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Early age strains and self-stresses of expansive concrete members under uniaxial restraint conditions

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HIGHLIGHTS

- Design of high expansion energy capacity concrete able to prestress structures.
- Cumulative force induced by restraint influences on restrained strains progress.
- Cumulative force induced by restraint is considered as an externally applied load.
- Proposed modified strains development model (MSDM) allows to estimate self-stress.
- Validity of the proposed MSDM is confirmed by the experimental data.

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ABSTRACT

Models for restrained strains and self-stresses estimation based on the concepts of the conservation law of chemical energy and initial strains calculation in the expansive concrete members are considered, together with their advantages and disadvantages. A modified strains development model (MSDM) is proposed, based on the initial strains calculation approach and extended by taking into account cumulative force induced by the reinforcement as an additional restraint for development of expansion strains. Validity of the proposed MSDM is confirmed by experimental results obtained from tests on uniaxially symmetrically reinforced high expansion energy capacity concrete members.

1. Introduction

Development of concrete technologies in the last decade has opened the door to the extended use of high performance concrete (HPC). Nevertheless this concrete isn't deprived of a number of disadvantages such as relatively low tensile strength and amplified shrinkage. Shrinkage in combination with low tensile strength, mainly in early age, leads to the risk of cracking in reinforced concrete structures, and as a result, a reduction of its durability. The use of expansive concrete is an effective way to compensate and reduce internal forces induced by shrinkage and temperature variations. There are two kinds of expansive concrete: shrinkage-compensating concrete (with low expansion energy capacity) and self-stressing concrete (with high expansion energy capacity). Application of self-stressing concrete not only permits to compensate shrinkage but also introduces so-called chemical prestressing of the structure. For this reason, a new wave of interest has overcome the field of the expansive concrete investigation and practical usage [1,2].

For the purpose of the self-stressed structures practical use, design models for the restrained expansion strains and self-stress values estimation are required. It should be noted that no recent codes include methods for self-stressed structure design. Only a limited number of guides, for example [3], have a chapter devoted to this concern. Even so, models for the estimation of restrained strains and self-stresses in expansive concrete at early age are intensively developed [4–8]. In general, these models are based on one of two basic concepts: conservation law of chemical energy or initial strains calculation. Moreover, a joint model based on both concepts and called CP method has been proposed [8].

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In this paper, a short review and brief analysis of the models based on these concepts is presented. Taking into account advantages and disadvantages of these models, a modified strains development model (MSDM) was formulated and verified on the experimental data from the testing on the expansion stage of uniaxially symmetrically reinforced expansive concrete members.

2. Models for analytical prediction of the restrained strains and self-stresses in expansive concrete members

2.1. Models based on the conservation law of chemical energy

One research line, developed mainly in Japan, is based on the concept of chemical energy conservation law for self-stresses prediction in expansive concrete members with different types of restraint [4,5]. This concept is based on the assumption that the work quantity U_{CE} that expansive concrete performs against restraint per unit volume, is a constant value regardless of the degree of restraint [4] and this work quantity should be established in «reference» restraint conditions ($\rho_l = 1\%$, $E_s = 200$ GPa). It is noticeable that this fundamental statement had already been formulated and described at the beginning of 1970s [9].

The semi-empirical multiplicative model based on the proposed concept for self-stresses estimation under different restraint ratios and restraint arrangements was developed and included in standards [3]. A distinctive feature of this model is the assumption of the self-stresses uniform distribution in the cross section (see Fig. 1b) of the expansive concrete member against the background of the linear strains distribution (see Fig. 1a).

For a given restraint ratio and restraint arrangement in the cross section, self-stress design value, σ_{CE}, is calculated in accordance with the next equation from TCP Code [3]:

$$\sigma_{CE} = f_{CE,d} \cdot k_s \cdot k_\rho \cdot k_e \cdot k_w \cdot k_0 \quad (1)$$

where, $f_{CE,d}$: self-stressing grade of the expansive concrete [10], and is defined as a value of the compressive stress in the prismatic specimen under uniaxial symmetrical restraint with stiffness equal to 1% (ρ_l) of steel cross sectional reinforcement ratio ($E_s = 200$ GPa) at the concrete expansion stabilization; k_s: factor that is equal to 1.0; 1.2; 1.5 for uniaxial, biaxial and triaxial reinforcement arrangement in the concrete member respectively; k_ρ: factor that represents influence of the cross sectional reinforcement ratio ρ_l and is calculated by the following formula:

$$k_\rho = \sqrt{\frac{1.57 \cdot \rho_l}{0.0057 + \rho_l}} \quad (1a)$$

k_e: factor that represents influence of the reinforcement eccentricity, e_s (distance between centroids of the longitudinal reinforcement and concrete cross section), and is calculated by the following formula:

$$k_e = 1 - \gamma_1 \cdot \frac{e_s}{d_s} \quad (1b)$$

where, γ_1: empirical factor that is equal to 1.26. d_s: cross section effective depth. k_w: factor that takes into account influence of the expansive concrete initial compressive strength at the beginning of moisture curing – $f_{CE,k0}$ and is calculated by the following formula:

$$k_w = (0.1 \cdot f_{CE,k0})^{-\alpha} \quad (1c)$$

where, α: empirical factor that is equal to 0.797. k_0: factor that takes into account self-stressed member curing conditions on the stage of the concrete expansion and takes values from 0.18 (sealed conditions) to 1.15 (immersion in water) in accordance with TCP Code [3].

The main advantage of this type of model consists in the possibility of predicting the self-stress value assuming a certain value of the expansive concrete self-stressing grade ($f_{CE,d}$). Such an approach allows to assess the value of the self-stresses without consideration of free expansion strains, Young's modulus development and a creep function of the expansive concrete at early age.

The assumption of uniform distribution of the self-stresses in the cross section of the member has got a limitation in practical use and contradicts in some cases experimental results [11], in particular, for the cases of the non-symmetrical single-layer reinforcement arrangement with a high value of eccentricity with respect to the centroid of the member cross section. For example, when all sectional reinforcement is arranged on the same depth, d_s, with eccentricity, e_s, and ratio is equal to $e_s/d_s = 0.5$, it is formally necessary to accept that self-stresses are distributed uniformly in the cross section, but the value of these compressive stresses (in accordance with Eq. (1)) is 2.7 times lower than the value of the stresses in the symmetrically reinforced member (all other conditions being equal). At the same time for the case of the single-layer reinforcement

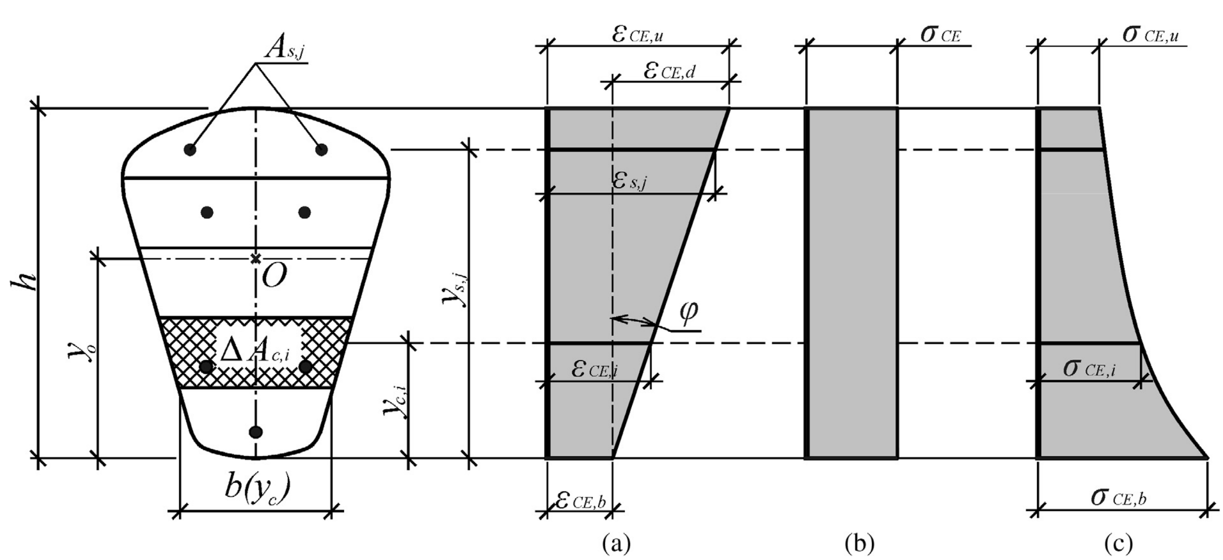

Fig. 1. Concrete strains and stresses distribution in the cross section of the self-stressed member ((a) – strains distribution in accordance with [3,4]; (b), (c) – self-stresses distribution in accordance with [3] and [4] respectively).