (2016). “Modelling of Evolution of Transfer Properties Due To Expansion of Concrete Induced By Internal Swelling Reaction.” *ICAAR 2016 - 15th international conference on alkali aggregate reaction*.

Kurihara & Katawaki. (1989). “Effects of moisture control and inhibition on alkali silica reaction.” *kyoto, Japan*, 629–634.

Larive, C. (1997). “Combined contribution of experiments and modelling to the understanding of alkali-aggregate reaction and its mechanical consequences (PhD thesis; in: French).”

Li, K., and Coussy, O. (2002). “Concrete ASR degradation : from material modeling to structure assessment.” *Concrete Science and Engineering*, 4(March), 35–46.

Lindgård, J., Andiç-Çakir, Ö., Fernandes, I., Rønning, T. F., and Thomas, M. D. A. (2012). “Alkali-silica reactions (ASR): Literature review on parameters influencing laboratory performance testing.” *Cement and Concrete Research*, 42(2), 223–243.

Lothenbach, B., Winnefeld, F., Alder, C., Wieland, E., and Lunk, P. (2007). “Effect of temperature on the pore solution, microstructure and hydration products of Portland cement pastes.” *Cement and Concrete Research*, 37(4), 483–491.

- Multon, S., Sellier, A., and Cyr, M. (2009). "Chemo – mechanical modeling for prediction of alkali silica reaction (ASR) expansion." *Cement and Concrete Research*, Elsevier Ltd, 39(6), 490–500.
- Multon, S., and Toutlemonde, F. (2004). "Water distribution in concrete beams." *Materials" and Structures*, 37(July), 378–386.
- Multon, S., and Toutlemonde, F. (2006). "Effect of applied stresses on alkali-silica reaction-induced expansions." *Cement and Concrete Research*, 36(5), 912–920.
- Nielsen, A. e. al. (1993). "Development of stresses in concrete structures with alkali-silica reactions." *Materials and Structures*, 152–158.
- Olafsson, H. (1986). "The effect of relative humidity and temperature on alkali expansion of mortar bars." *7th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 461–465.
- Owsiak, Z., Zapala-Slaweta, J., and Czapik, P. (2015). "Diagnosis of concrete structures distress due to alkali-aggregate reaction." *Bulletin of the Polish Academy of Sciences Technical Sciences*, 63(1), 23–29.
- Pesavento, F., Gawin, D., Wyrzykowski, M., Schrefler, B. A., and Simoni, L. (2012). "Modeling alkali-silica reaction in non-isothermal, partially saturated cement based materials." *Computer Methods in Applied Mechanics and Engineering*, Elsevier B.V., 225–228, 95–115.
- Poyet et al. (2007). "Chemical modelling of Alkali Silica reaction : Influence of the reactive aggregate size distribution." 229–239.
- Poyet, S., Sellier, A., Capra, B., Thèvenin-Foray, G., Torrenti, J. M., Tournier-Cognon, H., and Bourdarot, E. (2006). "Influence of Water on Alkali-Silica Reaction: Experimental Study and

- Numerical Simulations.” *Journal of Materials in Civil Engineering*, 18(August), 588–596.
- Prinčič, T., Štukovnik, P., Pejovnik, S., De Schutter, G., and Bosiljkov, V. B. (2013). “Observations on dedolomitization of carbonate concrete aggregates, implications for ACR and expansion.” *Cement and Concrete Research*, 54, 151–160.
- Rashidi, M., Kim, J. Y., Jacobs, L. J., and Kurtis, K. E. (2016). “Insights into alkali-silica reaction damage in mortar through acoustic nonlinearity.” *AIP Conference Proceedings*, 1706(2016).
- Sanchez, L. (2014). “Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction.” UNIVERSITE LAVAL.
- Sanchez, L. F. M. (2008). “Contribuição ao estudo dos métodos de ensaio na avaliação das reações álcali-agregado em concretos.” Universidade de São Paulo.
- Sanchez, L. F. M., Drimalas, T., Fournier, B., Mitchell, D., and Bastien, J. (2018). “Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms.” *Cement and Concrete Research*, 107(September 2017), 284–303.
- Sanchez, L. F. M., Fournier, B., Jolin, M., and Bastien, J. (2015a). “Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses.” *Construction and Building Materials*, Elsevier Ltd, 77, 20–32.
- Sanchez, L. F. M., Fournier, B., Jolin, M., and Duchesne, J. (2015b). “Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI).” *Cement and Concrete Research*, Elsevier Ltd, 67, 74–92.
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., and Bastien, J. (2017). “Overall assessment

- of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures.” *Cement and Concrete Research*, Elsevier Ltd, 93, 17–31.
- Sanchez, L. F. M., Multon, S., Sellier, A., Cyr, M., Fournier, B., and Jolin, M. (2014). “Comparative study of a chemo-mechanical modeling for alkali silica reaction (ASR) with experimental evidences.” *Construction and Building Materials*, Elsevier Ltd, 72, 301–315.
- Sanchez, L., Kuperman, S. C., and Helene, P. (2011). “Using the accelerated Brazilian concrete prism test (ABCPT) to evaluate alkali aggregate reaction (AAR).” *Ibracon Structures and Materials Journal*, 4, 575–581.
- Sanchez, L., Kuperman, S., and Helene, P. (2008). “Trials To Correlate the Accelerated Mortar Bar Test , the Standard and the Accelerated Concrete.” *13th International Conference on Alkali Aggregate Reaction (ICAAR)*, Trondheim, Norway.
- Saouma, V. E., Martin, R. A., Hariri-Ardebili, M. A., and Katayama, T. (2015). “A mathematical model for the kinetics of the alkali-silica chemical reaction.” *Cement and Concrete Research*, Elsevier Ltd, 68, 184–195.
- Saouma, V., and Perotti, L. (2006). “Constitutive model for alkali-aggregate reactions.” *ACI Materials Journal*, 103(3), 194–202.
- Schmidt et al. (2009). “AKR-Performance-Prüfung von flugaschehaltigen Betonen – Einfluss der Temperatur auf die Porenlösung und Möglichkeiten zur zielsicheren Bewertung.” *17. Internationale Baustofftagung, ibausil, F. A. Finger-Institut für Baustoffkunde, Bauhaus Universität Weimar, 23.-26. September 2009.In: Tagungsbericht, S. 2 0267 2 0276.*

- Suwito, A., Jin, W., Xi, Y., and Meyer, C. (2002). "A Mathematical Model for the Pessimism Size Effect of ASR in Concrete." *Concrete Science and Engineering*, 1–31.
- Urhan, S. (1987). "Alkali silica and pozzolanic reactions in concrete. Part 1: Interpretation of published results and an hypothesis concerning the mechanism." *Cement and Concrete Research*, 17(c), 141–152.
- Vivian, H. E. (1981). "The effect of drying on reactive aggregate and mortar expansions." *Proc., 5th Int. Conf. on Alkali Aggregate Reaction in Concrete*, 228–252.
- Winnicki, A., and Pietruszczak, S. (2008). "On Mechanical Degradation of Reinforced Concrete Affected by Alkali-Silica Reaction." *Journal of Engineering Mechanics*, 134(8), 611–627.

Chapter 5 Chapter Five: Summary and Conclusions

Alkali-Aggregate Reaction (AAR) is one of the most harmful distress mechanisms affecting the durability and serviceability of concrete infrastructure worldwide. One of the biggest challenges nowadays in the condition assessment of AAR-affected infrastructure is to establish the current expansion level reached by the structural member under analysis along with its potential for further distress. The latter is only possible whether mathematical models able to account for both physical and chemical parameters of the chemical reaction are established.

A number of analytical, numerical and empirical models have been proposed over the past decades to predict AAR-kinetics and induced expansion in the laboratory (i.e. materials level) and its impact on the mechanical properties and performance of affected structures/structural components in the field (i.e. structures level). In this context, Larive's analytical model is probably the most accepted approach by the AAR-community. Yet, it is a somewhat limited model since its parameters have no clear physicochemical meaning besides the need of being calibrated "case by case" with extensive testing and fitting.

In this research, a modified Larive's equation is proposed based on an extensive laboratory test campaign along with data gathered from the literature. The main findings of the current research are the following:

- The proposed approach is based on the most important parameters affecting AAR-kinetics and induced expansion such as the aggregates' type (coarse vs fine) and nature (reactivity), alkali content of the concrete, temperature and relative humidity of the environment. First, the impact of each of the above parameters on AAR-kinetics and ultimate expansion was understood; then, coefficients for each of them are attributed according to their influence on the

physicochemical reaction. Finally, these new coefficients are implemented in the current Larive's equation;

- The new model showed to be quite accurate to describe AAR-kinetics and unrestrained ultimate expansion for a wide variety of aggregates, concrete mixtures and exposure conditions. Scattering between the model and laboratory data as low as 5% was obtained;
- The interest of using the proposed approach instead of the conventional Larive's equation is that the modified approach makes possible the prediction of AAR-kinetics and induced expansion in the laboratory for a large variety of materials and exposure conditions without the need of further laboratory tests, calibration or fitting;
- The use of the proposed model may help to set time periods for accelerated test procedures performed in the laboratory at distinct exposure conditions to assess the potential reactivity of aggregates. It has been found that 60°C and 80°C procedures may lessen the required test periods in about 75% and 92%, respectively, when compared to the conventional 38°C test;
- It is still premature (although promising results were also obtained evaluating unrestrained blocks exposed outdoors or even reinforced slender structures) to think on using the current version of the proposed modified model to appraise AAR-affected concrete structures in the field. Further analyses should still be performed in this regard.

Chapter 6 Chapter Six: Recommendations for Future Research

After evaluating the outcomes of the current project, recommendations for future research may be drafted, as presented hereafter:

- An in-depth analysis on the influence of some parameters other than the ones accounted for in the proposed model such as alkalis leaching, exposure conditions and differences in temperature (laboratory vs field) should still be performed;
- It is well known that confinement effects may induce anisotropic swelling on AAR-affected concrete. Therefore, in order to use the proposed model to evaluate concrete infrastructure in the field, a parameter accounting for imposed anisotropy should be considered.
- The proposed model does not account for mechanisms other than AAR. However, AAR is often observed to be combined with other damage mechanisms in the field such as delayed ettringite formation (DEF), freeze and thaw cycles (FT) and/or steel corrosion. The combination of these mechanisms in a singular model would be extremely helpful to improve accuracy in the condition assessment of aging infrastructure.