PREDICTING SHRINKAGE DEFORMATION OF HIGH-STRENGTH CONCRETE

Elica Marusic (1) and Nina Stirmer (2)

(1) Laboratory for Concrete and Brick, Institute IGH, Split, Croatia

(2) Department of Materials, Faculty of Civil Engineering, University of Zagreb, Croatia

Abstract

Results obtained by testing shrinkage deformation on ten groups of concrete, using the total of thirty one mixtures, are presented in the paper. Concrete groups differed according to the quantity of water and mineral and chemical admixtures. In this way, a wide range of concrete compressive strength values, from normal concrete to high strength concrete, was obtained, in addition to different consistency values. The shrinkage of concrete specimens after a two-day cure in water was monitored over a period of more than one year. An another series of twenty-nine concrete mixtures was also prepared to monitor the autogenous shrinkage of concrete. The total shrinkage of concrete was defined as the sum of the autogenous shrinkage of concrete at one day of age, and the shrinkage of concrete after the end of curing. In this paper, the model was developed and used in order to predict concrete shrinkage values after initial curing, and total shrinkage values, as related to compressive strength of concrete.

1. INTRODUCTION

In case of high strength concrete, the autogenous shrinkage component as related to shrinkage due to drying, is much more pronounced when compared to the normal-strength concrete. The question can be put about the way in which the existing shrinkage-prediction models take into account the shrinkage of high strength concrete.

An overview of models that are currently widely used for predicting shrinkage and creep is given in ACI 209.2R-08 [1]. These models are: ACI 209R-92 model [2], Bazant-Baweja B3 model [3], CEB MC90-99 model [4], and GL2000 model [5]. Ultimate compressive strength values for which these models can be used are indicated in the models. They slightly exceed 50 MPa, which is also the compressive strength value that is considered the limit for defining the high strength concrete. Out of these models, only the CEB MC90-99 model makes the distinction between the components of shrinkage due to drying, and autogenous shrinkage. Other models comprise the total shrinkage from the start of measurement after initial cure. The new edition of the CEB Model Code 2010 [6], and Eurocode 2 in form of HRN ENV 1992-1-1 [7], differ very little from the model proposed in CEB MC90-99. Neville [8] indicates that official models are only the "least common denominator" agreed upon by several experts, and that the new edition of the model does not necessarily bring improvements. It can therefore be stated that a generally-accepted shrinkage-prediction model has not as yet been found.

In the available literature dealing with the issue of shrinkage, this phenomenon is often analysed on a limited number of concrete compositions, which rarely exceeds ten compositions, and where the focus is on a specific influence. Models can now be evaluated and compared [1], [3], [9], [10], [11] by means of the RILEM data base [12] which contains 412 sets of experimental results collected by more than one hundred researchers worldwide. Nevertheless, most of these data can not be compared to one another because comparable input data are unavailable, which is why the information contained in the database should be taken with caution [9].

It is considered that the principle of superposition of autogenous shrinkage and shrinkage due to drying is applicable to the total concrete shrinkage. However, it has been demonstrated that the autogenous shrinkage in drying conditions is smaller than the autogenous shrinkage of sealed specimens [13], [14]. This brings into question the principle of superposition.

Therefore, an experimental model was developed in this paper based on the analysis of dependence of concrete shrinkage on compressive strength. This model was used to predict concrete shrinkage values after initial curing, autogenous shrinkage at the age of one day, and total shrinkage values as their sum, all as related to the compressive strength of concrete.

2. EXPERIMENTAL PART

An extensive research was undertaken [15] in order to determine the dependence of shrinkage of concrete containing the cement CEM II/A-S on the compressive strength. The research consisted of two parts:

1. A series of 31 concrete mixtures was prepared, and the shrinkage was measured after a two-day water curing. The shrinkage was measured for more than one year.
2. A series of 29 concrete mixtures, with compositions similar to those of the previous mixtures, was prepared. The mixtures were subjected to the testing of autogenous shrinkage and influence of initial concrete curing in water. The shrinkage was measured for a period of three to four months.

Compositions of all prepared concrete mixtures, with indication of consistency classes, are presented in Table 1.

Results obtained during no more than one year of concrete shrinkage testing were analysed. The shrinkage measured from the stop of concrete curing, i.e. from specimen extraction from the mould, and autogenous shrinkage, were monitored separately. The total concrete shrinkage was obtained by adding the autogenous shrinkage at the concrete age of one day to the shrinkage measured after the end of concrete curing. The shrinkage measured as from the stop of concrete curing was measured in a conventional way.

The shrinkage was tested according to HRN U.M1.029 on prisms measuring (10 x 10 x 40) cm. After the concrete was placed into moulds, the specimens were covered with foil to prevent loss of moisture. They were left in the room at the temperature (20±2) °C and at relative humidity of >60%. After 24 hours, the specimens were extracted from the mould and bench marks were glued onto them at the distance of 150 mm. These marks were placed along the centre of the central line on two opposite sides of the specimen, i.e. at lateral faces of the specimen. This procedure was conducted within 10 minutes following specimen extraction from the mould.

Table 1: Concrete compositions

Group mark	Mixture mark	Water /cement ratio	Water /binding ratio	Cement	Water	Aggregate	Super-plasticiser		Retarder		Micro-silica	Consi-stency class
				kg	kg	kg	% cem.	kg	% cem.	kg	kg	
D1	D1-360	0.389	0.389	360	140	1963	1.5	5.4	0.2	0.7	-	S2 / F2
	D1-400	0.350	0.350	400	140	1908	1.5	6.0	0.2	0.8	-	
	D1-440	0.318	0.318	440	140	1885	1.5	6.6	0.2	0.8	-	
D2	D2-360	0.444	0.444	360	160	1923	1.5	5.4	0.2	0.7	-	S4 / (F4/F5)
	D2-400	0.400	0.400	400	160	1884	1.5	6.0	0.2	0.8	-	
	D2-440	0.364	0.364	440	160	1847	1.5	6.6	0.2	0.8	-	
D3	D3-360	0.500	0.500	360	180	1877	1.5	5.4	0.2	0.7	-	F6
	D3-400	0.450	0.450	400	180	1838	1.5	6.0	0.2	0.8	-	
	D3-440	0.409	0.409	440	180	1798	1.5	6.6	0.2	0.8	-	
S1	S1-360	0.500	0.462	360	180	1838	1.5	5.4	0.2	0.7	30	F6
	S1-400	0.450	0.434	400	180	1814	1.5	6.0	0.2	0.8	15	
	S1-440	0.409	0.383	440	180	1759	1.5	6.6	0.2	0.8	30	
S2	S2-360	0.444	0.427	360	160	1902	1.5	5.4	0.2	0.7	15	S5 / (F4/F5)
	S2-400	0.400	0.386	400	160	1860	1.5	6.0	0.2	0.8	15	
	S2-440	0.364	0.352	440	160	1826	1.5	6.6	0.2	0.8	15	
S3	S3-360	0.389	0.359	360	140	1919	1.5	5.4	0.2	0.7	30	S1 / F1
	S3-400	0.350	0.337	400	140	1879	1.5	6.0	0.2	0.8	15	
	S3-440	0.318	0.298	440	140	1843	1.5	6.6	0.2	0.8	30	
S4	S4-400	0.400	0.372	400	160	1844	1.5	6.0	0.2	0.8	30	S4 / F3
	S4-480	0.340	0.320	480	163	1763	1.5	7.2	0.2	0.9	30	
O1	O1-280	0.704	0.704	280	197	1905	-	-	-	-	-	S3 / (F3/F4)
	O1-320	0.625	0.625	320	200	1865	-	-	-	-	-	
	O1-360	0.556	0.556	360	200	1825	-	-	-	-	-	
	O1-400	0.500	0.500	400	200	1790	-	-	-	-	-	
O2	O2-320	0.659	0.659	320	211	1830	-	-	-	-	-	S4 / F5
	O2-360	0.603	0.603	360	217	1784	-	-	-	-	-	
	O2-400	0.550	0.550	400	220	1741	-	-	-	-	-	
	O2-440	0.507	0.507	440	223	1699	-	-	-	-	-	
O3	O3-360	0.547	0.547	360	197	1832	0.8	2.8	0.2	0.7	-	F6
	O3-400	0.500	0.500	400	200	1789	0.8	3.2	0.2	0.8	-	
	O3-440	0.461	0.461	440	203	1744	0.8	3.5	0.2	0.8	-	

The modification of the method described in the doctoral thesis by Drago Saje [14] was used for the autogenous shrinkage measurements.

3. TEST RESULTS

Shrinkage measurements started at the concrete age of 3 days, following 2 day of cure in water. These measurements were used as the basis for shrinkage deformation analysis. This analysis was made using results obtained by testing specimens from the first series comprising ten concrete mixture groups (31 mixtures) for which test results were available for specimens more than one year old.

All results obtained by testing shrinkage of concrete specimens exposed to drying at the relative moisture of (55 ± 5) % and at the temperature of (20 ± 2) °C are presented by means of approximation curves in Figure 1.

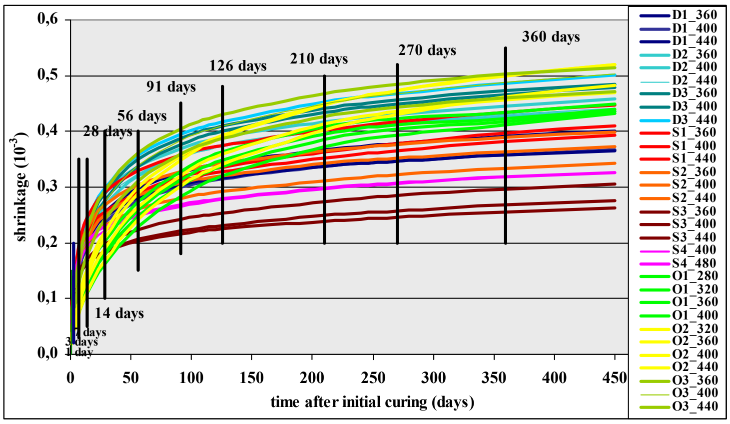

Figure 1: Concrete shrinkage test results for all compositions (specimens cured in water for two days) presented via shrinkage approximation curves

A general form of an approximation curve is given by the following expression:

$$\varepsilon_{sk} = \frac{t_s^{\ A}}{(t_s + B)^C} \cdot D \qquad (1)$$

where:

ε_{sk} - shrinkage measured in a conventional way, i.e. shrinkage after the end of concrete cure (10^{-3} or mm/m)

t_s - time after the end of concrete cure (days)

A, B, C, D -approximation curve coefficients for development of shrinkage over time

Test results for autogenous shrinkage of all groups of concrete in the period until 120 days are presented in Figure 2 together with approximate time curves.

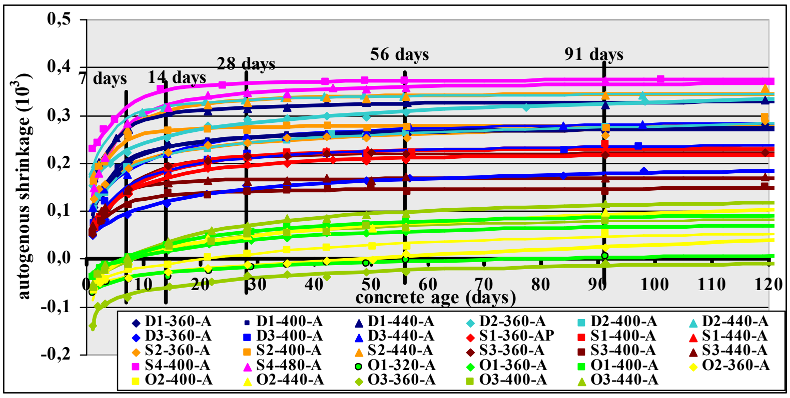

Figure 2: Autogenous shrinkage test results (measured values rather than corrected values are given for groups O1 and O2)

4. EXPERIMENTAL MODELS

Two concrete-shrinkage prediction models, namely DIS and DIS2V, in which compressive strength is a concrete composition parameter, were developed based on shrinkage test results, using regression methods. The time part of the shrinkage curve, and two members by which the model accuracy was increased in the first days of concrete shrinkage, are separated in one of these models, i.e. in DIS2V model, which will be presented in this paper. Other input parameters for modelling, which remained constant during the testing, i.e. relative moisture and mean thickness of cross section, were not considered in the paper as they can simply be taken over from one of the existing models, by defining an appropriate correction factor. The described procedure was used to develop basic alternatives of the DIS and DIS2V models, which are used for predicting shrinkage after the end of concrete cure. DIS and DIS2V model alternatives, aimed at predicting the total concrete shrinkage, were obtained by adding autogenous shrinkage at the concrete age of one day (approximated by parabola for the compressive strength of 41.7 MPa) to shrinkage values obtained by means of basic alternatives of DIS and DIS2V models.

4.1 Model of autogenous shrinkage of concrete at the age of one day

The autogenous shrinkage, corrected for deformation due to change in temperature and negative shrinkage, as presented in Figure 3, is approximated by parabola with the following equation:

$$\varepsilon_{ska1k} = 0{,}0000312 \cdot f_{cm28}^{\ 2} - 0{,}0013 \cdot f_{cm28} \tag{2}$$

where:

ε_{ska1k} - autogenous shrinkage corrected for deformation due to change in temperature and negative shrinkage (10^{-3} or mm/m)

f_{cm28} - mean compressive strength of concrete at 28 days, tested on a 15 cm cube

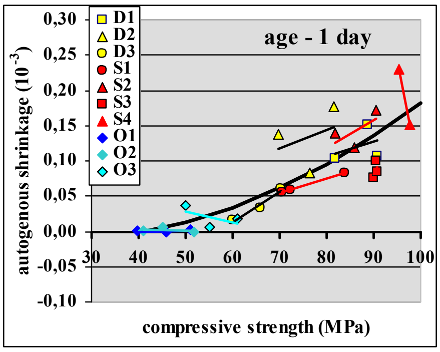

Figure 3: Autogenous shrinkage of concrete corrected for deformation due to change in temperature and negative shrinkage approximated by parabola

The equation has a zero point at 41.7 MPa. For concrete with compressive strength of less than 41.7 MPa, the autogenous shrinkage will be equal to zero.

4.2 Model of concrete shrinkage after initial cure – model DIS2V

The regression analysis of the function with two independent variables, namely the compressive strength and the time following the concrete cure, was made using measurement data, i.e. the data corrected in accordance with approximation curves. The model DIS2V is related to the prediction of the conventionally measured shrinkage of medium-thickness concrete specimens 50 mm in diameter, prepared using the cement type CEM II/A-S 42.5R, which were, after initial curing in water, exposed to drying at the temperature of (20 ± 2) °C and at the relative moisture of (55 ± 5) %. The set of curves presented in Figure 4 was obtained. This set of curves can be expressed with the following general equation:

$$\varepsilon_{sk} = \frac{f_{cm28}^{-2.615}}{-0.006288 + \frac{0.3803}{f_{cm28}^{2}} + 0.00579 \cdot f_{cm28}^{0.01759}} \cdot \left(\frac{t_s}{72.2 + t_s}\right)^{0.95} + 61.46 \cdot \frac{f_{cm28}}{(t_s + 188.9)^2} - 0.001157 \cdot \frac{f_{cm28}}{t_s^{1.2}} \quad (3)$$

where:

ε_{sk} - shrinkage measured in a conventional way (10^{-3} or mm/m)

t_s - time after the end of concrete cure (days)

f_{cm28}- mean compressive strength of concrete at 28 days, tested on a 15 cm cube

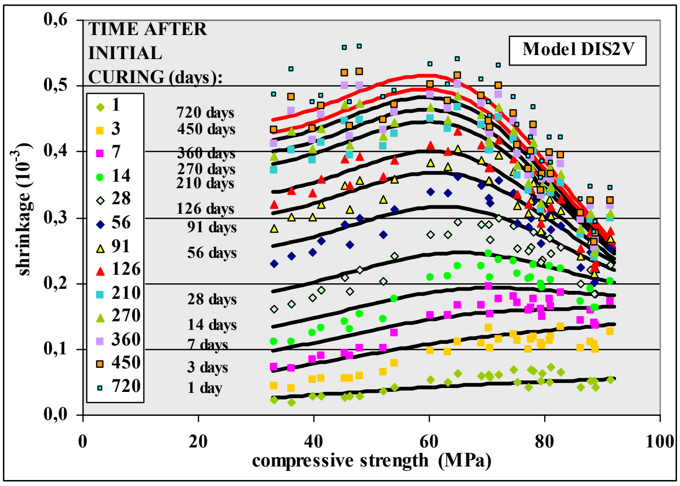

Figure 4: Relationship between shrinkage and compressive strength in different time intervals after the end of initial cure of concrete, with shrinkage approximation curves based on the DIS2V model

The final two members of the expression influence "correction" of the shrinkage curve in time intervals until 28 days, after which their influence ceases to be significant.

4.3 Total concrete shrinkage model

The total shrinkage according to the proposed experimental model for total shrinkage, DIS2V, is is shown in Figure 5 and described by the following expression:

$$\varepsilon_{sku} = \varepsilon_{sk} + \varepsilon_{skalk} \quad (4)$$

where:

ε_{sku} - total shrinkage of concrete (10^{-3} or mm/m)

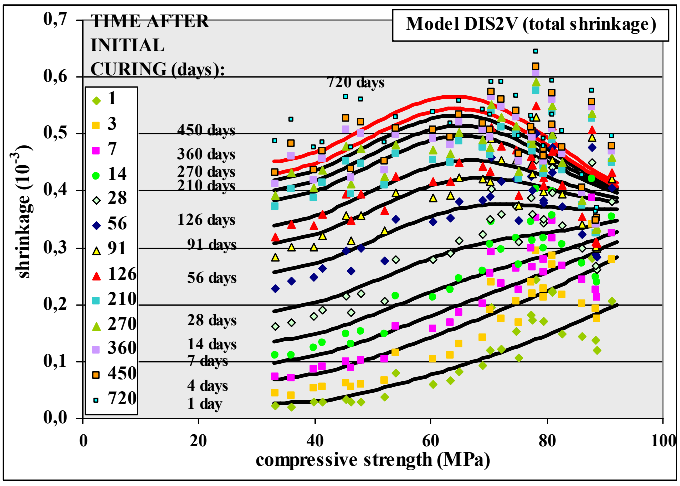

Figure 5: Shrinkage approximation curves according to the total-shrinkage experimental model DIS2V

5. COMPARISON WITH THEORETICAL MODELS

The CEB statistical indicators [1], i.e. coefficient of variation V_{CEB}, the mean quadratic error F_{CEB}, and the mean deviation M_{CEB}, as well as partial indicators in time intervals from 0 to 10 days, 11 to 100 days, and 101 to 365 days after concrete cure, are presented in Table 2. The BP variation coefficient value is also given.

Table 2: Statistical indicators for shrinkage prediction models (basic data set)

MODEL	CEB statistical indicators			Time after cure 0-10 days			11-100 days			101-365 days			BP variation coefficient
	V_{CEB}	F_{CEB} (%)	M_{CEB}	V_i	F_i (%)	M_i	V_i	F_i (%)	M_i	V_i	F_i (%)	M_i	ω_{BP}
SHRINKAGE AFTER INITIAL CURE – Experimental model													
DIS2V	**0,153**	**26,0**	**1,07**	0,235	43,0	1,18	0,097	10,0	0,99	0,074	8,4	1,03	**0,11**
SHRINKAGE AFTER INITIAL CURE – Theoretical models													
ACI	**0,593**	**62,9**	**1,34**	0,419	44,2	0,73	0,595	60,1	1,54	0,724	79,4	1,74	**0,79**
B3	**0,347**	**42,9**	**0,96**	0,526	68,3	0,96	0,247	25,2	0,93	0,151	14,9	0,99	**0,25**
GL2000	**0,328**	**50,8**	**1,05**	0,484	81,8	1,15	0,249	28,1	1,01	0,159	16,4	0,99	**0,26**
TOTAL SHRINKAGE - Experimental model													
DIS2V	**0,198**	**29,3**	**1,1**	0,285	47,4	1,2	0,151	13,9	1,0	0,116	11,9	1,0	**0,15**
TOTAL SHRINKAGE – Theoretical models													
EC2:2008	**0,467**	**72,1**	**1,3**	0,589	99,5	1,2	0,461	66,1	1,4	0,307	36,7	1,3	**0,58**
CEB MC90-99	**0,377**	**64,5**	**1,1**	0,571	104,9	1,2	0,272	33,4	1,1	0,165	18,7	1,0	**0,32**
MC2010	**0,435**	**85,7**	**1,3**	0,579	134,1	1,4	0,375	52,8	1,3	0,303	35,5	1,3	**0,53**

6. CONCLUSION

The paper presents the time model for predicting shrinkage of concrete of normal and high strength of up to 95 MPa, dependent on compressive strength (DIS2V models). The model analyses autogenous shrinkage at one day and shrinkage after initial cure, including the autogenous shrinkage component and the component of shrinkage due to drying. Other input factors for the model could be taken over from the Model Code 2010. The model is applicable to cement CEM II/A-S 42.5R and limestone aggregate. The expression for the autogenous shrinkage approximation at the concrete age of one day is proposed in the scope of the shrinkage prediction model. It is demonstrated that the definition of the concrete shrinkage model, based on data which intentionally include a great range of compressive strengths and consistencies of concrete with one type of components, can considerably improve accuracy of the shrinkage prediction model with respect to theoretical shrinkage models.

Acknowledgements

This research was conducted in the scope of the national research project entitled “From Nano - to Macro-structure of Concrete”, 082-0822161-2990, funded by Croatian Ministry of Education, Science and Sport.

References

[1] ACI COMMITTEE 209: Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete, report No. ACI 209R-08, 2008.

[2] ACI COMMITTEE 209: Prediction of creep, shrinkage and temperature effects in concrete structures, report No. ACI 209R-92, (1992), Reapproved 1997.

[3] Bazant, Z. and Baweja, S., RILEM Committee TC 107 'Creep and shrinkage prediction model for analysis and design of concrete structures – model B3' The Adam Neville Symposium: Creep and shrinkage – Structural Design Effects, SP-194, A.Al-Manaseer, ed., American Concrete Institute, Farmington Hills, MI, (2000), 1-83

[4] Federation Internationale du Beton: Structural concrete – Textbook on Behaviour, Design and Performance – Updated Knowledge of the CEB/FIP Model Code 1990, fib Bulletin 2, V.2, (1999)

[5] Gardner, N.J. and Lockman, M.J., 'Design Provisions for Drying Shrinkage and Creep of Normal-Strength Concrete', ACI Materials Journal, Vol. 98, No. 2, (2001), 159-167

[6] International Federation for Structural Concrete (FIB): CEB–FIP Model Code 2010, First complete draft , FIB, 2010.

[7] HRN EN 1992-1-1:2008, Eurocode 2: Design of concrete structures, Part 1-1: General rules and rules for buildings (EN 1992-1-1:2004+AC:2008), 2008.

[8] Neville, A.M., 'Creep of Concrete and Behaviour of Structures Part II: Dealing with Problems', *Concrete International*, Vol.24, No.6, June 2002, str. 52 - 55

[9] Altoubat, S.A., Lange D.A.: 'Creep, Shrinkage, and Cracking of Restrained Concrete at Early Age', ACI Material Journal, Vol.98, No. 4, July - August 2001, (2001), 323 – 331

[10] Al-Manasser, A. and Lam, J.P., 'Statistical Evaluation of Shrinkage and Creep Models', *ACI Materials Journal*, V. 102, No.3, May-June, (2005), 170-176

[11] Gardner, N.J., 'Comparison of Prediction Provisions for Drying Shrinkage and Creep of Normal Strength Concretes', *Canadian Journal for Civil Engineering*, Vol. 31, No. 5, (2004), 767-775

[12] RILEM TC-107-CSP-Subcommittee 5, Data Base on Creep and Shrinkage Tests, 1999.

[13] Ishida T., Chaube R.P., Kishi T., Maekawa K.: 'Microphysical approach to coupled autogenous and drying shrinkage of concrete', Proceedings of the International Workshop, JCI (Japan Concrete Institute), Hiroshima, Japan, 13-14.06.1998., ed. Tazawa, E., str. 301 – 312, 1998.

[14] Yang, Y., Sato, R., Kawai, K.: 'Autogenous shrinkage of high-strength concrete containing silica fume under drying at early ages', *Cement and Concrete Research*, 35, (2005), 449 – 456

[15] Marusic, E.: 'Predicting shrinkage deformation of high strength concrete', PhD Thesis, University of Zagreb, Faculty of civil engineering, 2012 (in Croatian)

[16] Saje, D., Compressive strength and shrinkage of high strength concrete, PhD Thesis No. 139, University of Ljubljana, Faculty of civil and geodetic engineering, 2001. (in Slovenian)