Experimental measurement and calculation of volume changes of concrete specimens

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Abstract: The paper describes experimental measurement of volume changes of cement concrete. Shrinkage is now becoming increasingly important with respect to concrete construction requirements, and it is important to be able to accurately measure and evaluate volume changes. Volume changes include swelling and shrinkage of cement concrete specimens. The experiment includes evaluating effects on volume changes and, depending on the environment, also evaluating individual types of volume changes in concrete such as drying shrinkage and thermal expansion. Volume changes was measured by string strain gauges both internal and external (with experimental casting method). The specimens were in the laboratory and in the outdoor environment, so it was possible to compare values from different environments. Within the experiment, the measurement methodology of string strain gauges was unified for future experiments, which was one of the experiment goals. The measured results are compared with the calculation models of shrinkage: Model B4 [5], CSN EN 1992-1-1 [8], ACI 209.2R-08 [11] and Model Code 2010 [14]. Comparison of shrinkage results with calculation models is important in designing concrete structures and developing other parameters for calculation models. The results from the experiment will serve to further investigate the volume changes depending on the subsoil. The concrete used in the experiment served as comparative, and the measured values would serve as a benchmark for dispersed reinforcement (steel fibers) concrete proposed in future experiments. Concretes with dispersed reinforcement using steel fibers has a positive effect on the reduction of volume changes and measurement of these concretes will be the next step of the research with the emphasis on building practice, especially industrial floors.

Key-Words: Concrete, Volume Changes, Shrinkage, Swelling, Calculation models, Cement

1 Introduction

The volume changes of cement concrete are a phenomenon that accompanies setting and hardening of concrete from the very beginning. From the point of view of the composition of conventional cement concrete (binder is cement), the volume changes have two phases. First phase is swelling which occurs in the first hours and days (depend on curing of concrete). From the aspect of hydration of cement, the swelling can be well described on a cement paste when Portland cement is used. If hydration of the cement paste occurs in water, the swelling occurs due to water intake. In the air this process is the opposite and the paste begins to shrink. Another phenomenon is clinker composition (forming of min. 95% Portland cement) containing hydrating minerals (C_3S; C_2S; C_3A and C_4AF) that show different volume changes during hydration. Dicalcium silicate (C_2S), one of the clinker minerals, shows significant swelling in the first 24 hours. In concrete, this process is the same, but the swelling has lower values because volume changes are reduced by the used aggregate. [1; 2; 7; 12; 13]

Swelling of concrete in a certain period will prevail in a gradual shrinkage. This is second phase of volume changes of concrete. In terms of composition, chemical and autogenous shrinkage occurs within the concrete. Regarding the environmental conditions, plastic shrinkage and drying shrinkage may occur. Literature often describe another types of shrinkage like thermal or carbonation. In this article, and with emphasis on the experiment, only the drying shrinkage will be discussed in more detail, as other types of shrinkage can be neglected or not reflected at all. Chemical shrinkage occurs in concrete, but the proposed curing (wet geotextile on the surface) prevents concrete from shrinking with this type of shrinkage. Chemical shrinkage is closely related to autogenous shrinkage. In some literature, these types of shrinkage are described as one, but it is very appropriate to separate them for different principles [3; 10; 13; 19]. Autogenous shrinkage takes on importance in concrete with a water-cement ratio lower than 0,46. It occurs also in concrete with a higher water-cement ratio, but its significance is so low that the values of this shrinkage can be neglected, see Fig. 1 [1; 2; 13, 19]. Plastic shrinkage occurs in fresh concrete when water is removed from the surface of the concrete by evaporation or by suction from the material that is in direct contact with the concrete (even soil) [1; 2; 7]. This shrinkage was avoided by the treatment and use of formwork from non-absorbent material. Drying shrinkage occurs at a time when hardened concrete is subjected to conditions where water evaporates. These conditions are related to the relative humidity of the air, which, when lower than 95 %, results in a gradual drying. This shrinkage is directly dependent on the amount of cement used and the water-cement ratio. So the higher the water-cement is, the greater this shrinkage is (Fig. 1). [1; 2; 7; 12; 20; 21].

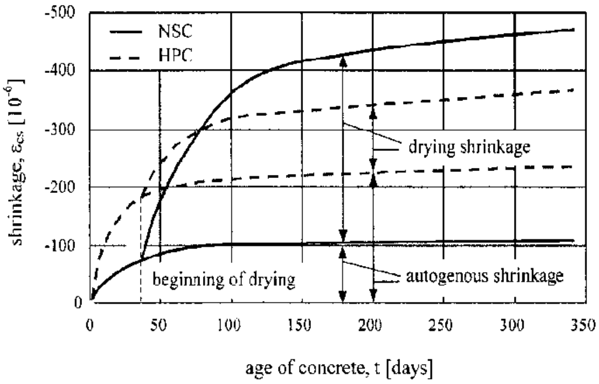

Fig. 1 – Drying and autogenous shrinkage on normal strength concrete (NSC) and high strength concrete [18]

This behavior can generally be described as volume changes. These volume changes are, in terms of composition, associated with hydration of the cement binder when chemical reactions occur. Depending on the composition of the concrete, the amount of cement and the size of the water-cement ratio, the volume changes are different. Although the volume changes due to hydration are well described theoretically, the whole process is not thoroughly investigated. Concrete also undergoes volume changes based on the environment it is exposed to (thermal volume changes) and it is necessary to be able to separate these effects on volume changes. This can be done by measuring the same specimens (size, composition) in different environments where at least one of them will have constant climatic conditions (laboratory). This will be further described in the experimental section. Negative effects of volume changes due to the composition of concrete can be prevented or minimalized by proper care (concrete curing). The negative impact of shrinkage of concrete, in the extreme case leading to cracks, can be reduced. [1; 2; 5; 10; 12]

Cracks in concrete can be tolerable and intolerable and there are currently many calculation models that can calculate and analyze shrinking by different approaches. Shrinkage is part of the phenomena (with creep etc.) through which the hardened concrete structure passes over time. With increasing demands for structural properties (lower dimensions of construction, higher strength and durability, long-life cycle) and consequent composition of concrete, they also add to the importance of negative design features, including shrinkage.

The experiment aims to separate the individual effects causing volume changes. A large-dimensional specimen placed in the laboratory will be subject to drying shrinkage due to the composition. A specimen located outside the laboratory, outdoors, will be subject to external climatic influences. In addition to drying shrinkage, volume changes due to temperature changes will also have to be considered here. Other types of shrinking may be neglected in this experiment. In particular autogenous shrinkage is not necessary due to the high water-cement ratio. [2]

2 Calculations models

For calculation shrinkage of concrete were selected the following calculation models. There are many models for calculating the shrinkage of concrete, but the ones listed below are most commonly used. The models are evolving over time, which is currently the case with model from Bazant (an improved model B4 [5] based on the previous model B3 [4]).

2.1 Model from CSN EN 1992-1-1 [8]

Calculation model from technical standard CSN EN 1992-1-1 or Eurocode 2 [8] is most commonly used regarding building practice and his importance is based on fact that is in base technical standard for designing concrete structures. In this model, it is possible to divide the calculation into autogenous shrinkage and drying shrinkage. For this experiment, it is important drying shrinkage, therefore it is not intended to deal with autogenous shrinkage. The equations for calculating shrinkage are as follows.

$$\varepsilon_{cd}(t) = \beta_{ds}(t,t_s)\, k_h\, \varepsilon_{cd,0} \tag{1}$$

$$\beta_{ds}(t,t_s) = \frac{(t-t_s)}{(t-t_s)+0{,}04\sqrt{h_0^3}} \tag{2}$$

$$h_0 = \frac{2\,A_c}{u} \tag{3}$$

$$\varepsilon_{cd,0} = 0{,}85\left[(220+110\alpha_{ds1})e^{\left(-\alpha_{ds2}\frac{f_{cm}}{f_{cm0}}\right)}\right]10^{-6}\beta_{RH} \tag{4}$$

$$\beta_{RH} = 1{,}55\left[1-\left(\frac{RH}{RH_0}\right)^3\right] \tag{5}$$

2.1 Model from fib Model Code 2010 14]

Model Code 2010 [14] deals with calculating of shrinkage almost similar way as model from Eurocode 2. Since the calculation model of the CSN EN 1992-1-1 [8] has its drawbacks a more progressive calculation model has been developed. Model Code 2010 [14] has particular changes in equations for autogenous and drying shrinkage. For this article are again important equations for drying shrinkage, which are as follows.

$$\varepsilon_{cds}(t,t_s) = \varepsilon_{cds,0}(f_{cm})\, \beta_{RH}(RH)\, \beta_{ds}(t-t_s) \tag{6}$$

$$\varepsilon_{cds,0}(f_{cm}) = \left[(220+110\alpha_{ds1})e^{(-\alpha_{ds2}\,f_{cm})}\right]10^{-6} \tag{7}$$

$$\beta_{RH} = -1{,}55\left[1-\left(\frac{RH}{100}\right)^3\right] \tag{8}$$

$$\beta_{ds}(t-\ t_s) = \sqrt{\frac{(t-t_s}{0{,}035h^2+(t-t_s}} \tag{9}$$

$$h = \frac{2\,A_c}{u} \tag{10}$$

2.3 Model B4 from Bazant [5]

Model B4 [5] is currently the most sophisticated shrinkage calculation model. It considers the most parameters and boundary conditions, and it is possible to incorporate as many variables into the calculation. This calculation model takes multiple parameters into consideration and adjusts coefficients for more realistic behaviour of the calculated specimen. Unlike the B3 model [4], B4 can be counted a particularly autogenous shrinkage and shrinkage by drying. Equations for drying shrinkage are shown below. [14; 20].

$$\epsilon_{sh}(\widetilde{t},\widetilde{t_s}) = \epsilon_{sh\infty}(\widetilde{t_0})\, k_h\, S(\tilde{t}) \tag{11}$$

$$\epsilon_{sh\infty}(\widetilde{t_0}) = -\epsilon_0\, k_{\epsilon a}\, \frac{E(7\beta_{Th}+600\beta_{Ts})}{E(\widetilde{t_0}+\tau_{sh}\beta_{Ts})} \tag{12}$$

$$\epsilon_0 = \epsilon_{cem}\,(\frac{a/c}{6})^{p_{\epsilon a}}\,(\frac{w/c}{0{,}38})^{p_{\epsilon w}}\,(\frac{6{,}5c}{\rho})^{p_{\epsilon c}} \tag{13}$$

$$E = E_{28}\sqrt{\frac{t}{4days+(6/7)t}} \tag{14}$$

$$\tau_{sh} = \tau_0\, k_{\tau a}\,(k_s\frac{D}{1})^2 \tag{15}$$

$$\tau_0 = \tau_{cem}\,(\frac{a/c}{6})^{p_{\tau a}}\,(\frac{w/c}{0{,}38})^{p_{\tau w}}\,(\frac{6{,}5c}{\rho})^{p_{\tau c}} \tag{16}$$

$$D = \frac{2V}{S} \tag{17}$$

$$k_h = 1-h^3 \tag{18}$$

$$S(\tilde{t}) = tan(h)\sqrt{\frac{\tilde{t}}{\tau_{sh}}} \tag{19}$$

2.3 Model ACI209.2R-08 [11]

The latest calculation model is the model ACI 209.2R-08 [11], which uses a different calculation approach. The basic value of the shrinkage is defined in the calculation and it is subsequently corrected by the input parameters. The model as the only one allows only the final shrinkage to be counted. It is not possible to separate autogenous shrinkage and drying shrinkage. [11].

$$\varepsilon_{sh}(t,t_c) = \frac{(t-t_c)^\alpha}{f+(t-t_c)^\alpha}\,\varepsilon_{shu} \tag{20}$$

$$f = 26{,}0\, e^{[1{,}42\cdot 10^{-2}(V/S)]} \tag{21}$$

$$\varepsilon_{shu} = 780\,\gamma_{sh}\cdot 10^{-6} \tag{22}$$

$$\gamma_{sh} = \gamma_{sh,tc}\,\gamma_{sh,RH}\,\gamma_{sh,vs}\,\gamma_{sh,s}\,\gamma_{sh,\psi}\,\gamma_{sh,c}\,\gamma_{sh,\alpha} \tag{23}$$

3 Experimental part

The description of the experiment is divided into three logical chapters, detailing the steps from design of concrete through curing to measurement of specimens.

3.1 Composition of concrete

The concrete C30/37-XC4 was designed for the experiment. Since the intention was to eliminate as much of the phenomena as possible in terms of composition, which could have an impact on volume changes, no admixture was given to the concrete and no aerated concrete was proposed. The strength class has been chosen in view of the frequent use of this strength class in practice and at the same time with a high dose of cement with the assumption of high shrinkage. Concrete has been designed in accordance with EN 206 [9], where requirements for the composition of this concrete are defined. The technical standard requires a minimum amount of cement (300 kg/m^3), maximum water-cement ration (w/c = 0.5) and strength class (25/30). The designed concrete meets stricter requirements to the standard, because 345 kg/m^3 of Portland cement CEM I 42.5 R was delivered, resulting in a higher strength class. The water-cement ratio was 0,5. The superplasticizing admixture has been dosed into the concrete to provide the desired water-cement ration and S3 consistency. After the concrete was cast into formwork, curing of concrete was started immediately at the beginning of setting and in the same time started measurements of volume changes using string strain gauges. For the determination of compressive strength and modulus of elasticity after 7 and 28 days, samples were taken at a quantity of 6 cylinders for each test. Determination of strength and modulus of elasticity is important for calculation models.

3.2 Specimens, casting and curing of concrete

Specimens were designed in size 150 x 500 x 6000 mm. One specimen was placed in the laboratory and the second was placed outside the laboratory in an outdoor environment where the specimen was exposed to external climatic conditions including precipitation. Concrete was cast into wooden formwork, see Fig. 2. The bottom of the formworks was covered with PE foil to ensure zero water removal from the lower surface (avoiding plastic shrinkage) as well as lower friction of the concrete (Fig. 2).

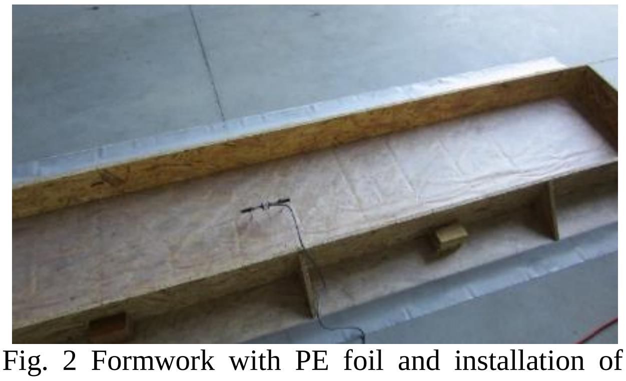

Fig. 2 Formwork with PE foil and installation of internal string strain gauges

Concrete was cast directly from the agitating truck by using a trough and compacted by a submersible vibrator. The specimens were immediately covered with geotextile at the beginning of the setting of the concrete and cured with water for 5 days (Fig. 3).

Fig. 3 Laboratory specimen covered with wet geotextile

Geotextiles were removed after end of curing, and lateral stripping was performed (Fig. 4). The specimen in the laboratory was kept permanently in an environment having a temperature of 20 ± 2 ° C and a relative humidity of air 55 ± 5%.

3.3 Measurement with string strain gauges

For measuring volume changes on specimens were used string strain gauges EDS-20-E. These string strain gauges have length 170 mm (active gage length 150 mm), range ± 1500 µ-strain, sensitivity 1 µ-strain and thermistor type YSI 44005 (3000 Ohm at 25 °C. The last mentioned specification allows to measure the temperature inside the specimen through the resistance. Three string strain gauges were placed in each sample at 1,5 m apart, counted from the edge of the specimen along the length. These internal string strain gauges were at a height of 50 ± 10 mm from the lower surface of the specimen. The internal string strain gauges were fixed using steel hooks and a binding wire (Fig. 2).

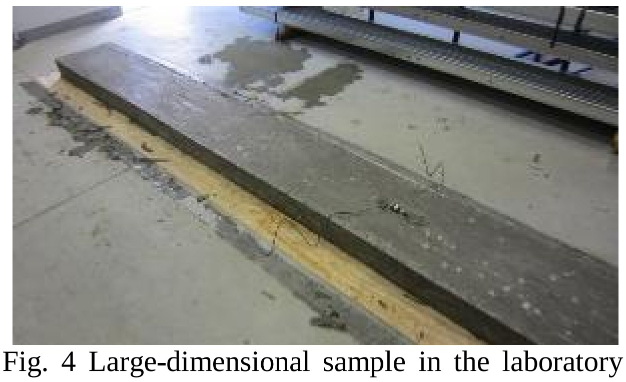

Fig. 4 Large-dimensional sample in the laboratory and installation of external string strain gauge

Experimentally, one string strain gauge was placed on the surface of the samples to half the length (3 m). String strain gauges on surface were fixed using steel U-profiles, which were vertically placed in a setting concrete to a depth of about 20 mm. String strain gauges were fixed on 10 mm long protruding ends above the surface. This joint was reinforced with covering thick layer of concrete (Fig. 5).

Fig. 5 – Detail on installation of external string strain gauge.

The value readings were performed using the Gage GT1174-3 control panel at least once every day since the concrete was cast.

4 Evaluation of results

The experiment was evaluated after 3 months from casting the concrete. Measurement of volume changes using string strain gauges is shown in the graph in Fig. 7 and Fig. 8 according to the environment. The measured values are already recalculated for correction to the temperature of the string strain gauge, since the influence of hydration also occurs in the laboratory at rapid temperature changes and these changes in the extensibility of the concrete and the string strain gauge it is necessary to consider. For non-laboratory specimen, this must be considered for changes in climatic conditions (temperatures). In view of the constant ambient conditions in the laboratory, a specimen placed in the laboratory will be commented on first.

It can be seen from the graph on the Fig. 6 that the specimen due to the higher temperature caused by the hydration of cement and the supply of water from the curing began to swell immediately at the beginning of the setting. Swelling is also caused by the creation of new hydrating minerals such as C_3A and C_2S, but the phenomenon is minimal in concrete and does not form the dominant part of the swelling compared to other influences [17]. Furthermore, swelling is lower on the surface where direct contact with cold water (and with generally lower ambient temperature) occurs. After 5 days when water curing was ended, the specimen began to shrink by drying. Again, a trend is observed when the shrinkage by drying is more dynamic on the surface, and in later stages it is slower and has lower values than volume changes within the sample.

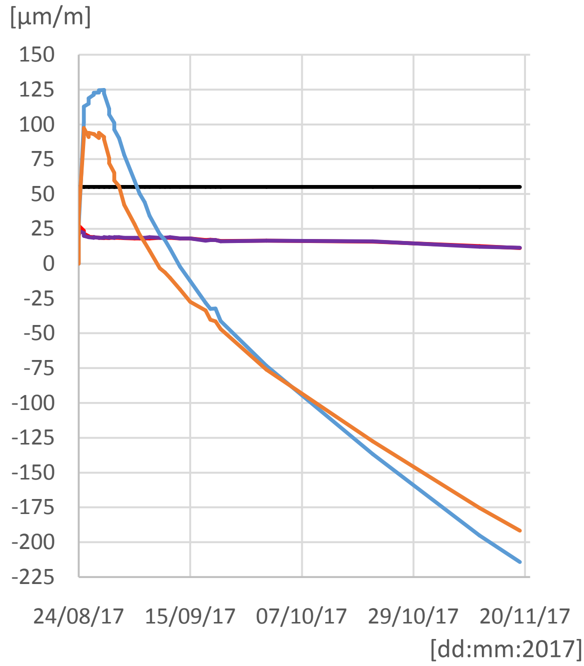

Fig. 6 – Volume changes of specimen in the laboratory.
Legend: Blue: Internal; Orange: External; Black: Relative humidity of air; Red: Temperature – inside; Purple: Temperature – outside.

For the specimen exposed to climatic conditions, the analysis in the above paragraph applies, but additional significant influences, variable temperature and relative humidity of air are added (Fig. 7). For this specimen, it can be stated that in the total sum of all influences, including the initial swelling, values of volume changes did not exceed the zero. Therefore, the curves are not in the range of the negative values that describe the shrinkage of the specimen, as is evident in the specimen placed in the laboratory. The shrinkage of drying is undoubtedly occurring (as will be explained in Fig. 9), but this phenomenon is denied by other influences such as concrete expansion and water absorption. Important effect on the behavior of volume changes of these specimens will also have a polyethylene foil (subsoil) that ensures low friction and another effect is thickness of the specimens. These effects will be the subject of further research as the subsoil is likely play a significant role in the shrinkage development (but swelling as well) especially in industrial floors [6; 15; 16].

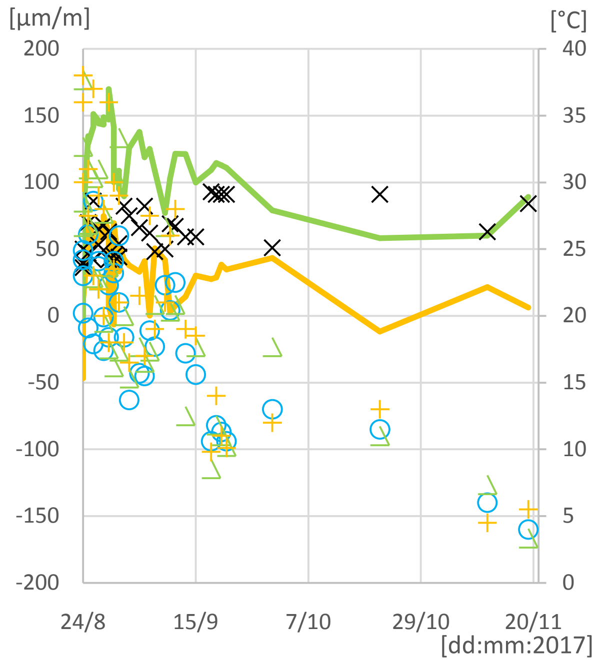

Fig. 7 – Volume changes of specimen in the outdoor environment.
Legend: Green: Internal; Yellow: External; Black crosses: Relative humidity of air; Green triangles: Temperature – inside; Yellow crosses: Temperature – on surface of specimen; Turquoise circles: Temperature – outside.

Fig. 7 illustrates the climate conditions at the time of reading, which are very variable and it is difficult to evaluate any trend. For better clarity, the temperature inside the concrete is assigned to the same color for the volume change curve inside the concrete. The same procedure was followed for volume changes on the surface of concrete. Furthermore, the graph was supplemented by the ambient temperature, where it is interesting to see how it differs from the temperature sensed by the string strain gauge on the surface of the concrete. It is certain that the final shrinkage values will always be lower than in the laboratory specimen, as the water is supplied due to precipitation and absorption of air humidity.

For a better overview, a graph is shown in Fig. 8, where only a comparison of volume changes within and on the specimen for a specimen in the laboratory and for a specimen in outdoor environment is shown. Fig. 8 shows a clear and gradual drying shrinkage of the specimen placed in the laboratory, while in the same specimen under outdoor conditions, volume changes are constantly changing and shrinkage is denied by other influences. For a specimen placed in outdoor environment, it is important to draw attention to the large difference in volume changes inside and on the surface of the specimen for such a thick specimen (only 150 mm). This phenomenon has a significant effect on the tension inside the sample, while in the laboratory the values in the longer period of time are almost the same.

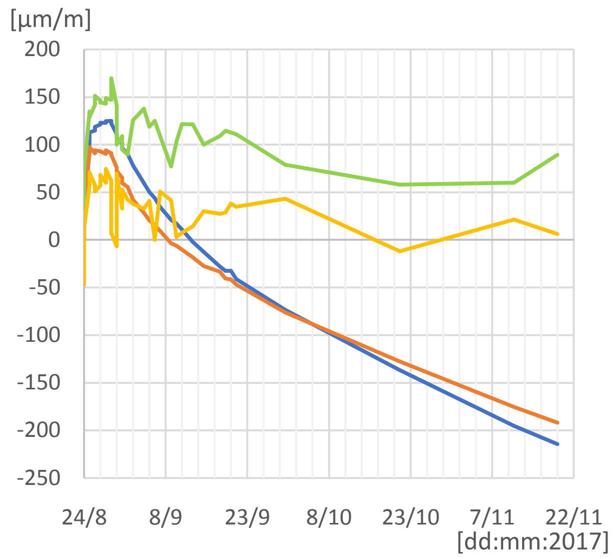

Fig. 8 – Comparison of volume changes of specimens.
Legend: Blue: Laboratory – internal; Orange: Laboratory – external; Green: Outdoor – internal; Yellow: Outdoor - external

In the graph in Fig. 9 a comparison of the final shrinkage after 3 months is made on large-dimensional specimens and the graph is further supplemented by the curves according to the calculation models Model B4 [5], CSN EN 1992-1-1 [8], Model Code 2010 [14] and ACI 209.2R-08 [11]. To compare specimen's shrinkage values with a calculation models that does not consider swelling due to hydration and during curing, it was necessary to recalculate the volume changes of the measured specimens and limit them only to shrinkage. The specimens began to shrink after ending of curing, which was after 5 days. The highest swelling value was defined zero for the calculation and the shrinkage began to count from this value. Therefore, the shrinkage values are higher than in Fig. 8. In addition, Fig. 9 confirms the statement from the above paragraph, when it is possible to observe the shrinkage of the specimen, which was placed in the outdoor environment, after recalculating the volume changes.

From the point of view of the calculation, it is worth noting that there were "constant" conditions in the laboratory environment, so it was easy to calculate the shrinkage over time in terms of boundary conditions. Variable climatic conditions in the outdoor environment cannot be considered in the calculation, it is possible to work with long-term average values. It is also advisable to add that only the relative humidity of the air, not the temperature, enters the shrinkage calculation.

Input data for specimens (all calculations models): Size of specimen – 150 x 500 x 6000 mm; Type of cement – CEM I 42,5 R; Time of curing – 5 days; Relative air humidity (RH) in RH in laboratory – 55 %; RH in outdoor environment – 70 % (long-term average RH in Czech Republic); Mean cylinder compressive strength after 28 days – 32,04 MPa. For model B4 [5] is added: Aggregates to cement ratio – 5,25; Water to cement ratio – 0,5; Amount of cement – 345 kg/m3. For model ACI 209.2R-08 [11] is added: Slump of fresh concrete – 160 mm; Amount of fine aggregate to total aggregate – 45 %.

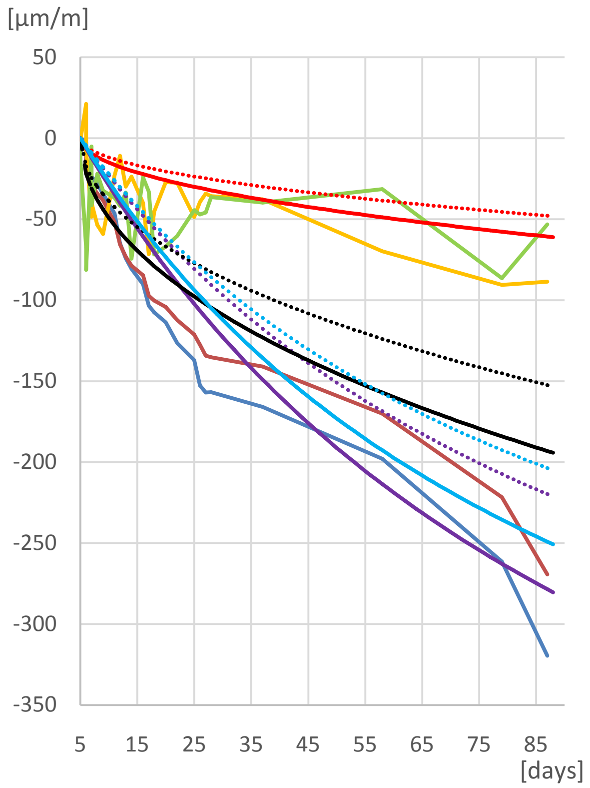

Fig. 9 – Comparison of shrinkage of specimens and calculation models.

Legend: Blue full line: Laboratory – internal; Orange full line: Laboratory – external; Yellow full line: Outdoor – internal; Green full line: Outdoor – External; Red dashed line: Laboratory – B4; Red dotted line: Outdoor – B4; Purple dashed line: Laboratory – EN 1992-1-1; Purple dotted line: Outdoor – EN 1992-1-1; Black dashed line: Laboratory – MC 2010; Black dotted line: Outdoor – MC 2010; Turquise dashed line: Laboratory – ACI 209.2R-08; Turquise dotted line: Outdoor – ACI 209.2R-08;

Fig. 9 shows a comparison of specimen's volume changes in different environments with calculation models. Each model has unified color for different environments and differs only in the line type of the curve. The results of the B4 model [5] are underestimated compared to the measured specimens, but the resulting values for outdoor environment are comparable to the specimen stored in the same environment. From the point of view of safe design and shrinkage modeling, the model from the technical standard CSN EN 1992-1-1 [8] is closest to the reality of the measured specimens. Very good results comparable to the model from the technical standard are offered by ACI 209.2R-08 [11]. The Model Code 2010 [14] model results range between measured specimens in the laboratory and the outdoor environment.

5 Conclusion

The paper describes the measurement of volume changes of cement concrete on large-dimensional specimens. Since it was an input "zero" experiment, the purpose was primarily to unify methodologies and procedures. The research will continue by measuring other concrete designs or by simulating other effects of volume changes. The author continues to measure the specimens, because after three months the volume changes continue as expected.

The experiment confirmed the known phenomena of volume changes in cement concrete, however the author also considers that in the case of large-scale specimens, the subsoil and the weight of the specimen are also significant in the shrinkage size. The actual weight of the sample affects the bottom surface and thus increases friction depending on the substrate material (subsoil). Further attention will be paid to this phenomenon and will be one of the other research directions.

Measured values of volume changes were compared with calculation models. Differences with theoretical calculations were found. Measured values were most closely approaching the model from the technical standard CSN EN 1992-1-1 [8] and very good values were offered by model ACI 209.2R-08 [11].

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References:

[1] AÏTCIN, Pierre-Claude. *Binders for durable and sustainable concrete*. New York: Taylor & Francis, 2008. ISBN 978–0–203–94048–8.

[2] AÏTCIN, Pierre-Claude a Sidney. MINDESS. *Sustainability of concrete*. New York: Spon Press, 2011. Modern concrete technology, 17. ISBN 978-0-203-85663-5.

[3] ALTOUBAT A. Salah and David A. Lange. Creep, Shrinkage, and Cracking of Restrained Concrete at Early Age. *ACI Materials Journal*. 2001, **98**(4). DOI: 10.14359/10401. ISSN 0889-325x.

[4] BAZANT, Zdenek and Sandeep BAWEJA. Creep and shrinkage prediction model for analysis and design of concrete structures—model B3. *Materials and Structures*. 1995, **28**(6), 357-365. DOI: 10.1007/BF02473152. ISSN 0025-5432.

[5] BAZANT, Zdenek. RILEM draft recommendation: TC-242-MDC multi-decade creep and shrinkage of concrete. Model B4 for creep, drying shrinkage and autogenous shrinkage of normal and high strength concretes with multi-decade applicability. Materials and Structures. 2015, 48(4), 753-770. DOI: 10.1617/s11527-014-0485-2. ISSN 1359-5997.

[6] CAJKA, Radim, Martina SMIRAKOVA and Jana VASKOVA. Experimental Testing of Shear Resistance on SFRC Slab Structures. Materials Science Forum. 2017, **893**, 363-368. DOI: 10.4028/www.scientific.net/MSF.893.363. ISSN 1662-9752.

[7] COLLEPARDI, Mario. The New Concrete. 2nd. Italy: Grafiche Tintoretto, 2010. ISBN 8890377720.

[8] CSN EN 1992-1-1. Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings. Prague: Czech standards institute, 2006.

[9] CSN EN 206. Concrete – Specification, performance, production and conformity. Prague: Czech Office for Standards, Metrology and Testing, 2014.

[10] ED. BY A. BENTUR. *Early age cracking in cementitious systems: report of RILEM Technical Committee 181-EAS 'Early Age Shrinkage Induced Stresses and Cracking in Cementitious Systems'*. Bagneux: RILEM Publ, 2003. ISBN 2912143330.

[11] Guide for modelling and calculating shrinkage and creep in hardened concrete. Farmington Hills, MI: American Concrete Institute, 2008. ISBN 978-0-87031-278-6.

[12] HAVLASEK, Petr and Milan JIRASEK. Multiscale modelling of drying shrinkage and creep of concrete. Cement and Concrete Research. 2016, **85**, 55-74. DOI: 10.1016/j.cemconres.2016.04.001. ISSN 00088846.

[13] HOLT, Erika E. Early age autogenous shrinkage of concrete. Espoo: Technical Research Centre of Finland, 2001. ISBN 9513858707.

[14] INTERNATIONAL FEDERATION FOR STRUCTURAL CONCRETE FIB. Model code 2010: first complete draft. Lausanne, Switzerland: Fédération internationale du béton, 2010. ISBN 978-288-3940-956.

[15] JANULIKOVA, Martina. Comparison of the Shear Resistance in the Sliding Joint between Asphalt Belts and Modern PVC Foils. Applied Mechanics and Materials. 2014, **501-504**, 945-948. DOI: 10.4028/www.scientific.net/AMM.501-504.945. ISSN 1662-7482.

[16] JANULIKOVA, Martina and Marie STARA. Reducing the Shear Stress in the Footing Bottom of Concrete and Masonry Structures. Procedia Engineering. 2013, **65**, 284-289. DOI: 10.1016/j.proeng.2013.09.044. ISSN 18777058.

[17] KROPACEK, Michal and Jiri SAFRATA. Volume changes of cements from different locations depending on time. Transactions of the VŠB – Technical University of Ostrava, Civil Engineering Series. 2015, 15(1), 11-20. ISSN 1213-1962.

[18] Structural concrete: textbook on behaviour, design and performance: updated knowledge of the CEB/FIP model code 1990. Lausanne: International Federation for Structural Concrete (fib), 1999. Bulletin. ISBN 2-88394-041-x.

[19] TAZAWA, Ei-ichi. Autogenous Shrinkage of Concrete. 1st Ed. New York: E, 1999,411 s. ISBN 04-192-3890-5.

[20] VINKLER, Marek and Jan L. VITEK. Drying shrinkage of concrete elements: Structural Concrete. Structural Concrete. 2017, 18(1), 92-103. DOI: 10.1002/suco.201500208. ISSN 14644177.

[21] YANG, Jun, Qiang WANG a Yuqi ZHOU. Influence of Curing Time on the Drying Shrinkage of Concretes with Different Binders and Water-to-Binder Ratios. *Advances in Materials Science and Engineering*. 2017, **2017**, 1-10. DOI: 10.1155/2017/2695435. ISSN 1687-8434.