Challenges related to structural modelling and assessment of concrete structures affected by alkali-silica reactions

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ABSTRACT

Alkali-Silica Reaction (ASR) in concrete is a chemical process between dissolved alkali and hydroxyl ions from pore solutions in the cement paste, and reactive (amorphous) silica within the aggregates. The product of the chemical reaction is an alkali-silica gel that will increase in volume by water absorption. The result is expansion of the concrete and degradation of material properties. The deteriorating impact of ASR on concrete structures might be reduction in load bearing capacity, durability and service life.

In this paper, the effects of ASR on concrete material are reviewed, and the challenges related to modelling the effects of ASR on the structural scale are addressed. Finally, plans for structural assessment on parts of an existing bridge in Norway are announced.

Key words: Concrete, Alkali-Silica Reactions, Modelling, Structural Assessment

1 INTRODUCTION

Alkali-Silica Reaction (ASR) in concrete is a chemical reaction between alkali and hydroxyl ions (present in the pore solution) and reactive silica within the aggregates, where the product is a hydrophilic gel that will expand by water absorption. The rate of gel production and total gel volume are dependent on the alkali content, moisture, temperature and type of aggregates. As the gel is swelling within a confining matrix, a pressure develops in the gel that is balanced by tensile stresses in the cement paste, eventually leading to micro cracking. Considering a Representative Volume Element (RVE) of the concrete (a size much bigger than the heterogeneity, but much smaller than the dimension of a typical structure), the ASR will cause expansion (strains) and degradation of material properties: Young's modulus, tensile strength and compressive strength. The spatial variation of ASR induced strains on the scale of a RVE also introduce stresses. From a structural point of view, the material expansion cause displacements that might introduce large inner forces if boundary conditions or other structural parts restrain the displacements. In all aforementioned levels, ASR cause eigen- stresses and strains plus deformation discontinuities as micro or macro cracks. Each level, from meso to a structural level, is important to investigate in order to create a comprehensive model for structural assessment of concrete structures.

The main objectives of this paper is to a) review the mechanical effects of ASR on concrete material level, b) address the challenges related to modelling the effects of ASR on the structural scale and c) announce plans for a structural assessment, with increasing level of sophistication, on parts of an existing bridge in Norway.

2 EXPERIMENTAL EVIDENCE ON THE EFFECT OF ASR

2.1 Anisotropic expansion

Larive [1] observed larger expansion in the casting direction than perpendicular to the casting direction of specimens under load-free conditions. The casting direction may influence the orientation of aggregates and pores within the concrete. This will in turn determine the orientation of the gel pressure load and location of weaker zones prone for micro cracking, explaining the intrinsic anisotropic expansion observed by Larive [1].

The expansion of ASR affected concrete is also dependent on the state of stress, where the expansion is reduced in the restrained/loaded direction and transferred to the stress free directions [2, 3]. Multon [2] concluded that the volumetric ASR induced strain is independent of the state of stress, but recent experiments by Bishnu [4] show reduced volumetric strain (induced by ASR) under tri-axial stress conditions. This might be explained by a) an increased diffusion of gel into the surrounding paste with increasing hydrostatic pressure and b) a reduced damage (micro cracking) of the concrete skeleton, and thus the stiffness, due to a triaxial confinement from the external load.

The total expansion/strain of an RVE can be split into elastic (recoverable) strains and inelastic (unrecoverable) due to micro cracks, which are displacement discontinuities on a subscale (meso-level). The deterioration of the material should be related to the micro cracking, which leads to the discussion about ASR induced strain as an appropriate damage/degradation parameter for mechanical properties.

2.2 Degradation of mechanical properties and expansion as a degradation parameter

Esposito [5] carried out an extensive literature survey on the relation of ASR-induced expansion and mechanical properties based on accelerated tests of concrete specimens under free expansion, and from her study, it is clear that compressive strength, tensile strength and Young's modulus all degrade with increasing expansion. This relation is an important input for structural models dealing with the effect of ASR. However, experiments performed by Giaccio [6] of specimens with different reactive aggregates showed that even for the same level of expansion, the degradation of the mechanical properties were different. The reason was explained by the different cracking morphology caused by the different aggregates; the deterioration is mainly attributed to micro cracks in the cement paste and fissures at the Interfacial Transition Zone (ITZ) rather than the micro-cracks in the aggregates. The different cracking morphologies were related to the location of the gel formation. The aggregates with a reaction rim caused more damage in the cement paste and ITZ compared to aggregates with internal gel production.

One reason for this might be gel flow (in the case of a formed reaction rim) into initial flaws and created micro cracks in the cement paste, which enhance the damage when the gel exert a pressure inside these fissures. Whereas swelling of gel inside an aggregate cause stresses on the cement matrix through the expansion of the aggregate, and as result cause less damage in the cement paste and ITZ.

Further, the state of (average) stress on a RVE of concrete will also influence the degree and orientation of the deterioration of mechanical properties. In analogue to the expansion transfer, the mechanical properties will degrade more in the non-stressed directions due to the preferred orientation of micro cracks parallel to the stressed direction.

In addition, it is believed that stress relaxation in the cement paste around the reactive aggregates will reduce the pressure exerted by the gel and thus the stresses in the cement paste, which in turn, reduce the degree of micro-cracks. This creep effect is a time dependent phenomena, indicating that the rate of gel expansion is important for the development micro-cracks and thus the mechanical properties.

Based on the preceding discussion, one can argue that the ASR induced expansion (only), is not an appropriate parameter to describe the damage of concrete and thus the deterioration of mechanical properties. The ASR induced expansion of a RVE is partly viscoelastic deformation and partly displacement discontinuities (micro cracks), in which the latter degrade the mechanical properties. Even if the overall ASR induced expansion of two specimens are the same, the degree of micro cracks might be different, due to e.g. type of aggregate, ASR kinetics and stress history. Thus, a general relation between ASR induced strain and degree of deterioration of mechanical properties is too ambiguous.

3 CHALLENGES RELATED TO STRUCTURAL MODELING

Many of the models that have been demonstrated and/or validated on a structural scale model the concrete as a homogenous continuum and include the effects of ASR as induced strain, e.g. [7], [8], [9] and [10]. However, as stated by Alnaggar et al. [11], the disadvantage of all aforementioned models is the inability to simulate micro-crack patterns and crack distribution due to ASR, which limits their ability to predict the deterioration of ASR on mechanical properties. In addition, it also limits the ability of such models to explain the relation between concrete state of stress and expansion. Constitutive modelling of homogenized ASR affected concrete is challenging because ASR is a phenomenon on a sub-scale of concrete material level. Consequently, assumptions on relations between e.g. states of stress, ASR induced expansion and change of mechanical properties are necessary.

The current state, i.e. displacements, mechanical properties, stresses etc., of an ASR affected structure is a result of its history of temperature, moisture, alkali-leakage, stresses/forces and strains/displacement, showing the complexity of modelling ASR.

Field measurement of mechanical properties and displacements can be used to “diagnose” the current state. However, numerical simulations [12] of unloaded concrete cores, during swelling, showed rapid cracking due to the vanishing external stresses. This indicates that mechanical properties obtained based on specimens extracted from a structure might not represent the in-situ properties, increasing the challenges to perform a proper structural assessment.

3 STRUCTURAL ASSESSMENT OF AN ASR AFFECTED BRIDGE IN NORWAY

In Norway, there is a need for an increased knowledge about the effects of ASR on the structural level in order to do proper structural assessments of an aging infrastructure. There are several bridges suffering from ASR, e.g. *Elgeseter bru, Tromsøbrua and Tjelsundbrua,* in which the last one will be used as a case in the present PhD project.

It is envisioned to perform a structural assessment of parts on *Tjelsundbrua*. First, a simplified assessment based on the current state of the structure will be carried out. This will be done in a two-step procedure: 1) calculation of change of load actions due to ASR induced displacements and 2) evaluation of cross-sectional load actions against corresponding capacities including effect of ASR. The current configuration of the bridge, obtained from a 3D scan, and tests of mechanical properties of cores extracted from the structure will form the basis for the current state of the structure. Finally, more comprehensive finite element models will be evaluated and applied to predict the evolution of ASR in time.

REFERENCES

[1] Larive, Catherine. *Apports combinés de l'expérimentation et de la modélisation à la compréhension de l'alcali-réaction et de ses effets mécaniques*. Diss. Ecole nationale des ponts et chaussees, 1997.

[2] Multon, Stéphane, and François Toutlemonde. "Effect of applied stresses on alkali–silica reaction-induced expansions." *Cement and Concrete Research* 36.5 (2006): 912-920.

[3] Berra, Mario, et al. "Influence of stress restraint on the expansive behaviour of concrete affected by alkali-silica reaction." *Cement and Concrete Research* 40.9 (2010): 1403-1409.

[4] Gautam, B. P., et al. "Multiaxial Expansion-Stress Relationship for Alkali Silica Reaction-Affected Concrete." *ACI Materials Journal* 114.1 (2017).

[5] Esposito, Rita, et al. "Influence of the Alkali-Silica Reaction on the Mechanical Degradation of Concrete." *Journal of Materials in Civil Engineering* 28.6 (2016): 04016007.

[6] Giaccio, G., et al. "Mechanical behavior of concretes damaged by alkali-silica reaction." *Cement and Concrete Research* 38.7 (2008): 993-1004.

[7] Charlwood, R. G., S. V. Solymar, and D. D. Curtis. "A review of alkali aggregate reactions in hydroelectric plants and dams." *Proceedings of the international conference of alkali-aggregate reactions in hydroelectric plants and dams*. Vol. 129. 1992.

[8] Léger, P., P. Côté, and R. Tinawi. "Finite element analysis of concrete swelling due to alkali-aggregate reactions in dams." *Computers & structures* 60.4 (1996): 601-611.

[9] Ulm, Franz-Josef, et al. "Thermo-chemo-mechanics of ASR expansion in concrete structures." *Journal of engineering mechanics* 126.3 (2000): 233-242.

[10] Saouma, Victor, and Luigi Perotti. "Constitutive model for alkali-aggregate reactions." *ACI materials journal* 103.3 (2006): 194.

[11] Alnaggar, Mohammed, Gianluca Cusatis, and Giovanni Di Luzio. "Lattice discrete particle modeling (LDPM) of alkali silica reaction (ASR) deterioration of concrete structures." *Cement and Concrete Composites* 41 (2013): 45-59.

[12] Morenon, Pierre, et al. "Impact of stresses and restraints on ASR expansion." *Construction and Building Materials* 140 (2017): 58-74.