Modelling of the mechanical behavior of concrete affected by alkali-aggregate reaction

Modelagem do comportamento mecânico do concreto afetado pela reação álcali-agregado

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Resumo

A Reação Álcali-Agregado (RAA) é uma das principais causas de danos químicos em estruturas de concreto, especialmente aquelas expostas à umidade, levando à fissuração, às deformações excessivas e ao aparecimento de tensões. Esse trabalho apresenta os resultados de um estudo numérico através do qual o comportamento mecânico de estruturas atingidas pela RAA é simulado sob a hipótese do acoplamento entre as tensões de confinamento e a reação.

Palavras-chave: Concreto, expansão química, método dos elementos finitos.

Abstract

Alkali-Aggregate Reaction (AAR) is a major cause of chemical damage in concrete structures, especially those exposed to moisture, leading to cracking, excessive strains and stress formation. This work presents the results of a numerical study where the mechanical behaviour of AAR attained structures is simulated under the assumption of coupling between confinement stresses and the reaction.

Keywords: *Concrete, chemical expansion, finite element method.*

1. Introduction

Overview of structural damages related to AAR

Alkali-Aggregate Reactions (AAR) are chemical processes involving alkalis present in Portland cement, siliceous minerals found in some kinds of aggregates and water (Capra and Sellier, 2001), having as main consequences on concrete the formation of an hygroscopic expansive gel, swelling and cracking. Bridges, pavements and dams are examples of structures susceptible to this deleterious reaction, which only occurs in the presence of water. Recently, in Brazil, the AAR was also identified in buildings foundations (Silva, 2007), representing considerable risks to structural safety. Economical as well as safety aspects justifies the numerous experimental (Grattan-Bellew, 1995; Ferraris et al., 1996; Larive, 1997; Multon and Toutlemonde, 2006) and numerical studies (Saouma and Perotti, 2006; Carrazedo and Lacerda, 2006; Comi et al., 2009; Grimal et al., 2009) concerning the characterization and modelling of the mechanical behaviour of attained structures.

The deleterious effects of AAR on concrete structures are due to several microscopic and random parameters related to the reaction itself and to the intrinsic complexity of the material (Grattan-Bellew, 1995; Larive, 1997). Although it is common sense that the AAR kinetics is affected by confinement stresses, the lack of experimental information concerning this subject led to the proposition of a number of models where the AAR is considered as uncoupled from stresses. Based on an extensive laboratory program, Larive (1997) concluded that such an assumption is valid for unconfined concrete members, which are free to expand in at least one direction. More recently, Multon and Toutlemonde (2006) indentified the reducing effect of confinement on AAR expansion by means of triaxial tests performed on reactive concrete samples, which presented a decrease on reaction evolution and gel formation.

The present work consists of the incorporation of AAR-stress coupling to the uncoupled model firstly proposed by Farage et al. (2004) based on Ulm et al. (1999), so as to extend its application to structures under more sophisticated loading and boundary conditions.

2. Materials and methods

Constitutive model of affected concrete

The main assumptions of the proposed model are: (a) AAR-evolution is coupled to confinement stresses; (b) the concrete damage and the anisotropic behaviour are represented by means of a smeared crack approach. The analogue model shown in Figure 1(a), which was adapted by Farage et al. (2004) from Ulm et al. (1999), represents the solid concrete skeleton and the expansive AAR-gel in parallel. The gel imposes an AAR-induced strain ε_{ch} to the system and is considered to behave linearly, as well as the concrete's solid skeleton, whose elasticity is limited by a cohesive joint element characterized by the tensile strength σ_i. The equilibrium and compatibility conditions are given, respectively, by Equation 1 and Equation 2:

$$\sigma = \sigma_m - p_g \qquad (1)$$

where σ is the total stress, σ_μ is stress on the concrete skeleton and p_g is gel pressure,

$$\varepsilon_\mu = \varepsilon - \varepsilon_{ch} \qquad (2)$$

where ε is the total strain, ε_μ is the concrete skeleton's strain and ε_{ch} is the AAR-induced strain. Gel pressure, p_g, is given by Equation 3:

$$p_g = E_g\,(\varepsilon_{ch} - \varepsilon) \qquad (3)$$

where E_g is the gel's Young's modulus.

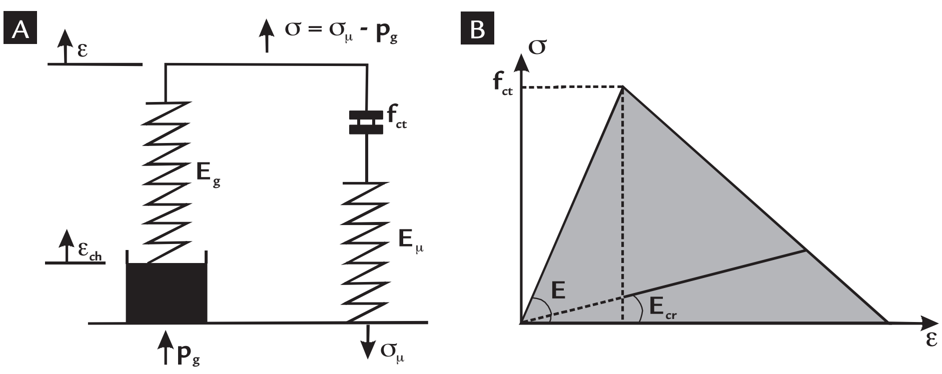

Figure 1
One-dimensional representation of the adopted constitutive model:
(A) Analogue model.
(B) Stress-strain relation.

Stress-strain relation and crack model

In the assumed one-dimensional representation of the stress-strain relation, shown in Figure 1(B), the tensile strength f_{ct} limits the intact state for the material. Such a behaviour is generalized for three dimensions through the Rankine strength criterion, adopted as a crack detection surface, given by Equation 4, where σ_i (with i = 1,2,3) are the principal stresses:

$$\sigma_i - f_{ct} = 0 \qquad (4)$$

In the framework of the classic theory of smeared crack finite element approach, the total strain rate ε is not decomposed into its intact and damaged contributions (Feenstra et al., 1991). The cracked material is represented in a homogeneous manner by replacing the original elastic isotropic tensor by an anisotropic one, which gradually introduces degradation to the system. This model derives from the concept of cohesive crack opening proposed by Hillerborg et al. (1976) and Lemaitre (1985), integrated to the crack band model (Bazant and Oh, 1983). In Figure 1(B), the pos-cracking modulus E_{cr} is defined as a function of the energy release rate required to crack a unitary area of the material, g_f, which is a material's property obtained experimentally from the stress-displacement relation. Regarding crack orientation, it was adopted the fixed orthogonal crack model - the amount of cracks at a point being limited by the number of stress components of the considered problem (3 in three-dimensional, plane strain and axisymmetric cases and 2 in plane stress cases) (Rots and Blaauwendraad, 1989).

Reaction kinetics coupled to confinement stresses

In Equation 2, ε is a function of AAR gel expansion ε_{ch}, given as input data to the model. In order to consider the AAR evolution as coupled to confinement stresses, the present work proposes the integration of two laws available in the literature to represent gel expansion: Curtis's empirical *coupled* law (Curtis, 1995) and Larive's *uncoupled* equation (Larive, 1997). Originally, Curtis (1995) describes AAR expansion rate in concrete $\dot{\varepsilon}_{ch}$ by means of Equation 5:

$$\dot{\varepsilon}_{ch} = \dot{\varepsilon}^u - K\log\left(\frac{p}{p_0}\right) \tag{5}$$

$\dot{\varepsilon}_{ch}$ is considered as constant ($\frac{\varepsilon_{ch}}{\varepsilon^u}$) under hydrostatic pressures up to a specific value p_0; pressures in the interval $p_0 \leq p \leq p_{max}$ have a reducing effect over the chemical strain rate and for $p > p_{max}$ the expansion rate is interrupted. K is an empirical quantity obtained from *in situ* measurements, from which p_{max} is obtained. In the present work, the effects of temperature and moisture conditions are incorporated to Curtis's equation by considering $\dot{\varepsilon}^u$ in Equation 5 as given by Larive's law, resulting in Equation 6:

$$\dot{\varepsilon}_{ch} = \left(\frac{\varepsilon_\infty\left(e^{\frac{T}{\tau_C}} + e^{\frac{-T+\tau_1}{\tau_C}}\right)}{\tau_C\left(1 + e^{\frac{-T+\tau_1}{\tau_C}}\right)^2}\right) - K\log\left(\frac{p}{p_0}\right) \tag{6}$$

where T is the time, ε^u is a function of three independent parameters: asymptotic volumetric strain ε_∞, latency time τ_1 and characteristic time τ_C. According to Larive (1997), ε_∞ is the maximum value reached by the chemical expansion in free conditions, while τ_1 and τ_C are parameters which express temperature and moisture influences on the reaction kinetics. Those three quantities may be obtained from experimental measurements taken from reactive concrete samples.

Numerical implementation and application

The model was implemented in a program developed in FORTRAN for nonlinear analysis of two-dimensional problems via Finite Element Method through three-nodded triangular elements, in plane strain state. The resulting system of nonlinear equations is solved by a Newton-Raphson iterative incremental technique. The initial stiffness matrix is used as approximation for the discrete Jacobian and kept constant throughout the elastic analysis. Post-cracking calculations are made on a new basis, determined by crack directions, which requires bookkeeping of the directions of principal stresses related to the instant of crack initiation (Farage et al., 2004). This coupled model is applied herein to simulate the mechanical behaviour of a dam wall subjected to AAR. It is important to notice that the aim of this application is to provide a means of comparison between the former uncoupled and the coupled model - a more realistic simulation relies on comprehensive parametric evaluations based on experimental observations.

Figure 2 shows the adopted geometric, boundary and loading conditions. The mesh comprises 1474 nodes and 2779 elements. For the water it was adopted γ_w=10kN/m^3 and for the concrete γ_μ=24kN/m^3 , ν_μ=0.23, E_μ=1.82x10^{4}MPa, g_f=4.80x10^{6}MPa.m and f_{ct}=3.50MPa. For the gel, it was assumed the same mechanical properties (E and ν) as those of concrete, as homogenized values for the whole material. According to Farage (2000), although no experimental information is available about the mechanical properties of the gel, these values were adequate. As the solution method adopted by the program does not update the stiffness matrix, such values did not affect the analysis of the problem. The adopted AAR-curve parameters (Equation 6) are: ε_∞=0.196, τ_1=3.34 years and τ_C=8.29 years - those values were adapted from Larive's experiments (Larive, 1997), which, up to this date, is considered as the most comprehensive experimental study on this subject available in the litterature.

3. Results and discussion

Figure 3 compares the gel pressure evolution (Pgel) in the concrete wall evaluated via the uncoupled and the coupled models. The following ages were chosen with respect to the AAR evolution: 10 years, when there is no evidence of AAR effects in an actual structure, 40 years when, in general, AAR cracking is more obvious and 48 years, when supposedly a stabilization occurs.

As one can notice by comparing the figures, in spite of the fact that the structural self-weight and water loading impose some confinement pressure to the lower right region of the wall, the uncoupled model predicts internal pressure due to AAR-gel expansion, which, consequently, leads to cracking in that part of the structure. That situation, though, does not correspond to the actual behaviour of an attained structure under confinement - concrete walls like the one simulated herein present cracks mainly on surfaces where the reaction evolves freely. On the other hand, the coupled model accounts for the reducing effect of confinement stresses on the reaction evolution, as reflected by the lower gel-pressure values in the confined regions and, as a consequence, by a decrease on the amount of cracked finite elements. For illustrative purposes, Figure 4 shows the cracking pattern obtained from the two models by considering a 48 year AAR evolution – as previously indicated in Figure 3, cracking spreads more widely when the uncoupled model is applied. When applying the coupled model, cracking is mostly concentrated around the free surface and also on the bottom left region, while the uncoupled one allows it to spread towards the structure's core.

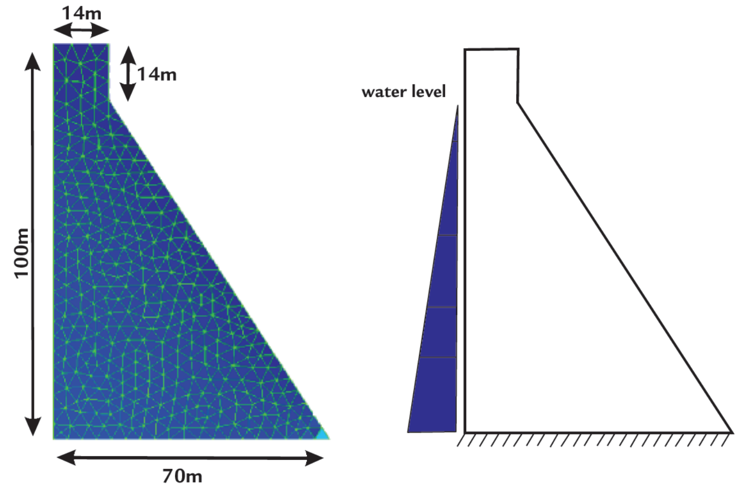

Figure 2
Geometric, boundary and loading conditions adopted for the modelled dam.

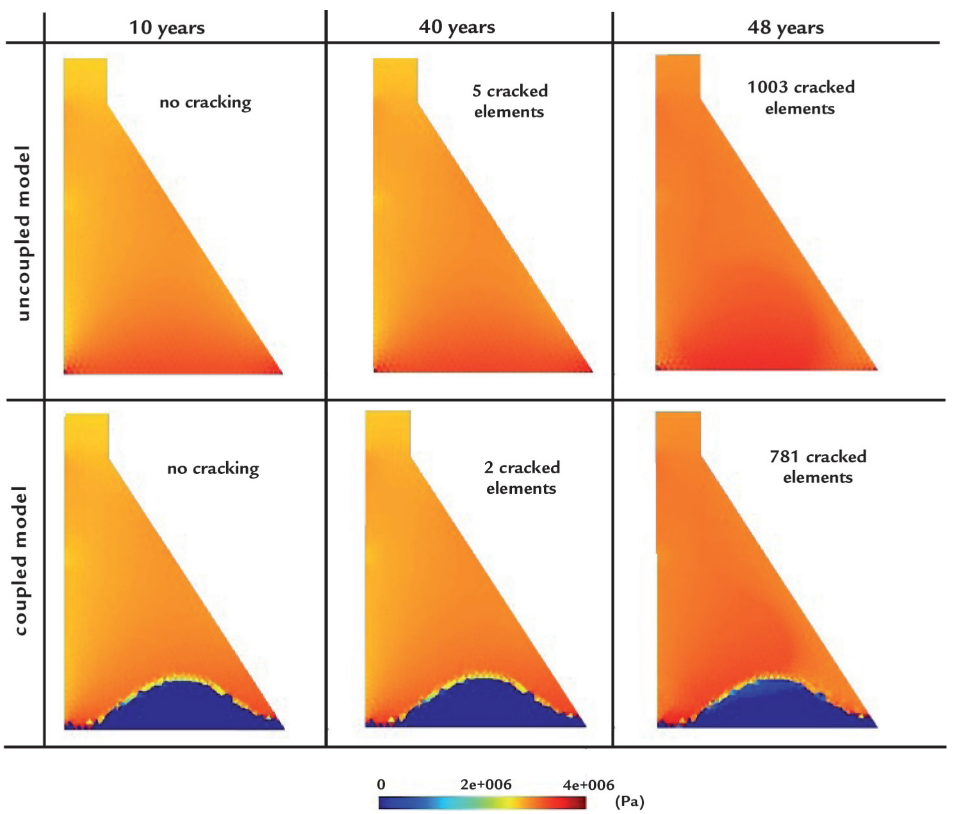

Figure 3
Internal pressure and cracking evolution obtained from the uncoupled and the coupled models at the ages of 10, 40 and 48 years (gel pressure given in Pa).

4. Conclusions

This work indicates that the proposed mechanical model of concrete attained by AAR is able to adequately simulate the coupling between the AAR expansion and confinement stresses. The obtained results encourage the application of the present model to real world problems, considering a higher level of complexity concerning geometry, loading and boundary conditions. To this end, the authors intend to spend some effort to improve the computational code, in order to optimize and to apply high performance computing platforms in a 3D version of the current program. Parametric studies concerning the AAR evolution and confinement effects are paramount so as to properly account for the mechanical-chemical coupling in the structural simulations.

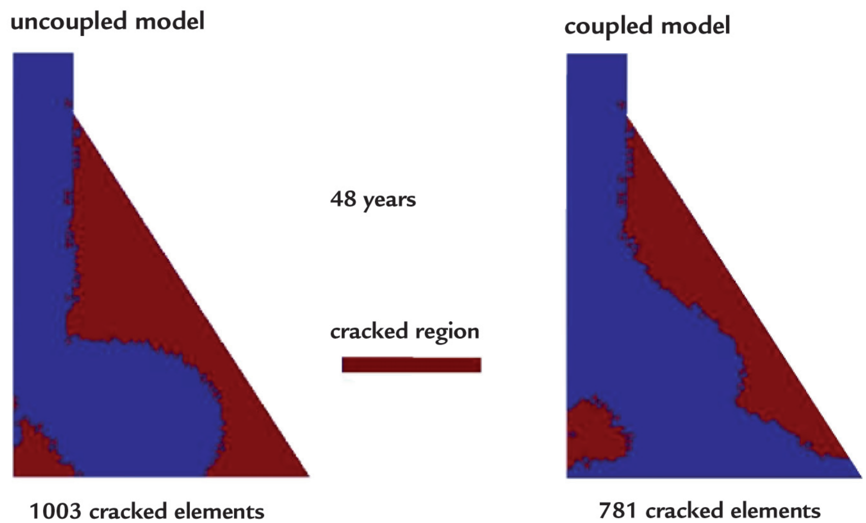

Figure 4
Cracking maps obtained from the uncoupled and coupled models at the age of 48 years.

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