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The differential drying shrinkage effect on the concrete surface damage: Experimental and numerical study

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ABSTRACT

This paper aims to study the relation between drying and the development of damage from concrete surface. For that reason, the experimental study aims to measure the internal relative humidity in four different locations during 500 days. In parallel, total shrinkage is monitored for 250 days in different positions of the specimen. Under drying conditions, low differential values are noticed. Higher porosity and pore radius in the specimen edge are observed. It can be explained by the effect of the drying on the cement hydration and the surface microcracks appearance. Based on the experimental results, a model which incorporates the main mechanisms for shrinkage is proposed. The difference between the free shrinkage provided by modeling and the measured strain profile allows determining the evolution of the internal stress by an iterative procedure. Finally, by defining the damaged depth in the specimen as the area where the tensile strength is exceeded, the evolution of this distance is deduced. The development of the damaged depth was very fast as long as the relative humidity was close to 100% in the specimen core with a high differential pore pressure between the center and the drying surface.

1. Introduction

As it often induces significant delayed deformations and cracking, shrinkage is a major parameter when designing reinforced and prestressed concrete structures. It is now a part of performance-based specifications for durability [1] [2]. Drying shrinkage parameters are often characterized at material scale. However, drying shrinkage tests induce structural effects due to moisture gradients and hydration-drying coupling when concrete is exposed to early drying. These effects must be well understood in order to define reliable shrinkage-related specifications and to design concrete cover to reinforcement for durability.

Concrete shrinkage is generally known as the strain measured without application of any external stress. The consumption of water by cement hydration (self-desiccation) and the water loss due to the moisture gradient with the external environment (drying) result in a decrease in relative humidity (RH) within the porous media. Thus, menisci are created and internal pressures are generated. Ulm et al. confirmed the poromechanics aspect of the cement-based materials which makes it sensitive to the pressure that develops in the porosity of these materials at different scales [3]. In the cases of autogenous shrinkage, drying shrinkage or the coupling between them, three mechanisms generate the strain from the water departure [4]: capillary pressure, disjoining pressure which shows an RH dependency similar to capillary pressure, and the specific surface free energy variation in adsorbed layer especially for a lower relative humidity [5–6].

Several models are proposed in literature to estimate shrinkage based on empirical approaches [7–10]. In parallel, models based on poromechanics are also developed. For a fully saturated porous medium, Mackenzie proposed a model linking strain and pressure [11], which is similar to Biot's model [12]. By using saturation factor, this model was extended by Bentz et al. for partially saturated porous media [6]. The same author took into account the first two presented mechanisms using the Kelvin-Laplace equation [13]. A similar poromechanical model was used for example to study the performance of shrinkage-reducing admixtures by Weiss et al. [14]. Then, the interface induced shrinkage was integrated in models. For instance, Bentz et al. [6] based his model on the statistical thickness given by Badmann et al. [15], and Coussy et al. included all three shrinkage driving forces in an effective pore pressure instead of an average pressure to calculate the shrinkage of cement-based materials with poromechanical constitutive functions [16]. This last method was used by Hajibabaee et al. to model concrete curling [17]. Benboudjemaa et al. proposed a viscoelastic approach to assess the drying shrinkage [18]. Grasley and Leung

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neglected the change in the interfacial energy but incorporated the aging viscoelasticity [19] and the effect of changing pore solution concentrations which was studied before by Lura et al. [20].

However, the free shrinkage, which is the strain assessed through these physical models, is completely different from the apparent shrinkage measured in the standard tests. This difference can be explained by the internal restraint between different concrete layers. Ayano and Wittmann actually compared measured shrinkage between solid and sliced specimens. The deformation of the solid specimen (restrained) was nearly independent of the position [21], contrary to the unrestrained case. Bazant and Wittmann showed that shrinkage mechanisms can only be deduced from strain measurements when unrestrained shrinkage occurred [22]. Day and Illston proposed miniature specimens to measure unrestrained response of material [23]. Hwan and Young and then Baroghel-Bouny and Godin applied a similar experimental procedure using specimens between 1 and 3 mm [24–25].

At the microstructure scale, a linear relationship is often assumed between free drying shrinkage and water content variation [26–28], whereas at the material/specimen scale, several stages are often observed before reaching ultimate value ε_∞, especially when concrete is exposed to drying at early age (Fig. 1) [29–30]. Before the linear variation, the first stage actually consists in a significant mass-loss with relatively low shrinkage. Several phenomena can be involved in this macroscopic behavior, namely: coupling between hydration and drying [31], micro cracks [18,32] and wall effect due to formwork [33–34]. However, these phenomena cannot be easily distinguished.

Bazant affirmed that the strains produced by non-uniform drying normally greatly exceed the strain value for the tensile strength limit of concrete. They cause tensile strain softening and cracking [35]. He demonstrated the difference in pore humidity within a thin specimen in the vicinity of saturation should not exceed about 2% to avert microcracking. Additionally, in the common case of sudden exposure to drying, the thickness would have to be unreasonably small [36]. Thus, in general drying case the microcracks apparition is almost unavoidable even if they are probably so fine that they cannot be seen by the unaided eye [22]. Nevertheless, Bisschop and Van Mier proposed an efficient method to observe drying shrinkage microcracks by fluorescence microscopy [37], which was used in many other studies [38–40,37].

The authors showed in a previous paper that the first stage of the drying shrinkage vs. mass-loss curve is related to a drying depth δ_H where the porosity and permeability of concrete are higher than in the core of specimens (Fig. 2) [29]. However, the phenomena involved in these variations could not be determined and quantified.

The objective of this paper is to estimate the evolution of the outer damaged depth based on a model using the long-term measurements of

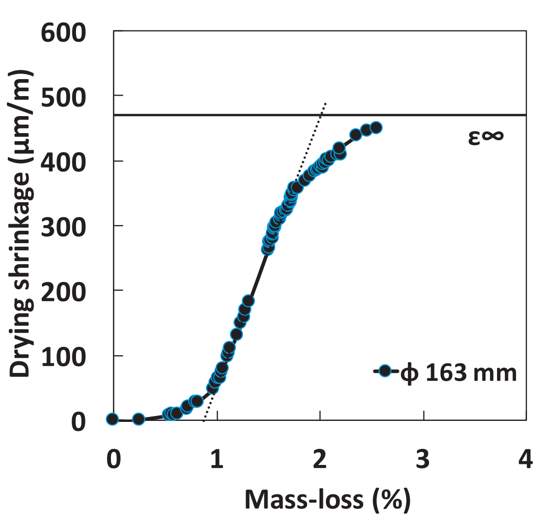

Fig. 1. Drying shrinkage and relative mass loss of Ø 16 × 32 cm^2 cylindrical specimens.

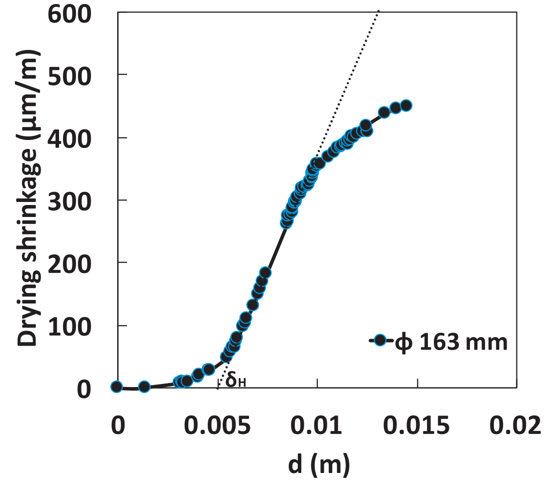

Fig. 2. Drying shrinkage versus equivalent drying depth.

the internal relative humidity and the differential shrinkage as input data. Tests were performed on self-consolidating concrete cylindrical specimens exposed to drying after one day.

First the experimental program is presented. It consists in the continuous monitoring of drying shrinkage and relative humidity at different locations on two cylindrical specimens. Water porosity and mercury intrusion porosimetry (MIP) tests were performed on a third specimen to determine the desorption curve for the modeling part. The model takes into account all the described shrinkage driving forces through the effective pore pressure, in order to provide the stress distribution and the extent of cracking as a function of drying time. Finally, the experimental and numerical results of the study are presented and discussed.

2. Experimental program

2.1. Materials and mixtures

One self-consolidating concrete (SCC) mixture was studied (Table 1). The water content W corresponds to the effective water content, which is the difference between total water content and water absorbed by aggregates.

An ordinary Portland cement CEM I 52.5 N was used for the mixture. Its chemical and physical properties are detailed in Table 2. Limestone filler was also used for the mixture. Its calcium carbonate proportion was 97%, its density was 2.7 kg/m^3 and its Blaine surface was 4350 cm^2/g. The coarse aggregates of sizes 10/14 and 6/10 mm were crushed amphibolite rocks with low water absorption (0.3%). The fine aggregate used in this study was a sea sand of granular class 0/4 mm. Its water absorption coefficient was 0.6%. Finally, a

Table 1
Concrete mix-design.

(kg/m^3)	SCC
Coarse aggregate 10/14 (G)	290
Coarse aggregate 6/10 (G)	550
Sand 0/4 (S)	780
Cement (C)	330
Limestone filler(A)	210
Superplasticizer	2.8
Water (W)	205
V_G/V_S	0.92
W/C	0.62
W/(C + A)	0.38
Paste volume (l)[a]	391

[a] $V_W + V_C + V_A$.