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INVESTIGATION OF SHRINKAGE OF CONCRETE MIXTURES USED FOR BRIDGE CONSTRUCTION IN LITHUANIA

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Abstract. The present paper reports results of the investigation on shrinking of the concrete mixture which is often used for casting the new bridges. The study is based on the experimental results obtained in three research projects which were performed under financial support provided by the *Lithuanian State Fund of Research and Studies* at the *Vilnius Gediminas Technical University* from 2005 to 2009. The accuracy of the most popular shrinkage prediction techniques was analysed using the test data. The analysis has shown that the *Eurocode 2* method has given the most accurate predictions. The attention was also pointed on the analysis of the steel fibres influence on the shrinkage deformations of the structural concrete. The performed statistical analysis has indicated that the steel fibres application as admixture significantly reduced the free shrinkage strains. The paper has concluded that utilisation of the steel fibres is very effective way of increasing the service properties of concrete bridges.

Keywords: shrinkage, calculation methods, experiments, steel fibers, concrete bridge, hypothesis test.

1. Introduction

Advanced civil engineering structures, especially bridges, are exclusively recognised in every society as a measure of culture, economical and social development. This development leads to steady increasing traffic. Therefore, in the modern societies, the civil engineers should secure the performance and durability of the transportation infrastructure. Naturally that the bridges, as a part of this infrastructure, are requested being reliable, efficient, and safe. The demerits in the concrete structures can arise from the mechanical and environment loading coupled with deleterious reactions. Moreover, concrete shrinks as it dries under ambient conditions.

The researches performed by the authors indicated that the shrinkage may reduce significantly the serviceability of the concrete structures (Gribniak *et al.* 2007, 2008, 2010; Kaklauskas *et al.* 2009a). It was found that the restrained shrinkage is one of the major causes of defects in the bridges all over the world. The shrinkage is among the most uncertain mechanical properties of concrete. Therefore, it is important for structural designers to know accuracy of shrinkage prediction models.

In last decades, steel fibre reinforcement is widely used in many countries as additive for concrete and cement mortar mixture for production of the concrete structures. Application of fibre reinforcement in Lithuania is often restricted to production of concrete floor for different purposes. Whereas, in other countries (USA, Japan, Germany, Australia, etc) application area of fibre reinforcement is much wider, for example: bridge decks, thin-walled structures (tunnels, reservoirs, etc), pavements, pipelines, pile foundations. Thus application of the fibre reinforcement is considered as one of the most important branches of engineering science.

This paper investigates shrinking of the concrete mixture which is often used for casting bridges in Lithuania. The following objectives of the study have been followed: 1) to investigate accuracy of the shrinkage prediction models; 2) to explore whether steel fibre reinforcement has influence on the shrinkage magnitude.

2. Consequences of restrained shrinkage cracking

The term free shrinkage is commonly used to describe the contraction of hardened concrete exposed to relative humidity less than 100%. Magnitude of the shrinkage depends on the concrete mixture proportions and material properties, method of curing, ambient temperature and humidity conditions, geometry of the element. It develops gradually with time; the word free refers to the case of a member that can shorten without restraint, thus producing no stresses. Fig. 1 illustrates how volumetric changes of the hardened concrete can result cracking. It compares development of the cracking resistance (time-dependent tensile strength) with the restrained shrinkage-induced stresses. The specimen will crack when the two lines representing the tensile strength and the shrinkage-induced stress, will intersect. Analogously, if the strength is always greater than the stress, no cracking occurs.

The restrained shrinkage-induced stress might be difficult to quantify. It is not equal to the 'elastic' stress, defined by multiplying the free shrinkage strain by the elas-

Table 1. Mix proportion of the concrete, kg/m³

Material	Amount
Sand 0/4 mm	$905 \pm 2\%$
Crushed granite aggregate 5/8 mm	$388 \pm 1\%$
Crushed granite aggregate 11/16 mm	$548 \pm 1\%$
Cement CEM I 42.5 (Class N)	$400\pm0.5\%$
Water	$123.8\pm5\%$
Plasticiser Muraplast FK 63.30	$2 \pm 2\%$



Fig. 1. Restrained shrinkage-induced stress



Fig. 2. The tested fibres

tic modulus due to the creep effect (Gribniak *et al.* 2007). Moreover, the shrinkage strain increases with time. The authors proposed the simple procedure for defining the stress taking an accompanying creep effect into consideration (Kaklauskas *et al.* 2009a).

Effects of shrinkage and accompanying creep of concrete, along with cracking, provide a major concern to the structural designer because of the inaccuracies and unknowns that surround them. These effects led to much deterioration in newly constructed or repaired reinforced concrete bridges all across Europe. Daly (1999) reported that restrained shrinkage-induced cracks cause 12% and 10–14% of deteriorations in the bridges in France and in Germany, respectively; in UK and Norway the shrinkage cracking is one of the major causes of such defects.

The fibre reinforcement is commonly used for mitigating cracking in newly constructed or repaired concrete bridge elements. The presented experimental investigations were performed avoiding the uncertainties that may arise during construction due to the influence of early-age concrete properties on the total stress state while focusing an attention on the influence of steel fibres on magnitude of shrinkage.

3. Shrinkage tests

This Section presents the results of the experimental investigations on the concrete shrinkage. The research projects were performed at the *Vilnius Gediminas Technical University* from 2005 to 2009 under financial support provided by the *Lithuanian State Fund of Research and Studies* (Kaklauskas *et al.* 2005, 2008, 2009b).

3.1. Material properties

Present study has been dedicated to investigation of shrinkage of concrete (grade C35/45 S3) which is commonly used in newly constructed bridges in Lithuania. In recent years, the concrete for bridge construction sites in Vilnius area is most frequently supplied by the industrial plant "*Betono Centras*". For this reason, the concrete produced at the "*Betono Centras*" plant was selected for the investigation. The tests cover a four-year period when a large number of different engineering structures (overpasses, high-rise buildings and so on) were constructed.

The present investigation is based on the test measurements given in the three research projects performed by the authors in 2005, 2008, and 2009. The database contains measurements of 72 specimens from 13 batches. The mix proportion was taken to be uniform for all the batches and is given in Table 1. The ordinary Portland cement and crushed granite aggregate (16 mm max nominal size) were used. Water/cement and aggregate/cement ratio by weight were taken as 0.42 and 2.97, respectively. Some of the specimens were cast using the steel fibres reinforced concrete. Two different types of fibres were used: *Krampe-Harex KP* 35/1.95 and *Duoloc* 55/1 (Fig. 2). In Table 2 the fibre-concrete mixtures are noted as F1 and F2, respectively.

In order to determine material properties of concrete, 12 of \emptyset 15×300 mm cylinders, 12 of 150 mm cubes, 15 of 100×100×400 mm and 17 of 300×280×350 mm prisms were cast. The cylinders and prisms were used for shrinkage measurements. The compressive strength was measured at the test finish day and at three time intervals during the tests, approximately 1, 2 and 4 weeks after casting. 3 cylinders, 3 of 150 mm cubes and 3 of $100 \times 100 \times 400$ mm prisms were tested at each age for each mixture determining the compressive strength and the stress and strain relationship. Variation of the compressive strength in time is given in Table 2, where f_{cm} and $f_{cm,cube}$ are the mean values of concrete compressive strength obtained from \emptyset 150×300 mm cylinders and 150 mm cubes, respectively.

The results given in Table 2 indicate that all the mixtures at early age reached the design value of compressive strength (C35/45). The strengths of most mixtures (shown

Table 2. The compressive strength of concrete, MPa

Mixture	Producing data	Parameter	Measurements				
Ι	2005-09-30	f _{cm.cube}	-	36.9	40.9	-	47.3
		Age, days	-	7	14	-	47
II	2005 10 07	f _{cm,cube}	_	34.4	39.9	48.7	48.2
	2003-10-07	Age, days	_	5	11	28	29
III	2005 10 14	f _{cm,cube}	_	32.4	37.7	41.2	41.6
	2003-10-14	Age, days	_	6	15	31	32
13.7	2005 10 24	f _{cm,cube}	-	45.4	47.7	55.5	52.9
1 V	2003-10-24	Age, days	_	7	14	31	35
		f_{cm}	-	-	_	42.5	48.3
V	2008-09-19	f _{cm,cube}	_	44.2	50.4	48.7	56.3
		Age, days	-	7	14	28	69
		f_{cm}	-	-	-	45.5	49.7
VI	2008-09-26	f _{cm.cube}	43.4	50.8	54.6	52.9	64.7
		Age, days	3	7	14	28	76
	2008-10-03	f_{cm}	-	-	-	49.5	52.8
VII		f _{cm.cube}	-	50.7	59.7	66.3	68.0
		Age, days	-	5	14	28	77
	2008-10-03	f_{cm}	-	-	-	49.5	50.5
VIII(F1)		f _{cm.cube}	-	45.4	54.4	58.4	72.3
		Age, days	-	5	14	28	77
	2008-10-16	f_{cm}	-	-	-	43.7	44.6
IX		f _{cm.cube}	40.3	_	48.6	55.4	61.5
		Age, days	4	-	14	28	50
	2008-10-16	f_{cm}	-	-	-	43.8	46.5
X(F1)		f _{cm.cube}	39.8	_	51.4	55.7	60.9
		Age, days	4	-	14	28	50
	2009-05-26	f_{cm}	-	-	-	46.2	54.8
XI(F2)		f _{cm.cube}	37.4	-	_	50.5	65.7
		Age, days	2	-	_	28	176
XII(F2)		f_{cm}	-	-	_	42.0	48.1
	2009-05-29	f _{cm.cube}	36.2	-	-	47.4	55.6
		Age, days	3	-	-	28	173
XIII(F2)	2009-06-03	f _{cm}	_	_	_	46.9	52.6
		f _{cm.cube}	36.8	-	_	51.1	61.7
		Age, days	2	-	_	28	168

in the gray-filled cells) were found to be greater than the nominal strength. Due to the fact that the compressive strength is traditionally assumed as the quality indicator of the technological process and is continually controlled at the plant, the obtained results can be considered quite natural. However, shrinkage (another important characteristic of structural concrete) often is not controlled. Therefore, this study deals with shrinking properties of concrete.

3.2. Free shrinkage measurements

In the first project (2005), the mechanical strain gauges were used for the shrinkage measurements, whereas, in other two projects (2008 and 2009), the *Demec*-200 strain gauge (Fig. 3) was applied. The measurements started 2–5 days after casting and were performed daily on $100 \times 100 \times 400$ mm and $280 \times 300 \times 350$ mm prisms and $\emptyset 150 \times 300$ mm cylinders. After start of drying, ends of the cylinders and $280 \times 300 \times 350$ mm prisms were isolated with a polyester film. The experimental set-up is presented in Fig. 4.



Fig. 3. Shrinkage measurement using the Demec strain gauge



Fig. 4. Experimental set-up of the test specimens

Projects'	n _m	п	RH	V_{f}	t_0	t _{max}	Sh	V/S
year	members	pts	%	% (by volume)		days	_	mm
2005	11	336	65	0	1-4	31-55	3	25.0-72.4
2008	43	2031	76	0, 0.3, 0.6	1 - 4	49-89	2/3	25.0-72.4
2009	18	1932	73	0.5, 1.0, 1.5	3	161-172	2/3	25.0-72.4

Table 3. Structure of the te	est data
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4. Analysis of the test results

The reference database contains 4299 test points. The structure of the test data is given in Table 3. In this table, n_m and n are the numbers of the specimens and the observation points, respectively; RH is the relative humidity in %; V_f is the amount of the fibres in mixture in % by volume; t_0 and t_{max} are the member's ages at start of drying and at finish of test in days, respectively; Sh is the shape of the member (2 and 3 represent the infinite cylinder and the square prism, respectively); V/S is the relationship between the volume of element and its surface subjected to drying in mm.

As it was reported previously (Gribniak *et al.* 2007), the drying shrinkage effect on the cracking behaviour of reinforced concrete structures is limited to relatively short period (about 2–3 months after casting). When this period is finalised, the shrinkage effect becomes un-significant. Due to this the shrinkage measurements performed at time period of 90 days were accepted for the analysis. This reduces number of the reference test points to 3293 measurements under consideration.

The study was performed in two steps. 1^{st} – the accuracy of the most popular shrinkage prediction techniques was analysed and 2^{nd} – the influence of the fibre reinforcement on the shrinkage was investigated. These steps are presented below.

4.1. Accuracy of the shrinkage predictions

The comparative study was based on the predictions made by *EN 1992-1-1:2004 Eurocode 2: Design of Concrete Structures – Part 1: General Rules and Rules for Buildings* and by *ACI 209.2R-08 Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete; B3 model* (Bažant, Baweja 1995a; 1995b); and *GL 2000 model* (Gardner, Lockman 2001). Accuracy of the methods was analysed in term of a relative prediction:

$$\Delta = \frac{\varepsilon_{cs, calc}}{\varepsilon_{cs, obs}}, \qquad (1)$$

where $\varepsilon_{cs, calc}$ and $\varepsilon_{cs, obs}$ are the calculated and the measured free shrinkage strains of concrete, respectively. The relative prediction is considered as a random variable. Therefore, statistical methods can be used for assessment of the accuracy. Central tendency and variability statistics were used for this purpose. The central tendency can be regarded as the precision parameter of a calculation method. The postulate of min variance was used to evaluate consistency of a model.

The experimental data was divided into 2 groups separating the measurements of ordinary and fibre rein-



Fig. 5. The shrinkage prediction of ordinary concrete

forced concretes. Fig. 5 shows the relative prediction of the shrinkage of ordinary concrete.

It should be noted that Fig. 5 gives the relative predictions in logarithmic scale. The logarithmic transformation was performed securing equal contribution of underestimated and overestimated predictions to the accuracy estimation. As can be observed, all the methods underestimate the shrinkage effect, whereas the *EN 1992-1-1:2004* demonstrates the best accuracy: after 28 days *EN 1992-1-1:2004*, *ACI 209.2R-08*, *B3* and *GL 2000* methods underestimated the shrinkage at average of 14.6, 43.6, 128.1 and 16.2%, respectively. The *EN 1992-1-1:2004* method, as the normative document accepted in the EU, was chosen for the further analysis.

4.2. The effect of fibres on the shrinkage

It is important that the statistical evaluation should be performed only for data, which is nominally identical, with variation due to random effects. However, it was found that the drying period has a systematic effect on the accuracy of the shrinkage prediction methods (Bacinskas *et al.* 2009). Therefore, the analysed data was separated into groups according to the specimen's age. A normality test was used to include data point in the group. For this purpose, a statistical procedure has been developed (Gribniak 2009). Results were divided into 2 groups. The 1st group (I) contains the measurements, performed on the specimens which age do not exceeded 21 days. The 2nd group (II) represents the data obtained after 21 day. As was mentioned, Δ does not allow objective interpretation of the accuracy due to the uneven contribution of underestimated and overestimated predictions. Therefore, the logarithmic scale of Δ was introduced in Figs 5 and 6. The following analysis is based on the arithmetical error:

$$\varepsilon_{\Delta} = 100\% \times \begin{cases} \Delta - 1, \ \Delta \ge 1; \\ 1 - \Delta^{-1}, \ \Delta < 1. \end{cases}$$
(2)

Fig. 6 presents the shrinkage predictions for ordinary and fibre-reinforced concretes. This Fig also gives the 95% confidence intervals of the expectation of the *EN 1992-1-1:2004* predictions (considered as estimator of the central tendency). The confidence intervals have become narrower for the concrete reaching 21 days of age. The upper and lower bounds of the obtained intervals are presented in Table 4. This Table gives the main statistics of the *EN 1992-1-1:2004* predictions in terms of the arithmetical error. In



Fig. 6. The shrinkage prediction errors of ordinary and fibre reinforced concretes

 Table 4. The arithmetical errors of the EN 1992-1-1:2004

 predictions

	Age group, days		Arithmetical errors ε_{Δ} , %				
Concrete		n _{obs} , pts	Mean	The 95% confi- dence bounds			
				lower	upper		
Ordinary	I (≤ 21)	580	-14.5	-18.0	-7.8		
	II (22–90)	1148	-23.1	-24.3	-20.6		
Fibre-	I (≤ 21)	342	-8.3	-12.0	-1.5		
reinforced	II (22–90)	1223	-9.9	-10.9	-8.0		

this Table, n_{obs} is the number of the measurements in the age interval.

The calculation method is assumed to be precise (with 95% probability), if the confidence interval covers unity. It can be observed that in both cases the *EN 1992-1-1:2004* underestimates the shrinkage (Fig. 6), whereas the deformations of the fibre-concrete seem to be more accurate. This statement can be supported statistically using the hypothesis test procedure. This procedure can be used for deciding between two hypotheses. In each age interval, two hypotheses were formulated. The null hypothesis states that the accuracy of the *EN 1992-1-1:2004* in both cases is equal:

$$H_0: m_1 = m_2,$$
 (3)

where m_1 and m_2 are the sample means of the shrinkage predictions of ordinary and fibre-concrete, respectively. The alternative hypothesis identifies that the shrinkage of the fibre-concrete was predicted more accurate. Due to the fact that the shrinkage was underestimated in both cases; the alternative hypothesis can be formulated as

$$H_1: m_1 < m_2.$$
 (4)

The two-step one tailed test procedure was used for the analysis. The procedure was linked to the modified *Fisher's ANOVA* (analysis of the variance) test (Mardia, Zemroch 1978) and *Satterthwaite's* criteria for the mean comparison (Satterthwaite 1946). The hypothesis test was considered being significant (at the 5% level). This leads to the decision rejecting H_0 to the benefit of H_1 . In other words, the shrinkage prediction for the fibreconcrete was admitted more accurate than for the ordinary one. The accepted hypothesis H_1 stands the following inequality:

$$m_1 < m_2 < 1.$$
 (5)

This indicates that the sample mean of fibre-concrete is closer to unity than the mean of ordinary concrete. Taking into account the Eq (1), it allows to state that the shrinkage of fibre-concrete was less significant (in a statistical sense) than the ordinary one. This finding supports the results obtained by Swamy and Stavrides (1979) who found that the shrinkage was reduced by about 15–20% due to the presence of 1% of steel fibres. Barr *et al.* (2003) reported that the fibres effect reducing the shrinkage rises gradually with the increase of the concrete strength.

However, free shrinkage is not really a useful needle of the effectiveness of the fibres in reducing the shrinkage problems. It is not the free shrinkage strains which should be reduced, but the cracking associated with the restrained shrinkage (Zanuy 2010; Lampropoulosa, Dritsos 2011; Kaklauskas, Gribniak 2011). Shah *et al.* (1994) reported that 0.5% (by volume) of steel fibres reduced the average crack width by 90%. The authors obtained analogous results (Kaklauskas *et al.* 2009b).

4.3. Discussion on the findings

Table 4 indicates that the *EN 1992-1-1:2004* method (the most accurate among the analysed ones) for ordinary concrete has underestimated shrinkage almost by 20%. The authors recommend introducing the correction factor 1.2 for the calculated value of shrinkage of industrial concrete mixture C35/45 S3. The analysis demonstrates that the application of the steel fibres as an admixture was capable of reducing the shrinkage deformation of concrete. It can be observed that fibre-reinforced concrete with given amounts of fibres has shrunk almost 10% less than the ordinary one.

5. Concluding remarks

Present paper investigates drying shrinkage strain of the concrete mixture which is usually used for casting the newly constructed bridges in Lithuania. As the shrinkage effect on the cracking behaviour of such structures is limited to relatively short period (about 2–3 months), the time period of 90 days was accepted for the investigation.

Accuracy of the well-known shrinkage prediction techniques was analysed. It was obtained that all the methods employed in the analysis (i.e. *EN 1992-1-1:2004*, *ACI 209.2R-08*, *B3* and *GL 2000*) have underestimated the shrinkage strain. Among these four techniques, the *EN 1992-1-1:2004* have demonstrated the best accuracy giving 14.6% error of the mean value of shrinkage of concrete C35/45 at the age of 28 days. The analysis has resulted in 43.6, 128.1 and 16.2% errors for the *ACI 209.2R-08*, *B3* and *GL 2000* methods.

The authors have also studied the influence of steel fibres on the shrinkage deformations. It was statistically proved that the application of fibre in concrete resulted in the reduction of shrinkage strain. The study indicates that the application of the steel fibres as an admixture is an effective way of decreasing shrinkage of concrete.

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