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EXPERIMENTAL VERIFICATION OF THE CONCRETE SHRINKAGE STRAINS COURSE ACCORDING TO EN 1992-2 STANDARD

ABSTRACT

The article provides basic information about the shrinkage of concrete and discusses the major impact on the size and course of the shrinkage. There are the guidelines to estimate the shrinkage strain of concrete bridge structures for the high tensile strength-SCI in accordance with PN-EN 1992-2. The article presents the results of experimental studies which aim was to analyze the course of shrinkage in two types of specimens made of different composition mixes. The studies have also made possible to verify the actual size of the shrinkage strain and designated ones on the basis of the PN-EN 1992-2.

Key words: *shrinkage, concrete, Eurocode standard PN-EN 1992-2, experimental studies*

INTRODUCTION

Concrete structures mainly bridge constructions in which there are long or massive items are exposed to scratching due to the shrinkage strain i.e. rheological strains not connected to the mechanical load. The resulting shrinkage of the concrete elements scratches can contribute to the reduction of utility functions and reducing the objects durability [1–4]. The immediate cause of shrinkage strain is the loss of water which occurs in the concrete due to physical and chemical processes associated with its binding, hardening and drying [1, 5–7]. The development of such strain is not equal in time. Initially there is a so-called autogenous shrinkage, which is the result of water loss due to hydration of cement and water evaporation from the outer layers of grout. Autogenous shrinkage comprises a binding phase and the initial phase of the hardening of concrete, increases very rapidly during the first hours after concreting, but has no significant impact on the overall shrinkage strain in the structure [1, 8–10]. However, there is a period when the concrete has low tensile strength. When this limit is exceeded it can lead to concrete scratches, thereby reducing its protective function. To reduce the negative impact of autogenous strain the proper care of concrete is needed especially in the first days after the cementing [1, 8, 10–11]. In the hardened concrete the physical shrinkage occurs called drying shrinkage associated primarily with the evaporation of water adsorbed by the cement gel and intragranular water. The shrinkage due to drying is growing much slower than autogenous shrinkage but for many years and has a decisive influence on the size of the total shrinkage strain [1–3, 5–6, 10–13]. The size and the shrinkage strain increase depend directly on both the quantity of water contained in the concrete mix and water in the concrete surrounding. Therefore, the main factors affecting the shrinkage include the ratio w/c grout as well as the humidity and environmental temperature which affect the rate of water evaporation from the concrete. For this reason it is very important the concrete proper care especially in the first 7 - 14 days after cementing. Less important, but also important are: the type of cement, the type and amount of aggregate, the dimensions of the component and the shrinkage restriction, for example different types of reinforcement used. Certainly an important factor is the age of the concrete, as the deformation grow over time most intensively during the first days of cementing, if the concrete is not cared for enough (humidity of the environment ≥ 90%) [2, 7–9]. Intensive shrinkage growth lasts for about three months then the systolic strain continue to increase, but at a much slower pace. In some cases, where the concrete humidity is over 90%, it may cause shrinkage inhibition even shrinkage strain may be reduced [1–3, 5–6, 7].

The PN-EN 1992-1-1 [15] and PN-EN 1992-2 [16] give guidelines to estimate the total shrinkage strain [14] and in the standard [15] there are the general guidelines for the design of concrete (described in [13]), while the standard [16] defines it in terms of bridge construction for high strength concrete, i.e. class C55/67 and higher.

In this paper the results of experimental studies are presented which show that included in the standard [16] model to estimate accurately reflects the course shrinkage also for concrete bridges with lower class than C55/67.

THE THEORETICAL METHOD FOR DETERMINING THE SHRINKAGE STRAIN ACCORDING TO PN-EN 1992-2 (IN CONJUNCTION WITH PN-EN 1992-1-1)

The size of the total shrinkage strain of concrete structures should be calculated on the basis of the guidelines set out in the standard [15], which refers to the standard [16] with the exception that high-strength concrete made of cement R class with or without the use of silica dust with the strength greater than C50/60 should the guidelines set out in A annex a of standard [16] be adopted. Given the above, according to [15], the total systolic strain (ε_{cs}) regardless of the strength of concrete is calculated as the sum of the strain caused by autogenous shrinkage(ε_{ca}) and the strain due to drying (ε_{cd}): (ε_{cd}):

$$\varepsilon_{cs} = \varepsilon_{ca} + \varepsilon_{cd} \tag{1}$$

But both autogenous shrinkage and drying shrinkage due to both standards are described by different models. The standard [16], which relates to high-strength concrete, defines more precisely autogenous shrinkage growth within 28 days of the cementing (i.e. the standard time frame indicating compressive strength). In this case, autogenous shrinkage depends on the concrete hardening speed, which is expressed by a coefficient ($f_{cm}(t)/f_{ck}$) which determines the method of strain estimating ε_{ca}. If the hardening of the concrete is relatively slow ($f_{cm}(t)/f_{ck}$) <0.1, the autogenous shrinkage in this case is very small and can be ignored. If ($f_{cm}(t)/f_{ck}$) ≥ 0.1, the concrete hardening speed is so high that it can lead to extensive build up of shrinkage strain. These relations the following formulas describe:

$$\varepsilon_{ca}(t) = 0, \quad dla\ \frac{f_{cm}(t)}{f_{ck}} < 0{,}1 \tag{2}$$

$$\varepsilon_{ca}(t) = (f_{ck} - 20)(2{,}2\frac{f_{cm}(t)}{f_{ck}} - 0{,}2) \cdot 10^{-6}, \quad dla\ \frac{f_{cm}(t)}{f_{ck}} \geq 0{,}1 \tag{3}$$

where: ε_{ca} – autogenous shrinkage strain occurring between the bonding time and the time t, t – concrete age [days], f_{ck} – characteristic compressive cylinder strength of concrete at 28 days, f_{cm} – mean compressive strength for time t.

However, after 28 days according to [16] the strain size of autogenous shrinkage can be estimated by the formula:

$$\varepsilon_{ca}(t) = (f_{ck} - 20)\left[2{,}8 - 1{,}1\exp\left(-\frac{t}{96}\right)\right] \cdot 10^{-6} \tag{4}$$

About the size of shrinkage due to drying the nominal shrinkage strain decide when drying ($\varepsilon_{cd,0}$) depends mainly on the humidity of the environment, as well as the properties of the material (concrete class, the type of cement used), and the concrete area which is subjected to drying expressed by authoritative dimension element ($h_0 = 2A_c/u$) Therefore, to estimate the size of strain caused by the drying of high-strength concretes is given by the formula (5) given in [16]:

$$\varepsilon_{cd}(t) = \frac{K(f_{ck})[72\exp(-0{,}046 f_{ck}) + 75 - RH](t - t_s)10^{-6}}{(t - t_s) + \beta_{cd} h_0^2}, \tag{5}$$

where: $K(f_{ck}) = 18$ (for $f_{ck} \leq 55$ MPa), $K(f_{ck}) = 30 - 0{,}21 f_{ck}$ (for $f_{ck} > 55$ MPa), f_{ck} – characteristic concrete compressive cylinder strength [MPa], RH – ambient relative humidity [%], t – the age of the concrete [days], t_s – the age of the concrete at the beginning of the process of drying (or swelling) [days], h_0 – notional size (mm) of the cross-section ($h_0 = 2A_c/u$), A_c – concrete cross-sectional area, u – perimeter of that part of the cross-section which is exposed to drying, $\beta_{cd} = 0{,}007$ (for concrete with silica dust), $\beta_{cd} = 0{,}021$ (for concrete without silica dust).

Accordingly to this the shrinkage strain in concrete with a humidity of 80% can be estimated.

EXPERIMENTAL STUDIES

Experiments were conducted on two kinds of specimens varying in composition of concrete mixtures. The type and quantity of ingredients used to implement the various mixtures are given in Table 1. The ingredients were dosed by weight. Concentration of compound was done in moulds on a vibrating table.

Table 1. *Composition of concrete mixtures*

The concrete mixture composition	Specimens of first type (**A**)		Specimens of second type (**B**)	
	Mixture **M1**		Mixture **M2**	
	Type	Quantity [kg/m^3]	Type	Quantity [kg/m^3]
cement	CEM I 52,5 HSR NA	390	CEM I 42,5R MSR NA	360
aggregate	basalt grit f. 8/16	694	basalt grit f. 8/16	731
aggregate	basalt grit f. 2/8	617	basalt grit f. 2/8	581
sand	river sand	660	river sand	691
water	from water supply	155	from water supply	144
addition	superplasticizer	1,84	superplasticizer	1,98
addition	aerator	0,47	aerator	0,36
ratio w/c	0,40		0,40	
consistency	S1		S1	
concrete class	**C45/55**		**C40/50**	

On the basis of the PN-EN-206-1: 2003 [17] to the compressive strength of cubic specimens was performed and then the average strength was calculated as well as the standard deviation and coefficient of variation for specimens of both types. Table 2. summarizes the results obtained.

Table 2. *Results of concrete compressive strength for specimens A and B*

	Specimens **A** (**MI**)	Specimens **B** (**MII**)
Average strenght, f_{cm} [MPa]	66,7	63,54
Standard deviation, s[MPa]	5,49	5,71
Coeffitien of variation, ν	8,23	8,98
Characteristic cube strength, $f_{ck,cube}$ [MPa]	**57,70**	**55,14**
Characteristic cylinder strength, f_{ck} [MPa]	**46,16**	**44,11**

On this basis the concrete class for each type of sample was specified [18]: A specimen made of M1 mixture was qualified for concrete class C45/55, and specimen B from the mixture M2 class C40/50. Although it should be noted that the differences in the values of strength were small.

Shrinkage measurements were carried out based on the guidelines provided in ITB Instruction 194/98: "The study of the mechanical properties of concrete on specimens taken in the moulds" [19]. The shrinkage was measured on each side of the prepared specimens. The basic for measurements were two metal benchmarks on each side placed in a 1/3 of the sample height. For the measurement of the strain gauge socket Demec (N° 4938) was used of WH production Mayes & Son of base 200 mm (8 inches) and accuracy of 0.002 mm; extensometer was 0.79 x 10-5. Measurements took place at certain intervals, taking into account the guidance given in the manual [19]: for the first 10 days daily, from 10 to 26 of every four days, and then every 10 days for 68 days.

ANALYSIS OF THE RESULTS

On each side of tested specimen the average values were determined for the shrinkage strain of both types of specimens. Strain diagrams for specimens A and B are shown in Figure 1 based on the measurements.

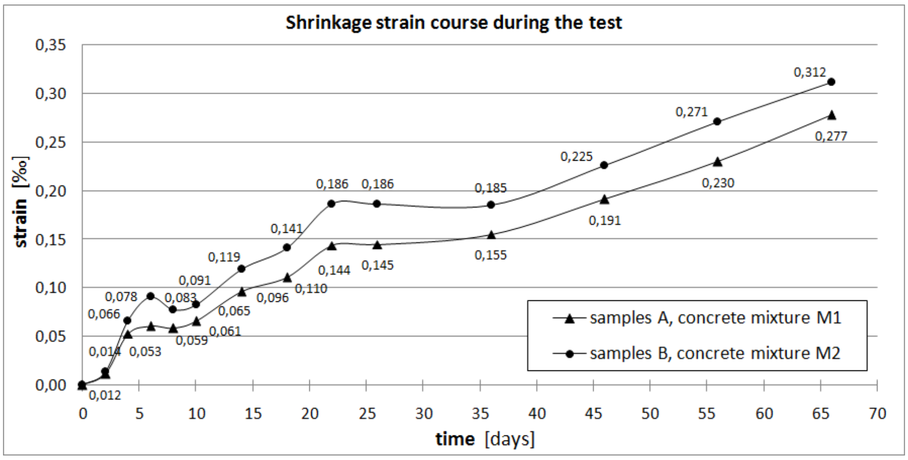

Fig. 1. Graph of average shrinkage strain for the two types of specimens

Analysing graphs (Fig. 1) it can be seen that the systolic strain in both types of specimens are carried out quite similarly. For the first four days course of strain measurements were almost identical. Between 4 and 6 day for specimen B there was a significant higher increase in strain than in specimen A. The difference in strain between the specimens B and A was $\Delta\varepsilon = 0.03‰$. This difference (with minor differences between 8 and 18 days of measurements) was maintained until the end of the study.

On the graphs of shrinkage strain, both for the specimen A and B, three distinct stages of strain growth were observed at intervals of 0-6 days, 8-22 days or 36-68 days (Table 3). The largest increase in strain was observed in the first week of the study (day 6). In this period, the average rate of increase of specimen strain A was 0.010 ‰/day and for specimen B 0.015 ‰/day. After this period the short expansion occurred. The second stage of strain growth was observed during the period of 8 to 22 days. During this period the growth rate of shrinkage was slower in relation to stage I. Specimen A strain showed a growth rate of 0.0061 ‰/day, whereas the specimen B 0.0077 ‰/day. After the second stage, for about 14 days, systolic strain remained more or less at the same level. In the last stage, 36 to 68 day, in both specimens A and B further increase in strain speed was observed which was ~ 0.004 ‰/day. The observed results are presented in Table 3.

Table 3. *Growth of shrinkage strain during the test divided into 3 stages*

Stage	Testing period [days]	Number of days [t]	Specimens A			Specimens B		
			$\varepsilon_p \div \varepsilon_k$ [‰]	$\Delta\varepsilon=\varepsilon_k-\varepsilon_p$ [‰]	$\Delta\varepsilon/t$ [‰/day]	$\varepsilon_p \div \varepsilon_k$ [‰]	$\Delta\varepsilon=\varepsilon_k-\varepsilon_p$ [‰]	$\Delta\varepsilon/t$ [‰/day]
I	0 – 6	6	0 – 0,061	0,061	**0,010**	0–0,091	0,091	**0,015**
II	8 – 22	14	0,059 – 0,144	0,085	**0,0061**	0,078-0,186	0,108	**0,0077**
III	36 – 68	32	0,155 – 0,277	0,122	**0,004**	0,185-0,312	0,127	**0,004**

The rest of the research study was to verify the model to estimate the course of strain stated in the standard [16] based on the actual results obtained for the two types of specimens.

Since both types of specimen concrete mixtures composition was known as well as the specimens size the compressive strength was experimentally determined and during the test each day the level of humidity and temperature were recorded, it was possible to estimate both the autogenous shrinkage (ε_{ca}) which depends primarily on the medium and the characteristic compressive strength of concrete at a given age, and the shrinkage due to drying (ε_{cd}), depending mostly on the environmental humidity and the material parameters as well as the size of the surface subjected to drying.

According to the standards guidelines, using the formulas (1) - (5), the size of shrinkage strain on consecutive days was determined, which correspond to the actual days of the experimental measurements. Estimated in this way, the theoretical amount of shrinkage for specimens of both types are shown in graphs in Figure 2 for specimen A and Figure 3 for specimen B along with the diagrams of the actual strain course.

As it is apparent from the comparison of the actual shrinkage strains and ones based on the estimated in standard [16], there is the consistency between them, both the specimens A and B. In addition, due to the same measurement conditions and shape of the specimens and small differences in the compressive strength (Table 2), the strain course estimated by [16] is almost the same for both types of specimens.

In specimen A made of concrete class C45/55 strain was slightly less effective than is apparent from the model presented in [16]. The greatest differences in their actual and theoretical strain was observed in the 2 and 10 day of the measurements ($\Delta\varepsilon$ = 0.035‰) and at 8 and 14 ($\Delta\varepsilon$ = 0.03‰). In other days these differences did not exceed 0.02‰ decreasing gradually as the measurements were being taken.

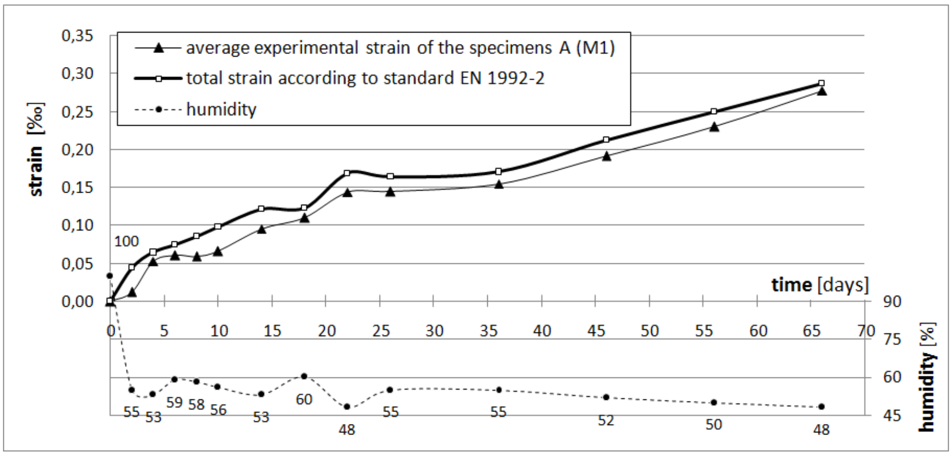

Fig. 2. The graph of actual and estimated shrinkage strain according to EN 1992-2, together with the distribution of humidity during the study

In the specimen B made of concrete class C40/50 the actual and theoretical shrinkage values were closer than in the case of specimen A. The maximum difference in the volumes of strain occurred on the second day of measurement and was $\Delta\varepsilon$ = 0.03‰. However, for specimens of this kind (specimen B) the actual systolic strains (except the three measuring points) were higher than estimated by [16], and as research was carried out this difference did not decrease.

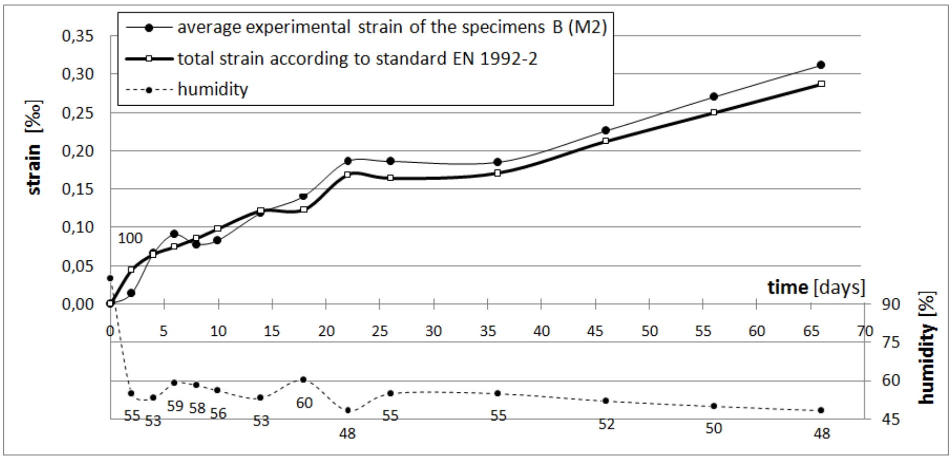

Fig. 3. The graph of actual and estimated shrinkage strain according to EN 1992-2, together with the distribution of humidity during the study

In both specimens A and B the largest differences in their actual and theoretical shrinkage occurred in the first two days of measurements. Probably due to the fact that before the actual measurements of the specimens were kept in the moulds which reduced the evaporation of water and thus the real humidity of the specimens environment was higher than the overall humidity (HR = 53%), which the theoretical model takes into account.

Based on observations of graphs it can be seen that the more environmental humidity changes it affects the theoretical values of shrinkage strains than this is due to the actual measured values.

CONCLUSIONS

On the basis of experimental studies and their analysis it can be concluded that the theoretical model to estimate the shrinkage strains included in the PN-EN 1992-2 [16] and recommended for concrete class C55/67 and higher well reflects the course of the shrinkage strain in the concrete bridge also in the lower classes, i.e. C40/50 and C45/55. We must add however, that analysis applied only to the early strain, including 68 days of measurements and can be assumed that in the next days the systolic strain increased significantly for at least one month [1-3], which could have led to changes in the size of the actual and theoretical strain.

Number of strains in time for the two types of specimens was fairly similar, but the specimen A, made of concrete class C45/55 showed a slightly lower increase in shrinkage than specimen B, made of concrete C40/50, while the average compressive strength for both specimens did not differed significantly (section "experimental studies"). The differences in their strains in the first days of concrete hardening probably depended on the type of cement used. Specimens were made of cement 52,5N HSR/NA with normal early strength, while sample B with cement 42.5 MSR/NA with high early strength, which had a direct impact on the autogenous shrinkage which depends on the speed of concrete hardening. In the following parts of the measurements the shrinkage increase in both types of specimens has already been equal (with persistent initial difference).

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