CONCRETE MODELLING FOR EXPERTISE OF STRUCTURE AFFECTED BY ALKALI AGGREGATE REACTION

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Abstract

The alkali aggregate reaction (AAR) affects numerous civil engineering structures and is responsible for irreversible expansion and cracking which can affect their functional capacity.

In order to control the safety level and the maintenance cost of its hydraulic dams, Electricité de France (EDF) must reach a better comprehension and a better prediction of the expansion phenomena. For this purpose, EDF develops a numerical model based on the finite element method in order to assess the mechanical behavior of degraded structures. Obtaining a good prediction of expansive phenomena requires the identification and realistic modelling of the physical, chemical and mechanical phenomena.

The model takes into account the following phenomena:

- The mechanical damage
- The creep of concrete
- The stress induced by the formation of AAR gel.

Coupling between the different phenomena (creep, AAR and anisotropic damage) are taken into account through a rheological modelling. Experimental results obtained on concrete cylinders and beams affected by AAR are simulated to verify whether the model can describe the behavior of degraded structures. The results showed the capability of the model to predict the experimental behaviour of beams subjected to AAR. In order to obtain such prediction, it is necessary to take into account all the phenomena occurring in concrete.

Keywords: Alkali aggregate reaction; durability; modelling; structure expertise

1 INTRODUCTION

Concrete can be subjected to various degradation mechanisms which reduce the durability of the structure. One common form of degradation is the reaction between the reactive siliceous phases of the aggregates and alkalis of the cement. This reaction develops swelling and cracking involving a decrease of the functional capacities of civil engineering structures such as hydraulic dams. The reaction results in the formation of a gel that absorbs water. Gel precipitates in the cement paste pores connected to the reactive aggregates. When the volume of gel reaches the volume of the available porosity, a swelling pressure leads to expansion and cracking. In order to evaluate the safety level and the maintenance costs of its dams, "Electricité de France" (EDF) needs a better understanding and a better prediction of the swelling phenomena. In this context, a numerical model integrated in a finite element computer code has been developed by EDF and LMDC to simulate AAR-affected structures. One of the purposes of this model is to quantify both swelling and damage in terms of anisotropy and amplitude. Recent experimental results [1] are simulated to check the model robustness. This paper is divided in two parts: first a brief summary of the model is given, and then the behavior of various reinforced concrete reactive beams stored in different moisture and loading conditions has been reproduced. Finally, results are discussed regarding model assumptions.

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2 MODEL DESCRIPTION

The main developments brought by this model concern interaction between AAR gel and long term strain (creep) [2] on the one hand, and the swelling anisotropy induced by oriented cracking on the other hand. A particular attention is also paid to model moisture effects both on AAR and long term strain (shrinkage). As a consequence the AAR swelling depends on all these elementary phenomena.

Acker [3] suggested that the basic creep of concrete is mainly due to the CSH behaviour (CSH sliding and consolidation). Recent experimental evidences proposed by Bernard [4] confirm this assumption. Therefore, we develop a Visco-Elasto-Plastic (VEP) orthotropic damage model including chemical AAR pressure. To model CSH sliding and consolidation the model is separated in two levels: A first rheological level (VEP in Figure 1) is based on a division of the strain and stress state in a spherical part (module VEP^s in Figure 2(a)) and a deviatoric part (module VEP^d in Figure 2(b)). The response of the CSH structure under hydrostatic stress (consolidation) is modeled by the spherical part while the deviatoric part takes into account the CSH sliding (without volumetric change) under shear stress.

A second plastic level (VD^t in Figure 1), linked to an orthotropic AAR traction damage model allows to model large strains encountered into AAR problem. In Figure 2, P_w is the capillarity pressure present in the porosity of the concrete. P_g represents the AAR gel pressure. The plastic level (VD^t) allows relaxation of self equilibrated tensile stresses induced by the gel pressure around reactive aggregates in order to regulate the tensile damage. The rheological module (VEP^s and VEP^d) also contributes to the tensile damage mitigation and allows a realistic modelling of triaxial compressive creep.

2.1 Rheological module

The detailed rheological model is presented in Figure 2(a) for the spherical part and in Figure 2(b) for the deviatoric part. It accounts for the multiscale porous structure of the cement paste: '1' for the micro capillary porosity and '2' for the CSH inter layer porosity. The constitutive relations used for each module are basically the same, differences remaining in the fitted coefficients used.

2.2 AAR Plastic module

This VD^t module takes into account an increase of plastic strain when the concrete is submitted to tensile stresses induced by AAR. The AAR plastic strain rate is given by equation 1:

$$\dot{\varepsilon}_{vp} = \varepsilon_0 \frac{1}{\left(1 - D_{AAR}\right)^2} \dot{D}_{AAR} \tag{1}$$

In this phenomenological equation, ε_0 is a parameter fitted in accordance with experimental results given in [1,5], D_{AAR} is the AAR damage second order tensor. According to the previous works the damage eigen values are estimated with effective tensile stresses evaluated in the rheological model (Figure 2(a) and (b)):

$$D_{AAR} = 1 - \exp\left[-\frac{1}{m} \left(\frac{\min\left(\tilde{\sigma}, b_g.P_g\right)}{\tilde{\sigma}_u} \right)^m \right] \tag{2}$$

Where $\tilde{\sigma}$ is a principal effective tensile stress governed by the Rankine orthotropic criterion, $b_g.P_g$ is the gel pressure effect on the concrete skeleton (P_g is the gel pressure defined below and bg is a constant parameter playing the same role of the Biot coefficient in the porous mechanic theory) . m and $\tilde{\sigma}^u$ are damage evolution law parameters. The constitutive law linking different states variables of the model is defined by:

$$\sigma = (1-D):\left(\underbrace{C^0 : (\varepsilon - \varepsilon_{vep} - \varepsilon_{vp} - \varepsilon_{th})}_{\tilde{\sigma}} - (b_g P_g + b_w P_w) I \right) \text{ with } D = \max(D_{AAR}, D_{mech})$$

$$\text{and } D_{mech} = 1 - \exp\left[-\frac{1}{m}\left(\frac{\tilde{\sigma}}{\tilde{\sigma}_u} \right)^m \right] \tag{3}$$

In this law, σ is the apparent stress, C^0 the stiffness matrix of sound material, ε the total strain, ε_{vep} the total creep and shrinkage strains, ε_{th} the thermal strains, $b_w P_w$ the water pressure effect and $b_g P_g$ the AAR gel pressure effect.

2.3 Modelling of alkali aggregate reaction

The gel pressure modelling is based on the assumption of uncoupling between stress and AAR gel formation. Eq. 4 gives the swelling pressure induced by AAR "P_g":

$$P_g = M_g \left[A V_g - (A_0 V_g + b_g tr\varepsilon)^+ \right]^+ \tag{4}$$

Where M_g is an elastic modulus, b_g is an effective strain coefficient, V_g is the maximum gel volume fraction that can be created by the AAR and $(\,)^+$ is the positive part of equation. A is the chemical advancement of the reaction (increasing from 0 to 1), $A_0 V_g$ is the gel volume necessary to fill the porosity connected to the reactive aggregates. Eq. 5 gives A by a law inspired from Poyet's works [6,11]:

$$\dot{A}(Sr,t) = \alpha_0 . \exp\left[\frac{Ea}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_{corr}} \right) \right] . \frac{(Sr - Sr^0)^+}{1 - Sr^0} . [Sr - A(Sr,t)] \tag{5}$$

Where α_0 is a relevant parameter for the kinetics, Ea is the activation energy of the AAR, R the gas constant, T_{ref} is the absolute temperature of the test where α_0 is evaluated and T_{corr} is the temperature where the test is carried out. Sr and Sr^0 are, respectively the current saturation degree, and the smallest saturation degree necessary to allow the chemical reaction.

3 MODELLING TEST ON REACTIVE CONCRETE BEAMS

In order to validate such models, the "Laboratoire Central des Ponts et Chaussées" (LCPC) with EDF as a partner, carried out a large experimental program. The experimental results are given by [1]. The behaviors of beams and specimens placed in various moisture and mechanical conditions were measured in order to investigate the coupling influence of the stress state and supply of water on the swelling development. After a calibration phase, detailed in [7], of the model parameters on specimens, we have simulated the beams of this experimental program to verify whether the model was able to describe their behaviors. Once the model parameters of both sound concrete and AAR pressure are fitted, we test the model on various concrete beams studied in [1]. These beams have been kept during nearly two years in controlled atmosphere at 38°C and 30% RH. Lateral faces were water isolated and submitted on the upper and lower faces to moisture boundary conditions specified on Figure 4*:* the lower parts of these beams were continually immerged in 70 mm of water in chemical equilibrium with the pore solution of the concrete. During the first 424 days of the test, the upper faces of these beams were subjected to drying conditions. Then, these faces were saturated. A large number of moisture sensors, strain and displacement sensors allowed following their behaviors. Moreover a weighing system has allowed the knowledge of the mass variation induced by water exchanges during the different phases of the test.

3.1 Hydrous transfer modelling

The moisture dependence makes it necessary to treat the water concentration simulation with attention. That is difficult considering the strong dependence of the moisture diffusion coefficient on the water concentration and on the moisture history of concrete (sorption or desorption). The beam is divided in two complementary parts in order to improve the water concentration simulation: the lower assumed continually in sorption and the upper which is firstly in desorption (0-420 days) and next in sorption (420-700 days). The concrete porosity is equal to 15.8%. The moisture transfer modelling was done according to the water mass balance equation (including a non linear moisture diffusion coefficient) solved by a finite element method. Figure 5 gives the results of the water concentration simulation in terms of relative mass variations to be compared to experimental data.

3.2 Beams behavior modelling

For each time step of the nonlinear numerical procedure, the corresponding moisture content profile is taken into account to compute the AAR advancement according to Eq 5. Afterwards, the stress and the damage state are provided by the rheological model coupled with the orthotropic damage model and the gel pressure law. We discuss bellow results obtained on two beams differentiated by their reinforcement: a normally reinforced beam (NRB) and a highly reinforced beam (HRB) (Figure 6).

The simulated mid span deflection of the beams can be compared with the experimental ones in Figure 8 for the NRB and Figure 9 for the HRB. In the first part of these curves (until 424 days in figure 8 and 9) corresponding to the drying phase of the top part, the deflection is due to the development of AAR in the bottom part of the beams and at the same time to the shrinkage in the top part. After 424 days, water is supplied to the top of the beam, and the deflection reversing is due to swelling caused by moisture absorption and the development of AAR in the upper part of the beams.

The magnitude of the deflection reversing of a non reactive beam is low compared to deflection reversing of a reactive beam (both normally reinforced – Figure 7). As shown in Figure 7, the deflection reversing of the non reactive beam, due to water swelling, is about 0.5 mm. For the reactive beam, the deflection reversing, due to water and AAR swellings, is about 1.7 mm. Therefore, a large part of the deflection reversing of the reactive beam appears to be due to AAR swelling.

The great moisture dependence of the reactive concrete is reflected by the deflection history. Both the curves aspect and amplitude are correctly simulated by the model, the reinforcement effect on deflection is notably well reproduced, in fact the highly reinforced beam has a smaller deflection during the drying phase due to the AAR occurring in the bottom where reinforcement limits the longitudinal swelling.

Observable deviation between experiment and simulation can have multiple causes, the first one being surely the difficulty to simulate the water concentrations profiles with accuracy (Figure 5). Beside the mid span deflection, the damage fields simulated can be compared to the crack patterns given in [1,8,9].

Figure 10 shows the tensile damage fields 'Dtx', 'Dty' and 'Dtz' predicted for the normally and highly reinforced beams. We can see an anisotropic cracking pattern (anisotropic damage field) in accordance to experimental observations [1,9] reported in the last column of Figure 10.

Moreover, the highly reinforced beam shows a smaller longitudinal damage (Dtx in Figure 10) and a larger transversal damage (Dty) than the normally reinforced beam, what is also in agreement with experimental observations. In fact, the more the longitudinal rebar section is important, the more the crack opening is restrained in the longitudinal direction, causing the increase of the gel pressure until a transversal crack opening occurs. This swelling transfer towards unrestrained directions highlights the anisotropic behavior of reinforced concrete affected by AAR and justifies the anisotropic damage model requirement to get the stress state in a reinforced concrete structure affected by AAR.

4 CONCLUSIONS

Physical phenomena involved in structural effects of AAR were investigated and a model proposed for each of them, leading to a global phenomenological modelling. In this modelling AAR acts on the concrete via a gel pressure depending on temperature, moisture content and maximal gel volume coming from reactive siliceous parts of the aggregates. The long term behavior of concrete including basic creep and shrinkage phenomena is controlled by a rheological model. An orthotropic damage model based on the effective stress concept allows taking into account swelling transfer between strains constrained directions and free swelling directions. After the calibration phases, presented in [5] the model has been tested in an experimental program constituted of various reinforced reactive concrete beams. A comparison with experiments is done and shows the model capability to reproduce with an acceptable accuracy the mid span deflection of beams and their crack pattern. After this development and test phases, a French dam affected by AAR has to be evaluated by the model [10].

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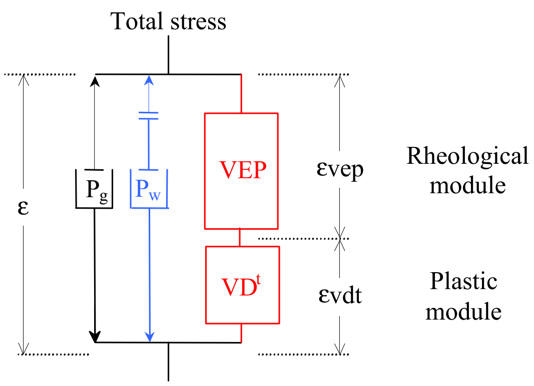

Figure 1: Rheological model principle

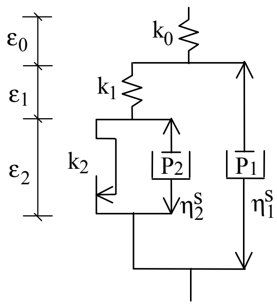

Figure 2(a). Spherical part of VEP module (VEP^s) CSH consolidation

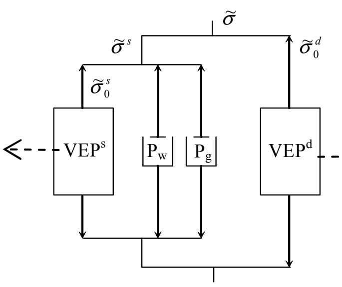

Figure 2. Visco elasto plastic module (VEP)

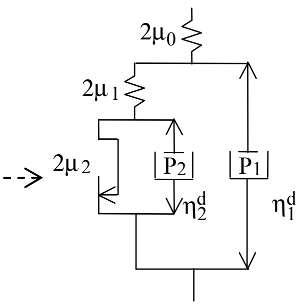

Figure 2(b). Deviatoric part of VEP module (VEP^d) CSH sliding

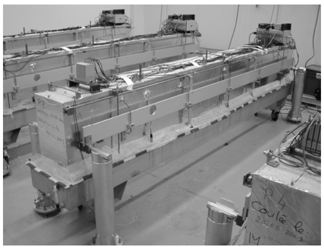

Figure 3. Experimental beams test [1]

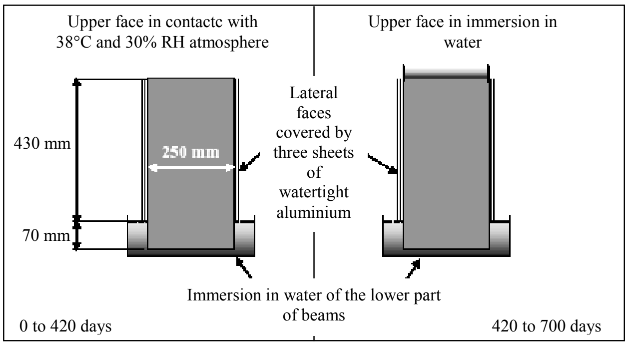

Figure 4. Moisture controlled environment of beams

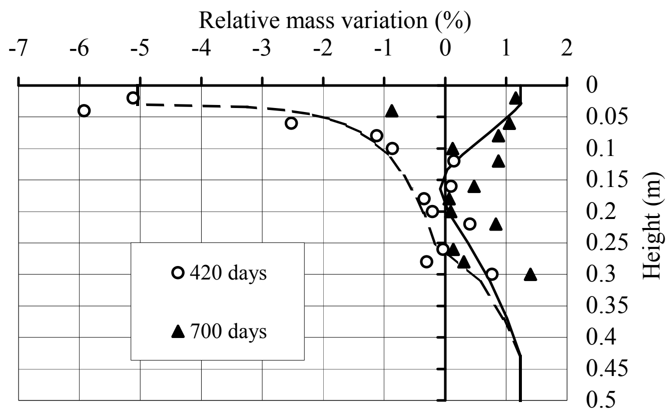

Figure 5. Relative mass variation along the height of the beam

(dotted line for simulation at 420 days and continued line for simulation at 700 days)

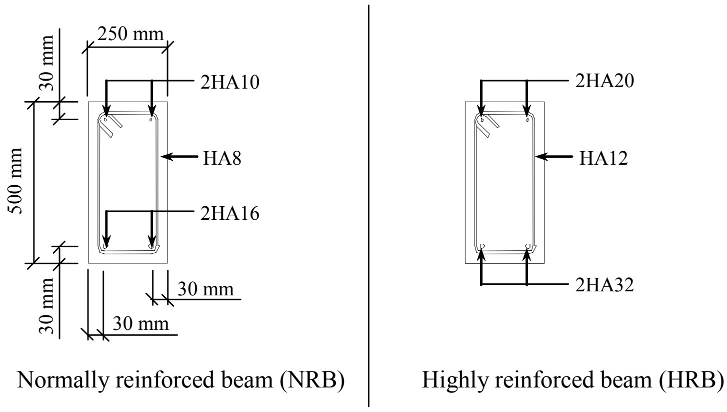

Figure 6. Reinforcement scheme

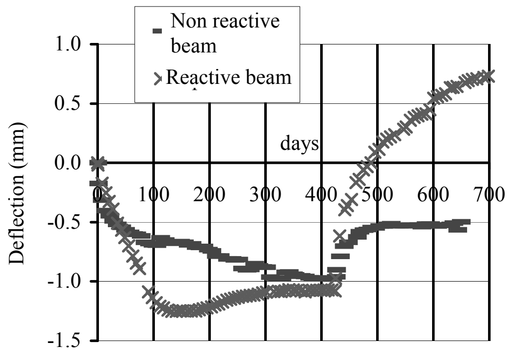

Figure 7. Experimental mid span deflection of the normally reinforced beam (NRB) reactive or not

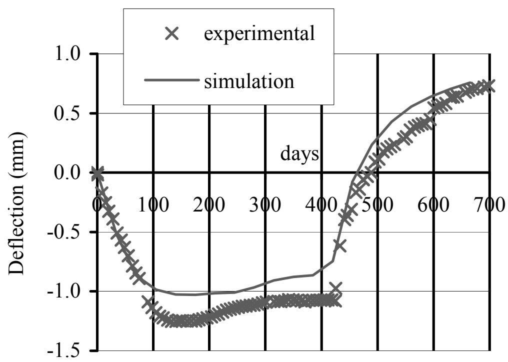

Figure 8. Mid span deflection of the normally reinforced beam (NRB)

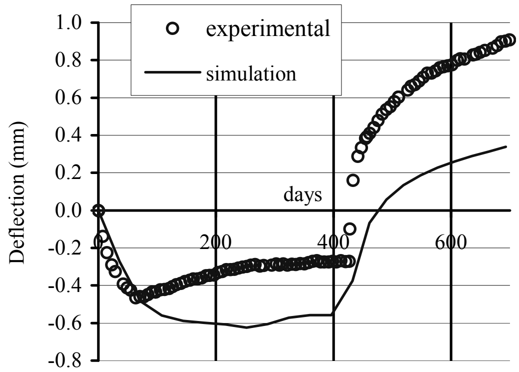

Figure 9. Mid span deflection of the highly reinforced beam (HRB)

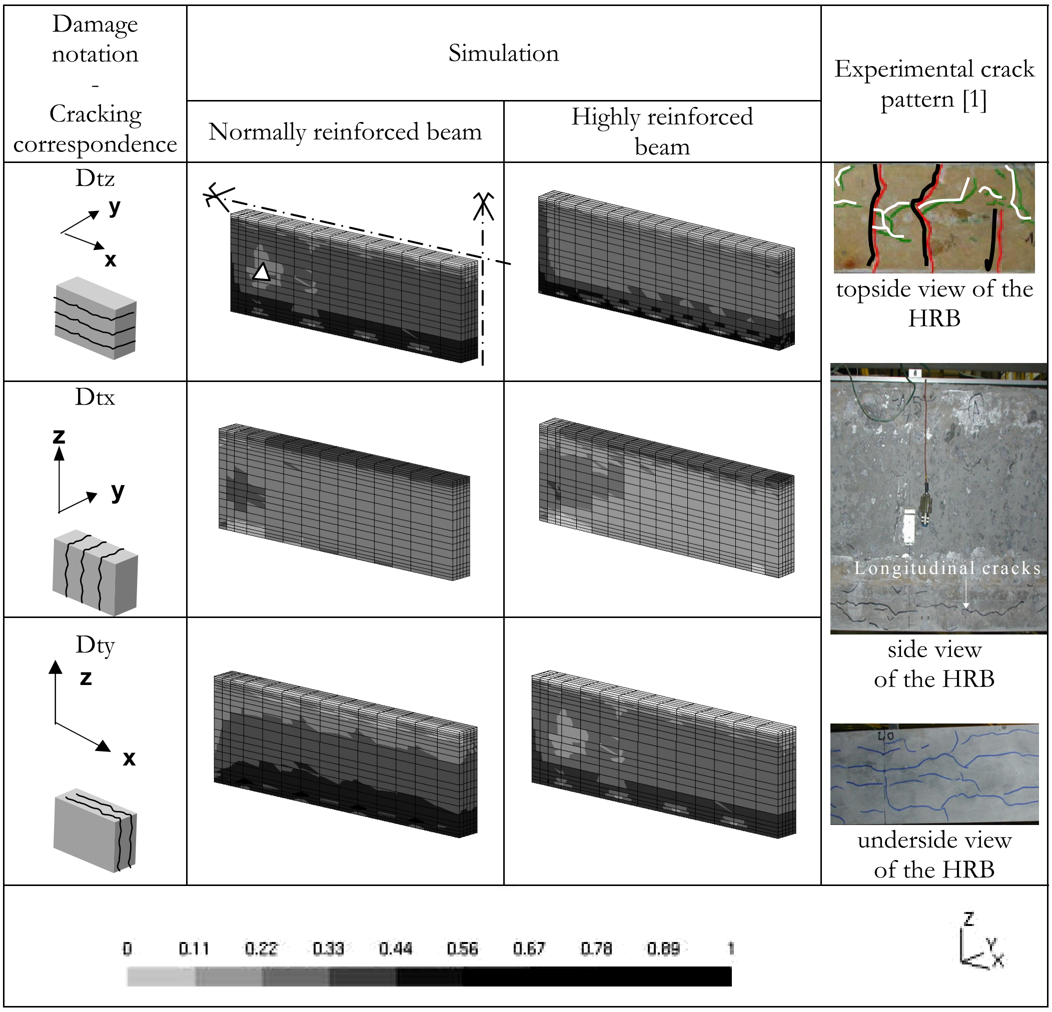

Figure 10. Damage fields of the quarter beams (420 days) [7] (for the topside, highlighted in black: cracks appeared during drying – after 420 days, in white: cracks appeared after the water supply [1])