Ullah, Farid; Al-Neshawy, Fahim; Punkki, Jouni

Early Age Autogenous Shrinkage of Fibre Reinforced Concrete

Published in:
Nordic Concrete Research

DOI:
10.2478/ncr-2018-0015

Published: 01/12/2018

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Ullah, F., Al-Neshawy, F., & Punkki, J. (2018). Early Age Autogenous Shrinkage of Fibre Reinforced Concrete. *Nordic Concrete Research*, *59*(2/2018), 59-72. Article 5. https://doi.org/10.2478/ncr-2018-0015

Nordic Concrete Research – Publ. No. NCR 59 – ISSUE 2 / 2018 – Article 5, pp. 59-72

ISSN online 2545-2819
ISSN print 0800-6377

Received: Sept. 26, 2018
DOI: 10.2478/ncr-2018-0015
Revision received: Nov. 27, 2018
Accepted: Nov. 28, 2018

Early Age Autogenous Shrinkage of Fibre Reinforced Concrete

Farid Ullah
M.Sc., Structural Engineer
Insinööritoimisto Mäkeläinen Ltd
(Engineering Office Mäkeläinen Ltd);
Äyritie 12 C, 01510 Vantaa, Finland

Fahim Al-Neshawy
D.Sc. (Tech.), Staff Scientist
Aalto University School of Engineering
Department of Civil Engineering
P.O.Box 12100, FIN-00076, Espoo, Finland
fahim.al-neshawy@aalto.fi

Jouni Punkki
D.Sc. (Tech.), Professor of Practice, Concrete Technology
Aalto University School of Engineering
Department of Civil Engineering
P.O.Box 12100, FIN-00076, Espoo, Finland
jouni.punkki@aalto.fi

ABSTRACT
Concrete is often sensitive to cracking during the hardening process, and these cracks could be the result of early-age shrinkage. One method to reduce shrinkage is to add different types of fibres to concrete. The aim of this study was to study the effects of different types of fibres on the early-age autogenous shrinkage of concrete. Three different types of fibre materials were used in the research. A "Schleibinger Bending-drain" test setup was used to record early-age autogenous shrinkage of fresh concrete immediately after mixing. The results show that, a fibre dosage of 0.38% by volume was found to be effective in reducing the effects of early-age autogenous shrinkage of concrete.

Key words: Autogenous shrinkage, cracking, steel fibre, thermal deformation, hydration.

1. INTRODUCTION

1.1 Volumetric deformation of concrete

Volumetric deformation of concrete results from many contributing factors. Excessive shrinkage deformation may result in cracking of concrete members, which is detrimental to the durability of concrete structures. Loss of water over long duration due to drying is a common cause of shrinkage. However, shrinkage may also occur when the loss of water is prevented. This type of shrinkage is called autogenous shrinkage. Concretes with low water-to-binder ratio are more susceptible to shrinkage than concrete with high water-to-binder ratio. Shrinkage cracking or high probability of cracking in fresh concrete, presented in Figure 1, is a great concern and has been the focus of recent research in this field (name few references).

Figure 1. Plastic shrinkage cracking of concrete [1].

Shrinkage can be divided into many types based on the factors affecting the volume stability of concrete. However, overall shrinkage of concrete occurs in two phases, early-age and long-term shrinkage. Figure 2 shows the stages and types of shrinkage in concrete composites [2]. This paper is focusing on the early-age deformations occurring when concrete is setting and starts hardening in the first 24 hours.

Shrinkage		
	Early Age (<24 hours)	Drying
		Autogenous
		Thermal
	Long Term (>24 hours)	Drying
		Autogenous
		Thermal
		Carbonation

Figure 2. Division of shrinkage stages and types [1].

1.2 Autogenous shrinkage

Autogenous shrinkage is a result of the internal chemical reactions of concrete raw materials without moisture loss to the surroundings. The various stages of hydration manifest themselves in different stages of volumetric deformations of concrete. The deformation rate keeps on changing from the time of mixing water and cement, during setting and then hardening. The driving forces for the early-age deformation could be summed up as: (i) internal reactions of the mixture components and (ii) temperature and relative humidity (ambient conditions).

Loss of water, either due to evaporation or due to consumption in the hydration, gives rise to change of pore water configuration in the capillary pores. This type of deformation, with moisture loss due to evaporation, at an early-age is known as plastic shrinkage. During the very first hours of mixing, concrete is liquid and acts as a plastic. In high-performance concretes, which has less free water, autogenous shrinkage (when water is drawn from pores for hydration) is an important part of the total concrete shrinkage [3] [4] and [7]. Due to less amount of free water in high-strength concrete, water is drawn from the pores that develops a pore pressure, which becomes a driving force for shrinkage, as shown in Figure 3. Interplay of contracting forces such as capillary pressure and swelling forces such as thermal heating during early hydration, control the overall nature of the early age autogenous shrinkage.

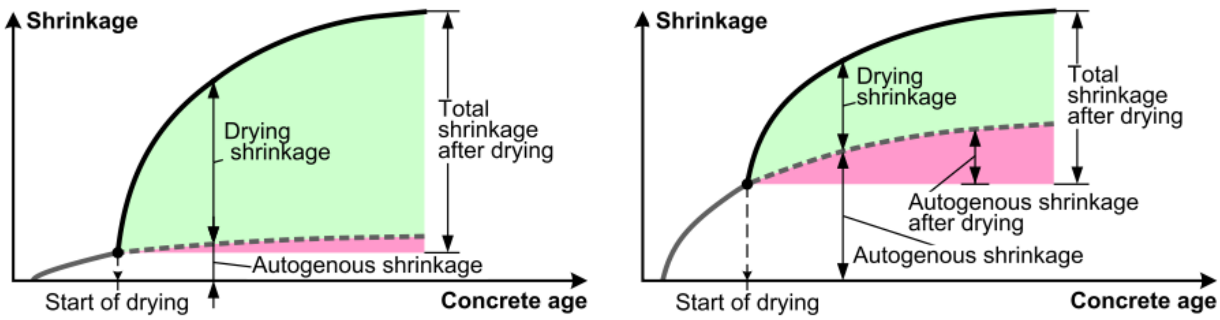


Figure 3. Shrinkage strain components in normal (left) and high-strength (right) concrete [8].

2. EXPERIMENTAL PROCEDURE AND METHOD

2.1 Raw materials and concrete mix design

Measurements of the shrinkage on specimens were carried out according to the European standard EN13892–9:2017 [5]. The effect of fibres on the shrinkage of fibre reinforced concrete involved studying ten concrete mixtures using three cement types and three fibre types. All cement types were produced by Finnsementti Oy, Finland [9]. The types and specifications of fibres used in the research are presented in Table 1 and Figure 4.

Table 1. Types and specifications of the used fibers.

Type of fibers	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Density (kg/m³)	No. of fibres /kg
Hooked–End steel fibre (ArcelorMittal, HE 1/50) [12]	50	1.00	1150	7850	3100
Plastic fibre (BASF, MasterFiber 246) [13].	40	0.75	448	910	~65000
Glass fibres (Owens Corning, Anti-Crack HP24) [14]	24	0.016	1000 – 1700	2680	

Steel Fibres (HE 1/50) - ArcelorMittal	Plastic Fibres (Master Fibre 246) - BASF	Glass Fibres (Anti - Crack HP24) - Owens Corning

Figure 4. Types of the used fibres.

Granitic aggregates were used in concrete mixtures with Plus and SR-cement, while limestone aggregates were used with white cement mixtures. Aggregates were washed, dried and graded by sieving. Concrete mixes were made by using the same aggregate grading. The water used was tap water from the water distribution system of Espoo city, Finland. The water's temperature was approximately + 20°C. Summary of composition of the test mixtures is given in Table 2.

Table 2. Mix proportions of concrete.

Mixture Code	PL-REF	PL-SF	PL-PF	PL-SF-SRA	WH-REF	WH-PF	WH-GF	SR-REF	SR-SF	SR-PF
Cement and water										
Plus Cement	✓	✓	✓	✓	-	-	-	-	-	-
White Cement	-	-	-	-	✓	✓	✓	-	-	-
SR Cement	-	-	-	-	-	-	-	✓	✓	✓
Cement (kg/m^3)	385	385	385	385	350	350	350	385	385	385
Water (kg/m^3)	194	194	194	194	194	194	194	194	194	194
w/c	0.50	0.50	0.50	0.50	0.55	0.55	0.55	0.50	0.50	0.50
Aggregate (kg/m^3)										
Filler TY 63	-	-	-	-	353	353	353	-	-	-
Limestone 22R 0/2	-	-	-	-	705	705	705	-	-	-
Limestone 22R 2/5	-	-	-	-	353	353	353	-	-	-
Limestone 22R 4/12	-	-	-	-	353	353	353	-	-	-
Filler 96	143	143	143	143	-	-	-	143	143	143
0.1/0.6 mm	161	161	161	161	-	-	-	161	161	161
0.5/1.2 mm	161	161	161	161	-	-	-	161	161	161
1 /2 mm	268	268	268	268	-	-	-	268	268	268
2/5 mm	268	268	268	268	-	-	-	268	268	268
5/10 mm	214	214	214	214	-	-	-	214	214	214
8/16 mm	572	572	572	572	-	-	-	572	572	572
Admixtures										
SP (kg/m^3)	1.425	1.425	1.425	1.425	3.85	3.85	3.85	1.425	1.425	1.425
AEA (kg/m^3)	-	-	-	-	0.15	0.15	0.15	-	-	-
SRA (kg/m^3)	-	-	-	3.85	-	-	-	-	-	-
Steel fibres	-	✓	-	✓	-	-	-	-	✓	-
Plastic fibres	-	-	✓	-	-	✓	-	-	-	✓
Glass fibres	-	-	-	-	-	-	✓	-	-	-
Volume of fibres %	-	0.38	0.38	0.38	-	0.38	0.38	-	0.38	0.38
Air (dm^3/m^3)	20	20	20	20	50	50	50	20	20	20

The coding of the concrete mixes based on the cement type, fibre type and used admixture are presented below:

1) Plus cement (CEM II/B-M (SLL) 42.5N) concrete mixtures:
    1) **PL-REF** - Reference (plain) concrete
    2) **PL-SF** - Concrete with steel fibres
    3) **PL-PF** - Concrete with plastic fibres.
    4) **PL-SF-SRA** - Concrete with steel fibres and Shrinkage Reducing Admixture - SRA.
2) White cement (CEM I 52.5R) concrete mixtures:
    5) **WH-REF** - Reference (plain) concrete
    6) **WH-PF** - Concrete with plastic fibres
    7) **WH-GF** - Concrete with glass fibres.
3) SR cement (CEM I 42.5N SR) concrete mixtures:
    8) **SR-REF** - Reference (plain) concrete
    9) **SR-SF** - Concrete with steel fibres
    10) **SR-PF** - Concrete with plastic fibres

2.2 Preparation of the test specimens and measuring procedure

The effects of internal hydration reactions on the dimensional stability of fresh fibre concrete were investigated on a one-meter long shrinkage - rig called Bending-drain - curling profile apparatus from Schleibinger Testing Systems [15], presented in Figure 5.

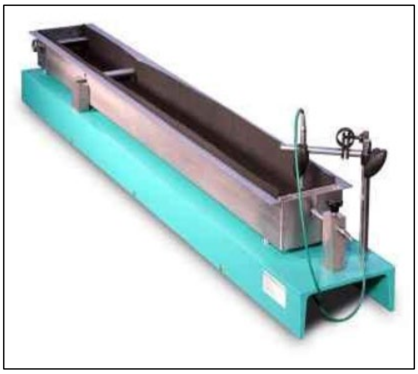


Figure 5. Early-age deformation test with the Schleibinger Bending-Drain – rig.

The ten concrete mixtures (one sample / concrete) were tested in the shrinkage rig in which the samples were sealed to stop evaporation. The specimen temperature and linear deformation history for 48-hours in a control room of 20°C were recorded for each mixture type. These tests were started approximately 40 minutes after water and cement were mixed together. The testing was carried out according to European standard EN13892–9:2017 [5]. The method determines the unrestrained linear movement, shrinkage and swelling, of cementitious screed materials in a 1000 mm bending-drain apparatus. The deformation results were used to study the physical processes controlling different stages of the early-age deformation in fresh concrete. The results were presented as deformation–time graphs, which were plotted for each mixture after separating the thermal deformations from the raw data. Thermal deformations were calculated based on maturity (age and strength development) of concrete samples from the specimen temperature history.

In order to compare the different fibre materials in different cement mixtures, they were used in the same dosage (0.38% by volume). Due to different material densities, 0.38% by volume represents 30 kg/m^3 of hooked end steel, 3.82 kg/m^3 of plastic and 10.24 kg/m^3 of glass fibres respectively. The strength of concrete was C30/37, the consistency class was S3-class and the water-to-cement ratio was 0.50 for Plus and Sulfate Resisting (SR) cement concrete and 0.55 for White cement concrete mixtures.

3. RESULTS AND DISCUSSION

3.1 Early-age deformation measurement

The early-age horizontal deformation (autogenous shrinkage + thermal deformation) measurement can be divided into three distinct stages. These stages are marked in the Figure 6 and described as follows:

- **Stage A: ~ (0 – 2½ hours)**
  At the start of the test, large horizontal shrinkage is recorded. The concrete at this stage is still fluid enough not to induce any harmful stresses due to this shrinkage. As the sample is placed in the U-shaped steel mould, the vertical placement exerts a force on the movable plate, which is partly cast into the sample for detecting horizontal deformation. This excessive early deformation does not exist for stiff or dry (little or no bleeding) mixtures.

- **Stage B: ~ (3 – 14 hours)**
  Thermal effects and bleed water reabsorption cause expansion of the sample from 3 - 14 hours into the test. Extra bleed water rises to the surface of the concrete sample as aggregates and cement particles settle. At a time when bleed water is completely absorbed into the concrete sample, the on-going hydration develops capillary pressure rise that is understood to be a main cause of early-age autogenous shrinkage deformation. Hydration reaction-controlled thermal expansion exceeds the capillary suction and causes large expansion.

- **Stage C: ~ (14 + hours)**
  At the end of hydration heat generation, the sample starts cooling which results in contraction of the concrete sample. The shrinkage during this continuing stage is somewhat exaggerated due to the cooling effect. With the progression of hydration, water availability becomes lesser within the microstructure of concrete sample, and capillary suction contributes to the autogenous shrinkage.

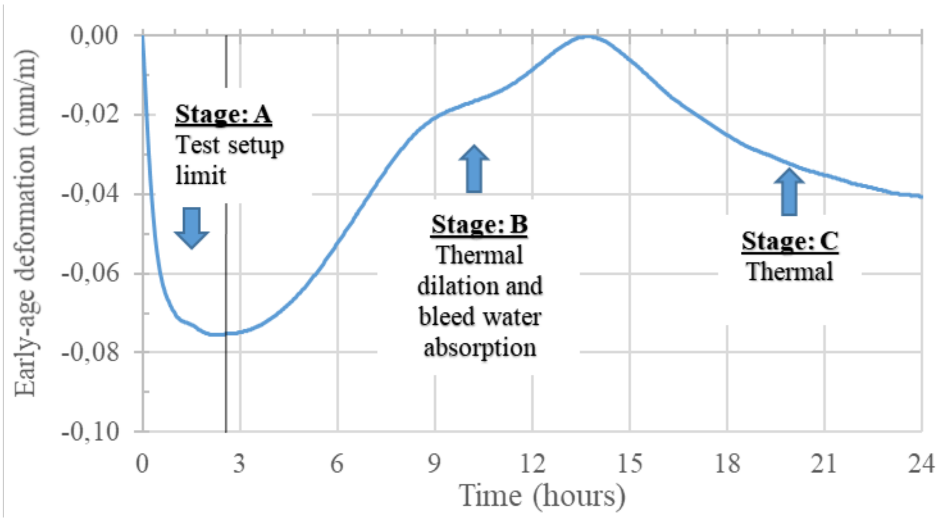


Figure 6. Stages of first 24 hours of the early-age deformation result for Plus cement concrete at w/c =0.50.

For evaluating the early-age autogenous shrinkage results for the aim of comparison, an engineering data interpretation approach was used [2]. The measured deformation of the test specimens over time consisted of (i) variations due to the shrinkage of the concrete, and (ii) variations due to changes in the temperature of the specimen.

The temperatures in the middle of the test specimens, and the corresponding changes in specimen length, were measured simultaneously. The variations over time of specimen shrinkage were determined from the differences between the development over time of the measured deformations, and the temperature expansion of the test specimens due to variations in temperature. Because the concrete temperature varied only during the period of rapid hydration of the cement (24 hours after mixing) and later approximately it was equal to the ambient temperature, the influence of temperature variations on the actual variations of specimen length has to be considered within the first 24 hours only. The variations over time of the test specimen deformation due to temperature variations in the period of rapid setting of the cement, i.e. in the first 24 hours, were determined analytically from the coefficient of thermal expansion of the concrete, and the measured variations over time of the temperature [4]. For estimating the thermal expansion coefficient (α_T) of concrete during the early-ages for time between 3-24 hours, Equation (1) was used.

$$\alpha_T = 193.9 \times t^{-0.86} \tag{1}$$

where: α_T = thermal expansion coefficient, (μ/°C), and
t = time between 3-24 hours, hours.

Constant values the thermal expansion coefficient are considered outside these time limits (for t < 3h, the $\alpha_T \approx 73 * 10^{-6}/°C$ and for t > 24h, $\alpha_T \approx 12 * 10^{-6}/°C$) [2]. The thermal expansion coefficient (α_T) is adjusted for each mixture based on the maturity concept. This helps to correct and take into account the temperature and strength development. The concrete age was adjusted according to Equation (2). This equation is valid for concretes made of Portland cements or cements containing only low amounts of components other than Portland cement clinker [6].

$$t_T = \sum_{i=1}^{n} \Delta t_i \times \exp\left[13.65 - \frac{4000}{273 + \frac{T_i}{T_0}}\right] \tag{2}$$

where: t_T = temperature adjusted concrete age.
Δt_i = number of hours where a temperature T prevails.
T_i = temperature during the time period Δt_i.
T_0 = 1°C.

The thermal expansions is calculated by multiplying the maturity adjusted thermal expansion coefficient (α_T) with temperature differences from temperature history of concrete specimen using equation (3). An example of the calculated thermal expansions is presented in Figure 7.

$$\varepsilon_{\Delta T} = \alpha_T \times \Delta T \tag{3}$$

where: $\varepsilon_{\Delta T}$ = the thermal expansion, (mm/m).
α_T = thermal expansion coefficient, (μ/°C).
ΔT = the temperature differences, (°C)

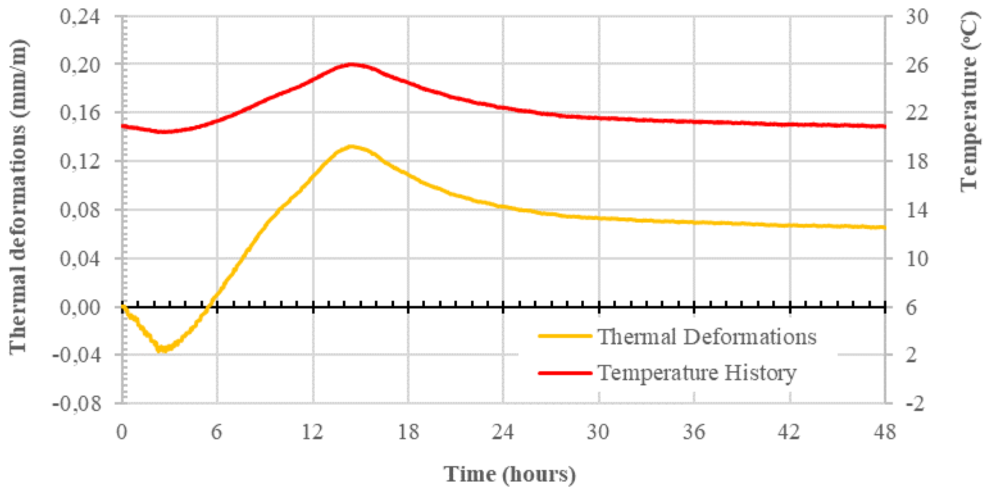


Figure 7. Temperature development and consequent thermal deformations calculated from maturity-adjusted thermal expansion coefficient.

The early-age horizontal deformation is corrected following the development of thermal deformation calculation.

$$AD_{corr} = Measured\ deformation - thermal\ deformation$$
$$AD_{corr,zeroed} = AD_{corr} - Measured\ deformation\ value\ at\ the\ beginning\ of\ stage - B$$

Figure 8 shows the measured values of horizontal deformation from the Bending-drain test, thermal deformations calculated from maturity-adjusted thermal expansion coefficient, the corrected shrinkage following the thermal expansion (AD_{corr}) corrections and zeroed-corrected autogenous shrinkage ($AD_{corr,zeroed}$), which zeroed at the beginning of stage-B, see Figure 6.

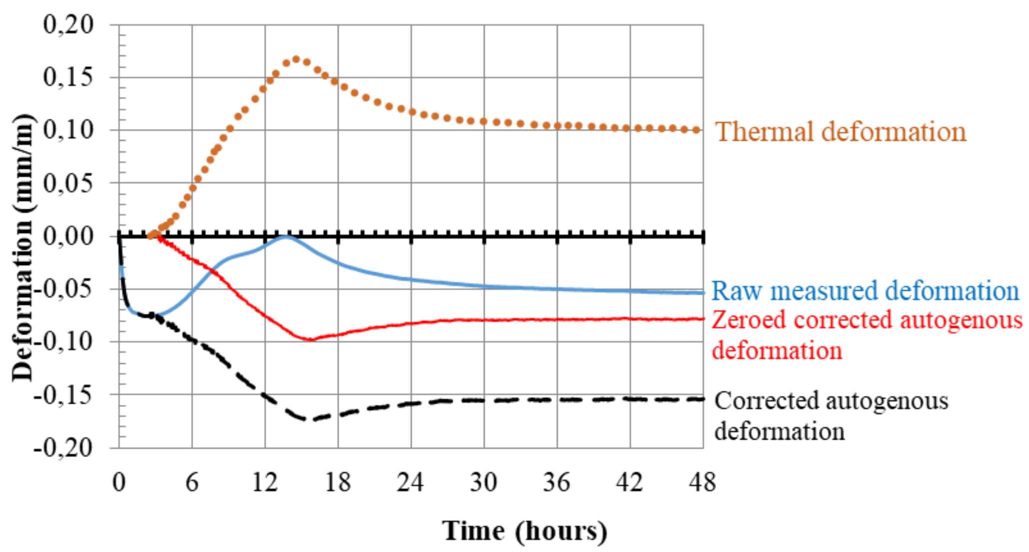
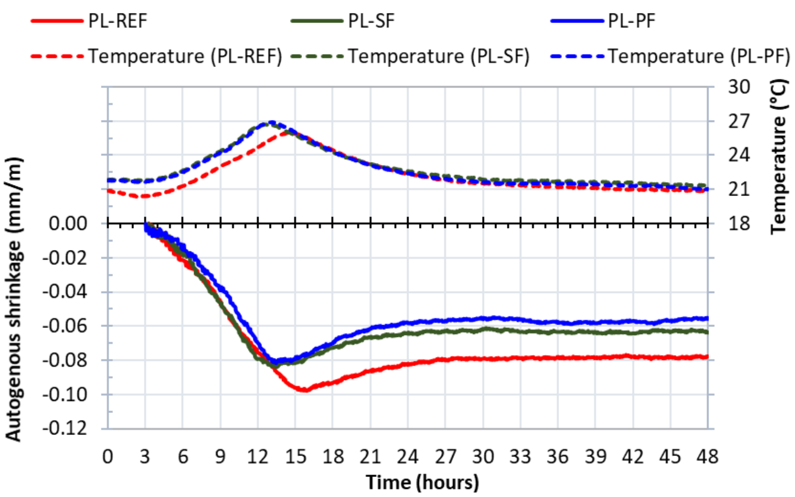


Figure 8. Measured autogenous deformation and corrected autogenous shrinkage.

3.2 Effect of different type of fibres

There is a general agreement among researchers that the addition of fibres to concrete have reducing effect on both the interior strain (due to autogenous effects) and the thermal expansion coefficient [16] and [17]. The fibres disrupt the interconnection of pores, reducing the overall water content in the capillary pore [18]. Increasing dosage of fibres in the concrete will reduce the overall thermal expansion coefficient of FRC.

The zeroed-corrected 48 hours autogenous shrinkage (along length) and temperature history (at the middle of specimen height) of Plus, White and SR cement concrete mixtures are shown in Figure 9, Figure 10 and Figure 11, respectively.

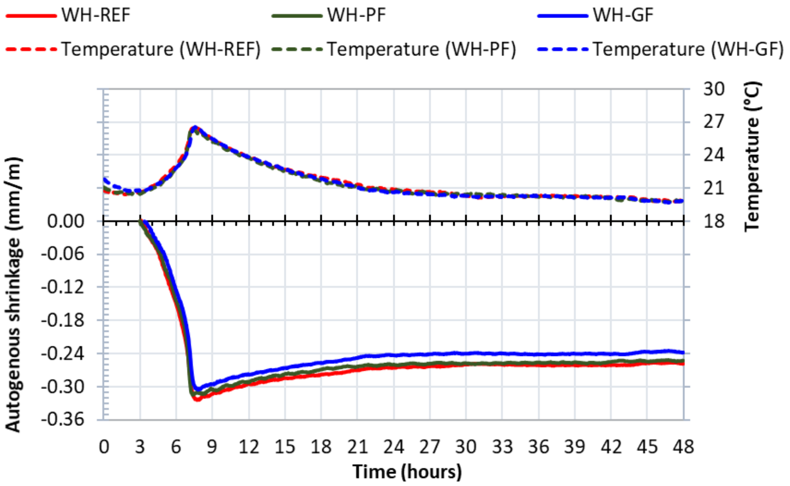


PL-REF: Plain concrete
PL-SF: Steel fibre RC
PL-PF: Plastic fibre (0.38% by volume) RC

Figure 9. Autogenous shrinkage and temperature history of Plus cement concrete mixtures.

For Plus cement concrete mixtures, it can be seen that early-age autogenous shrinkage of plain concrete was greater than with the fibres. The maximum autogenous shrinkage of steel fibre concrete was approximately 14% less than autogenous shrinkage of the plain concrete. Moreover, the maximum autogenous shrinkage of plastic fibre concrete was approximately

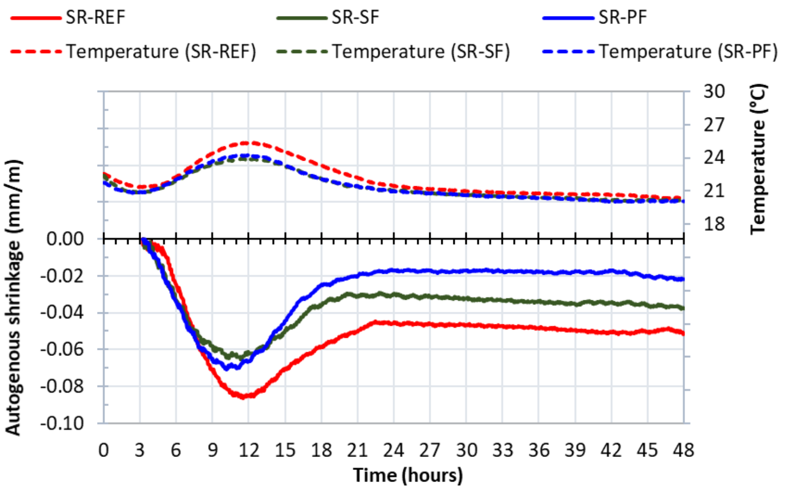
16.5% lesser than the maximum autogenous shrinkage of the plain concrete. At the end of test at 48 hours, the autogenous shrinkage of steel fibre concrete was approximately 18% less and the autogenous shrinkage of plastic fibre concrete was approximately 28% lesser than the autogenous shrinkage of the plain concrete mixture. It could be concluded that, with same dosage of fibre volume, plastic (polypropylene) fibres reduce the early-age autogenous shrinkage more than steel fibres do.



WH-REF: Plain concrete
WH-PF: Plastic fibre RC
WH-GF: Glass fibre (0.38% by volume) RC

Figure 10. Autogenous shrinkage and temperature history of White cement concrete mixtures.

For White cement concrete mixtures, the fibrillated glass fibres performed almost twice as good in reducing shrinkage as the plastic fibres in case of White cement concrete. However, there was not much difference in total autogenous shrinkage of plain or fibre concrete for White cement. It could be concluded that, for the range of fibre content used in this work for White cement concrete, the fibres did not have a considerable effect on autogenous shrinkage like the case of Plus and SR fibre reinforced concrete mixtures.



SR-REF: Plain concrete
SR-SF: Steel fibre RC
SR-PF: Plastic fibre (0.38% by volume) RC

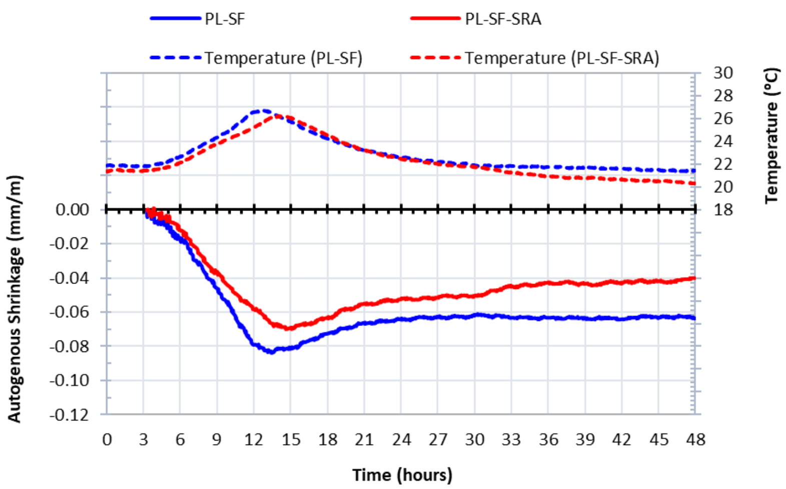
Figure 11. Autogenous shrinkage and temperature history of Sulfate Resisting (SR) cement concrete mixtures.

For Sulfate Resisting (SR) cement concrete mixtures, the early-age autogenous shrinkage of SR plain concrete was greater than with the addition of fibres. The maximum autogenous deformation of steel fibre concrete mix was approximately 24% less than that of maximum autogenous shrinkage of plain concrete mix. The maximum autogenous shrinkage for plastic fibre concrete was found to be approximately 18% less than the maximum autogenous shrinkage of the plain concrete mix of SR cement. At 48 hours, the autogenous deformation of steel fibre concrete was approximately 27% less, and that of plastic fibre concrete was approximately 57% lesser than that of the plain SR cement concrete. The plastic fibres reduce the early-age autogenous shrinkage more than the steel fibers in the case of SR cement concrete too.

It was observed that the fibre reinforced concretes behaved similarly to plain concrete in the first few hours of the test. However, there were noticeable difference in the maximum and 48 hour autogenous shrinkage values. The autogenous shrinkage of fibre reinforced concrete was found to be lesser than that of plain concrete mixtures for all three types of cement mixtures. It might be because fibres reduce the autogenous shrinkage when they are subjected to the shrinkage-induced tensile stresses, by shear along the fibre-matrix interface [19].

3.3 Effect of Shrinkage Reducing Admixture (SRA)

To demonstrate the effect of Shrinkage Reducing Admixture (SRA), 1% (by weight of binder) dosage of BASF MasterLife 815 SRA was added to steel fibre reinforced concrete (SFRC) using Plus cement, see Figure 12.



PL-SF: Steel fibre RC
PL-SF-SRA: Steel fibre concrete with 1% SRA by volume

Figure 12. Shrinkage Reducing Admixture effect on autogenous shrinkage and temperature history of steel fibre reinforced concrete mixtures.

A noticeable feature in Figure 12 is the delayed peak temperature rise and delayed maximum early-age autogenous deformation with the use of SRA. This side effect has been reported in previous studies and mentioned in the manufacturer's product documents. However, the perceived delay is within 1-hour period. The use of SRA reduced the maximum early-age autogenous deformation of SFRC by approximately 16.5%. Whereas, the reduction of early-age autogenous deformation at 48-hours was greater than 37%. However, the mixture containing 1% SRA showed greater workability (slump) and apparently more free water. This is a direct effect of reduced surface tension of the mixing water in the liquid stage.

3.4 Effect of cement type

Figure 13 shows the changes in autogenous shrinkage for plain concrete samples of the Plus, White and SR cement types. Same mixture design was used for Plus and SR cement types, with w/c ratio of 0.50. Mixture design for White cement concrete had a w/c ratio of 0.55 with four limestone 22R aggregate factions, more than twice amount of filler and maximum aggregate size of 12 mm.

The different clinker compositions and initial setting times of the cement types also reflected in the thermal changes as seen in the temperature history. In Figure 13, the shrinkage data was referenced at the start of thermally controlled deformations. The mixture with White cement (WH-REF) showed less bleed-water. After the peak temperature during hydration, rapid shrinkage was observed with white concrete mixtures. Other mixtures with Plus and SR cement exhibited thermal expansions exceeding the amount of early-age shrinkage.

Apart from the maximum magnitudes of the mixture temperatures and autogenous shrinkage, it can be seen that these temperature histories and autogenous shrinkage measurements are characteristic in nature. Qualitatively, they represent the material properties of the corresponding cement type mixture and the test arrangement. The temperature histories (PL-REF for Plus, WH-REF for White & SR-REF for SR) of plain concrete mixtures suggest that hydration reactions occur in a different way in these cement types. The high early heat of hydration causes thermal swelling in Plus and SR cement type mixtures. Whereas, it only resists the autogenous shrinkage deformations in the White cement mixtures. The thermal effects were removed from the raw autogenous deformation data using maturity adjusted thermal expansion coefficient. The corrected results confirm the same logic as White cement mixture type showed large amounts of corrected autogenous shrinkage, followed by Plus and SR type mixtures.

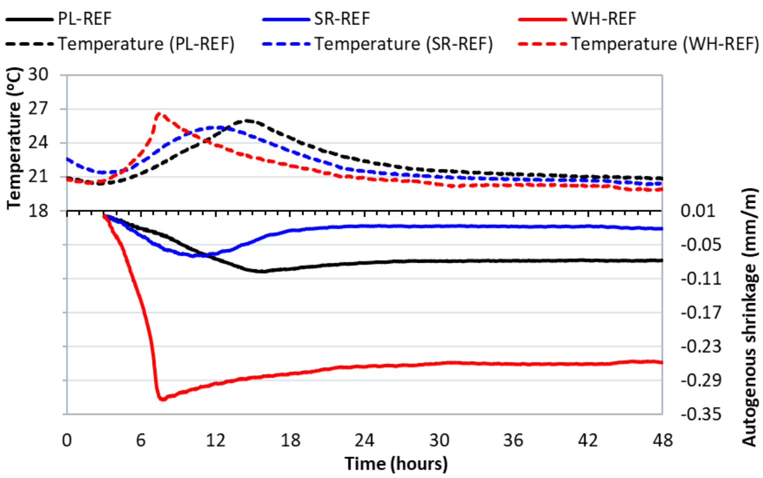


Figure 13. Comparison of autogenous shrinkage and temperature history of plain concretes with Plus, Sulfate Resisting and White cement.

4. CONCLUSION

The autogenous shrinkage is of great concern since concretes with lower w/c ratios are more commonly used in applications such as high-performance concrete. With material optimization for structural concrete, autogenous shrinkage is of increasing concern as it can dictate the quality of concrete throughout the lifecycle of a structure. Fibre reinforced cement composites are increasingly being used to address the problems of volumetric deformation-induced cracking. This experiment work was aimed to identify the beneficial effects of fibres in controlling the forces that drive both the early-age autogenous and long-term drying shrinkage deformations in concrete composites. A new experimental setup was used to study the effects of different types of fibers in concrete mixtures with different cement types.

Following trends are concluded from the tests of early-age autogenous shrinkage in this study:

- The early-age autogenous shrinkage of plain concrete samples was more than that of fibre-reinforced samples for all cement types. The fibre dosage of 0.38% by volume was found to be effective in reducing the effects of early-age autogenous shrinkage deformations.
- For the same dosage of fibres (0.38% by volume), the plastic (polypropylene) fibres were more effective than hooked-end steel fibres in reducing the early-age autogenous shrinkage.
- The effect of fibres in reducing early-age autogenous shrinkage in White cement concrete was less than the effect of fibres addition in Plus and SR cement concrete mixtures.
- Regarding the effect of cement type, the SR cement concrete exhibited both lesser early-age autogenous shrinkage and long-term drying shrinkage as compared to the Plus cement concrete. This effect is attributed to the difference in clinker composition of the respective cement types. Plus type cement, with a higher C3A, showed greater early-age autogenous and long-term drying shrinkage.
- The use of 1% by weight of cement of the Shrinkage Reducing Admixture (SRA) proved to be effective in reducing the early-age autogenous and long-term drying shrinkage deformation.

The general opinion that fibres allow more moisture escape by bridging the pores could not be established as similar average water loss (kg/m^3) was recorded for both the plain and fibre reinforced concrete mixtures.

REFERENCES

1. Orosz K: "Early Age Autogenous Deformation and Cracking of Cementitious Materials – Implications on Strengthening of Concrete Structures," *Doctoral thesis*, Luleå University of Technology Department of Civil, Environmental and Natural Resources Engineering. ISBN 978-91-7583-909-7 (pdf). Luleå, Sweden, 2017.
2. Holt E: "Early Age Autogenous Shrinkage of Concrete," *VTT Publication* No. 446, Technical Research Centre of Finland -VTT Publication 446, Espoo, Finland, 2001. [Online] http://www.vtt.fi/inf/pdf/publications/2001/P446.pdf. [Accessed 3.10.2018]
3. Barr B & El-Baden A: "Shrinkage Properties of Normal and High Strength Fibre Reinforced Concrete," *Proceedings*, Institution of Civil Engineers - Structures and Buildings, 2003, Volume 156:1, pp. 15-25. doi: 10.1680/stbu.2003.156.1.15.
4. Saje D, Bandelj B, Šušteršič J, Lopatič J & Saje F: "Autogenous and Drying Shrinkage of Fibre Reinforced High-Performance Concrete," *Journal of Advanced Concrete Technology*, Volume 10, No. 2, 2012, pp. 59-73
5. EN 13892-9 "Methods of Test for Screed Materials - Part 9: Determination of Shrinkage and Swelling," German and English version prEN 13892-9:2017.

6. CEB-FIP Model Code (1990): Design Code. Comité Euro-International du Beton, Bulletin d'Information no. 213/214, Ed. Thomas Telford, 1993.
7. Zhao S, Li C, Zhao M & Zhang X: "Experimental Study on Autogenous and Drying Shrinkage of Steel Fiber Reinforced Lightweight-Aggregate Concrete," *Advances in Materials Science and Engineering*, Vol. 2016, Article ID 2589383, 9 pp, 2016. doi:10.1155/2016/2589383
8. Gribniak V, Kaklauskas G, Kliukas R & Jakubovskis R: "Shrinkage Effect on Short-Term Deformation Behavior of Reinforced Concrete – When It Should Not Be Neglected", *Materials and Design*, Vol. 51, 2013, pp. 1060-1070, ISSN 0261-3069. [Online] https://doi.org/10.1016/j.matdes.2013.05.028 [Accessed 3.10.2018].
9. Finnsementti Oy, Cements. [Online] http://www.finnsementti.fi/en/products/cements [Accessed 3.10.2018].
10. SFS-EN 12617-4:2002. "Products and Systems for the Protection and Repair of Concrete Structures. Test Methods. Determination of Shrinkage and Expansion." The Finnish Standards Association SFS.
11. ISO 1920-8:2009 "Testing of Concrete - Part 8: Determination of Drying Shrinkage of Concrete for Samples Prepared in the Field or in the Laboratory".
12. ArcelorMittal steel fibers [Online] http://ds.arcelormittal.com/wiresolutions/steelfibres/products/ [Accessed 3.10.2018]
13. BASF. Master Builders Solutions. [Online] https://www.master-builders-solutions.basf.fi/fi-fi/products/masterfiber/354 [Accessed 3.10.2018].
14. Owens Corning. "Owens Corning - Innovations for Living". [Online] http://www.cem-fil.com/ [Accessed 3.10.2018].
15. Schleibinger Testing Systems [Online] http://www.schleibinger.com/cmsimple/en/?Shrinkage:Bending_Drain [Accessed 3.10.2018].
16. Bazant Z P: "Delayed Thermal Dilatations of Cement Paste and Concrete due to Mass Transport," *Nuclear Eng. & Design*, 1970, pp. 308–318.
17. Sellevold E J & Bjøntegaard Ø: "Coefficient of Thermal Expansion of Cement Paste and Concrete: Mechanisms of Moisture Interaction," *Mater. Struct.*, Vol. 39, No. 9, 2006, pp. 809–815.
18. Lei Y & Cao, X: "Study on Thermal Dilation Coefficient of Fibre Concrete at Early Stage," *Applied Mechanics and Materials*, Vol. 99-100, 2011, pp. 777-781.
19. Mangat P & Azari M: "A Theory for the Free Shrinkage of Steel Fibre Reinforced Cement Matrices," *Journal of Material Sciences*, Vol. 19, No. 7, 1984, pp. 2183-2194.