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Structural Modelling of ASR-affected Concrete: The approach developed in the PAT-ASR project

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ABSTRACT

The Alkali-Silica Reaction is a harmful reaction which can compromise the integrity and capacity of concrete structures. Due to its nature, a multiscale material model has been chosen to perform structural analyses. The model aims to couple the chemical and mechanical effects in order to characterize the affected concrete into the structures, which is considered as an evolving material. The model has been developed in the project Performance Assessment Tool for Alkali-Silica Reaction (PAT-ASR), which started in 2010 at Delft University of Technology and involves collaboration with the Norwegian Public Roads Administration.

Key words: Alkali-Silica Reaction (ASR), structural effects, material modelling, confinement, PAT-ASR project.

1 INTRODUCTION

The concrete infrastructure comprising bridges, dams and other civil works may be at risk due to deterioration caused by alkali-aggregate reaction. In this group of reactions the Alkali-Silica Reaction (ASR) is considered one of the most harmful processes, because it generates an expansive gel. This reaction, which begins at microstructural level, may eventually cause serious damage with consequent loss of structural capacity.

Due to the nature of the phenomenon, it should be studied from different points of view in order to understand the impact. For this reason, in 2010 at the Delft University of Technology the project Performance Assessment Tool for Alkali-Silica Reaction (PAT-ASR) [1] has been developed. The main goal is an understanding of the consequences of ASR by employing experiments and modelling approaches, both at different scales.

A large experimental campaign focussing on the characterization of a reference material with various tests method has been carried out. Meso-scale modelling of the experiments with the Delft Lattice Model [2] is performed to investigate the reaction kinetics and the damage evolution. Meanwhile a material model for structural analysis [3, 4] is under development in order to couple the chemical and mechanical loading action in ASR-affected concrete structures.

In this paper the idea and the motivations behind the formulation of the material model for the assessment of the structural effects induced by ASR are explained. A literature review is included.

2 EXPERIMENTAL OBSERVATIONS

ASR is a chemical process between the alkali available in the cement and the silica originating from the aggregate. Its product is a hydrophobic gel which expands and builds up a pressure because it is confined by the concrete skeleton.

ASR has been studied by different researchers during several decades. Geologists and chemists investigated the mechanism of the gel formation; whereas civil engineers studied the mechanical impact both at material and structural level.

2.1 ASR mechanism and concrete expansion

The chemical mechanism can be described by a two-stage process [5]. In the first stage the silica on the surface of the aggregates dissolves and reacts with the alkalis in the pore solution, thus creating the alkali-silica gel. In the second stage the gel comes in contact with the moisture and expands.

When the reaction is established, the gel can be observed in different parts of the microstructure. Microscopic investigations show the presence of the gel within the aggregates as well as in the cement paste and at their interfacial zone. As reported by Saouma [6] "Reaction initiates inside some selected (i.e. reactive) aggregates, gel forms, and in the presence of water swells. As it swells in a confined environment, the aggregates eventually will crack to relieve the internal pressure and thus allow the gel to expand inside the newly formed void. One can speculate that the accumulated internal strain energy is much higher than the surface energy of the aggregate itself and that the excess energy drives the crack dynamically into the surrounding matrix and aggregates."

The expansion of ASR gel can lead to a macroscopic swelling of the concrete with formation of cracks. However, before the gel expansion is visible as concrete swelling the gel flows and fills the existing porosity, afterwards the internal pressure leads to microcracks formation and swelling of the concrete. The swelling appears to stop when either the alkali content is too low to react or the water does not reach the reactive site.

The swelling process can be influenced by the environmental conditions. Elevated temperatures can lead to a faster reaction [7]. Besides, the moisture content is a relevant parameter. Laboratory tests have shown that if the relative humidity is lower than 50% the concrete does not expand, even if the gel has been formed [8].

The swelling process is also influenced by the microstructure. Zhang et al. [9] have reported that the smaller the aggregate size, the greater the concrete expansion, for aggregates between 0.15-10 mm. Multon et al. [10] have shown that if the concrete contains only large reactive aggregates its expansion will be slower with respect to a concrete with different reactive aggregate sizes; this phenomenon can be explained with the difficulty of the alkali solution to enter the aggregates. Moreover when multiple aggregate sizes are considered the behaviour can be different on the basis of the ratio between the coarse and fine particles. This ratio determines how large the porous crown zone around the aggregates is: the larger the porous zone, the smaller the expansion because the gel has more space before pressurizing the concrete skeleton.

2.2 Structural effects

Anisotropic behaviour

The swelling process of concrete affected by ASR appears to be characterized by an intrinsic anisotropic behaviour, as shown by Larive [7]. She observed that a sample in free expansion condition prefers to swell in the direction parallel to the casting direction; the expansion in this direction ranges from 1.3 to 2.8 times the expansion in the perpendicular directions (Figure 1(a)).
Tensile tests on sound concrete specimens with the same aggregate size show, as well known, that the tensile strength is lower along the casting direction. This suggests that the distribution of pores with various shapes and orientations determines both the direction with the weakest tensile strength and the preferred expansion direction. Before microcracking occurs, the swelling is nearly isotropic. Afterwards the gel expansion will induce the propagation of the cracks in the weakest zone (perpendicular to the casting direction), which will mutually influence the further swelling. In conclusion, anisotropic cracking resulting from anisotropic strength properties influences the anisotropic expansion.

The same conclusion could be used to explain the swelling redistribution concept [11, 12]. In specimens subjected to uniaxial compressive loading or lateral constraining the imposed expansion is lower in the restrained direction. Once again the gel expansion induces the crack propagation in the direction which requires less energy dissipation. When the constraints are applied in the lateral direction the gel tends to expand along the longitudinal one (Figure 1(b)).

The anisotropic behaviour induced by the stress state is more relevant than the intrinsic one. This phenomenon is particularly important when the attention is focussed on the behaviour of ASR-affected concrete structures, where the concrete is always constrained or (pre-)stressed. It is thus expected that concrete in ASR-affected structures can be seriously influenced by the coupling between chemical and mechanical loading and constraints.

Mechanical degradation

The ASR reaction appears to degrade the mechanical properties of concrete differently than a mechanical loading [13]. Tests performed by Swamy and Al-Alasi [14] showed that: “the losses in engineering properties do not occur at the same rate or in proportion to the expansion undergone by the ASR-affected concrete”.

In Figure 2 the degradation of the Young's modulus and the splitting tensile strength is collected using data reported in literature [7, 14-17]. The values of the mechanical properties have been normalized with respect to the values at 28 days. The comparison is made for concrete samples stored in high humidity at a temperature between 20 and 40 ºC. The stiffness appears to be the most sensitive property; it can reach degradation levels up to 80%. Moreover the stiffness and the strength degrade at a different rates.

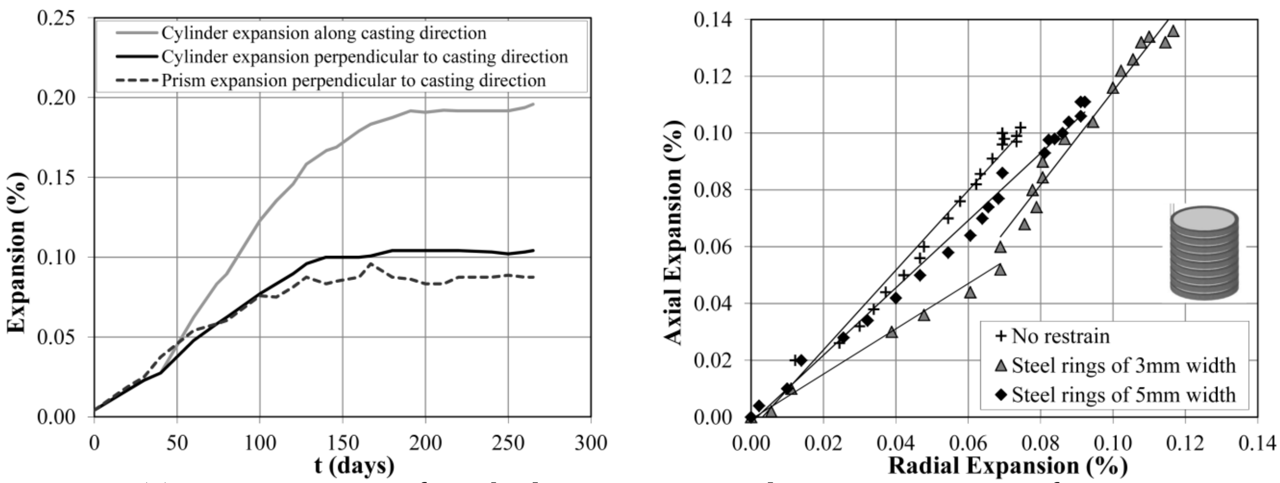
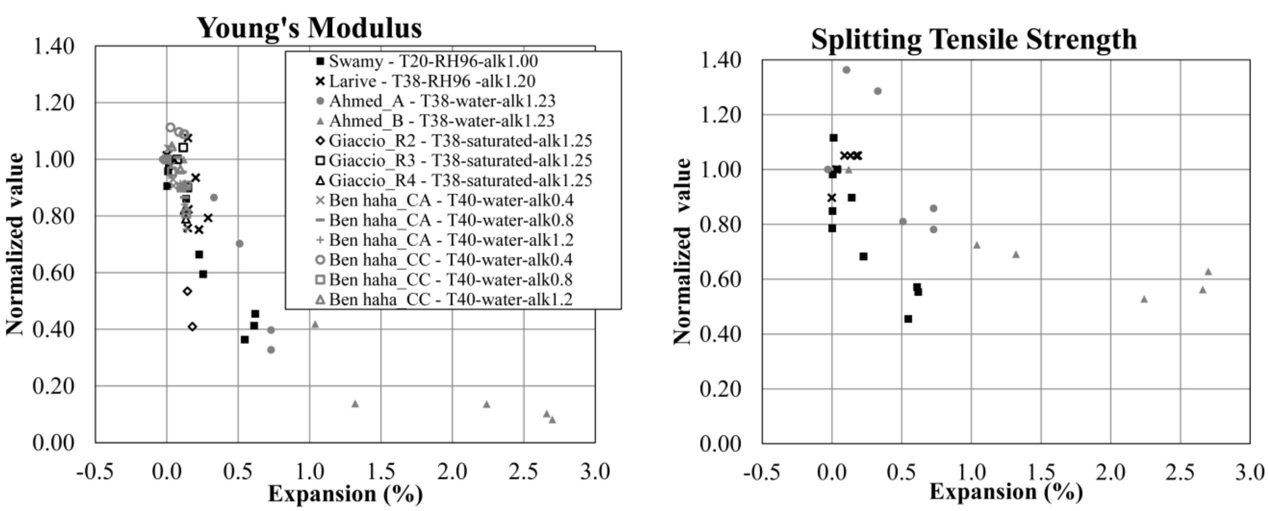


Figure 1 - (a) Expansion curves for cylinders specimens and prisms specimens in free expansion conditions [7], (b) Expansions for specimens subjected to lateral constrains.[11].



(a) (b)

Figure 2 - Degradation of mechanical properties in ASR-affected concrete samples in free expansion conditions using data reported in literature [7, 14-17]: (a) Young's modulus; (b) Splitting tensile strength. The legend indicates the name of the author and sample, the temperature in degrees Celsius, the moisture condition and the Na_2O_{eq} content in %.

3 MODELING ASR IN CONCRETE

The alkali-silica reaction was first observed in large massive concrete structures as dams. In an early approach a thermal equivalence concept was adopted to model the concrete expansion [18] and the stress-induced anisotropic behaviour was obtained by considering the local principal stresses [19]. Later, the influence of the environmental conditions was accounted by Léger et al. [20] and Larive [7] with phenomenological formulas.

Saouma and Perotti [12] proposed an engineering approach that accounts for the swelling redistribution due to the stress state; they improved the method presented by Charlwood by introducing anisotropic expansion coefficients on the basis of experimental observations. Capra and Sellier [21] adopted a probabilistic approach to model the evolution of cracks in the concrete matrix, due to the internal pressure generated by the swelling gel. The concrete is modelled like a damageable material having elastic and inelastic strains. ASR is modelled using global kinetics including temperature and humidity effects.

Recently, the attention has been shifted to describe the interaction between the gel and concrete skeleton at pore level, by investigating the kinetics of the phenomenon. Lattice models have been employed by Schlangen and Çopuroğlu [22] and Anaç et al. [2] to model the gel formation and its expansion. Concrete is modelled at meso-scale and the particles distribution is determined by imagen analysis of samples. Different expansion points are randomly selected into the micro-structures. Dunant and Scrivener [23] adopted an extended finite element framework to perform micro-mechanical simulations of free expansion tests. They explain the damage induced by the ASR by introducing growing gel pockets in the aggregates.

Ulm et al. [24] and Bangert et al. [25] employed the porous media theory to describe the gel swelling and the development of the internal pressure as well as the chemomechanical coupling. Lemarchand et al. [26] were able to describe the kinetics beyond the S-shaped expansion curve and to capture the swelling redistribution effect by simulating the cracks' closure [27].

Furthermore micro-mechanical models have been formulated to describe the "pessimum size" effect, to obtain more efficient expansion test procedures. This effect is strongly related to the aggregate size distribution and it defines the worst (pessimum) size which leads to the highest concrete expansion within a short time. Bazant [28] proposed a micro-mechanical fracture theory that explained the aggregate size effect in a 2-weeks accelerated test. Suwito et al. [29], Poyet et al. [30] and Multon et al. [31] employed analytically-solved microscopic models to predict the size effect of the aggregates on the concrete expansion in a 1-year accelerated test.

4 PAT-ASR PROJECT: STRUCTURAL MODELING

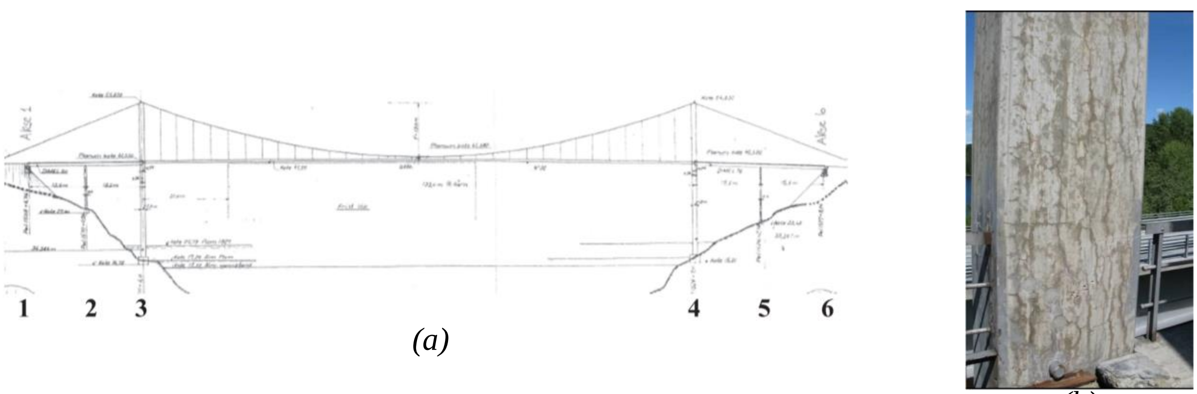
In 2010 the PAT-ASR project (Performance Assessment Tool for Alkali-Silica Reaction) has been established at Delft University of Technology in order to study the main aspects of ASR in concrete. The aim is to provide a tool able to characterize the reaction and its damage both at material level and in the sense of structural response.

4.1 Main case study: Nautesund bridge

Thanks to collaboration with the Norwegian Roads Public Administration, the main case study in the PAT-ASR project refers to the Nautesund bridge. The bridge was built in 1958 and demolished in 2009. Major signs of alkali silica reaction were found in the tower columns, which were extensively cracked. Prior to demolishing visual inspection and mechanical tests on cores and members were performed at the SINTEF Laboratory [32].

The ASR effects were stronger in the tower columns (sections 3 and 4 in Figure 3(a)) rather than in the support column (section 2 in Figure 3(a)). This can possibly be explained from the different confinement effects, induced passively by the reinforcements and actively by the loads. The damaging effect of a swelling ASR gel appears to be strongly influenced by compressive stresses, as reported in literature. The coupling effect between chemical and mechanical loading on ASR damage is a key point for testing this hypothesis.

Inspired by this observation, the PAT-ASR team performed an extensive experimental campaign to characterize the concrete adopted in the Nautesund bridge by performing micro to macro investigations. Furthermore modelling approaches at meso and macro level have been developed. The material model for structural analysis is based on the coupling between the chemical and mechanical loading and aims to be a complementary tool to be used in a structural assessment procedure. The experimental results regarding the mechanical tests on the Nautesund bridge are helpful data for the validation of the model.



(a)

(b)

Figure 3 – The Nautesund bridge: (a) configuration; (b) ASR damage in tower leg [32].

4.2 The structural modelling approach

Considering that a proper material characterization is extremely relevant, a multiscale material model [3, 33] has been selected to perform structural analyses (Figure 4). The model accounts for the micromechanical changes provoked by the ASR swelling. It is able to describe the stress-induced anisotropy effect of ASR, as well as the degradation of the mechanical properties resulting from the combined effect of chemical and mechanical loading. The coupled effect of chemical and mechanical loading is seen as a crucial point for explaining differences between results from laboratory tests and the observed behaviour of ASR-affected structures.

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 erosion of the aggregate and its swelling, together with a possible macro-mechanical load, can lead to crack propagation. The overall mechanical properties of concrete are analytically determined with the Mori-Tanaka homogenization method [34]. This theory defines the average 3D 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. The damage is related to crack families with different orientations. The damage evolution is based on the principles of linear fracture mechanics [35].

Even with a relatively simple micro-mechanical model, which allows analytical homogenization, the model turns out to well predict the behaviour of both sound and ASR-affected concrete and to achieve the goal of modelling the chemomechanical coupling. An analytical homogenization is preferred in order to facilitate its implementation in a finite element program.

This approach allows employing the outputs of the model in a more straightforward approach to be used in practice. Moreover, the model can be helpful to interpret and supplement laboratory tests, which are usually requested to assess the material behaviour of an existing concrete structure suffering by ASR.

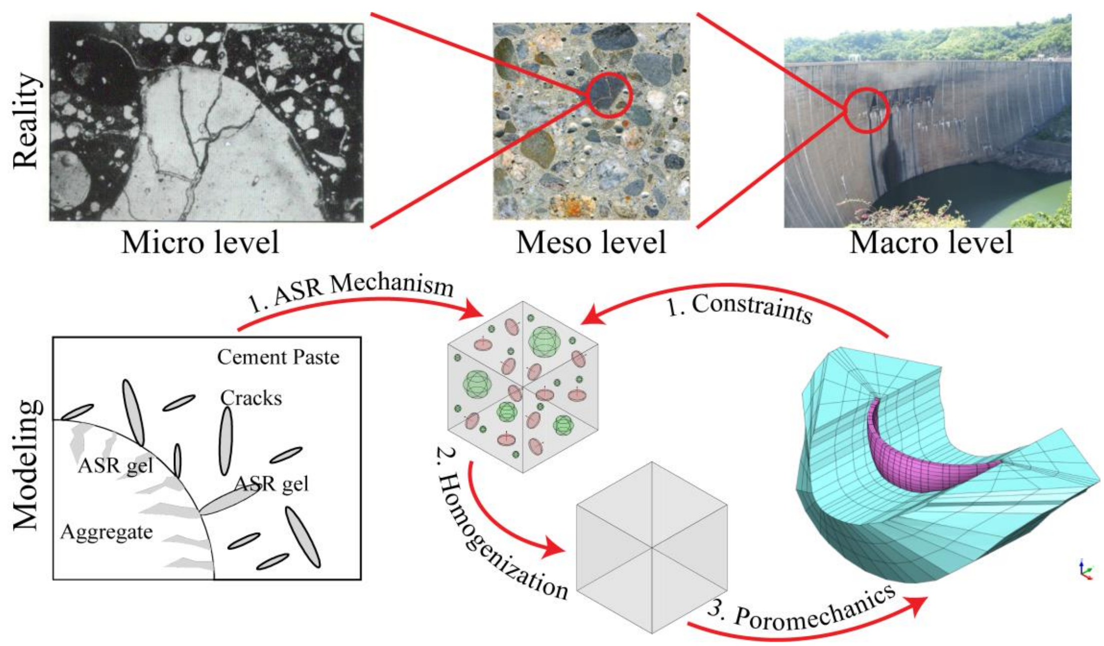


Figure 4 – Modelling procedure for structural analyses.

5 CONCLUSIONS

The alkali-silica reaction is a harmful reaction which can compromise the integrity and serviceability of concrete structures. Involving silica and alkali, respectively available in aggregates and cements, it creates a hydrophilic gel which expands and cause damage. This phenomenon is widely studied in different fields. Geologists and chemists investigated the mechanism of the gel formation; whereas civil engineers studied the mechanical impact both at material and structural level.

Regarding affected structures, one of the most important influencing factors are the mechanical boundary conditions. The damaging effect of the expansive gel appears to be subjected to compressive stresses, which can result in an anisotropic behaviour. In a structure the confinement effect on the gel can be induced passively from the reinforcements and actively from the loads. This is the major difference with most laboratory samples, stored in free expansion.

The main goal of the Performance Assessment Tool for Alkali-Silica Reaction (PAT-ASR) project [1] is an understanding of the consequences of ASR by employing both experiments and modelling approaches, at different scales. A large experimental campaign, involving various tests methods, has been carried out focussing on the characterization of a reference material, which belongs to the main case study: the Nautesund bridge. The experimental campaign has been established thanks to collaboration between Delft University of Technology and the Norwegian Public Roads Administration.

A multiscale material model for structural analysis [3, 33] is under development in order to couple the chemical and mechanical loading action in ASR-affected concrete structures. The model is able to couple the effects of chemical and mechanical loading, which appears to be a major characteristic of affected concrete in structures. The approach is based on a simplified micro-mechanical model to facilitate a further implementation in a finite element framework. The model appears as a complementary tool which can be adopted in combination with laboratory tests in structural assessment procedures.

ACKNOWLGMENTS

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