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Multiscale model of ASR-induced damage in concrete

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Micro Abstract
A multiscale micromechanical model for the prediction of the deterioration of concrete caused by Alkali Silica Reaction is presented. The gel pressure results in microcrack growth in the reactive aggregate and the surrounding cement paste. This damage process is formulated in the framework of linear elastic fracture mechanics applied at the scale of the aggregate and the cement paste. The model predictions are compared with selected experimental data.

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Introduction

Concrete structures such as pavements, dams and bridges, which contain reactive aggregates and sufficient moisture in the pore space, are susceptible to damage caused by the Alkali-Silica Reaction (ASR) [1]. ASR is a chemical reaction between alkali ions and silica in the aggregates leading to the formation of an expansive gel. This ASR gel swells in the presence of moisture, applying internal pressure in the voids and flaws existing in concrete. As a consequence, microcracking of concrete at the microscale is observed that manifests itself as overall material degradation and expansion at the macroscale [10]. In this extended abstract we present an overview of a micromechanics model for ASR degradation and expansion recently developed in [3], focusing on the role of internal pressure generated by ASR gel expansion in the pre-existing microcracks in aggregates and cement paste (see Figure 5 right).

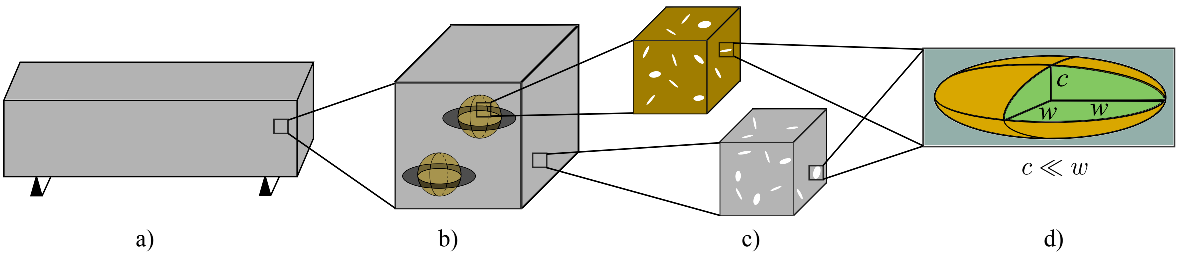


Figure 1. Multiscale characterization of concrete: a) Laboratory specimen; b) REV of concrete with distributed spherical aggregates; c) REV of cement paste and aggregate containing distributed microcracks; d) geometry of a penny-shaped microcrack.

1 Multiscale micromechanics model

The model is based on a multiscale approach (Figure 1). We consider REVs (Representative Elementary Volume) at two scales of observation: At the concrete level, characterized by distributed spherical aggregate particles embedded in the cement paste matrix, and at the level of individual aggregates and cement paste, characterized by microcracks embedded into the intact homogeneous aggregate and cement paste material. The microcracks are assumed to be penny-shaped with crack radius w and crack width c ($c \ll w$) that evolve due to an internal pressure induced by ASR gel. The relation of the rate of growth of microcracks in the aggregates and the cement paste is assumed to be governed by a gel distribution coefficient α, which represents the distribution of the ASR gel in the concrete composite.

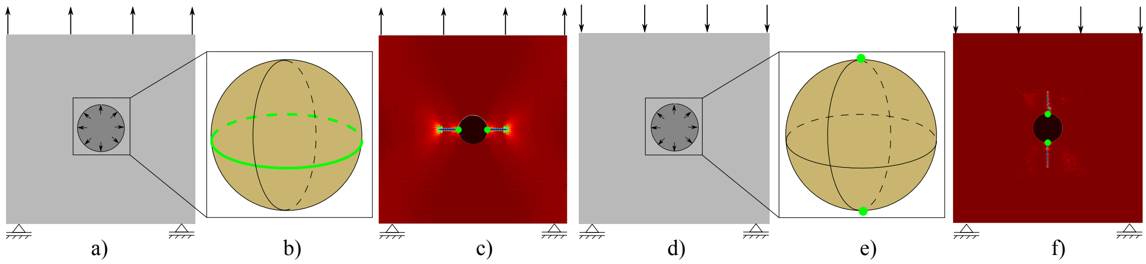


Figure 2. Crack initiation and propagation around an **expanding** aggregate subjected to uniaxial tension (a-c) and uniaxial compression (d-f). Figures a) and d) show the geometry and loading conditions, b) and e) show the micromechanical model predictions of the position of crack initiation while c) and f) show the crack path obtained from a numerical crack analysis using an interface fracture model [4]. Green points and lines denote the location of crack initiation.

The internal pressures are computed from the GRIFFITH energy balance [2] and then are inserted into the microporomechanics state equations [2] in order to obtain the volumetric expansion of the aggregates and the cement paste caused by growth of pre-existing microcracks. Considering the absence of external loading, these expansions can be viewed as Eigenstrains of the aggregate particles and the cement paste, which can be upscaled using LEVIN'S theorem to obtain the overall stress-free expansion of the concrete at the macroscale. The stiffness of concrete at the structural level can be determined using the framework of mean field homogenization [2, 9] assuming spherical aggregates with stiffness $\mathbb{C}^a$ embedded in the cement paste matrix with stiffness $\mathbb{C}^c$. Tensors $\mathbb{C}^a$, $\mathbb{C}^c$ take into account the distribution and density of microcracks in the aggregate and the cement paste, respectively.

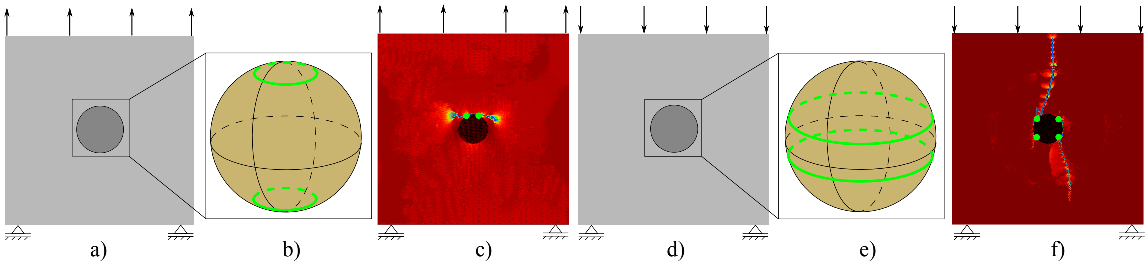


Figure 3. Crack initiation and propagation around a **non-expanding** aggregate subjected to uniaxial tension (a-c) and uniaxial compression (d-f). Figures a) and d) show the geometry and loading conditions, b) and e) show the micromechanical model predictions of the position of crack initiation while c) and f) show the crack path obtained from a numerical crack analysis using an interface fracture model [4]. Green points and lines denote the location of crack initiation.

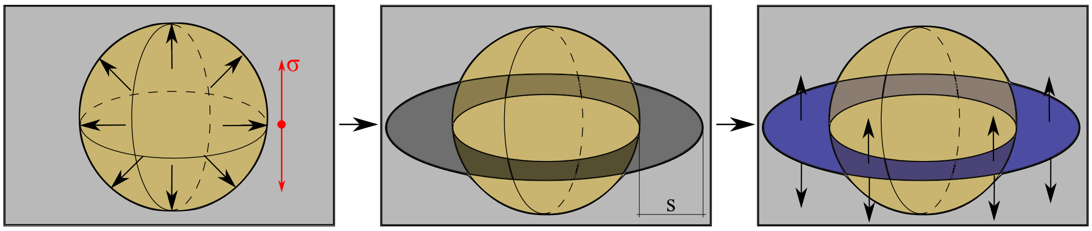
1.1 Aggregate expansion induced damage of cement paste

In addition to concrete deterioration due to growth of pre-existing microcracks, the aggregate expansion induces additional tensile stresses in the cement paste that could further lead to formation of new cracks in the cement paste. The tensile stresses around the aggregates can be computed using the exterior point ESHELBY tensor. For the case of expanding spherical aggregates without applied external loads or constraints, the stresses in the cement paste matrix around the aggregates are uniform. For now we will consider an applied load in order to determine the initiation point and shape of the crack which could form around the expanding aggregate. Imagine one expanding spherical particle embedded in the cement paste matrix. On the boundaries of the matrix, tensile (Figure 2a) and compressive (Figure 2d) loads are applied.

The location of maximum principal stresses, i.e., the presumable location of crack initiation, is shown in Figures 2b and 2e. Comparison of the micromechanical predictions with explicit numerical simulations (Figure 2c and 2f), using a variational interface model [4], are in agreement. Moreover, the results obtained numerically suggest an annular crack morphology forming around the expanding aggregates. Without any external loads or constraints, the annular cracks can form at any point around the aggregate since the stress state is theoretically uniform as was mentioned before. For simplicity, we assume the annular cracks to be aligned along the three orthogonal directions x, y, z. Here it should be noted that crack formation mechanisms around expanding and non-expanding aggregates are different. As an example, the location of crack initiation and crack path around non-expanding aggregate are shown in Figure 3.

1.2 Formation and propagation of annular crack

The aforementioned concept of annular cracking is employed in the proposed micromechanics model as follows: Firstly, the tensile stresses in the cement paste caused by aggregate expansion (Figure 4a) are calculated using the exterior point ESHELBY tensor. These tensile stresses lead to the formation of annular cracks of size s (Figure 4b) which can be found by calculating the stress intensity factor for annular crack propagating from the aggregate surface into the cement paste matrix. Thereafter, the ASR gel is assumed to i) fill the formed annular crack, ii) swell and iii) generate an internal pressure which drives annular cracking (Figure 4c). Finally, given the size of the annular crack, the additional expansion and additional degradation [7] of cement paste matrix are computed.



a) b) c)

Figure 4. Formation and growth of an annular crack: a) tensile stresses in the cement paste around the aggregate due to its expansion; b) initiation of annular crack of size s; c) ASR gel fills and pressurizes the annular crack.

1.3 Comparison with experimental data

The model predictions for concrete behavior at the macroscopic scale are compared with the experimental findings [5, 6, 8, 10]. Figure 5 presents the relation between ASR-affected concrete expansion and degradation: experimental point data and model predictions of the upper and lower bounds obtained using a realistic range of material parameters and microstructural geometrical properties [3]. As can be observed, the ranges of experimental and model results coincide. The parametric study and complete comparative analysis of experimental and simulation data can be found in [3].

Conclusions

In this work, a multiscale micromechanics model for concrete deterioration and expansion due to ASR gel induced microcracking in the aggregates and cement paste is discussed. Additional deterioration of cement paste due to aggregate expansion is accounted for by adopting the annular crack concept, which has been investigated analytically and numerically. Experimental observations lie within the theoretical bounds predicted by the micromechanics model.

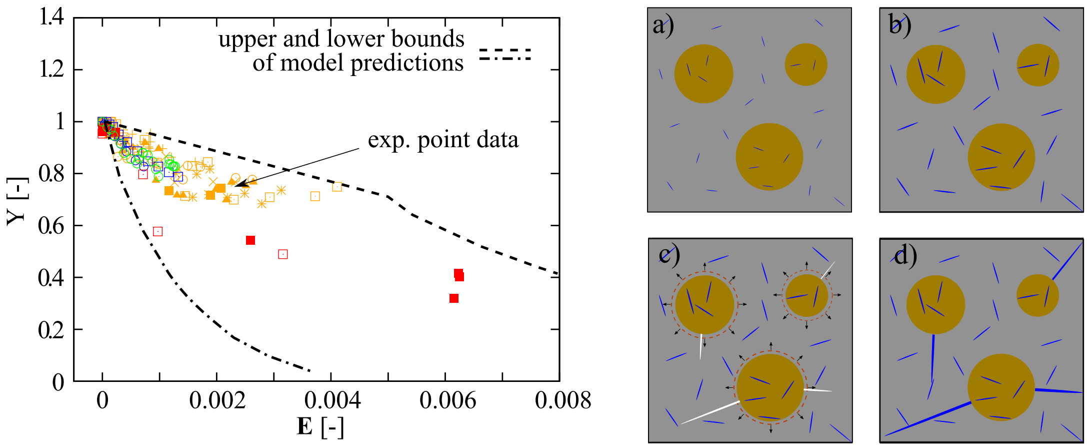


Figure 5. Left: Experimental predictions [5, 6, 8, 10] (denoted by orange, green, red and blue colors respectively) and model bounds for the expansion $\mathbf{E}$ vs. the normalized elasticity modulus Y of concrete at the macroscale. Right: Mechanics of the damage model of concrete due to ASR induced gel expansion: a) gel fills the microcracks in aggregates and cement paste; b) ASR gel swelling induces internal pressure, and microcracks grow; c) aggregate expansion causes formation of new cracks in the cement paste; d) newly formed cracks are filled with ASR gel and propagate due to its swelling.

Acknowledgements

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