DOI: 10.2478/adms-2014-0005

P. G. Kossakowski*, W. Raczkiewicz

Kielce University of Technology, Faculty of Civil Engineering and Architecture, Department of Strength of Materials and Concrete Structures,
*Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, * kossak@tu.kielce.pl*

COMPARATIVE ANALYSIS OF MEASURED AND PREDICTED SHRINKAGE STRAIN IN CONCRETE

ABSTRACT

The article discusses the issues related to concrete shrinkage. The basic information on the phenomenon is presented as well as the factors that determine the contraction are pointed out and the stages of the process are described. The guidance for estimating the shrinkage strain is given according to Eurocode standard PN-EN 1992-1-1:2008. The results of studies of the samples shrinkage strain of concrete C25/30 are presented with a comparative analysis of the results estimated by the guidelines of the standard according to PN-EN 1992-1-1:2008.

Keywords: *shrinkage, shrinkage strain, concrete, eurocodes, experimental test*

INTRODUCTION

Physico-chemical processes that occur during bonding, hardening and drying of concrete cause a number of phenomena resulting in structure changes [1–3]. One the results of these structural changes is called shrinkage phenomenon. This shrinkage is spontaneous rheological strain which happen during the bonding, hardening and drying of concrete due to loss of water (Fig. 1). Importantly, this shrinkage is not caused by mechanical stress ([4–7].

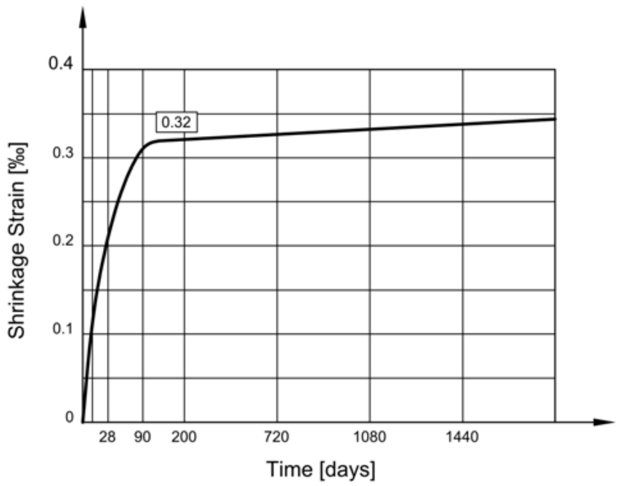

Fig. 1. Changes of shrinkage strain in time [8]

In the initial phase of concrete bonding the reduction of its volume occurs as a result of chemical reactions of cement hydration causing the strain known as chemical shrinkage. The arisen grout loses the water while it is still malleable causing plastic shrinkage. These changes, associated with the loss of water in the phase of concrete, lead to the so-called autogenous strain (also called self arisen). These systolic strain that arise soon after laying fresh concrete and within a few hours grows at a rapid pace [2, 3, 9].

In the next phase the hardened concrete loses water due to drying. The water is absorbed by the cement gel and internally crystal water. As a result of its loss the strains occur mainly on the surface of the concrete. These are the physical strain termed as shrinkage strain caused by drying of the concrete. Unlike the autogenous shrinkage the physical shrinkage can grow for a long time even over the several years. Therefore, strain caused by the drying of the concrete is the most important because of the potential shrinkage cracks (Fig. 2) in the concrete structures [7, 10–12].

Shrinkage depends on many factors. The biggest influence on the amount of shrinkage comes from environmental conditions, especially temperature and humidity which affect the rate of water evaporation. The size of shrinkage strain also depends on the type and the class of cement, the quantity of grout, in the ratio *w*/*c*, the type and the granulation of aggregates, concrete classes and age groups, the dimensions of the component and the mechanical limits of strain in the concrete, e.g. as a result of reinforcement located there ([2– 4, 13, 14].

Fig. 2. Effect of shrinkage strain in concrete structure

The process of shrinkage is related to the greatest extent to the losses of water from the cement grout. The water vapour from the empty pores has no effect on the shrinkage. As mentioned, the greatest impact on the shrinkage has the humidity – and when it is above 90 % this phenomenon is intermitted [2, 3]. Moreover, in a case of the humidity increase or concrete rewetting it is possible partially to divert the process of contraction and thus reduce the already existing deformations [9, 12].

ESTIMATION OF SHRINKAGE STRAIN ACCORDING TO PN-EN 1992-1-1

The phenomenon of shrinkage and strain associated with it have been included in many standards for design the concrete structures and reinforced concrete structures for many years. In this regard, the particular interest is paid to the European standards – Eurocodes.

The Eurocodes are a set of European standards for structural design of buildings and structures elaborated by the European Committee for Standardization (Fr. Comité Européen de Normalisation, CEN). The European Eurocode Standards are the result of the Treaty of Rome of 1975, when the European Commission decided to take action to eliminate technical obstacles to trade and set the harmonization of the arrangements in this regard. This resulted in the development of a harmonized set of technical laws (including standards) for the design of buildings structure. Nowadays, the laws in the form of Eurocode standards replace the standards used in different member countries of the European Union.

Shrinkage issues in the design of concrete buildings are included in the standard PN-EN 1992-1-1 [13]. This standard allows to specify the estimated shrinkage strain, as well as a guideline for the design requirements and methods to minimize the negative effects of shrinkage in different situations and structural elements. The requirements and methods for estimating the shrinkage strain in concrete buildings according to PN-EN 1992-1-1 [13] are presented below.

Shrinkage strain ε_{cs}

The shrinkage issues of concrete are discussed in several chapters of PN-EN 1992-1-1 standard [13]. It is reported that the shrinkage is time-dependent properties of concrete. Its effects should generally be taken into account for the verification of serviceability limit states.

Standard PN-EN 1992-1-1 [13] requires that the effects of shrinkage would be considered at the ultimate limit states only where its effects are significant, for example in the verification of ultimate limit states of stability where second order effects are of importance. In other cases these effects need not be considered for ultimate limit states, provided that ductility and rotation capacity of the elements are sufficient.

As stated in PN-EN 1992-1-1 [13] shrinkage depends greatly on the ambient humidity, the dimensions of the element and the composition of the concrete. The total shrinkage strain ε_{cs} is the sum of two components: autogenous strain and strain caused by drying:

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

where: ε_{ca} – autogenous shrinkage strain, ε_{cd} – drying shrinkage strain.

Autogenous shrinkage strain ε_{ca}

Autogenous shrinkage strain develops during hardening of concrete. Reaches its highest value within a few days after placing fresh concrete (casting). It is a linear function of the strength of concrete. Autogenous strain should be considered especially in cases where on the hardened concrete is placed the casting. This is due to differences in shrinkage stress of the adjacent layer of concrete that can cause cracking. Autogenous shrinkage strain developing in time $\varepsilon_{ca}(t)$ is defined by the function:

$$\varepsilon_{ca}(t) = \beta_{as}(t) \cdot \varepsilon_{ca}(\infty) \tag{2}$$

where: $\beta_{as}(t)$ – contraction coefficient determining the change in function of time, t – concrete age (days), $\varepsilon_{ca}(\infty)$ – final autogenous shrinkage strain.

Drying shrinkage strain ε_{cd}

Strain caused by drying shrinkage is related to the migration of water through the hardened concrete. This strain develops and grows slowly over a long period of time. The final value of strain caused by drying shrinkage of concrete $\varepsilon_{cd,\infty}$ is given by formula:

$$\varepsilon_{cd,\infty} = k_h \cdot \varepsilon_{cd,0} \tag{3}$$

where: k_h – coefficient depending on the notional size h_0, $\varepsilon_{cd,0}$ – nominal unrestrained drying shrinkage strain.

Value of $\varepsilon_{cd,0}$ is determined by the function:

$$\varepsilon_{cd,0} = 0.85 \cdot \left(220 + 100 \cdot \alpha_{ds1}\right) \cdot \exp\left(-\alpha_{ds2} \frac{f_{cm}}{f_{cm0}}\right) \cdot \beta_{RH} \cdot 10^{-6} \tag{4}$$

where: f_{cm} – average compressive strength of concrete (MPa), $f_{cm,0}$ = 10 MPa, $\alpha_{ds,1}$, $\alpha_{ds,2}$ – coefficients depending on the type of cement, RH – relative humidity of the environment (%), RH_0 = 100%, β_{RH} – coefficient depending on the relative humidity of the environment.

Shrinkage strain values connected with concrete drying in time function $\varepsilon_{cd}(t)$ can be estimated by the formula:

$$\varepsilon_{cd}(t) = \beta_{ds}(t, t_s) \cdot k_h \cdot \varepsilon_{cd,0} \tag{5}$$

where: t – age of concrete in days, t_s – age of concrete at the beginning of the process of drying or swelling in days, $\beta_{ds}(t, t_s)$ – coefficient depending on the age of the concrete, k_h – coefficient depending on the notional size h_0, $\varepsilon_{cd,0}$ – nominal value of unrestrained shrinkage.

The value of $\beta_{ds}(t, t_s)$ coefficient depending on the concrete age can be calculated using the following formula:

$$\beta_{ds}(t, t_s) = \frac{t - t_s}{t - t_s + 0.04\sqrt{h_0^3}} \tag{6}$$

where: t – age of concrete in days, t_s – age of concrete at the beginning of the process of drying or swelling in days.

EXPERIMENTAL STUDIES OF THE SHRINKAGE STRAIN IN CONCRETE

In order to verify the amounts of strain determined by the recommendations of PN-EN 1992-1-1 [13] the experimental studies have been conducted involving the measurement of strain in the concrete samples. Shrinkage strain measurements were made in accordance with the outlines of ITB Instruction 194/98 [15].

The study was subjected to eight cuboids samples with dimensions of 100×100×300 mm made of concrete C25/30, consistency S2, w/c = 0.45. The composition of the concrete mix are summarized in table 1. The ingredients were dosed by weight. The thickening of the mixture were carried out on a vibration table. Samples were stored and cared for in the laboratory hall in normal conditions of temperature and humidity.

Table 1. *Composition of concrete mix for concrete C25/30*

Ingredient	Amount
Portland cement CEM I 42,5 R	420 [kg/m^3]
Aggregate I – basalt grit f 5/11 mm (mine Górażdże)	769 [kg/m^3]
Aggregate II – basalt grit f 11/16 mm (mine Górażdże)	319 [kg/m^3]
Mine sand (mine Suków)	788 [kg/m^3]
Water – water supply	145 [l]
Super plasticizer – Kamafluid	~ 1% of cement weight

The accompanying study on the cuboids samples 150 × 150 × 150 mm allowed for the experimental designation of concrete classes. On the basis of the PN-EN 206-1 [16] the average compressive strength of concrete was determined, which was f_{cm} = 34.97 MPa, standard deviation equals to s = 1.58 MPa and coefficient of variation ν = 4.51. On this basis concrete class was qualified as C25/30.

The measurements of shrinkage strain (Fig. 3) were made by extensometer Demec WH production of Mayes & Son of base 100 mm, the accuracy of 0.002 mm and a constant equal to 1.6×10^{-5}.

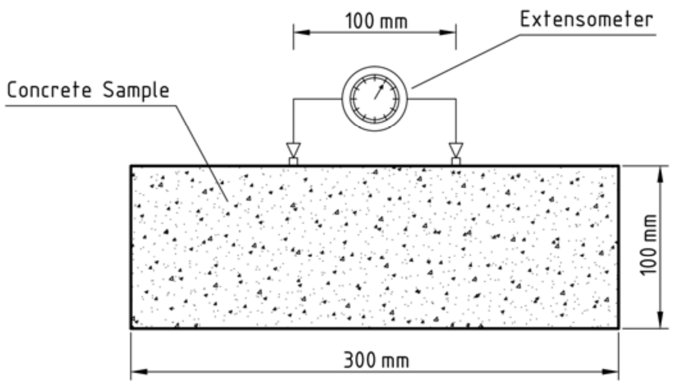

Fig. 3. Schematic shrinkage strain measurement by extensometer

Measurements were carried out according to the recommended schedule reported in [15] in the interval from 1 to 10 days – every 2 days, from 10 to 26 days – every 4 days, from 26 to 86 days – every 10 days, from 86 to 330 days – every month for nearly a year. The last measurement was carried out on 330 day since the samples were cemented. The process of shrinkage strain during this time is presented in Figure 4. As can be seen, there are eight curves representing the eight tests samples (each of this curves is the result of averaging the measurements of the four side walls of the test samples) and one curve is representing the average values of all samples.

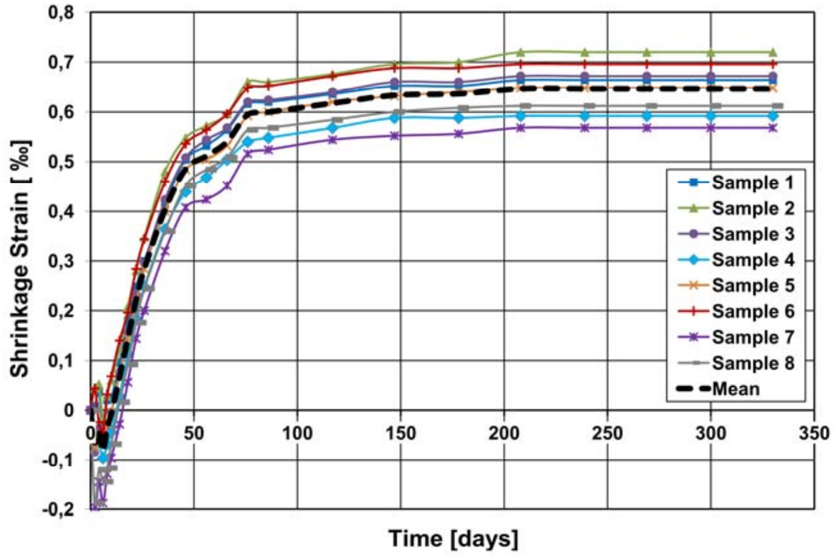

Fig. 4. Shrinkage strains measured during the test of concrete sample C25/30

For the experimental samples the shrinkage strain was estimate according to the guidelines given in PN-EN 1992-1-1 [13]. The equations (1) ÷ (6) were used. The actual dimensions of the samples were included to determine the coefficient k_h, the characteristic strength of concrete compressive strength were taken and the average for the concrete class C25/30 and the value of the coefficients $\alpha_{ds,1}$, $\alpha_{ds,2}$ for cement CEM I class N, corresponding to the parameters of samples. The samples were not stored in a climatic chamber, thus the constant temperature and humidity conditions were not provided. Because the humidity measurements were not performed regularly, for the formulas four gradually changing humidity sections were adopted: 100 % for the first 10 days, when the samples were stored in water, 80 % to 28 day after cementing, 70% up to 56 day after cementing and 50 % for the next days. This allowed to estimate the size of the shrinkage strain designated for the same interval as in the experimental studies.

ANALYSIS OF RESULTS AND CONCLUSIONS

Shrinkage strain diagrams obtained from both the experimental and the estimates on the basis of Eurocode PN-EN 1992-1-1 [13] is shown in Figure 5, in which the actual strain of the average of shrinkage measurements performed on eight samples indicated by the dashed line and the shrinkage strain based on Eurocode PN-EN 1992-1-1 [13] indicated by solid lines.

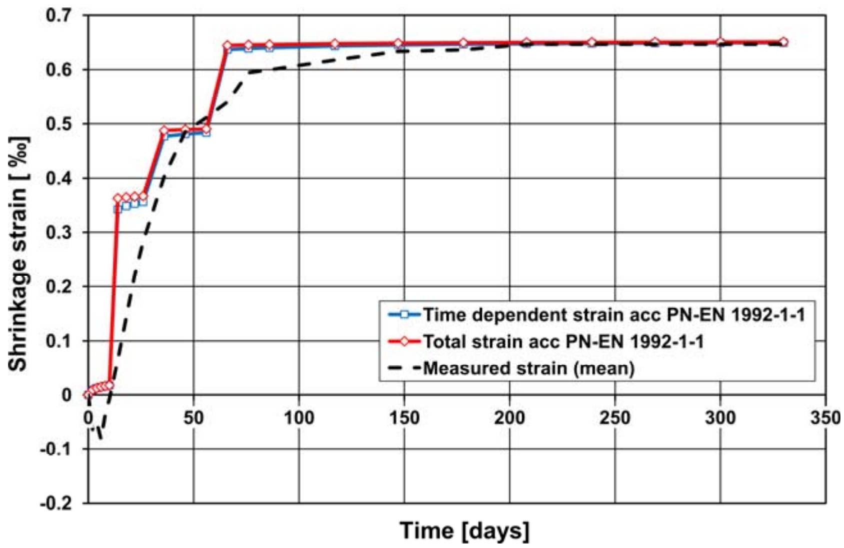

Fig. 5. Shrinkage strains – comparison of actual and estimated values according to PN-EN 1992-1-1 [13]

The analysis of the actual measurements reveal that in the first ten days in concreted samples the swelling occurred (up to a level of about 0.08 ‰), which was the result of intensive care and storage of the samples in water. After taking samples out of the water a regular increase of shrinkage strain was recorded. During the first three months the increase was the greatest – in the samples gradually and evenly the shrinkage strains were observed with 76 day average strain of 0.6 ‰. The subsequent measurements were carried out for approximately six months showing a much slower increase of shrinkage. On 178 day of measuring the average shrinkage strain reached a value of 0.64 ‰. It can be concluded that at this level the shrinkage has stabilized – further measurements showed only a minimal increase of shrinkage strain. On the last 330 day of measurements the shrinkage strain was 0.65 ‰.

Figures obtained by estimating shrinkage strain according to [13] are based on the (1), but for one of them, denoted as *Total strain acc PN-EN 1992-1-1*, the part describing strains due to the drying, is determined from (3), which are estimated by total shrinkage strain regardless the age of the subjected samples, while for the second, denoted as *Time dependent strain acc PN-EN 1992-1-1* which are based on (5), the strains caused by drying are determined as a function of time. Comparing these graphs it reveals that in the first three months of the size of the estimated shrinkage strain versus time are slightly lower than the strains which do not take into account the age of the concrete, but these graphs get together and from about 90 days after cementing we can say that they have almost identical course.

Comparison of the strains resulting from actual measurement values and estimated on the basis of PN-EN 1992-1-1 [13] is shown in Figure 5. As can be seen, there is a good agreement between the actual strain in the concrete and the strain value estimated in accordance with PN-EN 1992-1-1 [13]. The largest differences occur in the first three months of cemented samples. After this period differences in actual and estimated strain decreased reaching about 180 day of measurements of nearly identical values. From that moment it can be assumed that the shrinkage stabilized.

One of the main reasons for the initial differences between actual and estimated strain was certainly the intensive care of the samples. During the first 10 days, the samples were stored in water made their measurements indicated the swelling (ε_m ~ 0.08 ‰). According to the instruction [15] of the test contraction samples should not be kept in the water, but the authors consciously applied such care due to the nature of the whole research on concrete, which were carried out, and is not included in this article. Because, according to the guidelines [13] and

[15], such an intensive care is not assumed, using the formulas (1)÷(6) from the first day after of concreting some shrinkage strain values that grow between the following days are obtained. These strains result in this case only in the autogenous shrinkage, $\varepsilon_{ca}(t)$ estimated at the time, because for the shrinkage caused by drying, the ambient humidity is RH = 100 % and finally ε_{cd} = 0. These strains have very little value, however, due to the opposite sign strains presence in the tested samples in the first 10 days of concreting, there could be no compliance in the actual and estimated strains during this period. These initial differences influenced the further shrinkage course, which can be seen by comparing the curves in Figure 5.

A problem in the comparison of actual and estimated strain was the fact that the samples were not stored in a climatic chamber and it was not provided with constant temperature and humidity conditions. Therefore, when estimating the shrinkage strain the humidity value could not have been introduced. The humidity values were assumed on the basis of irregular measurements made during the study. These inconsistencies were evident mainly in the first three months of cemented samples, a period when shrinkage strain growth was the greatest, mainly associated with drying. The influence of ambient humidity during this period was of the great importance and lack of regular measurements influenced the results. In the tested samples the shrinkage growth was continuous, whereas the estimated shrinkage by the [13] grew incrementally when abruptly changing moisture values were introduced.

SUMMARY

The shrinkage strain measurements carried out on concrete samples and their estimation based on the recommendations of PN-EN 1992-1-1 [13] made it possible to analyze the results obtained. On this basis, it was found that for the tested samples of certain specific parameters, there is a good agreement between the actual and estimated shrinkage. Experimental studies were performed on eight samples of the same size and material parameters and therefore the conclusion may relate only to the samples of the type of these specific parameters. Furthermore, since during testing the ambient temperature and humidity were not measured continuously, the estimated shrinkage values are defined approximately. Nevertheless, taking into account the work of other researchers [5, 17, 18] where the course of ordinary concrete shrinkage was quite similar, it can be concluded that the accuracy of actual and estimated results is big.

REFERENCES

1. Neville A.M.: Properties of concrete [in Polish]. Polski Cement, Kraków, 2000.
2. Jamroży Z.: Concrete and its technologies [in Polish]. Wydawnictwo Naukowe PWN, Warszawa 2009.
3. Mertol H.C., Rizkalla S.H., Zia P., Mirmiran A.: Creep and shrinkage behavior of high-strength concrete and minimum reinforcement ratio for bridge columns. PCI Journal 55 (2010), pp. 138-154.
4. Flaga K.: The shrinkage of concrete and its effect on load carrying capacity, serviceability and durability of reinforced and pre-stressed concrete structures [in Polish]. Monograph in Zeszyty

Naukowe Politechniki Krakowskiej, Seria Inżynieria Lądowa nr 73, Wydawnictwo Politechniki Krakowskiej, Kraków 2002.

5. Barr B., Heseinian S.B., Beygi M.A.: Shrinkage of concrete stored in natural environments. Cement and Concrete Composites 25 (2003), 19-29 .
6. Kurdowski W.: Chemistry of cement and concrete [in Polish]. Polski Cement, Kraków 2010.
7. Flaga K.: Shrinkage stress and subsurface reinforcement in concrete structures [in Polish]. Monograph 391, Seria Inżynieria Lądowa, Wydawnictwo Politechniki Krakowskiej, Kraków, 2011.
8. Łapko A.: Design of reinforced concrete structures [in Polish]. Arkady, Warszawa 2001.
9. Piasta W.: Self-deformations of aerated concretes [in Polish]. Przegląd Budowlany 4 (2009), 28-31.
10. Flaga K.: Anti shrinkage reinforcement, calculation, design recommendations in the building industry [in Polish]. Proceedings of XVII Ogólnopolska Konferencja Warsztat Pracy Projektanta Konstrukcji, Ustroń 2002, pp. 1-43.
11. Flaga K., Klemczak B., Knoppik-Wróbel A.: Calculation methods for prediction of cracking risk in bridge abutments [in Polish]. Inżynieria i Budownictwo 5 (2013), 271-276.
12. Domagała L.: Shrinkage and expansion of lightweight aggregate concrete modified with fibres [in Polish]. Czasopismo Techniczne. Budownictwo 105 (2008), 21-40.
13. PN-EN 1992-1-1: 2008 Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings.
14. Kossakowski P., Raczkiewicz W.: Estimating of shrinkage strains in concrete bridges structures by the Eurocodes [in Polish]. Mosty 4 (2013), 28-30.
15. Brunarski L.: The study of mechanical properties of concrete samples made in molds. ITB Instruction 194/98 [in Polish]. Instytut Techniki Budowlanej, Warszawa, 1998.
16. PN-EN 206-1:2003 Concrete – Part 1: Specification, performance, production and conformity.
17. Zamorowski W, Gremza G.: Investigation of the concrete shrinkage effect on the deflections and deformations of the steel and concrete composite beams [in Polish]. Przegląd Budowlany 2 (2006), 18-22.
18. Sikora H., Piasta W.: Rheology of air entrained concretes and cements with mineral additives [in Polish]. Budownictwo i Inżynieria Środowiska 3 (2012), 141-146.