International Journal of Civil and Structural Engineering– IJCSE
Volume 2 : Issue 1 [ISSN : 2372-3971]
Publication Date: 30 April, 2015

Long-term Behaviour of Fibre Reinforced Cement Composites

[Andina Sprince, Leonids Pakrastinsh and Nikolai Vatin]

Abstract—**The aim of this paper was to study the behaviour of new high-performance fibre-reinforced cement composite materials (FRCC) that are reinforced with polyvinyl alcohol (PVA) fibres and subjected to long-term loading. In these composites, part of the cement has been replaced with micro and nano fillers. The creep and shrinkage deformations of the new compositions were determined. In addition, the compressive strength, modulus of elasticity and creep coefficient of the material was determined. The results of the experiments permitted the prediction of long-term deformations of the FRCC. Wider use of FRCC material would provide a possibility to reduce the impact on environment because the high strength concrete (HSC) have lower water/ cement ratio. The cement production process accounts for up to 10% of the total carbon dioxide emissions in the world. It will also permit the construction of sustainable next generation structures with thin walls and large spans that cannot be built using the traditional concrete.**

Keywords—**fibre reinforced concrete, PVA fibres, cement-based matrix, compression strength, modulus of elasticity, long-term deformation, shrinkage, creep, creep coefficient**

I. Introduction

Concrete is an important structural material used in every country of the world and in every type of construction. Moreover, the complexity of structures and their size have continued to increase, and this has resulted in a greater importance of their deformation characteristics and in more serious consequences of their behaviour [1-5]. The deformation characteristics of concrete are important also in the design of sustainable structures because these can significantly contribute to the cracking risk [6-11]. Two types of delayed deformations play a major role in successful and continuous use of structures — creep and shrinkage [6, 9-14]. Creep deformations appear due to long-term loading of the structural element, and shrinkage is a reduction in the volume of concrete as it hardens during the hydration process [6, 9, 15, 16]. If appropriate attention is not devoted to these effects, structural reliability in terms of serviceability and, in some cases, of ultimate safety may be unfavourably affected [8, 17]. Therefore, designers and engineers need to know the creep and shrinkage properties of concrete and must be able to take them into account in the structure analysis [1, 2, 5, 9, 18, 19].

Shrinkage and creep phenomena in cementitious materials have been given a great deal of attention during the past century motivated by the need to calculate the long-term deformation and behaviour of nuclear reactor containments and other multifaceted or long-span structures [6, 19-21]. Recent research relates the creep and shrinkage response to the packaging density distributions of calcium-silicate-hydrates [22]. But these phenomena are thought to be caused by several different and complex mechanisms not yet fully understood [1, 6].

For the last 30 years, concrete development has gone in a new direction: high performance concretes. This kind of building materials is defined as a concrete in which certain characteristics are developed for a particular application and environment; these characteristics are not only strength, but improved durability, increased resistance to various external agents, high rate of hardening, better appearance, etc. [23, 24]. Very important disadvantage of this concrete is its brittleness [19]. One of the most perspective products is fibre-reinforced high performance concrete. Adding fibres in concrete can provide improved mechanical and physical properties of the material, which results in a composite material that is characterized by an enhanced post-cracking tensile residual strength, also defined as toughness, due to the fibre reinforcement with fibres bridging the cracks [7, 25-27].

This paper summarizes the recent state of research on elastic and time-dependent deformations of new high-performance fibre-reinforced cement composite materials (FRCC) that are reinforced with polyvinyl alcohol (PVA) fibres and subjected to a long-term, uniform compressive load. In these composites, part of the cement has been replaced with micro and nano fillers. The experimental studies of creep in compressionand shrinkage were performed. The results of the experiments permitted to create a comprehensive database of creep and shrinkage test for the prediction of long-term deformations of the FRCC.

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II. Characterization of materials

This study investigates new FRCC with the compressive strength more than 140 MPa, in which micro and nanofillers are used as an integral component of the system cement + microfiller + nanofiller, which ensures efficient particle packing and maximum density of the concrete microstructure, as well as increases the binder/aggregate transition zone density [13, 14, 22, 28-30].

The following considerations were taking into account when selecting mix proportions: use of local, commercially available raw components; the lowest possible water/cement ratio; the possibility to mix components in the available laboratory mixer; high flowability of the concrete mix allowing easy filling of the moulds; maximum aggregate size < 1 mm (D_{max} = 1 mm); paste content about 60% allowing high fibre concentration; PVA fibre REC 15 combination of 8 mm and 12 mm and minimization of price.

The experimental work included the preparation of two FRCC compositions with PVA fibres 2% from the total amount of cement with and without nano silica. In this paper these batches will be called batch with micro silica (SF) and batch with micro and nano silica (NN). The mix compositions are given in Table 1. The PVA fibre properties are listed in Table 2.

TABLE I. CONCRETE MIX COMPOSITION

Concrete mix composition	Component, [kg/m³]	SF	NN
	Cement *Alborg white* CEM I 52,5 N	1000	1000
	Quartz sand 0-1mm	260	260
	Quartz sand 0.3-0.8 mm	400	400
	Quartz sand 0-0.3 mm	300	300
	Silica fume Elkem 971 U	150	150
	Plasticizer Sikament 56	30	30
	Nano silica	0	20
	Water	195	195
	PVA fibres MC 40/8	10	10
	PVA fibres MC 200/12	10	10
	W/C	0.19	0.19

TABLE II. PROPERTIES OF PVA FIBRES

Properties of PVA fibres	Fibre type	Ø [μm]	L [mm]	f_t [GPa]	E [GPa]
	MC 40/8	40	8	1.6	42
	MC 200/12	200	12	1.0	30

Proportions of the mix components (see Fig.1) were selected taking into account our previous experiments with high strength concrete mixes [30].

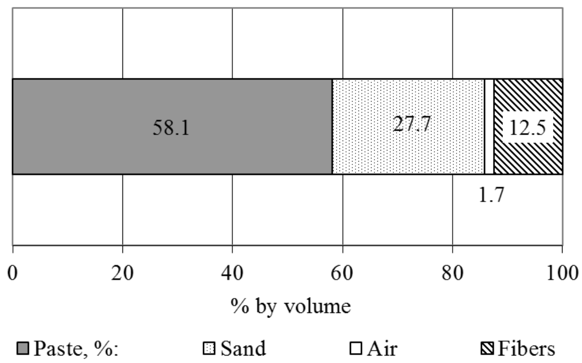

Figure 1. Volume of FRCC components [30]

The mix design is based on the ideal grading curve method in order to provide dense packing of particles and good flowability of the concrete mix. The optimal proportions of the aggregate were calculated, which ensure that the composition is as close to the ideal curve as possible. The ideal curve used is Fuller's parabolic correlation between the particle size (sieve hole opening) and the passing value: $Y_i = (D_i/D_{max})^n \cdot 100$, n=0,25 for mix (aggregate + cement). Grading curves are summarized in Fig. 2.

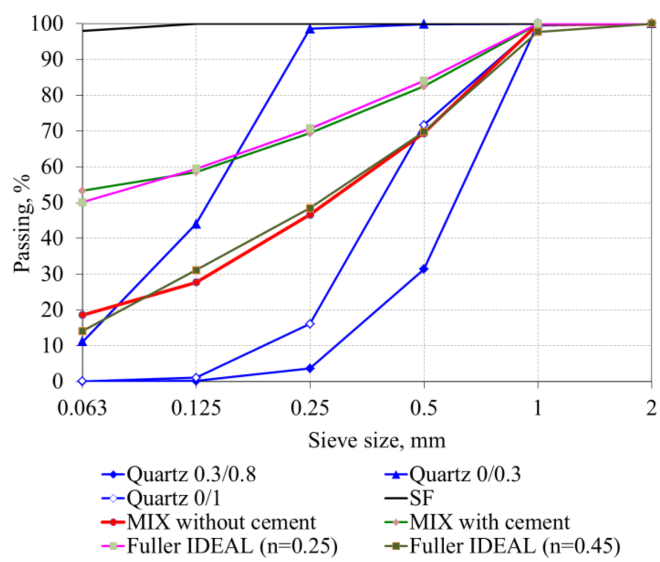

Figure 2. Particle size distribution

Concrete components were measured out and then mixed in a laboratory twin-shaft mixer for 4 minutes. Standard cube specimens of 100x100x100 mm and cylindrical specimens of 47x190 mm were produced. For each concrete mix, 6 cubes and 16 cylindrical specimens were cast. Six of the cylindrical specimens were used for long-term creep measurement and four of them were used to measure shrinkage, while the other six were used for determination of the compressive strength. Concrete mixtures were cast into oiled moulds without vibrating because this is a self-compacting concrete. After one day specimens were de-moulded. Standard ageing conditions (temperature 20±2ºC, RH > 95±5%) were provided during hardening until certain concrete ages were reached.

III. Experimental test programm

A. *Compressive strength tests and determination of modulus of elasticity*

The compressive tests were performed after 7 and 123 days of FRCC hardening in standard conditions. After creep tests the cylindrical compressive strength of the specimens at the age of 123 days was determined.

A compression testing machine with accuracy of ±1% was used, the rate of loading was 0.7 MPa/sec [31].

The modulus of elasticity was obtained from initial deformation part during creep test loading. The load was applied gradually in four steps and as fast as possible. The modulus of elasticity was obtained after 28 days of FRCC hardening.

B. *Creep and shrinkage tests*

The creep was measured for hardened FRCC specimens subjected to a uniform compressive load which was kept constant over a long period of time and shrinkage was measured for the same specimens without loading [15, 16, 32]. During the test, the stress level of all mixes was 25% of the maximum strength of the FRCC, which had been determined during destructive tests. Specimens were kept under a constant load for 90 days, and for recoverable creep they were kept without load for 30 days.

Six aluminium plates had been centrally and symmetrically glued onto three sides of the creep specimens in order to provide a basis for the strain gauges. The distance between the centres of the two plates was 50 mm. Three ±0.001 mm precision strain gauges were symmetrically connected to each specimen (Fig. 3) and then the specimens were put into a creep lever test stand and loaded (Fig. 4, 5).

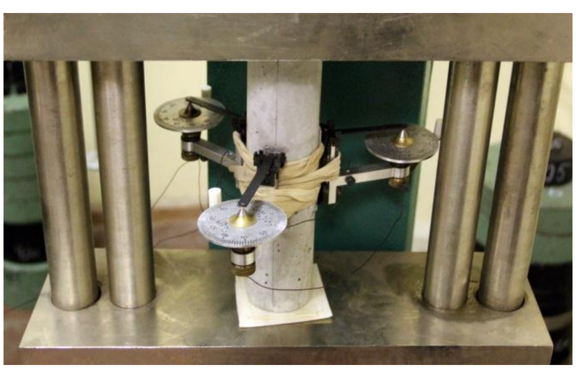

Figure 3. Specimen with strain gauges

Figure 4. Specimen with strain gauges

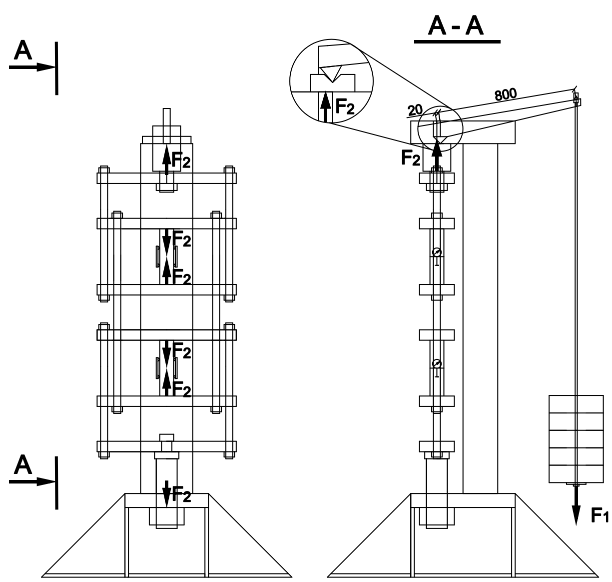

Figure 5. Creep lever test stand scheme

The creep coefficient and specific creep were determined after creep results.

Two steel plates had been centrally and symmetrically glued onto ends of the shrinkage specimens (Fig. 6) and strains were measured with a shrinkage clamp.

Figure 6. Specimens prepared for shrinkage test

The creep and shrinkage specimens were tested in two extreme conditions: in one case they were kept in 100% humidity ensured by preventing the desiccation of the FRCC and in the other case specimens were air-dried. All specimens were kept in a dry atmosphere of controlled conditions: temperature 20±1°C and relative humidity 48±3% [15, 16].

IV. Results and discussion

A. Compression strength and modulus of elasticity

High cement content and low water/cement ratio provides rapid concrete hardening process with high strength gain. High compressive strength had developed in the cubes after the first 7 days of hardening, and continuous compressive strength growth was observed [14]. Avarage compressive strength of the cubes after 28 days had reached 110 MPa and after 123 days – 140MPa for both concrete batches (Fig. 7).

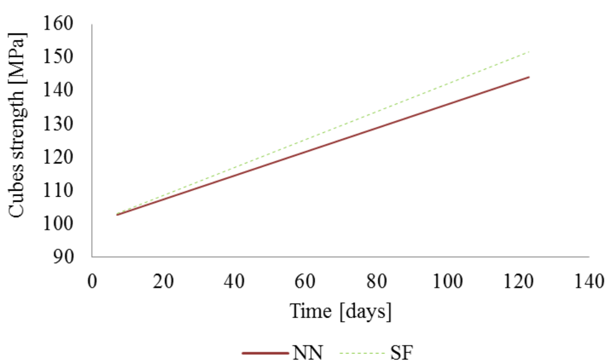

Figure 7. Avarage compressive strength of FRCC

The compressive strength of the cylindrical specimens after 123 days was obtained approxemately 115 MPa for both concrete batches.

It was observed that the modulus of elasticity in all conditions is approxemately similar for both mixes, and it was 47 GPa.

B. Total deformation

The total deformation are given in Fig. 8. The results of the FRCC indicate that the highest total deformation was observed for micro silica specimens in both conditions but the largest difference between the moist and dry conditions was for specimens with nano silica. The average difference between the specimens with nano silica hardened in moist and in dry conditions was approximately 17%.

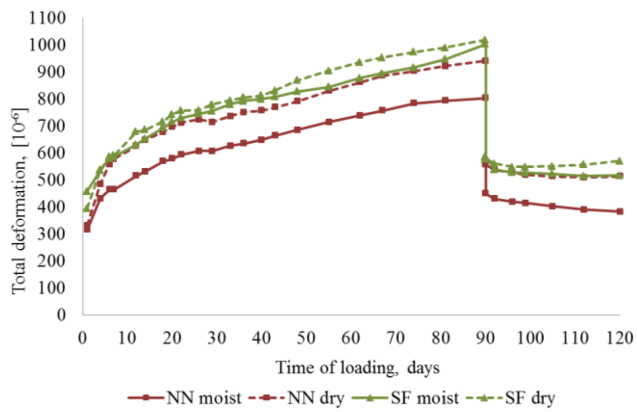

Figure 8. Total deformation of FRCC at air-drying and moist conditions

After 90 days of loading, the load was removed. The creep recovery was measured 30 days after the loading period. The largest part of recoverable creep deformation is instantaneous. For both mixes the largest difference of irrecoverable creep strain was exhibited by moist-hardened specimens. The highest residual creep deformations also were observed for specimens with micro silica.

C. Shrinkage deformation

Shrinkage results were obtained from the same shape and concrete mix specimens as the creep specimens, and the strains were measured during creep tests. Fig. 9 shows that the shrinkage deformations are decreasing with time. The lowest shrinkage deformations were observed for all concrete specimens in moist conditions. The average difference between specimens with micro silica hardened in moist and in dry conditions is approximately 22% but for specimens with nano silica hardened in moist and in dry conditions the difference is higher — 30%.

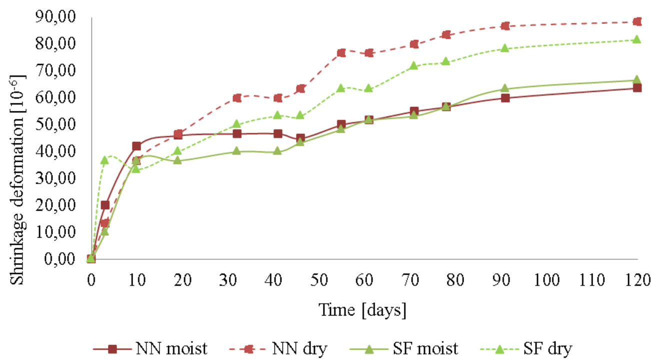

Figure 9. Shrinkage deformation of FRCC specimens hardened in dry and moist conditions.

D. *Creep coefficient*

The highest creep coefficients were established for concrete specimens with micro silica (Fig.10) in the both conditions and it was approximately 3.0. The lowest creep coefficient was exhibited by the specimens with nano silica in the moist conditions and it average value was 2.3.

The creep coefficient reduces significantly with the growth of the concrete strength (Fig.7 and Fig.10). The creep coefficient increases with time at an ever-decreasing rate. The final creep coefficient is a useful measure of the creeping capacity of concrete.

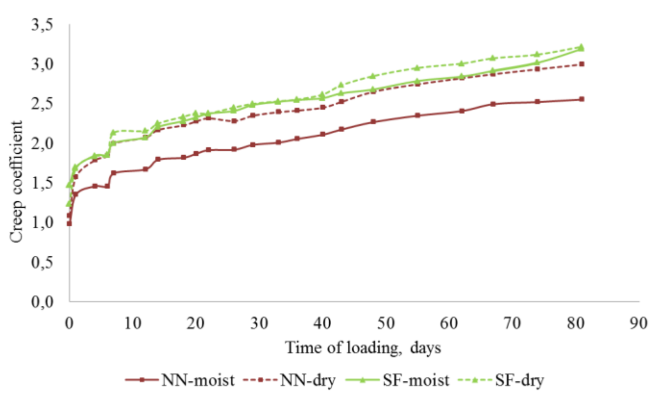

Figure 10. Creep coefficient of FRCC at air-drying and moist conditions

V. Conclusions

Two fibre-reinforced high performance concrete compositions (FRCC) with micro and nano silica as active additive were prepared for a laboratory examination. The compressive strength of the cubes and cylinders, modulus of elasticity, creep and shrinkage deformation, creep coefficient were determined.

High cement content and low water/cement ratio provides rapid concrete hardening process with high strength gain. High compressive strength had developed in the cubes after the first 7 days of hardening, and continuous compressive strength growth was observed.

During creep test initial part the modulus of elasticity was obtained. It was observed that the modulus of elasticity of samples hardened in moist and dry conditions is similar for both mixes.

The results of the experiments permitted the prediction of long-term deformations of FRCC. The highest total deformation was observed for micro silica specimens in both conditions but the largest difference between the moist and dry conditions was for specimens with nano silica. The creep deformations were found to decrease with concrete aging and time. The largest part of recoverable creep strain is instantaneous. For both mixes the largest difference of irrecoverable creep deformation was exhibited by moist-hardened specimens. The highest residual creep deformation were observed for specimens with micro silica.

The shrinkage results showed that for the moist conditions the shrinkage deformations were similar for both concrete mixes, but the lowest shrinkage deformations were observed in concrete specimens with micro silica hardened in dry conditions.

The creep coefficient reduces significantly with the growth of the concrete strength. The highest creep coefficients were established for concrete specimens with micro silica and the lowest creep coefficient was exhibited by the specimens with nano silica.

The utilization of the new generation of extra high strength cement composite materials in structures permits rational use of natural resources by reducing the cross-section and weight of structural elements, which in turn enables to reduce cement consumption and costs. It will also permit the construction of sustainable next generation structures that cannot be built using the traditional concrete. The more complex a structure is, the more important are its strength and deformation properties. Taking into account and predicting the creep and shrinkage is part of a rational approach aimed at satisfying the deformation criteria.

Acknowledgment

This work has been supported by the European Social Fund within the scope of the project “Support for the Implementation of Doctoral Studies at Riga Technical University”.

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