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SIZE EFFECT ON THE ULTIMATE DRYING SHRINKAGE OF CONCRETE – MODELING WITH MICROPRESTRESS-SOLIDIFICATION THEORY

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Abstract: *Drying shrinkage of concrete is a distinctively long-term process which is affected by many factors ranging from concrete composition, curing and ambient conditions to the dimensions and shape of the investigated structural member. In the case of standard-size structural members the ultimate value of drying shrinkage is reached within several decades, which hampers the experimental verification. In a reasonable time scope (e.g. 1 year) even the standard laboratory-size specimens provide only the initial evolution of shrinkage which cannot be extrapolated owing to the ill-posed nature of the problem. Furthermore, the experimental data indicate that there is a non-negligible size effect on the ultimate drying shrinkage which makes the transition from laboratory to structural size even more difficult. The objective of the current research is to assess this size effect from the perspective of the experimental data found in the literature, the design codes and prediction models for the long-term behavior of concrete, and finally, the coupled FEM simulations with the advanced constitutive model based on the Microprestress-Solidification theory.*

Keywords: Drying shrinkage, Concrete, Size effect, modeling.

1. Introduction

The interplay among drying shrinkage, creep and micro-cracking of concrete is extremely complex and even nowadays it is not fully described and understood. Concrete member exposed to an environment with lower relative humidity undergoes gradual drying which gives rise to non-uniform drying shrinkage strains which are internally restrained and thus produce self-equilibrated stresses. Time development of these stresses and strains is governed not only by the evolution of the drying process, but also by the rheological properties of concrete which depend on the maturity and are both temperature- and humidity-dependent. Furthermore, if the tensile stress exceeds tensile strength of concrete cracking starts.

Drying shrinkage kinetics as well as its ultimate value is influenced by many factors ranging from concrete composition, curing and ambient conditions to the shape and the dimensions of the investigated structural member. The current objective is to identify the size effect on drying shrinkage by means of experimentally validated numerical simulations. In the future, this relationship might help to establish the transition from the very small laboratory specimens to real-size structural members.

This aspect has been approached by (Torrenti, 2013) and more recently by (Samouh, 2017) but both studies used very limited experimental evidence and the analytical as well as the numerical analysis did not show a good agreement with the experimentally observed trends.

Recently, the present authors have analyzed structures (Dohnalová, 2019 and 2020) the experimental data from the NU database (Hubler, 2015) and from the literature and compared the identified trends of the size effect on drying shrinkage with the current prediction models and design codes for time-dependent behavior of concrete. In this contribution these findings are summarized and the size effect on drying shrinkage is evaluated from the numerical simulations in which the behavior of concrete is described with several alternative formulations of the model based on Microprestress-Solidification (MPS) theory (Jirásek, 2014). As shown in (Bažant, 2014) the model can be improved to fix the size effect on drying creep.

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2. Prediction models, design codes vs. experimental evidence

The size effect on the ultimate drying shrinkage is in the most frequently used codes of practice (Eurocode 2 (CEN, 2005) and ACI 209.R-08 (ACI, 2008)) and the prediction models (B3 (Bažant, 2000) and B4 (RILEM, 2015) models, *fib* Model Code 2010 (fib, 2012)) incorporated by distinctly different approaches. In order to establish a clear comparison between the models, here, the size effect is evaluated with respect to the notional specimen size D defined as $D = 2V/S$ in which V is the volume and S is the area of drying surface. For example in the case of a wall/slab drying from both sides, D is equal to its thickness. Additionally, to eliminate the effect of other parameters and to establish a coherent comparison with the experimental data, the values of the ultimate shrinkage strain is normalized with respect to $D = 60$ mm.

All investigated experimental data which fulfilled all necessary requirements are shown in Fig. 1 left. Filled and empty marks correspond to experiments with sufficiently/insufficiently long duration, respectively. The trend is very uniform up to D = 100 mm, then the scatter increases but more importantly the experimental data become scarce and the shrinkage evolution can be rarely considered as finished.

The prediction models are compared to the experimental data in Fig. 1 right. As shown by the red curve, the B3 and B4 models exhibit considerable size effect for $D \leq 50$ mm, for larger sizes it vanishes. The fib MC 2010 completely neglects this size effect. The European EC2 shown in blue color provides guidance only for $D \geq 100$ mm where it nicely matches the prematurely terminated Bryant's experiment on slabs. By far the best agreement gives the American standard as shown by the black color.

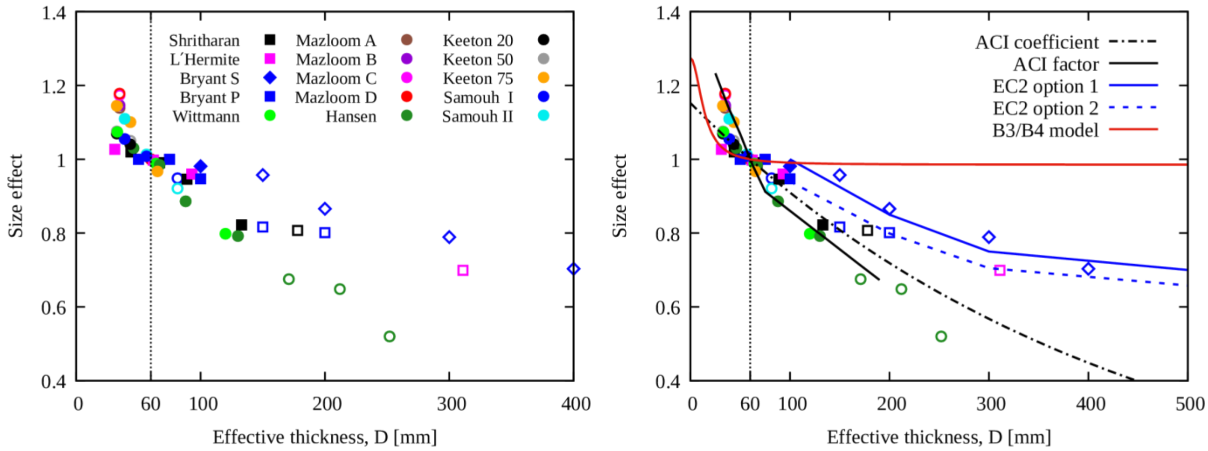

Fig. 1: Size effect on drying shrinkage determined from experiments (left) and comparison to design codes (right). Empty symbols denote the last measured value in insufficiently long experiments.

3. Finite elements simulations

The size effect on drying shrinkage was computed for six different alternatives of the widely used model based on the MPS theory in its reformulated and modified version. All finite element simulations were carried out using the finite element package OOFEM (Patzák, 2012). In all investigated cases, except for the basic creep in which the humidity was assumed constant; the analysis was driven by a staggered scheme in which the humidity transport described by the Bažant-Najjar (Bažant, 1972) model was followed by the mechanical analysis. The rheological scheme of the MPS model (Bažant, 2018) consists of several serially coupled units including a non-aging spring, a solidifying Kelvin chain, an aging dashpot, and finally a shrinkage unit. Additionally, this chain was further extended by a unit capturing tensile cracking with crack-band regularization. The aforementioned modifications of the MPS model deal primarily with the differential equation for the microprestress. Recently it was shown (Jirásek, 2014) that the microprestress can be completely eliminated from the formulation and the governing equation can be rewritten in terms of viscosity η of the aging dashpot.

$$\dot{\eta} + \frac{1}{\mu_S}\left|\frac{\dot{h}}{h}\right|(\mu_S\eta)^{\frac{p}{p-1}} = \frac{\psi_S}{q_4} \tag{1}$$

In this equation h is the relative humidity, ψ_S is a humidity- and temperature-dependent factor, and μ_S is a material parameter with the meaning of fluidity. The order of this differential equation is determined by the value of parameter p. In the original formulation, with $p = 2$, the model exhibits inverse size effect on drying creep which can be solved by setting $p < 0$ (here $p = -1.5$) or even completely eliminated if $p = \infty$. In the last case the differential equation becomes linear and the parameter μ_S is replaced by a dimensionless factor k_3. The second point of interest which might possibly influence the size effect on drying shrinkage was the relationship between the rates of shrinkage and the relative humidity, which is in the original formulation established via constant parameter k_{sh}. Two alternatives are investigated here in which the constant parameter is replaced by a maturity-dependent or a humidity-dependent function. The first modification is inspired by the justification of this size effect presented in the original paper on B3 model, the second one by the nonlinear relationship between the ultimate shrinkage and the ambient relative humidity.

Prior to the investigation of the size effect, the models for transport and creep needed to be calibrated which was done on Bryant's (Bryant, 1987) experimental data which comprise basic creep with aging, drying shrinkage and total creep for various sizes and also different ages at loading. In the experiment the relative humidity was constant, $h_{\text{env}} = 0.6$, this value was also adopted in this study. The following values of material parameters gave the most satisfactory agreement and were used in the subsequent modified models. For the B3 basic creep: $q_1 = 18$, $q_2 = 52$, $q_3 = 23$, $q_4 = 7.5$ all in 10^{-6}/MPa, for the Bažant-Najjar moisture diffusion model: $C_1 = 30\ \text{mm}^2/\text{day}$, $\alpha_0 = 0.15$, $h_c = 0.65$, $n = 12$, and the surface factor in the mixed boundary condition $f = 1\ \text{mm/day}$. The parameters related to the drying shrinkage, k_{sh}, and drying creep, μ_S or k_3, needed to be recalibrated individually for each modification of the constitutive model based on the magnitude of drying shrinkage and total compliance, see Tab. 1.

In terms of parameter p, the best overall behavior is obtained with $p = \infty$ (see Fig. 2 left). The original formulation ($p = 2$) underestimates the size effect for smaller specimen sizes but it gives the strongest and the best size effect for large D. With $p = -1.5$ the size effect is captured well for smaller sizes but once $D \geq 100$ mm the size effect it starts increasing which contradicts the experimental observations.

As demonstrated in Fig. 2 right, the time-dependence of k_{sh} yields by far the best results, the humidity dependence has a minor influence. Interestingly, with tensile cracking the size effect becomes shallower.

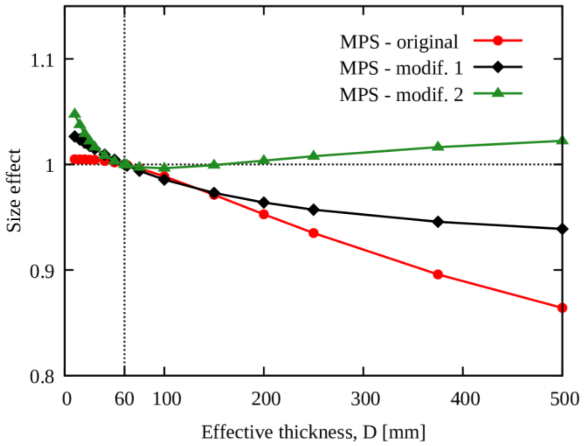

Fig. 2: Size effect on drying shrinkage of prisms of different sizes. Results were obtained with MPS model with different values of parameter p (left) and with parameter p = ∞ and modified shrinkage relationship or cracking (right).

Tab. 1: Summary of the MPS alternatives shown in Fig. 2 with specified values of material parameters and with the normalized values of shrinkage strain for prisms and slabs with D = 500 mm.

	p [-]	k_{sh} [$\times 10^{-4}$]	k_3 [MPa^{-1} day^{-1}]	μ_S [-]	$\tilde{\varepsilon}_{sh}^{\infty}$ (P1000) [-]	$\tilde{\varepsilon}_{sh}^{\infty}$ (S500) [-]
MPS original	2	19.4	N/A	$1.40 \cdot 10^{-5}$	0.864	0.936
MPS modif. 1	∞	19.7	26	N/A	0.939	0.955
MPS modif. 2	-1.5	20.6	N/A	$2.85 \cdot 10^{-10}$	1.022	0.990
k_{sh} time dependent	∞	19.5	26	N/A	0.835	0.848
k_{sh} humidity dep.	∞	25.1	26	N/A	0.922	0.942
MPS with cracking	∞	19.7	26	N/A	0.962	0.963

4. Conclusions

All investigated experimental data prove the existence of the size effect on the ultimate drying shrinkage of concrete. However, the data is scarce and for larger specimen sizes the experiments are often prematurely terminated because of enormous time demands. The analyzed design codes of practice and the prediction models introduce this size effect in different ways. The worst performance shows the B3/4 model and the fib MC 2010.

The results obtained from the coupled finite element simulations with the MPS model show that the correct size effect is reached only with $p = \infty$ in the entire range of sizes, even though this influence is significantly less pronounced than in the experiments which can be substantially improved if the constant which establishes the relationship between the shrinkage and relative humidity is replaced by a time-dependent function.

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