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Shape effect on drying behavior of cement-based materials: Mechanisms and numerical analysis

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ABSTRACT

The shape of the specimen or structure has a direct impact on the behavior of drying concrete. This effect is not taken into account in most of shrinkage models and codes. Only the current B4 model and its previous version B3 model incorporate a shape factor. The determination of this coefficient is based on the nonlinear moisture diffusion analysis, which can explain the shape effect on the shrinkage rate. However, the model integrates this coefficient in the ultimate shrinkage values as well. An experimental study has been performed to confirm and understand this behavior. The mass loss and drying shrinkage of cylinders showed higher rate and ultimate values than the prisms, for the same effective cross section thickness. To explain this result, the drying, the differential shrinkage, the internal stress and the damaged depth were determined for both shapes through numerical modeling. The main input data of the model were the measured mass loss and shrinkage. The calculated desorption isotherm curve of the cylinder was below that of the prism, which is consistent with its higher ultimate mass-loss. The determination of stress profiles indicates slower stress mitigation for the cylinder. The cylinder develops a larger relative damaged area, defined as the part of the specimen where cracking is likely to occur due to tensile stresses. The results actually show that differential shrinkage between the edge and the core is more pronounced for the cylinder and decreases with time.

1. Introduction

One of the main parameters which should be taken into account for the sustainable design of concrete structures is shrinkage. Concrete shrinkage is generally restrained in structures, which is likely to generate significant internal tensile stress and cracking. In a previous authors' study, shrinkage magnitude has been statistically linked to the cracking risk. Among 30 concretes, 13% of the studied mixtures with shrinkage under 500 μm/m cracked while 71% with shrinkage higher than 700 μm/m cracked [1]. Thus, cracking is not only influenced by shrinkage, but as it is a major parameter, performance-based approaches are now proposed for a good estimation of this delayed strain [2,3,4]. However, the transition from laboratory specimens to the real scale should take into account the size and the shape effects. The size effect is well-known and can be correctly reproduced through the effective thickness h_0 defined by Eq. (1). Its relation to shrinkage is based on the diffusion analysis of drying and can be found in different predictive models as: ACI [5], B3 [6,7], B4 [8,9], Eurocode 2 [10], fib MC2010 [11] and GL2000 [12].

$$h_0 = \frac{2v}{s} \tag{1}$$

where v represents the volume of specimen and s its drying surface.

Concerning the shape effect, few studies provide experimental data. Hansen & Mattock have studied the shrinkage and creep of I shape and cylinder specimens [13]. After 1200 days of measurements, for specimens with the same volume/surface ratio, the cylinder actually developed the highest shrinkage. This effect was even more pronounced for the small sizes. Concerning the experimental comparison between cylinder and prism, many previous studies did not dissociate the shape effect from the size effect. The different studied shapes did not have the same effective thickness of cross section [13,14]. Darquennes observed the shape effect as higher shrinkage was measured for the cylinder with the higher h_0 compared to the prism with the lower h_0 [15]. This last result shows that in some cases the shape effect can be more pronounced than the size effect.

Only the B4 model and its predecessor B3 among all, take shape into account [16,17]. Both models have the same general formula for shrinkage. They incorporate shape factor k_s in the characteristic time τ as shown in Eq. (2).

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$$\tau = \boldsymbol{k_h}(\boldsymbol{k_s h_0})^2 \tag{2}$$

where k_h is the empirical correction factor for environmental relative humidity.

Thus, specimen shape influences the time-dependent function as well as the ultimate drying shrinkage as shown in the simplified Eq. (3) given by Dönmez [18]:

$$\varepsilon_{dry} = \boldsymbol{k_h}\sqrt{\boldsymbol{0.99} + \frac{\boldsymbol{4.63}}{\boldsymbol{t_0} + \tau}}\,\varepsilon_\infty\ \boldsymbol{tanh}\sqrt{\frac{(\boldsymbol{t} - \boldsymbol{t_0})}{\tau}} \tag{3}$$

where t_0 the time at drying exposure.

The shape effect on the shrinkage rate was deduced from the nonlinear water diffusion analysis by Bazant and Najjar for 65% of relative humidity [19]. Recently, the determination of the shape factor has been extended by Dönmez and Bazant to variable relative humidity: 30%, 40%, 50%, 60%, 70% and 80% [18]. Based on the notion of the average radius, Hilaire proposed a slightly different shape factor [20]. Based on these coefficients higher shrinkage rate and ultimate shrinkage are predicted for the infinite cylinder than for the infinite prism.

Although experimental studies have shown the influence of shape on shrinkage, this is still partly taken into account in codes and the effect on shrinkage magnitude is not fully understood. The objective of the study presented in this paper is to provide experimental results on the influence of shape on drying shrinkage rate and magnitude at constant effective thickness then to understand the observed variations by modeling.

Mass-loss and drying shrinkage were monitored on cylindrical and prismatic specimens with the same effective thickness during 150 days. Finite element method was used to model the moisture evolution and poromechanics calculation was developed to estimate the differential shrinkage, the internal stress and the damaged area from experimental values of mass loss, autogenous and total shrinkage. Finally, the mechanisms behind the observed tendencies were discussed.

2. Experimental procedures

2.1. Materials and mixtures

One vibrated concrete noted VC was studied in this paper. The mixture proportions are given in Table 1. W in the table represents the effective water content (difference between total water content and water absorbed by the aggregates). A CEM I 52.5 N Portland cement, two granular classes (6/10 and 10/14 mm) of crushed coarse aggregates and a sea sand (0/4 mm) were used.

The compressive strength, tensile strength and Young's modulus were determined on ∅11x22cm cylinders. Young's modulus was deduced from the density and the natural frequencies of concrete using Spinner & Tefft's model [21].

2.2. Experimental procedure

The experimental program aims to study the effect of the specimen shape on long-term behavior. Two shapes were studied: cylinder and prism. One batch has been used for all specimens. After one-day sealed curing in an air-conditioned room at $T = 20^\circ \pm 1\,^\circ\mathrm{C}$ and $\mathrm{RH_b} = 50 \pm 5\%$, the specimens were demolded and stored in the same room.

Table 1
Mix design for the studied concrete.

$\mathrm{kg/m^3}$	VC
Gravel (Amphibolite) 10/14 (G)	875
Gravel (Amphibolite) 6/10 (G)	211
Sand 0/4 (S)	855
Cement (C)	303
Water (W)	182
V_G/V_S	1.1
W/C	0.60
Compressive strength at 28 days (MPa)	49.1
Tensile strength at 7 days (MPa)	3.0
Young's modulus at 28 days (GPa)	45.0

For both shapes, two boundary conditions were studied: i) sealed, to measure the autogenous shrinkage, ii) exposed to a bidimensional drying, for monitoring the mass-loss and the total shrinkage. For the first case, the specimens were protected against drying by a double layer of adhesive-backed aluminum foil [22,23]. For the second case, only the top and bottom surfaces were protected to achieve two-dimensional drying. Shrinkage was monitored by LVDT sensors with one-hour interval. A spherical cut was made in the frame steel for a small steel ball. The bottom center brass pin of the specimen vertically rested on this ball and the mechanical equilibrium of the specimen was reached. For each configuration one LVDT has been used and placed on the center of the top surface (Fig. 1). Two specimens have been used for each configuration. The presented results correspond to the average. The obtained mean deviation for shrinkage measurements was equal to 6%.

The drying shrinkage was estimated by the difference between the measured total shrinkage and the autogenous shrinkage [24]. In order to analyze the drying shrinkage data for both studied shapes, a hyperbolic model (Eq. (4), [13]) was used to determine the shrinkage half-time, and the ultimate drying shrinkage [5,10,25,26]. These two parameters can be obtained by minimizing the mean square error. Concerning the long-term extrapolation of drying shrinkage, the authors showed the efficiency of the hyperbolic model comparing to others of literature [27].

$$\varepsilon_{dry} = \frac{(\boldsymbol{t} - \boldsymbol{t_0})}{(\boldsymbol{t} - \boldsymbol{t_0}) + \boldsymbol{N_s}}\varepsilon_\infty \tag{4}$$

where ε_∞ is the ultimate shrinkage, $\mathrm{N_s}$ is shrinkage half-time and t_0 is the time when concrete is first exposed to drying ($t_0 = 1$ day).

The dimensions of specimens were chosen so as to have the same effective thickness of the specimen described by Eq. (1). Therefore, the dimensions of the cylinder and the prism were respectively: $\Phi 7 \times 28\,\mathrm{cm}^2$ (diameter of 7 cm) and $7 \times 7 \times 28\,\mathrm{cm}^3$. Both specimens had an effective thickness of 3.5 cm. All tests were performed for a minimum duration of 150 days, which allowed reaching more than 85% of ultimate shrinkage magnitude.

3. Model

The modeling part of the study aims at assessing the structural effects induced by drying from the measurements described in the previous section. Previous studies actually showed that internally restrained shrinkage is likely to induce cracking from the surface of concrete specimens. The existence of these microcracks induced by drying was actually proved in previous studies [28,29,30]. Bisschop and Van Mier compared different ways to use fluorescence microscopy to identify microcracks [31]. Then, Bisschop and Wittel proved visually the existence of drying microcracks by this method. They observed that depending on the drying disposition, the cracking depths for cement paste vary from 15% to 35% of the samples thickness [32].

Numerical models have already been used to analyze the consequences of drying in terms of internal stresses, damage, and microcracking [33,34,35]. These authors showed that it is necessary to take into account complex phenomena, including creep, damage, and hygromechanical coupling, in the model in order to agree with experimental evolutions of water loss and drying shrinkage. The analysis performed in this study is different as the experimental evolutions of mass loss and drying shrinkage are used as input data in order to determine first the global desorption isotherm of the specimen, and then the internal stresses and damaged depth as a function of time.

The procedure described in Fig. 2 provides the stress distribution