Modelling alkali-silica reaction effects for condition assessment and capacity evaluation of reinforced concrete structures

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under the supervision of Professor Jianchun Li,
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Certificate of Original Authorship

I, **Thuc Nhu Nguyen** declare that this thesis, is submitted in fulfilment of the requirements for the award of **Doctor of Philosophy**, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Dedication

To my father, who strongly encourages and believes in my journey, with love!

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THUC NHU NGUYEN

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List of Abbreviations

ACR	Alkali-carbonate reaction
AMBT	Accelerated Mortar Bar Test
ANN	Artificial Neural Network
ASR	Alkali-silica reaction
ASTM	American Society for Testing and Materials
BR	Bayesian Regularization
CPT	Concrete Prism Test
DRI	Damage rating index
FEM	Finite element modelling
FEA	Finite element analysis
HAPC	High-alkali Portland cement
ISE	Institution of Structural Engineers
LAPC	Low-alkali Portland cement
LM	Levenberg-Marquardt
NN	Neural network
RC	Reinforced concrete
RVE	Representative Volume Element
SCM	Supplementary cementing material

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Abstract

Alkali-silica reaction (ASR) is one of the most harmful distress mechanisms affecting concrete infrastructure worldwide. ASR is a chemical reaction that generates a secondary product, which induces expansive pressure within the reacting aggregate particles and adjacent cement paste upon moisture uptake. This in turn leads to cracking, loss of material integrity, and consequently compromises serviceability and capacity of the structure. In Australia, several concrete structures of various types such as dams, bridges and railway sleepers have been identified as affected by the reaction to varying extents. To date, the majority of experts agree that new concrete structures can be constructed in such a way to avoid ASR-induced effects by using either non-reactive aggregates classified by national and international standards, or supplementary cementitious materials to mitigate the reaction. However, there is currently a lack of a comprehensive plan for diagnosis and prognosis of existing concrete structures affected by ASR. This is despite its importance in providing efficient rehabilitation methods and management strategies for the infrastructure.

When investigating existing structures affected by ASR, two crucial questions need to be answered prior to specifying management strategies, i.e., (i) the current state of damage and its effects on structural capacity and serviceability; and (ii) the prediction of damage progress and its impact on the structure in the coming months or years. In this regard, two main effects of the deleterious ASR - expansion and mechanical properties degradation of the concrete - need to be evaluated prior to assessing the condition and capacity of the affected structures suffering from ASR. This study aimed to provide different modelling approaches for evaluating the degradation of mechanical properties, expansion of concrete in the field, and eventually assessing the structural behaviour of ASR affected structural members and structures.

First, a critical review on mechanical properties of concrete suffering from ASR is provided. Due to significant reduction in modulus of elasticity and its wide variation, two different models were implemented to provide better understanding and evaluations of the reduction in the modulus of elasticity. An artificial neural network (ANN) model was

proposed to investigate impacts of different factors (i.e., reactive aggregates, alkali content, design strength in addition to the expansion) to the modulus of elasticity and subsequently to provide a better estimation of the reduction. In another approach, a computational homogenization model was developed to model the impact of ASR-induced cracking in concrete on its stiffness. The proposed model was able to quantify the impact of ASR-induced internal cracking on the reduction of concrete stiffness.

Second, a novel semi-empirical model was proposed for forecasting expansion of unrestrained concrete in the field based on results of laboratory testing such as from the concrete prism test (CPT). The model accounted for effects of the reactive aggregate type and nature, alkali leaching, alkali contribution from aggregates and environmental conditions (i.e. temperature, relative humidity) on the ASR expansion. The semi-empirical model is capable of accounting for the effects of environmental conditions in the field for forecasting ASR-induced expansion of concrete field blocks. This is shown by excellent model outcomes for concrete blocks from three outdoor sites in Canada and the USA, which were made by different reactive aggregates and alkali contents.

Finally, as a continuation of the semi-empirical model, a finite element (FE) model was developed for modelling expansion and load-carrying capacity of reinforced concrete members. Two well-known empirical models to account for stress-dependency of the ASR expansion were adopted to account for the effect of reinforcement restraints on the ASR expansion development in reinforced concrete members. The model was implemented in the commercial FEA package ABAQUS/Implicit using different developed user subroutines, and the concrete damaged plasticity model. Impact of the variation in residual mechanical properties on expansion advancement and load-carrying capacity of reinforced concrete members was also investigated.

By providing different numerical investigations on the degradation of mechanical properties, expansion of the field concrete and consequently the structural capacity, this study provided a comprehensive approach for assessing condition and capacity of existing reinforced concrete structures suffering from ASR.