論文 An Integrated Analysis of Reinforced Concrete Beam Subjected to both Loading and Chloride Ion Ingress

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ABSTRACT: Due to a lack of an adequate analysis tool, structural design is still formally separated from durability design, despite the well accepted fact that there is a strong interaction between degradation of the material due to mechanical loading and structural performance under harsh environments. A critical need exists to establish the essentials of this dependence between mechanical performance and the physico-chemical environment. A method is proposed for the development of this tool within the general framework of continuum thermodynamics of reactive porous media. Such an energy approach allows one to account in a consistent way for the many different quantities affecting the mechanical and transport properties of the material. The usefulness of such an approach is illustrated through the classical case of a reinforced beam subjected to both mechanical loading and chloride ingress, where the interaction between these two deterioration mechanisms is shown to have a major impact on the long term performance of the beam.
KEYWORDS: Concrete durability, Design, Chemical attacks, Integrated analysis, Plasticity, Reinforced concrete beam, Chemo-mechanical coupling

1. INTRODUCTION

Over the last few years, durability has been identified as one of the major parameters controlling the long-term behavior of concrete structures [1]. Unfortunately, at the present stage of knowledge, durability design is practically independent from the structural design. Moreover, there is no rational design method for durability and only a few empirical prescriptions are being used. Clearly, a rational integrated structural-durability design method needs to be developed [2].

Durability of concrete structures in harsh environments has been shown to be controlled by the phenomena of mass transport within concrete, such as chlorides, acids etc. The combined transportation of heat, moisture and chemicals within the concrete mass, an exchange with the surroundings (microclimate) and the parameters controlling these transport mechanisms constitute the principal elements of durability. The presence of water or moisture is the single most important factor controlling the various deterioration processes apart from mechanical loading.

The physical and chemical degradation in concrete usually lead to the corrosion of reinforcement. As a consequence, one hopes to be able to determine the strength and stiffness of the materials making up the structure as a function of time so that they can be used in a computer code to analyze the long term performance of concrete structures. With such a simulation tool, new performance-based design codes can be established for the next century, believed to be the century of the environment [2,3].

Concrete structures are subject to both mechanical loading and environmental attacks during their entire lifetime. Each of these actions leads to a deterioration of the concrete material. As concrete is attacked by chemicals, the mechanical properties of the most exposed areas are changed and the load bearing capacity may be reduced. Mechanical loading on the other hand leads to creation of new cracks and/or extension and widening of existing ones inducing a higher permeability and hence accelerating the rate of chemical attacks .

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The field of integrated chemo-mechanical analysis in porous media is a new highly multidisciplinary area of research. In this paper, a preliminary attempt is made to bridge the gap between these different disciplines by coupling the simultaneous action of chemical and environmental attacks to the deterioration due to loading.

2. COUPLING CHEMICAL ATTACKS AND MECHANICAL LOADING

This paper explores the theory of reactive porous media, such as concrete, as a potential framework for modeling of material deterioration due to the coupling of mechanical loading and chemical attack. The formulation is based upon the thermodynamics of open porous media composed of a skeleton and several fluid phases occupying the porous space . A sketch of a general procedure for achieving this goal is described in this section.

The generalized Claussius-Duhem inequality, which expresses locally the second law of thermodynamics is given by

$$\Phi_1 + \Phi_2 \geq 0 \tag{1}$$

With Φ_1 being the intrinsic dissipation (irreversible behavior of the skeleton) and Φ_2 is the dissipation associated with chemical reactions. Φ_1 can be expressed in the following form:

$$\Phi_1 = \left(\sigma - \frac{\partial \Psi}{\partial \varepsilon} \right) : \frac{d\varepsilon}{dt} - \left(S + \frac{\partial \Psi}{\partial T} \right) \frac{dT^o}{dt} + \left(g_m^j - \frac{\partial \Psi}{\partial m_j} \right) \frac{dm_j}{dt} - \frac{\partial \Psi}{\partial \chi} \frac{\partial \chi}{\partial t} \geq 0 \tag{2}$$

where σ is the stress tensor, ε is the strain tensor, S is the entropy, T is the temperature, g_m^j is the chemical potential (free enthalpy per unit mass of fluid phase j), m_j denotes the mass of fluid phase per unit of macroscopic volume element (rve), and Ψ is the free energy of open elementary system. In the case of a reversible behavior, $\Phi_1 = 0$ and the constitutive laws reduce to state equations $\sigma = \frac{\partial \psi}{\partial \varepsilon}, S = \frac{\partial \psi}{\partial T}$ and $g_m^j = \frac{\partial \psi}{\partial m_j}$, $j = 1,....,N$. In the case of an irreversible behavior of the skeleton (matrix), these state equations are still valid and the dissipation law becomes

$$\Phi_1 = -\frac{\partial \Psi}{\partial \chi} \frac{\partial \chi}{\partial t} \geq 0$$
$$= \eta \, \dot{\chi} \geq 0 \tag{3}$$

Constitutive equations encompass the state equations and the complementary evolution laws which describe the irreversibility of the matrix. This latter law is usually expressed in terms of a relationship linking $\dot{\chi}$ to η.

The case of dissipation due to chemical reactions can be illustrated with the case of the following simple reaction

$$X \rightarrow Y \tag{4}$$

$\Phi_2 = A_m \xi^o \geq 0$, where $A_m = k(g_m^X - g_m^Y)$ is the affinity of the chemical reaction, ξ^o the chemical rate, and k is a constant linking the reaction rate to the mass creation associated with Eq. (4). This latter expression of Φ_2 holds irrespective of transport phenomena of the reactant and product phase through the structure.

By choosing a suitable free energy under the form $\psi = \psi(\varepsilon, T, m_i, \chi)$, $i = 1,...,N_c$ it should be possible to account for the effect of chemical attacks on the mechanical properties through the

chemical reaction evolution as represented by mass creation m_i and degradation of the material under external loading through the evolution of internal variables such as damage and/or plastic strains [4]. Similarly, it is perfectly possible to make the evolution of the transport properties depend on the extent of both the chemical attacks and material degradation under mechanical loading. As a first step, and due to the fact that many degradation mechanisms are not well understood at the present time, very simple and intuitive relationships have been assumed in this study in order to investigate the potential of the present approach in integration of structural and durability analysis [5,6,7].

3. REACTIVE TRANSPORT IN CONCRETE

Realistic modeling of the transport and chemical reactions of major solute species in concrete structures requires consideration of water flow, heat transport and prediction of the dynamic changes in solutes concentrations with space and time together with the chemical processes affecting them.

The governing flow equation for a two-dimensional isothermal Darcian flow of water in a variably saturated rigid porous medium is given by the following modified form of the Richard's equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iy}^A \right)\right] - S \qquad (5)$$

where θ is the volumetric water content, h is the pressure head, S is a sink term, x_i $(i=1,2)$ are the spatial coordinates, t is time, K_{ij}^A are components of a dimensionless anisotropy tensor $\mathbf{K}^A$, and K is the unsaturated hydraulic conductivity function given by

$$K(h,x,y) = K_s(x,y) \ K_r(h,x,y) \qquad (6)$$

where K_r is the relative hydraulic conductivity and K_s is the saturated hydraulic conductivity. The anisotropy tensor is used to account for an anisotropic medium. For an isotropic medium, $\mathbf{K}^A$ reduces to the identity tensor.

The partial differential equation governing two-dimensional advective-dispersive chemical transport under transient water flow conditions in a partially saturated porous medium is taken as

$$\frac{\partial \theta c_k}{\partial t} + \rho \frac{\partial \overline{c}_k}{\partial t} + \rho \frac{\partial \hat{c}_k}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta D_{ij} \frac{\partial c_k}{\partial x_j} - q_i c_k \right] \qquad k = 1,2,...,N_c \qquad (7)$$

where c_k is the total dissolved concentration of the aqueous component k, $\overline{c}_k$ is the total sorbed concentration of the aqueous component k, $\hat{c}_k$ is the total concentration of aqueous component k in the minerals which can precipitate or dissolve, ρ is the bulk density of the medium, D_{ij} is the dispersion coefficient tensor, q_i is the volumetric flux, and N_c is the number of aqueous components. The second and third terms on the left side of Eq. (7) are zero for components that do not undergo ion exchange or precipitation/dissolution.

Neglecting the effect of water vapor diffusion on transport, two-dimensional heat transport can be described as

$$C(\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left[\lambda_{ij}(\theta)\frac{\partial T}{\partial x_j} \right] - C_w q_i \frac{\partial T}{\partial x_i} \qquad (8)$$

where T is the temperature, $\lambda_{ij}(\theta)$ is the coefficient of the apparent thermal conductivity of the porous material, $C(\theta)$ and C_w are the volumetric heat capacities of the concrete and the liquid phase, respectively. Volumetric heat capacity is defined as the product of the bulk density and gravimetric heat capacity. The first term on the right hand side of Eq. (8) represents the heat flow due to conduction and the second term the heat transported by the flowing water. The transfer of latent heat by vapor movement is not considered in the above equation

4. MECHANICAL RESPONSE OF CONCRETE

The nonlinear response of concrete due to cracking is modeled here through the use of a tension limiting plasticity model, where beyond a given tensile stress plasticity occurs. In plastic analysis, the elastic strain rate $\dot{\varepsilon}_{ij}^{elas}$ is obtained from the total strain $\dot{\varepsilon}_{ij}$ rate by subtracting the plastic strain rate $\dot{\varepsilon}_{ij}^{plas}$ from the total strain rate according to the following equation

$$\dot{\varepsilon}_{ij}^{elas} = \dot{\varepsilon}_{ij} - \dot{\varepsilon}_{ij}^{plas} \tag{9}$$

with $\dot{\varepsilon}_{ij} = \dfrac{1}{2}\left(\dfrac{\partial v_i}{\partial x_j} + \dfrac{\partial v_j}{\partial x_i}\right)$ where v_i is a component of the velocity vector, and $\dot{\varepsilon}_{ij}^{plas}$ follows from the condition that the stress cannot exceed the yield surface. This condition is specified in this study by a tension limiting plasticity model which uses the following definition for the equivalent stress

$$\bar{\sigma} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} \tag{10}$$

where σ_1, σ_2 and σ_3 are the first, second and third principal stress respectively. Each of these is incorporated if it is a tension stress. The plasticity surface limiting the allowed tension stresses is then given by

$$\bar{\sigma} - \sigma_y = 0 \tag{11}$$

The size of the plastic strains rate is measured by the plastic parameter $\dot{\kappa}$ also used for piloting the isotropic hardening and defined by

$$\dot{\kappa} = \sqrt{0.5\, \dot{\varepsilon}_{ij}^{plas}\, \dot{\varepsilon}_{ij}^{plas}} \tag{12}$$

5. RC BEAM SUBJECTED TO EXTERNAL LOADING AND CHLORIDE ION INGRESS

Figure 1 shows dimensions of the beam, loading and support conditions and configuration of the reinforcement [7]. The concrete mix proportions contained a water to cement ratio of 0.45.

The chloride ions induced corrosion of the reinforcement which often leads to a loss of the cross sectional area of the reinforcing bars and cracking of concrete is represented in this study by a simple empirical rate type equation that relates the corrosion rate to the availability of water, oxygen and chlorides [8]

$$q = k(\alpha_0 + aC)\phi\, S\, C_{O_2}\, Exp\left\{-\dfrac{E}{R}\left(\dfrac{1}{T} - \dfrac{1}{T_0}\right)\right\} \tag{13}$$

where q is the rate of corrosion, k is a constant, α_0 is the referential rate coefficient, a coefficient for sensitivity of chloride effect, C_{O_2} is concentration of oxygen in the pore solution phase, T is temperature
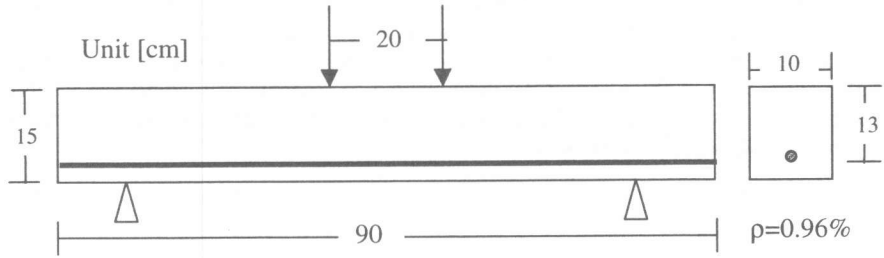
Figure 1. Schematic representation of RC beam

and E is the activation energy. The total corrosion loss can be obtained by integrating Eq. (13) over time and coupling it with the moisture and chloride ion transport model. It has been assumed that there is a sufficient amount of oxygen in the pore water.
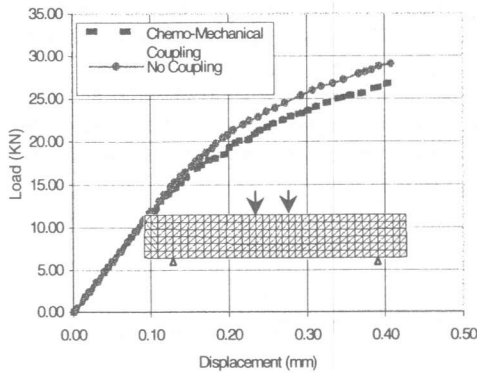

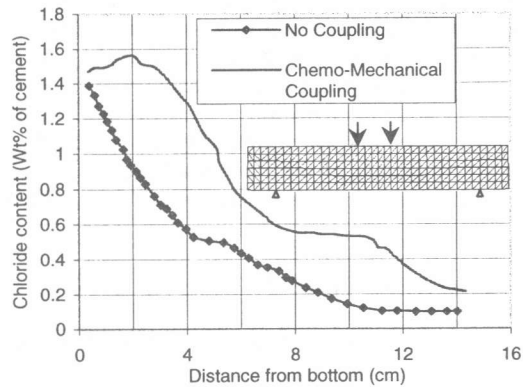**Figure 2. Load displacement response**

Figure 3. Chloride distribution along the central cross section

In the present study, the following parameters were used in the computations:
k=3.48, $\alpha_0 = 0.15 \ cm/day$, $a=16.9$, $C_{O_2} = 9.5 \times 10^{-6} \ g/cm^3$, and a uniform temperature $T = T_0 = 293K$. This simplifying assumption allows one to avoid the problem of estimating the activation energy E (Eq. 13). As far as the mechanical properties are concerned, we adopted the following values: $E_c = 26 \ MPa$, $v = 0.2$, $f_t = 2.5 \ MPa$ for the Young modulus, Poisson coefficient and cracking stress for concrete together with $E_s = 300 \ MPa$ and $f_y = 25 \ MPa$ for the Young modulus and elastic limit for steel.

Despite .the simplicity of the adopted models in this preliminary study, it is interesting to note that the simulations are able to account for the strong interaction between the external loading and environmental attacks on reinforced concrete. As can be seen in Figure 2, corrosion induced cracking may have a strong effect on the overall response of the reinforced concrete beam. It is worth noticing that practically there was no difference between the two curves up to the point of departure from linearity.

Thus, it can be concluded that the increase in chloride ingress due to cracking of concrete under external load may lead to a higher corrosion rate which in turn affects the overall response of the structure.

Similarly, Figure 3 shows the strong effect of external loading and corrosion induced microcracking on the final distribution of chloride ion concentration in the central area of the beam after 100 days. Indeed, it is very easy to see that there is a significant increase in the amount of chloride ingress when the material degradation due to mechanical loading and to corrosion of the reinforcement is accounted for. The results of this study illustrate the significance of the chemo-mechanical coupling in concrete structures.

6. CONCLUSIONS

Due to the complex nature of environmental effects on structures, it is believed that true improved performance cannot be achieved by improving the materials characteristics alone, but must also involve the elements of architectural and structural design, process of execution, together with inspection and maintenance procedures. As a consequence of the fact that durability and structural design issues are still being separately treated due to a lack of proper analysis and design codes, the need for the development of a powerful integrated analysis tool to assess the long term performance of concrete is stronger than ever. A viable approach that could be used in conjunction with this type of analysis is represented by the development and use of high performance materials that could extend the longevity of concrete structures [9].

The thermodynamics of reactive porous media has been introduced as a potential and very general framework for the integration of durability and structural analysis in concrete. Despite the relative simplicity of the models adopted in the present study, it has been shown that the chemo-mechanical coupling greatly affects the long term behavior of concrete.

7. AKNOWLEDGEMENT

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