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Macroscopic chemo-mechanical modeling of alkali-silica reaction of concrete under stresses

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HIGHLIGHTS

- Macroscopic chemo-mechanical modeling of alkali-silica reaction of concrete under stresses was proposed.
- Creep as well as chemical strain by alkali-silica reaction was taken into account as a prescribed strain.
- Damage model was also implemented to take into account the degradation of Young's modulus.
- The simulation turned out well consistent with the experimental results.

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ABSTRACT

Creep plays an important role for deformation of ASR-affected structures which are subjected to various stresses or restraint. It still remains controversial, however, how the combination of creep and stress states or restraints affects expansion. In this study, creep was taken into account as a "prescribed" strain computed at previous timestep and the model was implemented in a chemo-mechanical calculation. The calculation was validated with previous experiments in which the expansive behavior of concrete subjected to stresses had been monitored under different applied stresses and restraint conditions. The results showed that the calculations gave consistent results with the experiments, supporting the validity of the model and the importance of taking creep into account.

1. Introduction

The structures affected by Alkali-Silica Reaction (ASR) are frequently subjected to permanent loads such as dead weight, permanent external loadings or pre-stressing which make the strain variations within the structures rather complex to be analyzed. Steel reinforcement in concrete also restrains the expansion of concrete which can make the problem even more complicated [1]. In highly stressed or restrained concrete, ASR-induced expansion shows strong anisotropic behavior [2–7]. In concrete subjected to long-term stresses or restraint, creep plays an important role in the delayed deformation of ASR-affected structures. This may also have a significant influence when an ASR-affected structure is submitted to external pre-stressing or jacketing for mitigating ASR effects. The complex combination of ASR and creep therefore shall deserve refined modeling in order to provide efficient tools for structural re-assessment. Though some numerical approaches have been developed, it is not clear how to model and implement creep in the numerical analysis.

There have been numerous experiments for uni-axially compressed/restrained concrete while expansion data under multi-axial restraint are still lacking. The exhaustive experiments by Multon and Toutlemonde [2] revealed that volumetric expansion imposed by ASR is almost constant whatever the stress conditions. They also reported that expansion can transfer to less-compressed direction, resulting in strongly anisotropic expansion. This is called "expansion transfer effect" and has been confirmed by many experiments: restraint by steel bars embedded in concrete [4]; restraint by steel rods installed externally [5]. Dunant and Scrivener, however, claimed that the microstructural situation is more complicated, from expansion tests under uni-axial stresses (0, 5, 10 and 15 MPa) and numerical simulations [8]. They observed experimentally that the volumetric variations above 10 MPa are only derived from lateral expansion and that no expansion is observed in the longitudinal direction. The numerical simulation

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showed that the orientation of cracks changes the development of the expansive behavior. According to the experiments by Berra et al., expansion transfer effect may depend on the type of reactive aggregate [9].

In the previous experimental studies, the creep strains are subtracted from the measured strains with an assumption that the instantaneous and creep strains of ASR-reactive concrete are the same as those of non-reactive concrete. The experimental evidence, however, shows that mechanical properties, especially Young's modulus, are also degraded due to ASR expansion. These interactions should be taken into account when interpreting the experimental results, especially because characteristic times of creep and ASR development may be comparable.

Based on this perspective, numerical analysis is a promising way to cope with these phenomena [10–16]. Regarding how to model and implement creep in the analysis, different approaches have been performed by different numerical tools. In the model by Saouma et al. [11], the effective modulus was used to take into account creep effect. Multon and Toutlemonde [2] and LMDC model [12] also adopted an effective modulus equal to one third of the instantaneous modulus at 28 days. In Lattice Discrete Particle Modeling by Alnaggar et al. [13], creep strain was modeled with macroscopic B3 model [17] and added to mesoscopically simulated result. Grimal et al. developed a rheological model to take into account creep and mechanical damage [14]. A recent microscopic approach has been developed by Giorla et al. to simulate the realistic damage in the paste by ASR expansion [18].

It still remains controversial how the combination of creep and stress states or restraints affects expansion and how to implement creep effect in the calculation. Especially implementation of creep in the numerical analysis depends on the global frame of mechanical calculation such as elasticity, elasto-plasticity and so on. Complicated models would be beneficial from the scientific approach, but there are many parameters to be calibrated so that applicability of the model to various concrete with various aggregates is not obvious. A recent paper reported that the LMDC model shows reliable applicability to various concretes with various aggregates and various water-cement ratios [12]. From the practical viewpoint, the many physical properties should be calibrated with a small number of concrete cores extracted from the structures affected, thus, models with less unknown parameters to be calibrated might be recommended. Numerical analysis based on macroscopic chemo-mechanical models, in this regard, is a promising way to have as few parameters as possible. In macroscopic chemo-mechanical models, however, it has not been validated how to model and implement "superimposed" creep and ASR strains in the analysis.

This study describes the macroscopic chemo-mechanical model on the basis of a chemo-visco-elastic model proposed to take into account the influence of creep on the expansive behavior of concrete subjected to compression and restraint. The validation of the model with available experiments is carried out.

2. Macroscopic chemo-mechanical modeling

This study describes the macroscopic model on the basis of chemo-mechanical model proposed to take into account the influence of creep on the expansive behavior of concrete subjected to compression and restraint.

2.1. Chemo-visco-elasticity

Based on the theoretical chemo-elasticity of concrete [19,20], total strain can be expressed as a sum of strains including viscoelasticity, as in the following Eq. (1).

$$\varepsilon = \varepsilon_e + \varepsilon_\chi + \varepsilon_{cr} + \varepsilon_{sh} \quad (1)$$

in which the concrete total strain tensor ε is sum of four strains, respectively: elastic strain ε_e; ASR-induced chemical strain ε_χ; creep strain ε_{cr}; shrinkage strain ε_{sh}. Elastic strain relates to stress tensor by Hooke's law:

$$\sigma = (K - 2/3 \times G) tr\varepsilon_e I + 2G\varepsilon_e \quad (2)$$

where K and G are, respectively, the bulk modulus:

$$K = E_c/(3 \times (1 - 2\nu)) \quad (3)$$

and the shear modulus:

$$G = E_c/(2 \times (1 + \nu)) \quad (4)$$

where E_C is the Young's modulus and ν is the Poisson's ratio of the concrete.

Assuming that ASR, shrinkage and creep strains are known, stresses and strains can be calculated with Eq. (2).

The details for mathematical models for ASR expansion and creep are described in the following.

2.2. ASR expansion

2.2.1. Time-evolution model

According to the references [19,20], ASR-induced expansion can be formulated as the product of an expansion potential ε_∞ by a kinetic function $\xi(t)$.

$$\varepsilon_\chi = \varepsilon_\infty \xi_{(t)} \quad (5)$$

This kinetic function represents the dimensionless degree of reaction which evolves from 0, at the beginning of reaction, to 1, at the end of reaction and it can be described in a given moisture and temperature state with two parameters as in the following Eq. (6).

$$\xi_{(t)} = \{1 - \exp(-t/\tau_C)\}/\{1 + \exp(-(t - \tau_L)/\tau_C)\} \quad (6)$$

where t is elapsed time, τ_C and τ_L are characteristic time and latency time, respectively (for the schematic image, see Fig. 1) [7].

2.2.2. Intrinsic anisotropy

It has been sometimes observed that the expansion along the vertical direction (parallel to casting direction) is much larger than that of horizontal direction, when expansion tests on cylinder concrete specimens have been performed [7,21]. This intrinsic anisotropy is due to preferential orientation of microcracks and interfacial transition zone perpendicular to casting direction, especially in case of flat coarse aggregates resulting in larger expansion in the vertical direction. An intrinsic anisotropy coefficient α_i can be expressed as the ratio of horizontal expansion ε_h to vertical expansion ε_v, which can be written:

$$\alpha_i = \varepsilon_h/\varepsilon_v \leqslant 1 \quad (7)$$

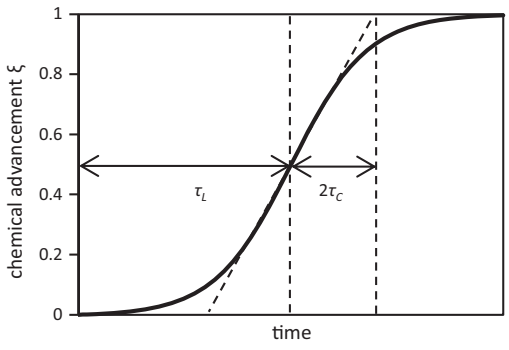

Fig. 1. Schematic representation of chemical advancement including physical meaning of latency and characteristic times. After [7].