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MODELLING OF CONCRETE STRUCTURES AFFECTED BY INTERNAL SWELLING REACTIONS: COUPLINGS BETWEEN TRANSFER PROPERTIES, ALKALI LEACHING AND EXPANSION

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Abstract

Alkali Aggregate Reaction (AAR) and Delayed Ettringite Formation (DEF) cause expansion of the affected concrete that generally leads to cracking and decrease of its mechanical properties. As a consequence, these pathologies raise severe problems in terms of serviceability, sustainable operation of the concrete works and structural integrity. To manage with considered suffering structures, it is necessary to provide predictive models able to re-assess their mechanical state. In this paper, we describe the RGIB model developed with this objective and we compare its predictions to the results of experimental tests specifically performed to validate it. The objective is to emphasize which processes are well taken into account and which improvements could be implemented.

Keywords: Alkali Aggregate Reaction, Delayed Ettringite Formation, Modelling, Coupling

1. INTRODUCTION

Alkali Aggregate Reaction (AAR) and Delayed Ettringite Formation (DEF) are both Internal Swelling Processes (ISP) that can affect concrete. In the first case, the reaction between the reactive silica contained in some aggregate and the alkalis in the concrete pore solution leads to the formation of an expansive gel [1]. In the second case, when the material has experienced high temperatures (typically above 65°C [2]) especially at early age (e.g. during precasting process or in massive cast-in-place structures), the ettringite turns unstable while the concrete is still plastic and forms again after cooling in the hardened material, thus generating swelling due to crystallisation pressure [3]. These two expansive processes have similar macroscopic local effects mainly consisting in cracking and decreasing of the mechanical properties which may cause large structural disorders due to unexpected deformations and additional stresses in concrete and reinforcement. Regarding the magnitude of expansion, DEF is generally believed to induce more deleterious effects than AAR (order of magnitude of 1-2% as compared to 0.1-0.5%) [4-5].
Thus, severe concerns exist for the serviceability and the structural integrity of the affected structures [6-7]. To manage them, it is necessary to provide numerical tools able to re-assess and to predict their mechanical state [8]. In this context, the French Institute of Science and Technology for Transport and Civil Engineering (Ifsttar, formerly LCPC) has developed the RGIB modulus in the CESAR-LCPC FE-code [9] allowing to re-assess AAR or DEF affected structures and taking into account several thermo-hydro-chemo-mechanical couplings.

To validate the model, its numerical predictions have to be compared to representative experimental data. Such studies are available in the literature [4-5]: laboratory tests were performed on ISP-affected concrete beams. This paper describes and compares the modelling of these tests to the experimental data. The new developments of the RGIB model were tested in the case of AAR and of DEF. The deviations are analyzed based on results of tests performed at the material scale with the final aim of highlighting the possible enhancements.

2. DESCRIPTION OF THE RGIB MODEL

In the RGIB model [10-11], the concrete strain tensor is described as a sum of an elastic (or elasto-plastic), a shrinkage and a chemically-induced contribution. The first one derives from the global mechanical computation. The second one corresponds to a linear evolution of shrinkage (characterized with the shrinkage coefficient k) as a function of the saturation degree [12]. The chemically-induced part describes an imposed strain evolution due to AAR or DEF. To describe the kinetics and magnitude of expansion for a given water content, equation 1 can be used [13-14]. In this equation, \( \varepsilon_\infty \) corresponds to the final expansion, \( \tau_C \) and \( \tau_L \) are the characteristic and the latency times respectively (corresponding to the swelling rate and the duration before the onset of expansion) and \( \varphi \) and \( \delta \) are two parameters used to introduce a linear expansion at the end of the swelling process. These parameters are fitted on the results of a free expansion test on cores either stored in an atmosphere at 100% Relative Humidity (RH) in the case of AAR [10;15] or immersed in water in the case of DEF [11]. To take into account the couplings between expansion and moisture content, \( \varepsilon_\infty \), \( \tau_C \) and \( \tau_L \) are weighted thanks to coupling functions (see equation 2) which depend on the saturation degree of the material \( S_r \) [16]. In these coupling laws, a saturation threshold \( S_{r0} \) below which no evolution occurs is used. A second parameter \( m_i \) allows to set up a non linearity. Finally, the imposed chemical strain is linked with the existing stress state in the structure as it was shown that applied stresses have an influence on the magnitude and the direction of expansion [17].

\[
\varepsilon(t) = \varepsilon_\infty \cdot \frac{1 - e^{-\frac{t}{\tau_C}}}{1 - e^{\frac{t}{\tau_C}}} \left\{ \begin{array}{ll}
1 - \frac{\varphi}{\delta + t} & \text{if AAR} \\
1 & \text{if DEF} 
\end{array} \right. \tag{1}
\]

\[
\left\{ \begin{array}{l}
f_i(S_r) = \left( \frac{S_r - S_{ri0}}{1 - S_{ri0}} \right)^{m_i} \\
\varepsilon_\infty(S_r) = f_{\varepsilon}(S_r) \cdot \varepsilon_\infty(l) \\
\tau_{cL}(S_r) = \frac{1}{f_{cL}(S_r)} \cdot \tau_{cL}(l)
\end{array} \right. \tag{2}
\]

Figure 1 illustrates the architecture of the RGIB model. Prior to any mechanical computation, two non linear diffusion calculations are performed to assess the thermo-
hydrous state of the structure. In the case of DEF, an additional computation of the early-age thermal history is first carried out to assess the potential magnitude of expansion of the material [9]. These calculations are used at each time step to calculate the imposed volume chemical expansion prior to the consideration of the stress state in the structure.

Figure 1: Resolution algorithm of the RGIB model

### 3. MODELLING OF CONCRETE STRUCTURES AFFECTED BY ISP

#### 3.1 Experimental data

To provide data necessary to validate the re-assessment tools, tests have been performed on AAR or DEF-reactive plain concrete beams (0.25x0.50x3.00 m$^3$, span of 2.8m) [4-5] named B1 and B4 respectively. The specimens were submitted to a vertical moisture gradient during more than 14 months according to figure 2. The storage temperature was 38±1°C. The local and global longitudinal strains were monitored as well as the mid-span deflection. The global water content was monitored thanks to a specific weighing device [18]. In the case of the AAR affected beams, the local water content in the upper 30cm was monitored thanks to a specific gammadensitometry device [18]. Results of tests performed on reinforced concrete beams of same composition as B1 (B2 and B3) and B4 (B5 and B6) are presented in the following sections to illustrate the scatter of the water content results.

The constitutive materials of the beams affected by AAR or DEF were designed to have similar mechanical and transfer properties although they differ in terms of cement and aggregate used. Each material can be characterized by its free expansion which is represented in figure 3. The estimations of the parameters of equation 1 are given in table 1.

| Table 1: Parameters describing the free expansion of the materials |
| --- | --- | --- | --- |
| | AAR | DEF | 
| Immersed 100% RH | Immersed 100% RH | 
| $\varepsilon_\infty$ | 0.28% | 0.21% | 1.60% | 1.31% |
| $\tau_C$ (days) | 28 | 37 | 11 | 13 |
| $\tau_L$ (days) | 71 | 50 | 82 | 89 |
| $\phi$ (days) | - | - | 24 | 18 |
| $\delta$ (days) | - | - | 119 | 120 |
3.2 Modelling

Modelling has been performed in the frame of the Finite Element Method (FEM). Due to the symmetry of the problem, only a quarter of a beam is discretized with quadratic solid elements (20 nodes) as described in figure 2.c, with a total of 1080 elements and 5869 nodes. Table 2 gives the mechanical properties of the materials used as input data for the mechanical computation [4-5] and the parameters used to describe the coupling between expansion and humidity. The hydro-coupling parameters were found in the literature [4;19], with parameters corresponding to $\tau_C$ and $\tau_L$ chosen to fit with the $f_\infty$ function as good as possible. Since the storage temperature has been kept constant during the whole test, no variations occurred and the corresponding computations are therefore not described here. Since no mechanical loading was applied to the beams, no creep effects were taken into account in this modelling.

Table 2: Input parameters of the model ($f_c$ and $f_t$=compressive and tensile strength respectively, $E$=Young’s modulus, $\nu$=Poisson’s ratio, $k$=shrinkage coefficient)

<table>
<thead>
<tr>
<th></th>
<th>$f_c$ (MPa)</th>
<th>$f_t$ (MPa)</th>
<th>$E$ (GPa)</th>
<th>$\nu$</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$S_{r_0}^{\infty}$</th>
<th>$S_{r_0}^{C.L}$</th>
<th>$m_\infty$</th>
<th>$m_{C,L}$</th>
<th>$S_{rini}$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAR</td>
<td>38.4</td>
<td>3.2</td>
<td>37.3</td>
<td>0.22</td>
<td>2397</td>
<td>0.832</td>
<td>0</td>
<td>1</td>
<td>25</td>
<td>0.98</td>
<td>1.1e-3</td>
</tr>
<tr>
<td>DEF</td>
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<td>5.0</td>
<td>30.8</td>
<td>0.18</td>
<td>2320</td>
<td>0.95</td>
<td>0</td>
<td>1</td>
<td>60</td>
<td>0.89</td>
<td>2.3e-3</td>
</tr>
</tbody>
</table>

3.3 AAR-affected beam

One of the main input computations of RGIB is the assessment of the hydrous state of the structure by resolving a non linear diffusion problem. To set the parameters of this problem, tests performed on cylinders (0.16m in diameter $\phi$, 0.32m in height $H$, 3 identical specimens of same composition of the beam affected by AAR) were used. These specimens were either...
immerged in water or dried at 30% RH and were monitored in terms of mass and strain. These tests were modelled in the CESAR-LCPC FE code with a 2D axisymmetric model and the corresponding parameters were calibrated. The results are given in figure 4 (r corresponds to the distance of the point considered to the symmetry axis of the cylinder, the error bar correspond to the scatter of the results).

Figure 5 represents the result of the moisture diffusion computation for the beam. A reasonably good correlation is obtained with the experimental results whether considering the global or the local water content. However, the computation seems to globally overestimate drying (see figure 5.a) while local drying is underestimated in the upper part (see figure 5.b). Difficulty for properly accounting for the saturation distribution in such structures has already been underlined [19-21].

Figure 4: Modelling of the hydro-mechanical behaviour of an AAR-cylinder (a. Degree of saturation; b. Longitudinal shrinkage at 30% RH)

Figure 5: Water content evolution of beams affected by AAR (a. global; b. local)

Figure 6 gives the result of the RGIB computation for the beam affected by AAR using input parameters from table 1 [10]. The results are given in terms of deflection and longitudinal strain since it was proven that the Strength of Materials theory applies[4;22]. The continuous lines correspond to the calculation with the mean free expansion of the material (see figure 3) whereas the dashed lines correspond to calculations performed with the lower and upper value of expansion. This represents the scatter of the structural behaviour when taking into account the discrepancy of the expansive behaviour of the constitutive AAR concrete. A fairly good correlation is observed between the computation and the experiment regarding the deflection. In terms of longitudinal strain, a significant deviation of the model is observed although the general behaviour is consistent with the experiment. Thus, the RGIB modulus appears to be well adapted to assess AAR-affected structures.
3.4 DEF-affected beam

Figure 7.a represents the result of tests performed on cylinders (Ø=0.11m, H=0.22m, 4 identical specimens with the same DEF concrete as the beam; the results presented for immersed specimens stand for cylinders initially cured at ambient temperature since no direct measurement of saturation could be performed in the case of heat-treated specimens [4]) and the corresponding simulation. The related parameters are used to model the global hydrous behaviour of DEF-affected beams (figure 7.b) (no experimental data are available concerning the local water content). It can be seen that the initial drying process is well reproduced. However, after a one-month exposure, significant deviations are noticed: experimentally, the beams exhibit a large water uptake that has been correlated to the opening of cracks acting as reservoirs [4;23]. Since no coupling has been provided to link mechanical effects (cracking) to transfer parameters, it clearly turns out that the moisture state is not satisfactory predicted.

Figure 8 represents the result of the mechanical computation (the deviation in the deflection measurements correspond to a mechanical blocking of the bearings during the test). Whatever the input data used to describe the expansive behaviour of the constitutive material (see table 1), no satisfactory result could be obtained. At the end of the test, the computed deformations are underestimated. This is consistent with the result of the hydrous calculation unable to transcribe the strong water uptake experimentally detected: since DEF develops above a high moisture threshold (see table 2), an underestimation of the water ingress in the structure corresponds to an underestimated DEF-affected area and thus to lower deformations. In terms of kinetics, it can be noticed that, at least initially, the expansive processes develop faster in the model than experimentally. This could be (at least partly) explained by an alkali
leaching phenomenon: it has been proven that the alkali content of concrete has a strong influence on DEF and that an increase of this parameter delays the onset of expansion [24]. Though, the tests on cylinders used as input data were performed in high moisture environments prone to alkali leaching. In comparison, the massive beams were probably less affected. Consequently, similarly to the hydrous and thermal calculations, an alkali diffusion computation could take this effect into account and thus enhance the prediction of the model.

Figure 8: Mechanical behaviour of the plain concrete beam affected by DEF considering as input data the expansion in water (modelling nr. 1) or at 100% RH (modelling nr. 2) (a. mid-span deflection; b. longitudinal strain at a depth of 0.23m)

4. CONCLUSIONS

The RGIB model developed to re-assess the structures affected by AAR or DEF takes into account several coupling effects including the influence of moisture. It has been applied to beams aged in controlled laboratory conditions and affected by AAR or DEF. In the case of AAR, it has been shown that the prediction of the structural behaviour is satisfactory as long as a good estimation of the saturation of the material can be reached. In the case of DEF, it has been emphasized that the absence of coupling between the hydrous and the mechanical calculations does not allow to take into account the experimental strong water uptake due to crack development. This has a direct impact on the mechanical calculation because of the strong coupling between DEF expansions and water supply conditions. Moreover, the role of alkali leaching depending on the shape of the studied specimen has also been pointed out as being a cause of deviation in the estimation of the kinetics of expansion. Thus, adding these two aspects in the RGIB model could improve the numerical predictions.

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