Ageing effects of alkali-silica reaction in concrete structures

Esposito, Rita; Hendriks, Max

Publication date
2016

Document Version
Final published version

Published in
Proceedings of the International Conference on Ageing of Materials and Structures AMS 14

Citation (APA)
Esposito, R., & Hendriks, M. (2016). Ageing effects of alkali-silica reaction in concrete structures. In K. van Breugel (Ed.), *Proceedings of the International Conference on Ageing of Materials and Structures AMS 14: Delft, The Netherlands* (pp. 1-7). Delft University of Technology.

Ageing effects of alkali-silica reaction in concrete structures

Rita Esposito[1*], Max A.N. Hendriks[12]
(1) Delft University of Technology, Delft, The Netherlands
(2) Norwegian University of Science and Technology, Trondheim, Norway

Abstract: The alkali-silica reaction (ASR) is a long-term deterioration process, which produces a hydrophilic and expansive gel causing damage. The ASR acts on concrete as an ageing phenomenon, modifying the material on the basis of its stress state. Focussing on the mechanical degradation of concrete, estimated trends for the mechanical properties in free expansive affected concrete are presented. These show the result of recent research which collected and statistically analysed laboratory tests on 54 concrete mixes performed by 11 authors. Comparable findings are also obtained through a multiscale material model, which aims to capture the micro and macro aspects of the problem. The ASR-affected concrete is seen as an evolving material, whose state should be followed over time taking into account chemomechanical coupling.

Keywords: Alkali-Silica Reaction (ASR), degradation, mechanical properties, damage assessment, multiscale modelling

1 Introduction

The Alkali-Silica Reaction (ASR) is a harmful deterioration process, which starts at aggregate level, with the combination of silica in the aggregates and alkali in the cement paste. Its product is a hydrophilic gel which swells and causes damage up to macro level, possibly influencing the integrity and capacity of the structure. The expansion process is directly related to the mix properties (e.g. aggregate and cement type, aggregate size, etc.) and to the environmental conditions. Moreover the stress state of the material has an influence on the redistribution of the gel in the concrete, thus on the swelling, and consequentially on the damage propagation. The reaction influences the performance of the material by leading to a relevant degradation of the mechanical properties.

Recently the authors studied the influence of ASR on the mechanical degradation of concrete, by analysing available literature data regarding laboratory tests on free expansive ASR-affected concretes [1]. The collection of data included 11 authors, actually groups of co-authors, who tested 54 different concrete mixes. Considering the observed expansion and expansion rates as given, the specific aim is to find a trend between the deterioration of the mechanical properties and observed concrete swelling due to ASR, independent of the wide variety of concrete mixes used and experimental conditions applied. The research highlighted that the evolution of elastic modulus, both static and dynamic, is the best indicator for the identification and progression of ASR in concrete. Conversely, the evolution of compressive strength might veil ASR damage. The splitting test is to be preferred to capture the influence of ASR on the tensile behaviour of concrete. The research highlighted that the ASR-affected concrete appears as a substantially different material with respect to sound concrete and the known engineering strength-stiffness relationships, developed for the latter, cannot be adopted in the structural assessment procedures.

Furthermore, considering that a proper material characterization is extremely relevant, a multiscale material model [2] has been selected to perform structural analyses. The model accounts for the micromechanical changes provoked by the ASR and its swelling. By employing this approach a more fundamental model is adopted, which is able to capture the micro and macro aspects. The ASR-affected concrete is seen as an evolving material, the state of which should be followed over time taking into account chemical and mechanical loading conditions.

[*] Rita Esposito,
Delft University of Technology, Delft, The Netherlands
e-mail: r.esposito@tudelft.nl

In this paper the attention is focussed on the mechanical degradation of concrete induced by ASR. First the recent findings regarding the statistical analysis of literature experimental date are presented. It includes different laboratory tests performed on free expansive ASR-affected concrete, to determine the evolution of concrete mechanical properties. The results are compared with a numerical simulation performed by adopting the proposed multiscale material model.

2 Mechanical degradation of concrete provoked by ASR

The alkali-silica reaction in concrete is a long-term deterioration process, whose consequences are strongly related to the environmental and mechanical state of the material. The coupling between the chemical load, provoked by the ASR gel swelling, and the mechanical load is the key point which make the laboratory tests different from the real behaviour of a ASR-affected structures. By understanding first the mechanical effect of ASR and secondly the coupling phenomenon, it is possible to explain the behaviour of ASR-affected concrete structures.

In order to quantify the mechanical degradation of concrete provoked by ASR, an extensive research was made [1]. Available literature experimental data [1, 3-11] was collected and statistically analysed to determine trends in degradation behaviour. The majority of the authors studied the degradation of the compressive strength (10 authors out of 11) and of the static elastic modulus (9 authors out of 11). The tensile behaviour was studied by 7 authors out of 11, who preferred the splitting tensile strength, above the modulus of rupture and the direct tensile strength. Non-destructive tests for the determination of the dynamic elastic modulus were chosen by 4 authors out of 11.

The data were statistically analysed applying a normalization procedure: each property was normalized with respect to its reference value, which was calculated at an expansion equal to 0.05%. After the normalized property values were plotted versus the concrete expansion values, curve fitting procedure was applied. The fitting included two degradation laws: the S-shaped curve, which is a revised version of the law proposed by Saouma et al. [12], and the piecewise linear curve.

In Figure 1a the best curve fitting results are presented together with the error band equal to 2σ. The piecewise linear curve is chosen for the description of the compressive strength behaviour, while the S-shaped curve was chosen for the other properties. The tensile strength behaviour is reported in terms of splitting test results. Both static and dynamic elastic modulus data are considered for the description of the stiffness degradation. The curve fitting defines the elastic modulus as the best indicator of ASR signs in concrete, in fact it presents a relevant deterioration already at early expansion; moreover its degradation rate is the fastest one. For high expansion values ($\varepsilon > 2.00\%$) the residual stiffness is 20% of the reference value. Conversely, the compressive strength behaviour is described with an initial gain of 15% and a maximum reduction of 46%. However the estimation error is high, around 13%. The tensile behaviour appears to be well described by the splitting test results. Its deterioration starts at higher expansion values with respect to the elastic modulus. Its residual value is 64%.

In Figure 1b the differences in degradation behaviour are shown in an alternative way. When the elastic modulus reaches 85% of its original value, both strengths reduce with a similar rate, but still slower than the degradation rate of the elastic modulus. At a normalized value of 0.50 for the elastic modulus, the normalized splitting strength reaches an asymptotic value of 0.60. The compressive strength is subjected to a drastic deterioration for a normalized value of the elastic modulus of 0.20.

In engineering it is common practice to express the stiffness and the tensile strength of sound concrete as a function of its compressive strength. Using the strength-stiffness relationships proposed by Model Code 2010 [13], it was found that for sound concrete, the degradation rate of compressive and tensile strength is lower than the one for the elastic modulus (Figure 1b). This demonstrated that for ASR-affected concrete, it is not allowed to use the engineering strength-stiffness relationships to determine the elastic modulus and the tensile strength from the measured compressive strength.

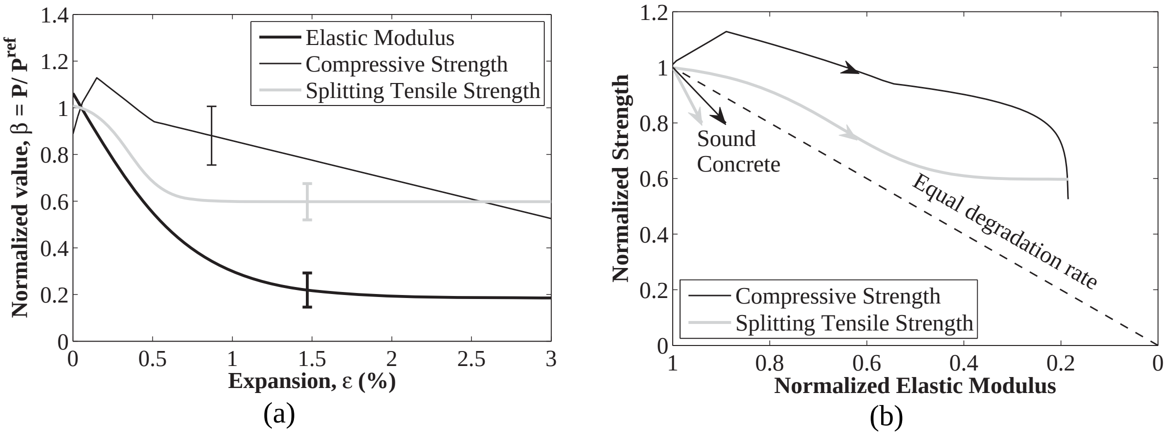


Figure 1 Results of the statistical analysis: (a) Evolution law for elastic modulus, compressive strength and splitting tensile strength as a function of concrete expansion induced by ASR; (b) Relation between normalized elastic modulus and normalized strengths.

3 Multiscale modelling approach

Since ASR was first discovered, many modelling strategies were developed to assess the behaviour of affected structures. Starting with rather straightforward engineering methods, the research moved to the material characterization adopting models on different scales. Micro-mechanical models focused on the reaction kinetics and mechanism, while macroscopic approaches tried to understand the damage effects observed in structures.

Considering that a micro-mechanical material characterization is relevant for the description of the overall structural behaviour, a multiscale material model [2] is adopted (Figure 2), in order to account for the strong interaction between micro-mechanical aspects and the complex macro-mechanical state. The approach found its basis in the work of Charpin and Ehrlacher [15] and of Lemarchand et al. [14]

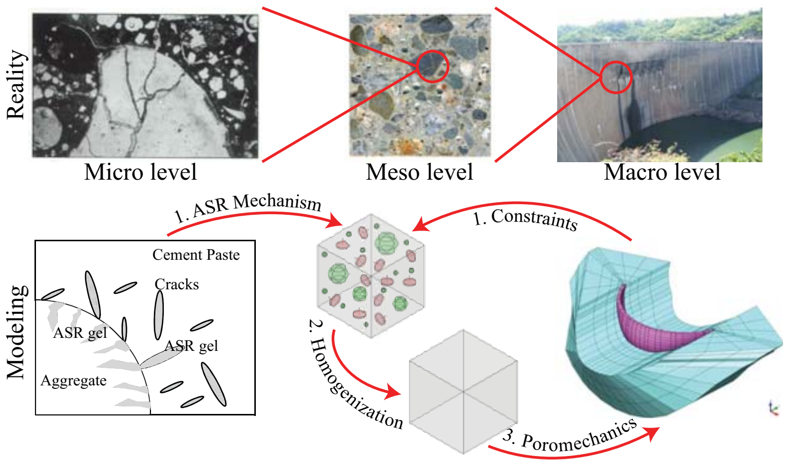


Figure 2 Modelling procedure for structural analyses.

The properties of concrete are evaluated considering a Representative Elementary Volume (REV), as reported in Figure 3a. The sound concrete is modelled as a heterogeneous material (Figure 3b) composed of aggregates and microcracks embedded in the cement paste. Each material is behaving elastically. The aggregates are modelled as spheres. The microcracks are modelled by three orthogonal families of penny-shaped inclusions.

The alkali-silica reaction is simulated by changing the microstructure. The chemical process starts at aggregate level by consuming the silica available and forming the gel, which is modelled as spherical inclusions into the aggregates (Figure 3b). It is assumed that the gel has a volume bigger than the volume of the eroded aggregate, therefore a pressure is generated. The gel flows into the cement paste by filling the microcracks around the aggregates. Eventually the pressure is high enough to generate damage in the system (Figure 3c). The chemical process is governed by the internal variable α which is defined for each family of aggregates (inclusion type 2) and it ranges between 0, not affected aggregates, and 1, completed eroded aggregates. The internal variable is also responsible for the link between time and expansion evolution.

The damage evolution is formulated in the framework of linear fracture mechanics by employing an energy-based damage criterion. Both the external mechanical loads and the internal pressure contribute to the description of the damage, which leads to an increase of the crack radii. The effective properties of the medium are analytically evaluated by the Mori-Tanaka homogenization scheme.

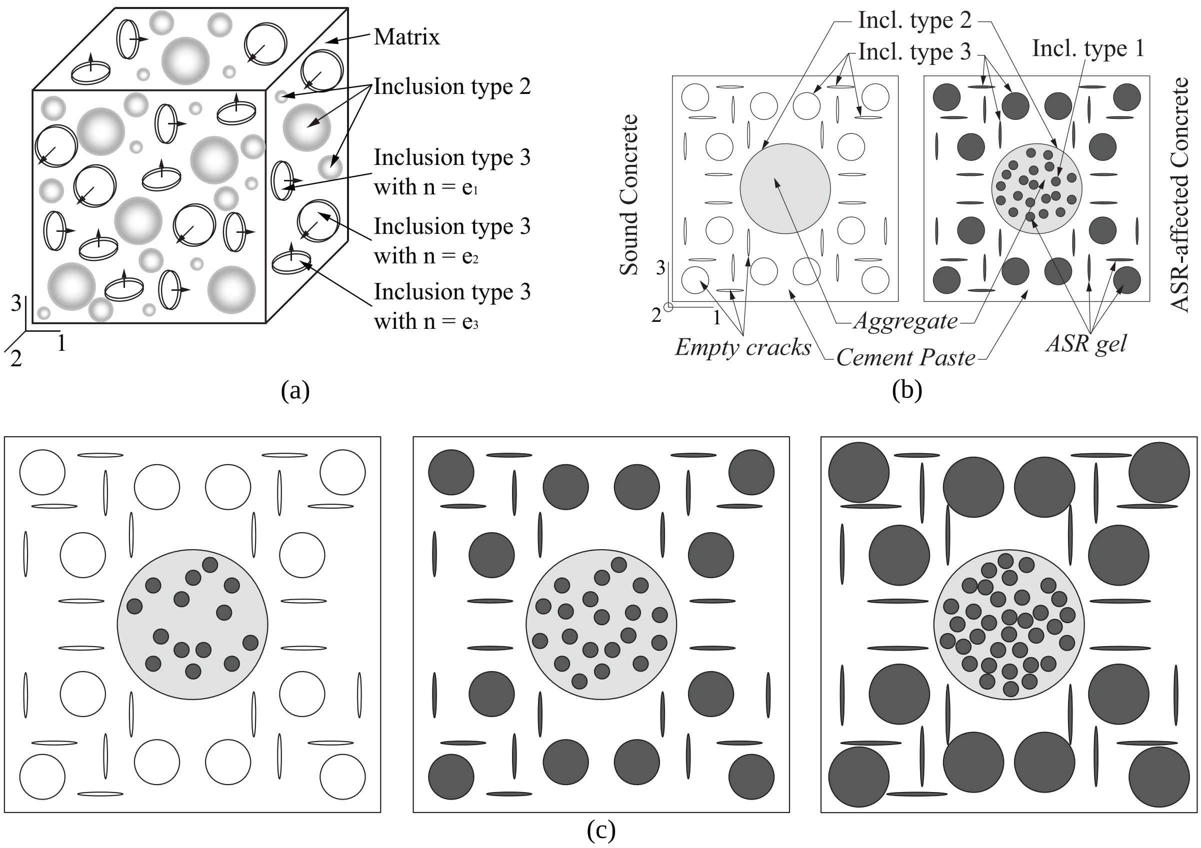
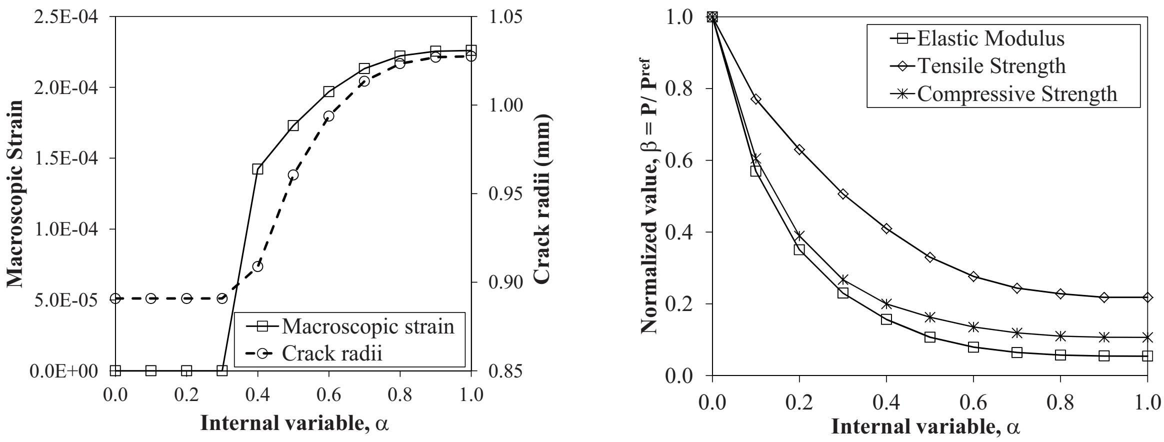


Figure 3 Micro-mechanical model of the REV: (a) 3D representation; (b) Sound and ASR-affected concrete; (c) Evolution of microstructures for ASR-affected concrete in free expansion conditions.

The model was adopted to simulate the degradation of mechanical properties in ASR-affected concrete samples in free expansion conditions. A sound concrete having an elastic modulus of 32188 MPa and a tensile strength of 3.20 MPa is considered. The example uses only one family of inclusions type 2 (aggregates), with a radius equal to the weighted average of the available aggregate sizes (d = 0 - 8 mm). Three families of inclusions type 3 (cracks), with the same initial crack radius and equally distributed in the three orthogonal crack planes are considered. The elastic moduli of aggregate and cement paste phases are assumed equal to 25000 and to 70000 MPa, respectively. The ASR gel bulk modulus is 1788 MPa. The compressive strength of the sound concrete is estimated, throughout a simulation of an uniaxial compressive test, equal to 30.43 MPa.

In Figure 4 the numerical results are reported. With a sample that is free to expand and identical distribution of the three crack families, the macroscopic strains evolve isotropically. The characteristic S-shaped expansion curve is obtained (Figure 4a). The crack propagation follows a similar trend: in the first stage the crack radii are constants, because the internal pressure is still low and the gel is filling the available space in the concrete, afterwards the cracks isotropically propagate.

In Figure 4b the degradation of the mechanical properties is reported as a function of the internal variable. They are evaluated at regular intervals of the internal variable, α, by simulating uniaxial tensile and compressive tests. The properties are normalized with respect to the values of undamaged sound concrete properties (elastic modulus 32188 MPa, tensile strength 3.20 MPa, compressive strength 30.43 MPa). The properties start to degrade immediately, and present an asymptote for high values of the internal variable, α. The elastic modulus is the property which degrades fastest and presents the lowest residual value. The compressive strength follows a similar trend. The model predicts a lower degradation in terms of tensile strength.



(a) (b)

Figure 4 Numerical results: (a) Evolution of macroscopic strain and crack radii; (b) Degradation of mechanical properties.

A through comparative study between the experimental and numerical results has still to be performed. However, preliminary comparison between Figure 1a and Figure 4b shows that the model is able to describe the degradation of the elastic modulus. Moreover the different degradation behaviour between elastic modulus and tensile strength is observed as well. However, the numerical results in term of compressive strength are not in agreement with experimental findings: the initial increase in compressive strength is not simulated and the predicted residual strength is too low.

It is emphasized that the numerical prediction in Figure 4 is shown as a function of the internal variable and not in terms of concrete expansion. Moreover, the simulation is performed by assuming only one family of aggregates and reasonable (but disputable) input parameters. A further validation of the model is needed.

4 Conclusions

The alkali-silica reaction is a long-term deterioration process which can slowly, but significatevly, influence the performance of concrete structures. The hydrophilic expansive gel, which is formed by the reaction between alkali in the cement and silica in the aggregates, can lead to concrete expansion with subsequent material deterioration.

Recently the authors collected and analysed literature data regarding the degradation of mechanical properties in free expansive ASR-affected concrete. The data collation analysed 54 different concrete mixes studied by 11 authors. The majority of the research was focus on the estimation of compressive strength and static elastic modulus. The tensile behaviour of concrete was evaluated mainly through splitting tensile strength tests. Some authors adopted non-destructive test methods to estimate the dynamic elastic modulus. The data, expressed as normalized property values versus concrete expansion, were analysed in terms of curve fitting, adopting the S-shaped or the piecewise linear curve.

The elastic modulus, both static and dynamic, results as the best indicator for the identification of ASR in concrete, showing relevant degradation at lower expansion values. Moreover its degradation rate is the fastest and it degrades by 90% of its original value. The behaviour of compressive strength, widely investigated probably because it is the principal test method adopted in the structural assessments, shows a non-monotonic trend. It displays an initial gain for expansion values lower than 0.15% and a subsequently reduction down to approximately 50%. The tensile strength, well described by the splitting test results, shows a delay in the degradation with respect to the elastic modulus. However a similar deterioration rate for expansion values between 0.10% and 0.50% is observed. It reaches a maximum reduction of 64%. Comparing the degradation behaviour of compressive and splitting tensile strength with respect to the elastic modulus, a non-linear relation is observed. As a result, the ASR-affected concrete appears as a substantially different material and the known engineering strength-stiffness relationships, developed for sound concrete, cannot be adopted.

In order to simulate the mechanical degradation of concrete due to ASR in free expansive concrete, a multiscale material model is adopted. The model aims to couple the chemical and mechanical effects in order to characterize the ASR-affected concrete in the structures, which is considered as an evolving material. The concrete is modelled at micro level as a multiphase material in which aggregates, cracks and gel formations are considered as embedded inclusions in the matrix, that is the cement paste. The development of the gel involves the aggregate's erosion and swelling, together with a possible mechanical load, which can lead to crack propagation. The overall mechanical properties of concrete are analytically determined in agreement with the Mori-Tanaka homogenization method. This theory defines the average stress and strain state of the concrete as well as the effective stiffness tensor, which depends on the amount, the shape and the orientation of the inclusions. Therefore the model can be mechanically defined as a three-dimensional smeared approach. The damage state variables are directly linked to the microscopic crack families and their propagation is based on the principles of linear fracture mechanics.

A preliminary comparison of the numerical results with the findings of the statistical analysis shows that the model is able to capture the degradation behaviour in terms of stiffness and tensile strength. The elastic modulus is confirmed as damage indicator, presenting the fastest degradation rate and the lowest residual value. Moreover the different degradation behaviour between elastic modulus and tensile strength is predicted as well. However, its performance in terms of compressive strength degradation should be improved.

In conclusion, the ASR-affected concrete appears as an ageing of the material where the degradation is strongly related to the stress state. It does not follow the known engineering strength-stiffness relationship, derived for sound concrete. The multiscale material model, which aims to characterize the ASR-affected concrete in structures, appears as a complementary tool adoptable in combination with laboratory tests in the assessment procedure.

Acknowledgments

The authors wish to express their thanks to the Dutch Technology Foundation STW for its financial support.

References

[1] Esposito, R., et al. (2014) The Influence of Alkali-Silica Reaction on the Mechanical Degradation of Concrete (in preparation).

[2] Esposito, R. and M.A.N. Hendriks (2013) Multiscale Material Model for ASR-affected Concrete Structures. in XII International Conferenceon Computational Plasticity.Fundamentals and Applications (COMPLASXII). Barcelona, Sapin.

[3] Swamy, R.N., ed. The Alkali-Silica Reaction in Concrete. 1992, Van Nostrand Reinhold, New York.

[4] Larive, C. (1998) Apports combinés de l'expérimentation et de la modélisation la comprehénsion de l'alcali-réaction et de ses effets mécaniques. Ph.D. Dissertation, Laboratoire Central des Ponts et Chaussées (LCPC).

[5] Monette, L.J., N.J. Gardner, and P.E. Grattan-Bellew (2002) Residual Strength of Reinforced Concrete Beams Damaged by Alkali-Silica Reaction- Examination of Damage Rating Index Method, ACI Mater. J., 99(1).

[6] Ahmed, T., et al. (2003) The effect of alkali reactivity on the mechanical properties of concrete, Construction and Building Materials, 17(2): 123-144.

[7] Multon, S. (2004) Évaluation expérimental et théorique des effets mécaniques de l'alcali-réaction sur des structures modèles. Ph.D. Dissertation, Université de Marne-la-Vallée (in collaboration with LCPC-EDF).

[8] Ben Haha, M. (2006) Mechanical Effects of ASR in Concrete Studied by SEM-Image Analysis École Polytechnique Fédérale de Lusanne (EPFL).

[9] Giaccio, G., et al. (2008) Mechanical behavior of concretes damaged by alkali-silica reaction, Cem. Concr. Res., 38(7): 993-1004.

[10] Sargolzahi, M., et al. (2010) Effectiveness of nondestructive testing for the evaluation of alkali–silica reaction in concrete, Construction and Building Materials, 24(8): 1398 - 1403.

[11] Lindgård, J. (2013) Alkali-silica reaction (ASR) - Performance testing. Ph.D. Dissertation, Norwegian University of Science and Technology.

[12] Saouma, V. and L. Perotti (2006) Constitutive model for alkali-aggregate reactions, ACI Mater. J., 103(3): 194-202.

[13] CEB-FIP (2012) Bulletin d'Information 65&66 - Model Code MC2010 Final Draft. Lausanne, Switzerland: International Federation for Structural Concrete (fib).

[14] Lemarchand, E., L. Dormieux, and F.J. Ulm (2005) Micromechanics investigation of expansive reactions in chemoelastic concrete, Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 363(1836): 2581-2602.

[15] Charpin, L. and A. Ehrlacher (2012) A computational linear elastic fracture mechanics-based model for alkali-silica reaction, Cem. Concr. Res., 42(4): 613-625.