Acta Polytechnica CTU Proceedings **26**:13–18, 2020
doi:10.14311/APP.2020.26.0013

SIZE EFFECT ON THE ULTIMATE DRYING SHRINKAGE OF CONCRETE - EXPERIMENTAL EVIDENCE AND ENGINEERING PRACTICE

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Abstract. The design and behavior of creep-sensitive structures can be to a large extent dependent on the evolution of drying shrinkage. Drying shrinkage of concrete measured on standard laboratory specimens is very time demanding, furthermore, the extrapolation based on the short-term measurements is an ill-posed problem and can lead to large errors. Additionally, the final magnitude of shrinkage is size-dependent which makes the transition from the laboratory data to real structure even more challenging. The present paper evaluates this size effect based on the data gathered in the Creep and shrinkage database developed at the Northwestern university and the data from the literature. Finally, this size effect is compared against the current codes of practice and recommendations.

Keywords: Drying shrinkage, size effect, concrete, design code, prediction model.

1. Introduction

Concrete drying is followed by its gradual contractive volume changes referred to as drying shrinkage. Similarly to autogenous shrinkage, which happens even under sealed conditions and is characteristic for modern high-performance concretes with small water-to-cement ratios, also the drying shrinkage is considered to be bounded. However, on contrary to autogenous shrinkage which is believed to be uniform within the volume of the member, drying shrinkage which is driven by the changing field of relative humidity gives rise to non-uniform stresses and can result into surface cracking.

The drying shrinkage of concrete is a complex phenomenon which is not fully understood even nowadays. The evolution and magnitude of drying shrinkage is influenced by many factors, and for this reason the codes of practice and the design codes comprise many parameters. The aim of this paper is to assess the influence of the size of concrete member on the final magnitude of the drying shrinkage.

In the case of concrete structures sensitive to creep and shrinkage, it is recommended to perform short-term measurements on laboratory specimens and consequently, if necessary, to adjust the parameters of the computational models based on the results. The purpose of these short-term measurements is to capture the influence of parameters such as the water-to-cement ratio, cement type, type of aggregate, additives, admixtures, etc., which significantly affect the behavior of concrete.

The updating of concrete compliance function works reasonably well. In the case of drying shrinkage the final value cannot be reached in a reasonable time; not even in standard tests on laboratory specimens, $75 \times 75 \times 285$ mm according to ASTM C157 [1] and $100 \times 100 \times 400$ mm as given by the ISO 1920-8 [2] standard. In both cases the values stabilize after approximately 1,000 days of drying [3] which is unacceptable in civil engineering practice.

Typically, the already measured drying shrinkage evolution can be accurately captured with a very simple formula with two parameters only: the characteristic time and the ultimate shrinkage. Despite that the drying shrinkage updating remains an ill-posed problem [4]. The estimated ultimate shrinkage strongly depends on the choice of the characteristic time which is unknown. Both drying shrinkage magnitude and the characteristic time are functions of concrete composition, dimensions and ambient humidity which influence concrete diffusivity and thus the drying rate.

If the size effect on drying shrinkage magnitude is fully understood and described, then the problem might be overcome by decreasing the specimen size, the characteristic time is approximately a square function of the characteristic size. The results obtained on smaller specimens might be polluted by the loss of representativeness if the ratio of the specimen size to the aggregate is too small. However, this influence can be incorporated in the size effect law if the governing mechanisms are fully understood.

The size of typical structural members exceeds the characteristic dimension of the laboratory specimens many times. For this reason, the duration of drying and shrinkage can easily reach decades until these processes cease. The currently available size effect laws on the ultimate drying shrinkage are based only on relatively limited laboratory measurements, beyond that range their applicability is questionable.

Two recent studies have already approached this topic. The first one [5] compares the size effect on drying shrinkage according to EC2 with two experimental series only and concludes that even the current coupled FEM simulations are unable to capture the phenomenon. The second, more recent paper [6] is oriented more on the extrapolation of the drying shrinkage rather than on the size effect law, however, the original data from this paper are adapted in the present study.

The first part of this paper summarizes the size effect on the ultimate value of drying shrinkage as it is described in the codes of practice and recommendations. The following section examines the relevant experimental data some of which served, very probably, as a reference used for the development and calibration of the codes and prediction models. The final part compares the models with the experimental data and summarizes the conclusions.

2. Design Codes and Prediction Models

This section summarizes the definitions of the size effect on drying shrinkage according to the most common codes of practice — the American standard ACI 209.2R–08 [7] and Eurocode 2 [8] — and selected recommendations for the long–term behavior of concrete — B3 model [9], B4 model [10] and *fib* Model Code 2010 [11]. In the models the total shrinkage is either taken equal to the drying shrinkage (EC2, ACI 209, B3) or is split into drying and autogenous shrinkage (*fib* MC 2010, B4), both being bounded. The influence of specimen size on time evolution of drying shrinkage is not of interest in the present study and for this reason the related formulae are not presented here.

2.1. Models B3 and B4

Even though the newer B4 model introduces the split of total shrinkage into drying and autogenous shrinkage, the general structure of the formula for drying shrinkage is adapted from its predecessor, model B3 whose capability is limited only to concretes with higher water-to-cement ration and which recognizes only drying shrinkage.

The B3/4 models reflect not only the influence of the specimen size, but also its shape. These parameters play role both in the evolution of shrinkage and in the formula for the ultimate shrinkage. Different shapes of the specimens can be treated by means of the cross-section shape factor k_s (1.0–1.55) which enters the formula for the shrinkage halftime and which influences the magnitude of the ultimate shrinkage. The specimen size is expressed using the effective cross-section thickness D defined as

$$D = 2\,V/S \tag{1}$$

where V and S are the volume and drying surface of the member, respectively.

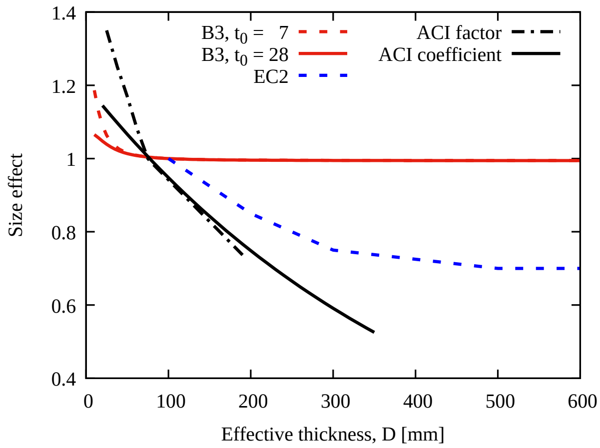

Figure 1. Size effect on ultimate drying shrinkage evaluated according to selected design codes and prediction models.

The ultimate shrinkage is defined by equation

$$\varepsilon_{sh}^{\infty} = \varepsilon_s^{\infty}\,\frac{E(607)}{E(t_0+\tau_{sh})} \tag{2}$$

where ε_s^{∞} is a size independent constant depending on concrete composition, curing method and 28-day compressive strength, t_0 is the age at the onset of drying, E is the modulus of elasticity and τ_{sh} is a shrinkage half-time expressed as

$$\tau_{sh} = k_t\,(k_s \cdot D)^2 \tag{3}$$

where k_t is parameter depending on 28-day compressive strength.

Red color in Fig. 1 corresponds to the size effect on drying shrinkage magnitude given by the B3 model. From the Figure it is evident that the size effect is observable only in the case of very small specimens while for structural members with realistic dimensions it completely vanishes. The size effect on drying shrinkage indirectly changes with the parameters which are in a certain way related to the evolution of stiffness during the initial phase of drying, especially the onset of drying t_0 and the compressive strength $\overline{f}_c$. However, these parameters only slightly influence the shape of the curve for very small specimens, $D < 50$ mm, and for $D > 100$ mm the size effect remains negligible.

2.2. Eurocode 2

Similarly to the B3 model also the Eurocode 2 recognizes the influence of the specimen size on the drying shrinkage rate and on the ultimate value. The specimen shape does not come into the calculation and the specimen size is represented by the notional size defined as

$$h_0 = 2\,A_c/u \tag{4}$$

where A_c is the area of cross-section and u is the perimeter of the member in contact with ambient environment. This expression coincides with (1) in the case of very (infinitely) long prismatic members.

The ultimate shrinkage strain is adjusted by factor k_h which is a decreasing piece-wise linear function of the notional size. The reference value $k_h = 1$ is specified for $h_0 = 100$ mm, $k_h = 0.85$ for $h_0 = 200$ mm, $k_h = 0.75$ for $h_0 = 300$ mm and $k_h = 0.7$ if h_0 reaches or exceeds 500 mm. For smaller notional sizes than 100 mm the code does not provide any guidance. The size effect is shown in Fig. 1 by blue dashed line.

2.3. ACI 209.2R–08

The size effect on drying shrinkage is in the American standard introduced by means of multiplicative correction terms which affect the ultimate value of shrinkage strain.

The evolution of drying shrinkage strain in time can be according to this standard treated by two distinctly different ways. Similarly to other standards, the first method prescribes a time function which depends on the V/S ratio; on contrary to this, the second method enables to use constant parameters independently of the size and shape of the concrete member and thus this method gives size-independent results.

The correction term reflecting the size effect on the ultimate drying shrinkage is introduced by two different ways, either it is called a *coefficient* or a *factor*. In order to be consistent with the preceding sections and the Figures, here we slightly modify the original formulae presented in the code, because the ACI uses a different definition of the characteristic thickness.

The size-dependent correction coefficient is prescribed by a single expression

$$\gamma_{sh,vs} = 1.2 \exp\left(-0.00236\, D\right) \tag{5}$$

The correction factor uses a piece-wise linear decreasing function for members with 25 mm $< D <$ 75 mm, for which the value is in the range 1.35–1.00, for larger members 75 mm $< D <$ 190 mm it offers a simple linear expression

$$\gamma_{sh,d} = 1.17 - 0.00228\, D \tag{6}$$

The correction coefficient and factor are shown in Fig. 1 by solid black and dash-dotted black lines, respectively.

2.4. *fib* Model Code 2010

Identically to EC2, the specimen size is in *fib* MC 2010 expressed by means of the notional size given by (4). Yet, the notional size affects only the shrinkage evolution which becomes faster with decreasing size. The ultimate shrinkage is entirely independent of the specimen size, for this reason the size effect does not need to be illustrated in Fig. 1.

3. Experimental Data

The experimental studies in which the evolution of drying shrinkage was measured on specimens with different sizes allow for identification of the size effect law on drying shrinkage. Naturally, the specimens had to be manufactured from the same concrete mixture and stored at the same conditions for sufficiently long period of time to reach the ultimate shrinkage strain.

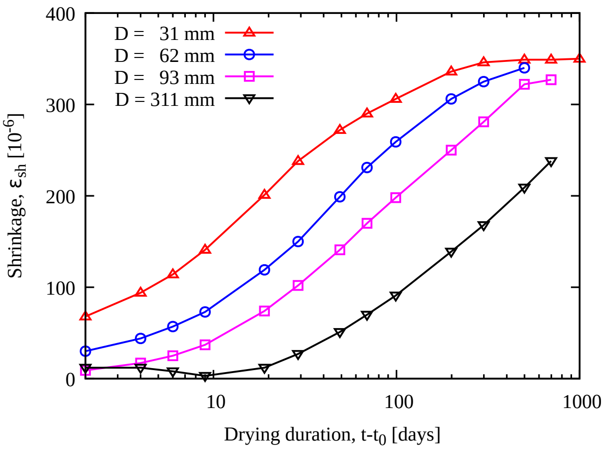

Figure 2. The experiment of L'Hermite (data adapted from [16]) shows incomplete drying shrinkage of the largest specimen with $D = 311$ mm. Such measurements were not discarded but are denoted by empty symbols in Fig. 4.

Except for the findings reported by Samouh [6], Keeton [14], and Bryant [12], the experimental data investigated in this study are adapted from the Creep and shrinkage database developed at the Northwestern University [16]. Keeton's original data on total shrinkage was preferred to the database which contains somehow modified values.

The database contains 61,512 values measured on 3,308 specimens (1,439 for creep and 1,869 for shrinkage) investigated within 340 experimental surveys (143 creep, 197 shrinkage). For the purpose of the present analysis it was necessary to narrow the shrinkage database only to those studies which examined shrinkage of concrete specimens of (at least two) different sizes made of the same concrete mixture. Furthermore, the curing type and duration had to be the same and so had to be the ambient relative humidity.

In total 21 experimental surveys met these criteria and from these 14 had to be discarded for some reason, most often because the duration of the experiment did not suffice to obtain stable value of the shrinkage strain of at least two specimens with different size. The setup and basic material properties of the suitable experiments are summarized in Table 1.

4. Discussion

A comparison of the size effect on drying shrinkage is presented in Fig. 1. It can be immediately noticed that the European and American standards use different member size as a reference. If both curves are normalized with respect to $D = 60$ mm, the differences (at least for 100 mm $< D <$ 200 mm) considerably diminish as documented in Fig. 5. The Eurocode 2

Experimental study	year	shape, D [mm]	t_0 [day]	a/c [-]	c [kg m^{-3}]	w/c [-]	$\overline{f}_c$ [MPa]	RH [%]	$t_{\max}$ [day]
Bryant P [12]	1987	P 50–200	8	5.09	390	0.47	50.0	60	1,950
Bryant S [12]	1987	S 100–400	8	5.09	390	0.47	50.0	60	1,880
Hansen † [13]	1966	C 46–252	8	6.00	303	0.71	41.3	50	1,750
Keeton 20 [14]	1965	C 33/44/65	8	3.74	452	0.46	46.5	20	897
Keeton 50 [14]	1965	C 33/44/65	8	3.74	452	0.46	47.5	50	897
Keeton 75 [14]	1965	C 33/44/65	8	3.74	452	0.46	46.8	75	897
L'Hermite † [15]	1970	P 31–311	1	5.06	350	0.51	NA	55	699
Mazloom †	2004	C 35/60	7	3.7–4.4	425–500	0.35–0.41	58–70	50	586
Samouh I [6]	2017	C 39/57/82	1	4.89 *)	320 *)	0.59 *)	49.6	50	300
Samouh II [6]	2017	C 39/57/82	1	6.03 *)	258 *)	0.74 *)	32.6	50	300
Shritharan †	1989	P 44–178	8	5.09	393	0.47	50.1	60	3,492
Wittmann †	1991	C 33/64/120	7	5.43	350	0.48	33.2	65	1,105

Table 1. Details of the experimental setup of the selected shrinkage experiments. The specimen shape is either a prism (P), cylinder (C), or a slab (S), D is the effective thickness, t_0 is the onset of drying, c, w, a is the cement, water and aggregates content, respectively, in the concrete mixture. The average compressive strength on cylinders at 28 days is denoted $\overline{f}_c$, RH is the ambient relative humidity, and t_{max} is the duration of the experiment (i.e. drying duration). In Samouh I and II, asterisks *) indicate that c corresponds to the content of OPC, not to the total amount of cementitious material, the data with symbol † are adapted from the NU database [16].

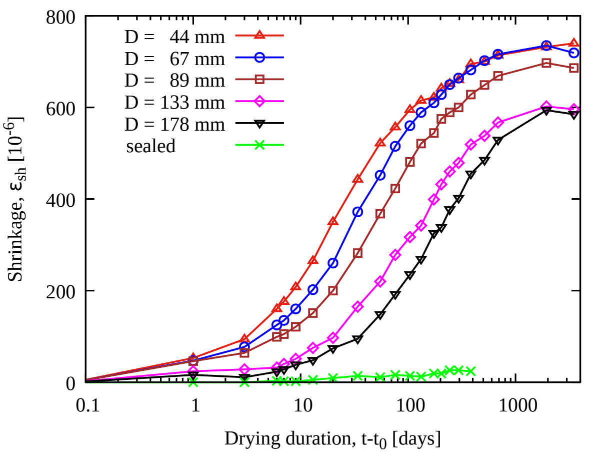

Figure 3. Evolution of drying shrinkage measured by Shritharan, the data adapted from [16] serve as an example of experiment in which the shrinkage of all specimens can be considered to have terminated.

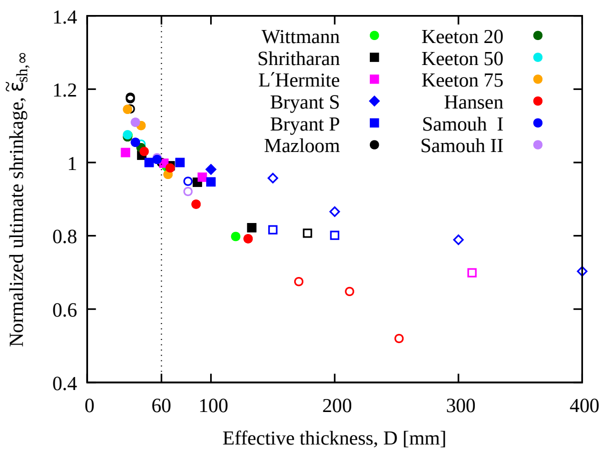

Figure 4. Influence of the effective thickness on the normalized experimentally measured ultimate shrinkage strain. The strain is normalized with respect to the value corresponding to $D = 60$ mm, empty symbols mark the last data points in prematurely terminated experiments.

does not define size effect on drying shrinkage magnitude for $D < 100$ mm; the value for 60 mm was linearly extrapolated from the interval 100–200 mm. In contrast to the other models, the *fib* MC 2010 and for $D > 100$ mm also the B3 model completely neglect the size effect on the ultimate shrinkage. Compared to other models, the B3 model is the only model which incorporates the onset of drying into the size effect on the ultimate drying shrinkage. However, this effect is limited only to specimens with $D < 30$ mm which makes the purpose of the entire proposed and rather complex formula (2) rather questionable.

A comparison of the processed experimental data is displayed in Fig. 4. The value of shrinkage strain at the end of the experiment was normalized with respect to the value corresponding to $D = 60$ mm (if missing, the value was obtained by the linear interpolation or linear extrapolation such as in the case of "slabs" specimens from Bryant's experiment). The filled points denote the experiments which were treated as terminal while the empty marks correspond to the experiments which did not last sufficiently long and in which further increase of shrinkage can be expected. The symbol type was selected to resemble the shape of the specimen (circle for a cylinder, square for a prism).

As documented by the Fig. 4, the experiments show a uniform and almost linearly decreasing trend in the range 30 mm $< D <$ 150 mm. However, there are almost no data for $D >$ 150 mm. This does not infer that the experiments above 150 mm do not exist at all but rather the experimental setup did not explore different sizes.

A very small size effect on drying shrinkage can be observed in the case of the "slab" specimens tested by Bryant. However, the results presented in Fig. 4 might be misleading: the smallest specimen size was $D = 100$ mm while the values are normalized with respect to $D = 60$ mm. This was done by extrapolation from the experiment with $D = 100$ mm and $D = 150$ mm which had almost the same value of shrinkage. Similar result offers also L'Hermite in whose experiment the specimens started drying already at the age of 1 day but very probably this is not the only reason. On the other hand, the steepest size effect on drying shrinkage was documented by Keeton. His experiment also demonstrates that the size effect is humidity independent.

Yet, there is no experimental evidence which could provide a clue to identification of the size effect in more massive members. It must be noted that the ultimate drying shrinkage of thick members might not be of interest because the design life-time might actually come earlier than the member dries.

Figure 5 compares the experimental data with the prediction models. The models which do not consider size effect on drying shrinkage — *fib* MC 2010 and model B3 (above 100 mm) — are evidently incorrect. The best agreement is reached with both alternative formulations in ACI 209 which somehow create a lower and upper-bound to almost all experimental data. Since the Eurocode 2 provides a recommendation only for $D > 100$ mm where very few experimental data are present, it is difficult to assess its performance. However, the slope of the EC2 curve in Fig. 5 is similar to the ACI 209 which provides a good agreement. Unfortunately, the newly prepared version of Eurocode 2 [17] which origins from the Model Code 2010 omits the size-dependent coefficient k_h from the formulation and thereby completely neglects the size effect on the ultimate drying shrinkage. This will lead to more conservative but less economic design.

5. Conclusions

The presented study analyzed the size effect on the ultimate drying shrinkage of concrete and compared the processed experimental data to the recommendations and codes of practice. The following conclusions can be drawn:

- According to the currently valid codes of practice, namely the Eurocode 2 and ACI 209.2R-08, the ultimate drying shrinkage is decreasing with increasing size (effective thickness). It can be stated that for members with effective thickness D between 100 mm and 200 mm this size effect is captured similarly.

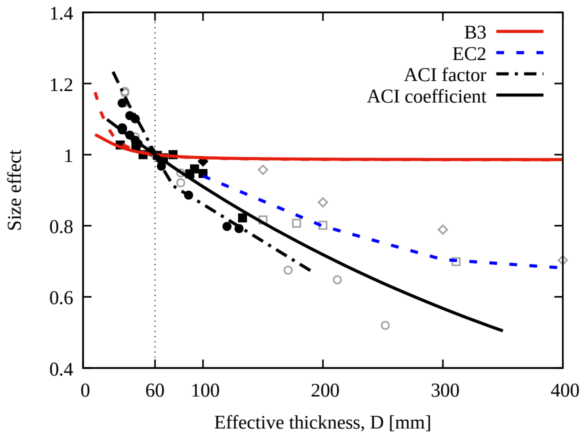

Figure 5. Comparison of the size effect according to the design codes and recommendations (curves) with the experimental data (filled black symbols = finished shrinkage, empty grey symbols = prematurely terminated experiments). The functions and the data are normalized with respect to the size $D = 60$ mm.

- As described by the B3/4 models the size effect is a function of the age when concrete starts drying and is very pronounced only for specimens with $D < 50$ mm, otherwise the size effect almost vanishes, similarly to the *fib* Model Code 2010 which ignores this size effect completely (and very probably so will do the new EC2).
- The experimental database [16] contains 6 suitable experimental studies which together with 2 additional studies from the literature provide consistent results confirming the presence of size effect on the ultimate drying shrinkage. None of the experimental studies exhibits opposite or no size effect on the drying shrinkage magnitude. However, it must be noted that sound experimental data for $D > 150$ mm are missing and thus cannot provide any evidence above this limit.
- For D in the range from 20 mm to 150 mm both approaches of the ACI 209 code exhibit by far the best agreement with the experimental data.
- The experimental data on the ultimate shrinkage of specimens with $D > 200$ mm are not available and very likely will not be available in the near future. In opinion of the present authors, the code-like expressions should not be constructed by a simple extrapolation beyond the experimentally explored range. More preferably, these expressions should origin from the FEM simulations exploiting properly calibrated and physically based material model which will perform well in the well-documented range 20 mm $< D <$ 150 mm.

Acknowledgements

The authors gratefully acknowledge financial support from the Grant Agency of the Czech Technical University in Prague, project number SGS19/032/OHK1/1T/11, and from the Czech Science Foundation, project number 19-20666S.

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