INFLUENCE OF STEEL FIBRE REINFORCEMENT ON THE PROPERTIES OF CONCRETE

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SUMMARY: To find out the influence of different fibre dosages on the mechanical and time-dependent properties of concrete, an experiment was carried out at the Faculty of Civil Engineering–Skopje. The experiment consists of 126 specimens in total, all manufactured with concrete class C30/37, but reinforced with different amount of fibres (0, 30 and 60 kg/m^3). According to the experimental results up to age of 400 days, addition of steel fibres has influence on most of the mechanical properties: around 4% increase of the compressive strength, around 14% increase of the splitting tensile strength, around 19% increase of the flexural tensile strength and almost no influence on the Modulus of Elasticity. The addition of steel fibres has almost no influence on the free drying shrinkage (decrease of 2%), while for the considered compressive stress level, steel fibres have a bigger influence on the creep (decrease of 12%).

KEY WORDS: concrete, steel fibres, mechanical properties, creep, shrinkage.

1 INTRODUCTION

When steel fibre reinforcement is added in concrete, it is assumed that the fibres are uniformly randomly oriented in the concrete matrix. However, after placing and vibrating, no one can be sure that this is true. This often leads to a large scatter in the test data and high variability in measured values due to the direction of loading in relation to the direction of casting.

When table vibration or excessive internal vibration is used, fibres tend to become horizontally aligned. They also show preferential parallel alignment close to the bottom and sides of the moulds. With electromagnetic measurements and X-ray photographs of the fibre distribution, it was proven that fibres showed not only preferential alignment, but also non-uniform distribution along the length of the steel fibre reinforced concrete (SFRC) beam. Therefore, small amounts of fibre reinforcement, less than 30 kg/m^3, should not be used because they lead to more non-uniform distributions. On the other hand, the preferential alignment can be good, if the fibres can be oriented in the direction of the acting stress. However, if all recommendations for mix design, mixing, handling, placing and finishing are followed, it is possible to produce SFRC with acceptably low variability in the fibre distribution and orientation [1].

The effectiveness of the fibres in improving the characteristics of concrete is dependent on the fibre matrix interactions, which are governed by the closer zone around the fibres, called interfacial transition zone (ITZ). This zone, just around the fibre, is significantly different from the other zones of the matrix. When fibres are added to the concrete, they act like special long aggregates that are preventing the aggregate to fulfill the spaces between other aggregates. In this way, there is more cement paste around the fibres to fill the empty space (wall effect) [2]. The three main fibre matrix interactions are [1]: physical and chemical adhesion, friction, and mechanical anchorage induced by deformations on the surface or by overall complex geometry.

Physical and frictional bondings between a steel fibre and a cementitious matrix are very weak and therefore mechanical anchoring is required. Fibres actually act through stress transfer from the matrix to the fibre by some combination of interfacial shear and mechanical interlock between the deformed fibre and the matrix. Up to the point of matrix cracking, the load is carried by both the matrix and the fibres. When cracking occurs, the fibres carry the entire stress by bridging across the cracked concrete until they pull out completely. Actually, the energy is dissipated as the fibre undergoes plastic deformation while being pulled out.

2 STATE OF THE ART

2.1 Physical and Mechanical Properties of Steel Fibre Reinforced Concrete (SFRC)

When the volume percentage of fibres is less than 2%, the Modulus of Elasticity and the Poisson's ratio of SFRC can be taken as equal to those of plain concrete [3].

The compressive strength is only slightly affected by the presence of fibers. The observed increases range from 0-15% for up to 1.5% fibers by volume, as reported in [3], or from 0-25% for up to 2% fibers by volume [1]. Although strength is not significantly increased, the energy absorption (post-cracking ductility) of the material under compression is improved [1].

The direct tensile strength is significantly increased for 30-40% with the addition of 1.5% fibres by volume [3]. This is valid for more or less randomly distributed fibres, while for fibres aligned in the direction of the tensile stress, the increase can be 133% for 5% smooth straight steel fibres by volume [1].

The flexural strength is much more improved by the addition of steel fibres. 50-70% increase has been reported using the usual fibre volume and standard third-point bending test [3]. The increase can be 100% or even 150% if bigger fibre volumes are used, if center-point bending test is performed or if smaller specimens are used. Except the fibre volume, the shape of the fibers and the aspect ratio also plays a crucial role, with deformed fibres and bigger aspect ratio being more effective [1].

The improvement in the residual strength of the concrete elements with the addition of steel fibres leads to an increase of shear capacity. For 1% steel fibres by volume, the shear strength was increased for 0-30% [3]. There is not much data about torsional strength, but different studies show an increase up to 100% [1].

The biggest improvement that is achieved by addition of steel fibres to plain concrete is in the energy absorption capacity or in the toughness. The flexural toughness can be defined as the area under the complete load-deflection curve or it is the total energy needed for a fracture. It increases with bigger fibre dosage, bigger aspect ratio and with the use of deformed fibers.

For normal strength concrete under flexural impact load, the peak loads for SFRC were about 40% higher than those for plain concrete. The fracture energy, which is the second most important parameter when observing impact loading, was increased for 2.5 times [3].

As fibres do not increase significantly the static compressive strength, there is also no significant improvement in the fatigue strength under compressive loading. On the other hand, as it is the case with the static tensile strength, fibres increase the fatigue strength under tensile loading. Steel fibres enable higher endurance limits, finer cracks and more energy absorption to failure [1].

2.2 Time-Dependent Deformation Properties of SFRC

The Report on FRC published by ACI [3] shows that, according to limited test data on creep and shrinkage of SFRC, if fibres are used to the amount of less than 1% of the volume, there is no significant improvement in creep and shrinkage strain. Edgington et al. have reported that shrinkage of concrete over a period of three months is unaffected by the presence of steel fibres [4].

Balaguru and Ramakrishnan found that 0.5% of steel fibres slightly increase the creep of concrete and lead to less shrinkage strains [5]. Houde et al. found that 1.0% of steel fibres increase the creep strain by 20-40%. On the other hand, Chern and Chang found that steel fibres reduce the creep strain [1]. Swamy and Theodorakopoulos have reported that inclusion of 1% fibres results in improved creep properties of concrete under flexure [6].

Swamy and Stavrides have reported that drying shrinkage is reduced by about 15-20% due to the addition of 1% fibres [7]. Hannant has reported that steel fibres have no significant effects on both creep and shrinkage properties of concrete [8]. Malmberg and Skarendahl, have reported that Steel fibre concrete with a fibre content of up to 2% undergoes less shrinkage than plain concrete [6].

Similar conclusion was reported by Young and Chern. They found out that the optimal volume fraction of steel fibres to reduce shrinkage is not more than 2%. Another conclusion from their research is that the larger aspect ratio of fibres leads to smaller shrinkage strains. They also proposed a modification of the BP model for calculation of the shrinkage of SFRC. The parameters that they included in the modification were the volume fraction and the aspect ratio of the steel fibres [9].

One of the most important researches in this field was done by Mangat and Azari [10,11]. They proposed theories of creep and shrinkage of SFRC based on experiments and knowledge about the behaviour of the material. At the end of their research, they gave simple equations for predicting creep and shrinkage of SFRC related to ordinary plain concrete According to their expressions, the decreasing of creep and shrinkage of SFRC, compared to plain concrete, ranges from 0 to 40 %.

3 EXPERIMENTAL PROGRAM

As a part of large experimental program that involved full scale beams from three types of concrete, control specimens were cast in order to test the compressive strength, flexural tensile strength, splitting tensile strength, elastic modulus and deformations due to creep and shrinkage.

In order to find out the influence of different fibre dosages on the properties of concrete, the investigated parameter in this research was the fibre dosage. The used steel fibres were hooked-end HE1/50, manufactured by Arcelor Mittal, produced of cold-drawn wire, with a diameter of 1mm, length of 50mm and tensile strength of 1100 N/mm^2. The shape of the used fibres is presented in Figure 1.

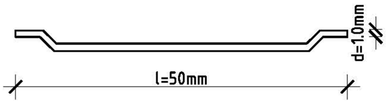

Figure 1: Hooked-end steel fibre HE1/50

The three types of concrete were denoted as:
- Reinforced concrete (C30/37);
- SFRC with 30 kg/m^3 steel fibres (C30/37 FL1.5/1.5);
- SFRC with 60 kg/m^3 steel fibres (C30/37 FL2.5/2.0).

The mixture proportioning was the same for the three types of concrete and is presented in Table 1.

Table 1: Mixture proportions for C30/37, C30/37 FL1.5/1.5 and C30/37 FL2.5/2.0

Mixture proportions	(kg/m^3)
Cement CEM II/A-M 42.5N	410
Water	215
Water/Cement ratio, w/c	0.524
Aggregate:	
0-4 mm (river sand), 50%	875
4-8 mm (limestone), 20%	350
8-16 mm (limestone), 30%	525
Fibres:	
C30/37	0
C30/37 FL 1.5/1.5	30
C30/37 FL 2.5/2.0	60

3.1 Testing of Control Specimens

For each concrete type, 42 control specimens were cast for testing of the mechanical and time-dependent properties of concrete at the age of 40 and 400 days. After 8 days of curing the specimens were transported to the Laboratory at the Faculty of Civil Engineering – Skopje, where they were kept under almost constant temperature with an average of 19.5°C and constant relative ambient humidity with an average of 60.2%, regulated with special humidifiers and dehumidifiers.

The mechanical properties at the age of 40 days were tested on 3 specimens for compressive strength, splitting tensile strength and Modulus of Elasticity and 6 specimens for flexural tensile strength. The mechanical properties were also tested at the age of 400 days on 3 specimens for compressive strength, splitting tensile strength and Modulus of Elasticity and 3 specimens for flexural tensile strength. The compressive strength, splitting tensile strength and Modulus of Elasticity were tested by use of hydraulic jack HPM3000, produced by ZRMK - Ljubljana, Slovenia.

The most specific testing was the testing of the flexural tensile strength (Figure 2), which was performed according to RILEM TC 162-TDF [12]. The deflection controlled testing was done on notched prisms with cross section dimensions of 15/15cm, length of 70cm and span of 50cm. Beams were notched by wet sawing with width of notch of 5mm and depth of 25mm. The application of the deflection was at a constant rate of 0.2mm/min by use of Wykeham Farrance, England, which is a 50kN machine with a big stiffness. During the tests, the load and the midspan deflection were recorded continuously by the data acquisition system produced by Hottinger Baldvin-HBM, Germany.

Compression creep was applied in creep frames (Figure 3) whereat the stress level of the 12x12x36cm prism specimens was 7.5MPa. The drying shrinkage was measured immediately after the opening of the moulds of the control specimens. The measurements were performed with mechanical deflection meter, type Hugenberger, Switzerland, with base of 250mm.

Figure 2: Testing of flexural tensile strength and concrete creep

3.2 Results from Testing

The mixture proportioning was done according to all recommendations, [13] and [3], in the up to date literature, so the slump of the concrete without fibres was 120mm. Since fibres decrease workability, the slump was decreased to 75mm and 50mm with addition of 30 and 60 kg/m^3 (Table 2).

Table 2: Slump of C30/37, C30/37 FL 1.5/1.5 and C30/37 FL 2.5/2.0

Type of concrete	Slump (mm)
Reinforced Concrete (C30/37)	120
Steel fibre reinforced concrete with 30 kg/m^3 (C30/37 FL 1.5/1.5)	75
Steel fibre reinforced concrete with 60 kg/m^3 (C30/37 FL 2.5/2.0)	50

The average results for the mechanical properties with the corresponding standard deviations, as well as, the increase in the mechanical characteristics with time, are presented in Table 3.

The testing of the flexural tensile strength at the age of 40 and 400 days resulted in force – deflection relations for the three concrete types. In Figure 3, the result only for the concrete type C30/37 FL 1.5/1.5 is presented. In the case of plain concrete, sudden brittle failure occurred, manifested by a sudden drop in force. From the force – deflection relations, stress – strain relations in tension were obtained where the biggest difference between plain and fibre concretes can be noted.

Table 3: Mechanical properties at age of 40 and 400 days of C30/37, C30/37 FL 1.5/1.5 and C30/37 FL 2.5/2.0

Mechanical properties	Age at test. t(days)	C30/37	σ (st.dev)	C30/37 FL 1.5/1.5	σ (st.dev)	C30/37 FL 2.5/2.0	σ (st.dev)
Compressive strength (MPa) (cubes 15/15/15cm)	40	42.89	0.18	41.63	4.79	44.59	1.83
	400	45.70	5.742	47.41	1.07	46.15	1.69
Increase (%)		6.55		13.88		3.50	
Splitting tensile strength (MPa) (cubes 15/15/15cm)	40	3.51	0.10	3.22	0.14	4.00	0.31
	400	4.17	0.02	4.58	0.13	4.24	0.13
Increase (%)		18.80		42.23		6.00	
Flexural tensile strength (MPa) (beams 15/15/70cm)							
-σ_1(stress at δ_L=0.05mm)	40	5.18	0.56	4.95	0.34	5.30	0.66
-σ_2(stress at $\delta_{R,1}$=0.46mm)				1.80	0.44	2.83	0.67
-σ_3(stress at $\delta_{R,4}$=3.00mm)				1.53	0.40	2.33	0.73
-σ_1(stress at δ_L=0.05mm)	400	5.00	0.66	4.40	1.32	5.95	0.13
-σ_2(stress at $\delta_{R,1}$=0.46mm)				1.38	0.28	2.90	0.44
-σ_3(stress at $\delta_{R,4}$=3.00mm)				1.15	0.47	2.38	0.32
Increase σ_1 (%)		-3.5		-11.11		12.26	
Modulus of Elasticity (MPa) (cylinders 15/30cm)	40	26956	127.2	26771	93.2	26120	423.2
	400	27041	811.4	30809	618.2	28224	674.2
Increase (%)		0.32		15.08		8.06	

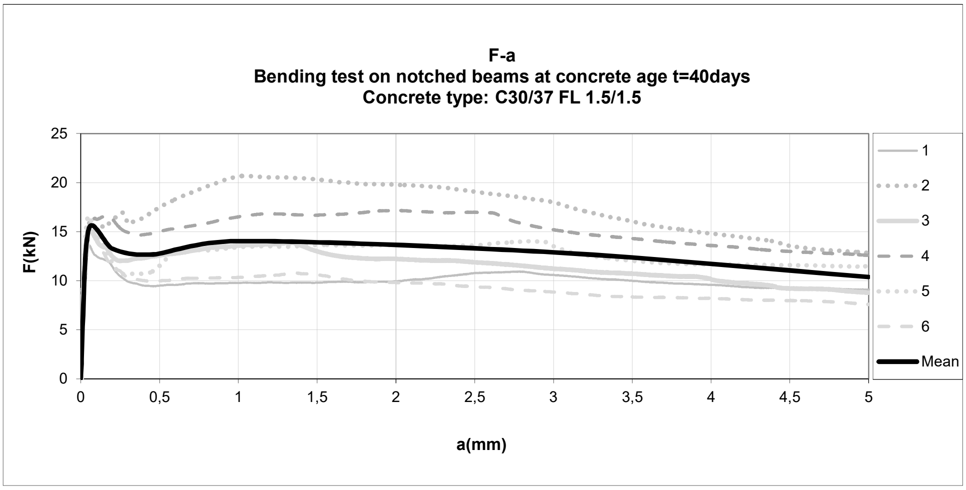

Figure 3: Bending test on notched beams at the age of 40 days for C30/37 FL 1.5/1.5

The time-dependent creep and shrinkage strains were measured on four sides of each prism, which means that for each type of concrete, the presented results in the Table 4, Figure 4 and Figure 5 are mean value of 12 measurement points. The obtained values of the time-dependent deformation properties for the three concrete types and the decrease for the SFRC types are presented in Table 4.

Table 4: Decrease of time-dependent deformation properties of C30/37 FL 1.5/1.5 and C30/37 FL 2.5/2.0

Time-dependent properties	Age t(days)	C30/37	C30/37 FL1.5/1.5	decr. % ↓	C30/37 FL2.5/2.0	decr. % ↓
Drying shrinkage ε_{ds} [μs]	400	808.0	805.0	0.4	794.9	1.6
Instantaneous strain ε_e [μs]	40	286.3	254.0	11.3	241.3	15.7
Creep strain ε_{cc} [μs]	400	429.7	374.7	12.8	385.0	10.4
Total strain $\varepsilon=\varepsilon_{ds400}+\varepsilon_e+\varepsilon_{cc}$ [μs]	400	1524.0	1433.7	5.9	1421.2	6.8

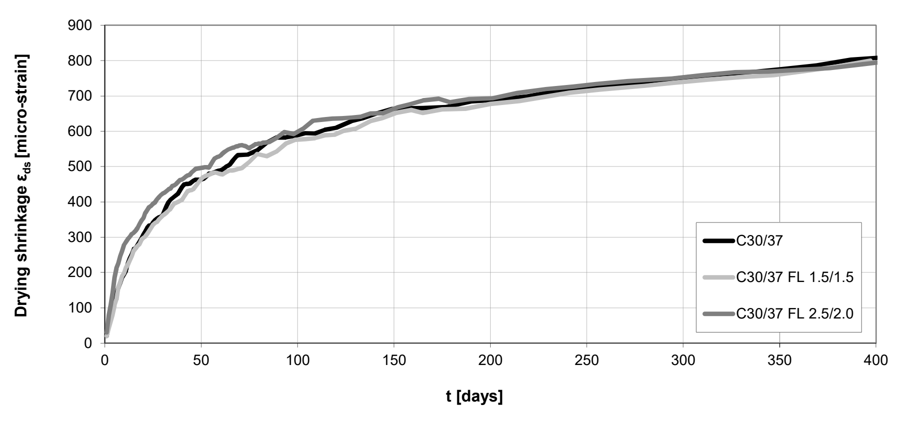

Figure 4: Drying shrinkage strain for the three concrete types

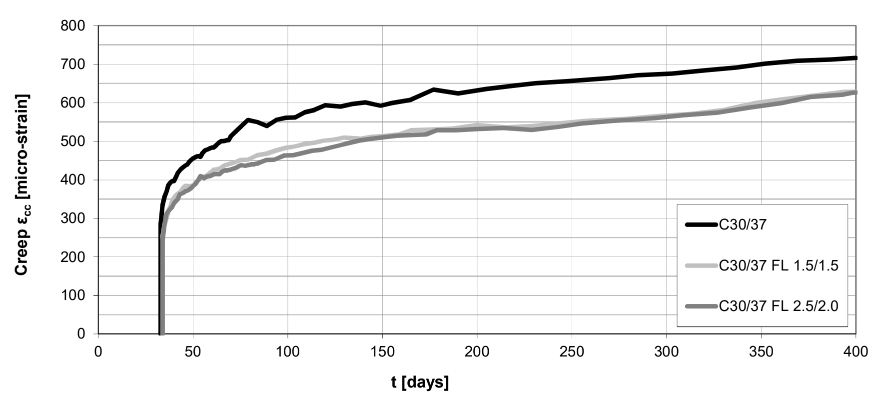

Figure 5: Creep strain for the three concrete types

4 CONCLUSIONS

From the experimental results, the following conclusions can be drawn:

- The addition of steel fibres has small influence on most of the mechanical properties: around 4% increase of the compressive strength, around 14% increase of the splitting tensile strength, around 19% increase of the flexural tensile strength and almost no influence on the Modulus of Elasticity. The increase of the mechanical properties was noted in the case of the concrete with 60 kg/m^3, while in the one with 30 kg/m^3 due to the fact that there is no uniform distribution because of the smaller amount of fibres, there is even a decrease in the mechanical properties. Usual increase of the mechanical properties with time was observed, as in the case of plain concrete.

- The biggest difference in the mechanical properties between the concrete without and with steel fibres is the appearance of residual tensile strengths.

- According to the experimental results at the age of concrete of 400 days, the addition of steel fibres has almost no influence on the free drying shrinkage (decrease of 2%). For the considered compressive stress level, steel fibres have a bigger influence on the creep (decrease of 12%).

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