FIBRE REINFORCEMENT – THE KEY TO SUSTAINABLE REINFORCED CONCRETE STRUCTURES

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SUMMARY: One of the main reasons for strengthening, repair or even demolishing of concrete structures is the appearance of large deflections or cracks developed in the service life of the structures, caused by many different reasons. On the other hand, sustainability of concrete structures can be achieved if we avoid these actions by design of more durable structures. The addition of fibres to concrete is well known measure that can help in achieving this goal, proven by now on many short term tests. Since there is a scarcity of long-term tests dealing with fibre reinforced concrete, to find out the influence of different types of fibre reinforcement on the long-term deflections and long-term cracks of concrete structures, an experiment was carried out at the Faculty of Civil Engineering–Skopje. The experiment consists of 12 full scale reinforced concrete beams, all manufactured with concrete class C30/37, but reinforced with different types (steel, macro and micro polypropylene fibres and their combination) and amount of fibres (0, 0.38%, 0.39% and 0.76% from the volume) and additional longitudinal and transverse reinforcement. The results from the long-term tests showed up that even small amount of added fibre reinforcement have big influence on both deflections and cracks, thus ensuring more durable structures and reducing the costs for their possible repair or strengthening in future.

KEY WORDS: fibre reinforcement, sustainability, experiment, long-term deflections, long-term cracks.

1 INTRODUCTION

According to the World Commission on Environment and Development of the United Nations, sustainability means “meeting the needs of the present without compromising the ability of the future generations to meet their own needs”. Since concrete is the mostly used man made material, there is no doubt that reducing any amount of the current production will contribute in reducing the carbon footprint. Big amounts of greenhouse gas emissions (7-8% of the total GHG worldwide) are released during the process of production of 4.4 billion tons Portland cement annually. This is the reason why many researchers are dealing with partial replacement of cement with other materials as fly ash, silica fume, slag or other industrial by-products. Another way of reducing GHG emissions is by using recycled aggregates. However, all these types of improvements of the concrete mixes should be taken with great care and taking into account durability issues [1]. On the other hand, reducing the maintenance costs and the need of strengthening, repair and demolishing of the structures, and especially infrastructure, in their service life can be obtained with enhancing the durability performance.

Concrete buildings are usually designed for service life of 50 years, while concrete bridges for service life of 100 years, with an expectation that minimal maintenance will be required in that period. However, the situation in practice is different, and we are evidencing many structures, mainly bridges, with a need of some structural intervention due to occurred damages. Therefore, design of structures from the aspect of durability is essential for prolongation of their service life. The well-known measures for increasing durability usually are: increasing the cover to the reinforcement, usage of non-reactive aggregates, low alkali cements, curing of concrete etc. Another measure can be adding of discrete reinforcing fibres to the concrete matrices and in that way obtaining new material, called Fibre reinforced concrete.

Composite materials, reinforced with different types of fibres have been used since ancient times. Approximately 3500 years ago, straw was used to reinforce sun-baked bricks [2], and horsehair was used to reinforce masonry mortar.

The first widely commercial use of fibres was the use of asbestos fibres in a cement paste matrix in the year of 1898. Since the beginning of the previous century, at various intervals, short pieces of steel have been included within concrete in an attempt to improve its strength, ductility, durability and to overcome the typical characterization of brittleness of the cementitious materials. However, there was not much interest by research organizations or by the construction industry until the year of 1963, when Romualdi and Batson published the results of an investigation carried out on steel fibre reinforced concretes [3]. In the beginning, it was assumed that short pieces of steel or steel fibres enhance mostly the tensile strength of composites. In the year of 1964, Broms and Shah systematically studied the mechanical properties of the new material. Since then, intensive investigations began not only for the mechanical characteristics of the fibre reinforced concrete, but also for the determination of the influence of the fibres on the behaviour of different concrete and reinforced concrete elements. It comes out that the major contribution of the fibres is in enhancing the toughness and the durability of the elements.

One of the most promising materials nowadays is HFRC or Hybrid Fiber Reinforced Concrete. It contains two or more different fibre types (hybrid reinforcement) that are mixed so that the overall material is optimized to achieve synergy. The overall performance of the composite exceeds the performance induced by each of the fibres alone [2]. The synergies were classified by Banthia and Gupta into three groups, depending on the mechanisms involved [2]: 1. Hybrids based on fibre constitutive response, where one fibre is stronger and stiffer and provides strength, while the other is more ductile. 2. Hybrids based on fibre dimensions where one fibre is small and provides microcrack control at earlier stages of loading to arrest microcracks and enhance the first crack and strength, while the other fibre, which is bigger, provides the bridging mechanisms across macrocracks and induces toughness at high strains and crack openings. 3. Hybrids based on fibre function where one type of fibre induces strength or toughness in the hardened composite, while the second type of fibre provides fresh mix properties suitable for processing.

The fibres used in HFRC can be made either from one material, but with different geometries, or can be composed of different materials, such as polyethylene microfibers for microcrack control and deformed steel fibres for macrocrack bridging [2].

Up to now, there are only few published research studies dealing with long term behaviour of SFRC beams. Tan et al. in 1994 studied the behaviour of SFRC beams under sustained load as a one year study [4] and later the same research was continued as a ten year study of the deflections and crack widths under sustained load by Tan and Saha in 2005 [5]. Another research by Vasanelli et al. in 2012 [6] is dealing with the influence of long term sustained loading on the cracking behaviour and consequently on the structural durability. Due to the smaller carbon footprint of the polypropylene fibers, with the experimental program presented as follows, an attempt was made to replace all or one half of the steel fibres with polypropylene, and to compare all concrete types regarding deflections and cracks width.

2 EXPERIMENTAL PROGRAM

The experiment was carried out at the University “Ss. Cyril and Methodius”, Faculty of Civil Engineering-Skopje, Republic of North Macedonia. It involved testing of 12 full scale beams constructed from reinforced concrete and different types of fibre reinforced concrete with additional reinforcement. The beams had a cross section proportioned 15/28cm and a total length of l=300cm, Fig. 1. Together with each series of beams, 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. Some results are presented in [7], [8], [9] and [10]. In addition to the tests on mechanical and time-dependent properties of concrete, the used reinforcement was also tested.

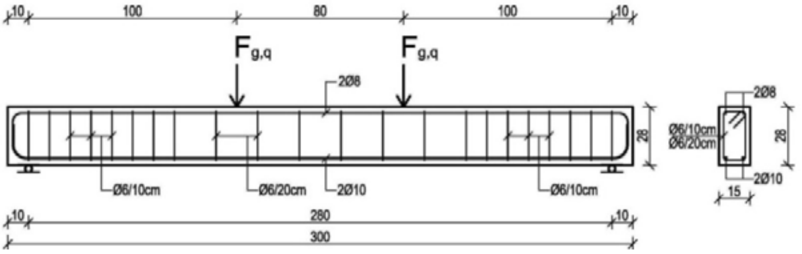

Figure 1: Geometry, reinforcement and loading scheme of full scale beams

All 12 beams were manufactured with concrete class C30/37. According to the used type of material, they were divided into three series, each containing 2 identical beams:

- Series A, Reinforced concrete (RC);
- Series B, Steel fibre reinforced concrete with 30 kg/m^3 steel fibres and additional reinforcement (SFRC1);
- Series C, Steel fibre reinforced concrete with 60 kg/m^3 steel fibres and additional reinforcement (SFRC2).
- Series D, Polypropylene fibre reinforced concrete with 3.46 kg/m^3 macro polypropylene fibres and additional reinforcement (PPFRC).
- Series E, Hybrid polypropylene fibre reinforced concrete with 3.46 kg/m^3 macro and 0.91 kg/m^3 micro polypropylene fibres and additional reinforcement (HyPPFRC).
- Series F, Hybrid polypropylene steel fibre reinforced concrete with 30 kg/m^3 steel fibres, 1.73 kg/m^3 macro and 0.91 kg/m^3 micro polypropylene fibres and additional reinforcement (HyPPSFRC).

The beams constructed of reinforced concrete were used for comparison with the beams constructed of fibre reinforced concrete. In each series, the plain reinforcement was kept the same. The longitudinal reinforcement was ribbed and of RA 400/500-2 quality, while the shear reinforcement was smooth, with GA 240/360 quality. Reinforcement 2Ø10, 2Ø8 and Ø6/10/20cm was used as tension, compression and shear reinforcement, respectively.

The used steel fibres were hooked-end HE1/50, produced of cold-drawn wire, manufactured by Arcelor Mittal, with a diameter of 1mm, length of 50mm and tensile strength of 1100 N/mm^2. The used macro polypropylene fibres were Durus, S400 monofilament fibre, manufactured by Adfil, with equivalent diameter of 0.9mm, length of 55mm, and tensile strength of 465N/mm^2. The used micro polypropylene fibres were Fibrin XT monofilament fibre, manufactured by Adfil, with equivalent diameter of 22μm, length of 13mm, and tensile strength of 380N/mm^2.

The mixture proportioning was done so that it was the same for the three types of concrete (Table 1).

Table 1: Mixture proportions for the three concrete types

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:	
RC (no fibres)	0
SFRC1 (steel fibres, 0.38%)	30
SFRC2 (steel fibres, 0.76%)	60
PPFRC (macro polypropylene fibres, 0.38%)	3.46
HyPPFRC (macro, 0.38% + micro 0.1% polypropylene fibres)	3.46+0.91
HyPPSFRC (steel, 0.19% + macro, 0.19% + micro 0.1% polypropylene fibres)	15+1.73+0.91

The beams and control specimens were cured for 8 days and then they 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%, which was regulated with special humidifiers and dehumidifiers.

The beams from the six types of concrete have been pre-cracked with permanent and variable load "g + q", and afterwards a long term permanent load with intensity "g" has been applied at the age of concrete of 40 days, and held up to 230 days. The idea with the pre-cracking was to activate the fibers, since their effect is negligible in the elastic behavior. In that period the strains, deformations and crack widths have been measured.

Each day, the strains in the concrete (D1-D15), in the middle section of the beam through the thickness as well as on the top of the beam, were measured by a mechanical deflection meter, type Hugenberger, Switzerland, with a base of 250mm. The mechanical measurement of the deflections was done at 5 points through the length of the beam and 2 points over the supports by using deflection meters produced by Stopani, Italy. The crack widths were also measured in the above mentioned time period, in the region with constant moment, by use of a crack microscope - product of Controls, Italy. The positions of the measurement points are presented in Figure 2.

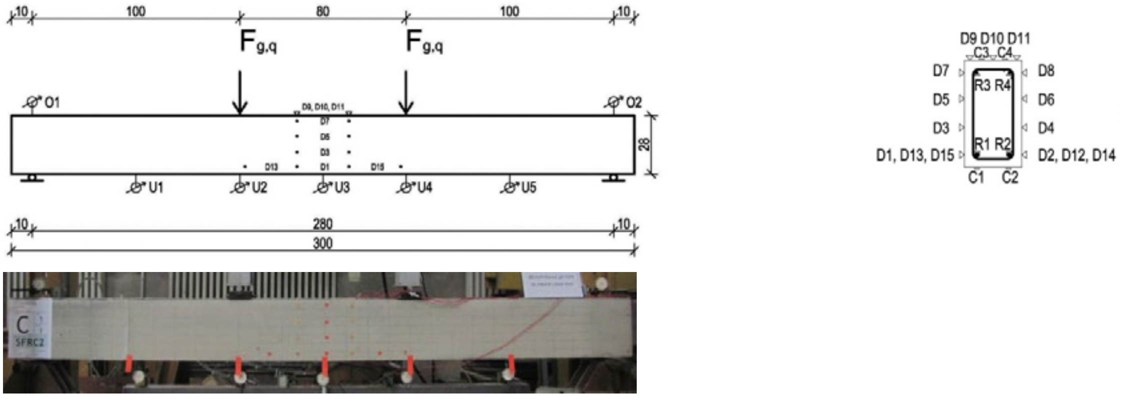

Figure 2: Positions of measurement points of full scale beams

The long term load, which consists of permanent sustained load “g”, after precracking of the beams with service load (permanent “g” plus variable load “q”), was applied by gravitation levers (Fig.3), which enabled an increase of the load for 13 times. The permanent load acts all the time, while the variable load was applied and removed after the precracking was done.

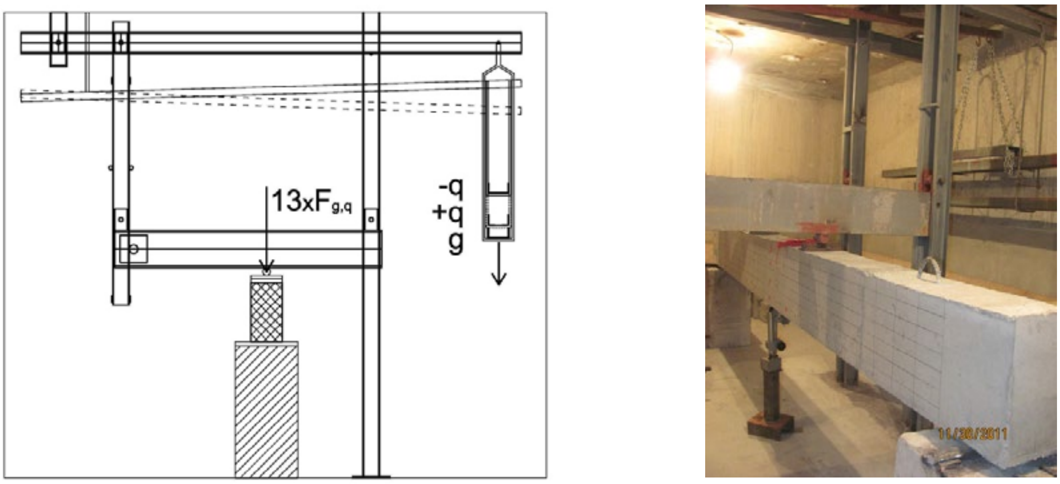

Figure 3: Gravitation lever

The bending moments are as follows: from self-weight of the beam, M_{sw}=1kNm, from permanent load “g”, M_g=5.0kNm, from variable load “q”, M_q=3.1kNm, from self-weight, permanent and variable load (precracking, service) M_{sw+g+q}=9.1kNm. The bending crack moment was M_{cr}=6.1kNm, while the ultimate bending moment M_d=15.6kNm. The intensity of the load was chosen so that the M_{cr} is bigger than M_{sw+g} and smaller than M_{sw+g+q}. The permanent load is 0.39 times the flexural strength, while the precracking load is 0.58 times the flexural strength of the beam without fibres.

3 SELECTED EXPERIMENTAL RESULTS

The results from the long term loading are presented in terms of time-dependent: deflections and cracks width.

3.1 Time-dependent deflections

All beams were first loaded with permanent load “g”. In order to induce cracks and activate the fibres, the beams were precracked with load “g+q” and then the load was returned to the level of permanent load which was acting in the period of 230 days. In Figure 4 and Figure 5, total and long term deflections in logarithmic scale are presented as an average value of two beams for each concrete type.

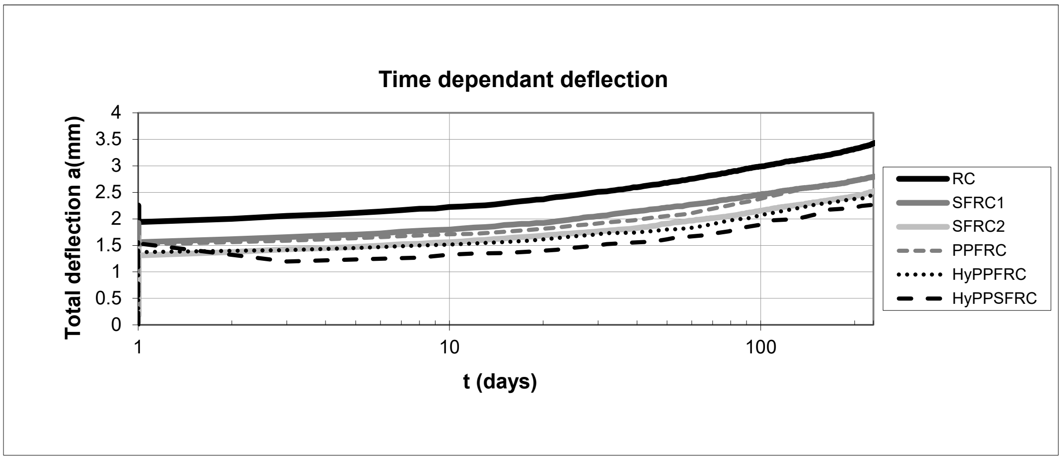

Figure 4: Total time-dependent deflections

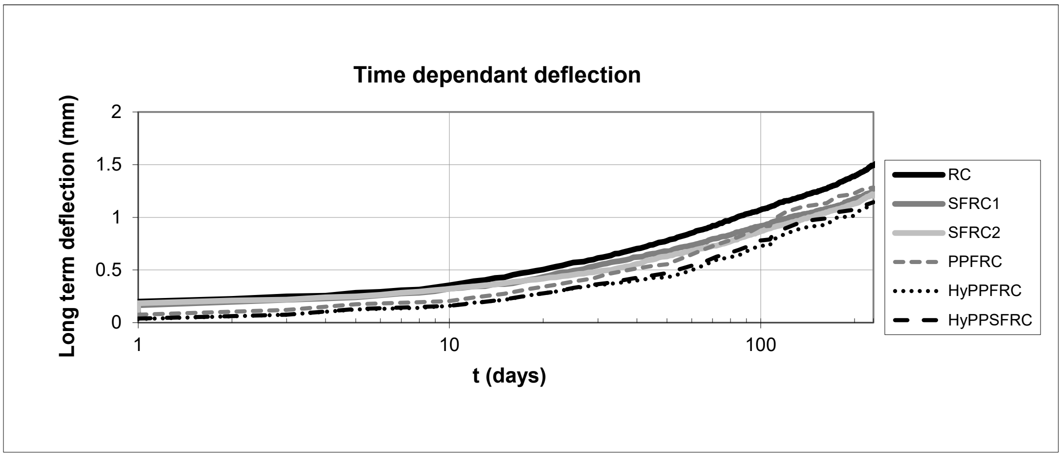

Figure 5: Long term deflections

From the figures can be noticed that the instantaneous, total and long term deflection decreased with the addition of fibres. Long term deflection, which is the total minus instantaneous deflection after precracking, at the level of permanent load “g”, for all concrete types decreased when compared to the ordinary reinforced concrete (RC) in the range from 13.3% to 24.7%. The decrease is as follows: 16.8% for SFRC1, 18.5% for SFRC2, 13.3% for PPFRC, 24.7% for HyPPFRC and 22.7% for HyPPSFRC. It can be noticed that in all concrete types deflections decreased with the addition of fibres, but the biggest decrease is at the hybrid fibre reinforced concrete types.

The values of the instantaneous and long-term deflections of the beams from all concrete types are presented in Table 2.

Table 2: Instantaneous and long-term deflections for all concrete types

Concrete type Deflection(mm)	RC	SFRC1	SFRC2	PPFRC	HyPPFRC	HyPPSFRC
a_0 (inst.) g	0.845	0.83	0.815	0.67	0.76	0.64
a (long-term) g	1.488	1.238	1.213	1.29	1.12	1.15

3.2 Time-dependent cracks width

Although all cracks that appeared during the application of the load or in the period of observing of 230 days, have been registered, the cracks width have been measured only in the middle third of the beams, i.e. in the part of the beams with constant bending moment. The time-dependent cracks widths for all concrete types are presented in Figure 6 and the final observed cracks widths are shown in Table 3.

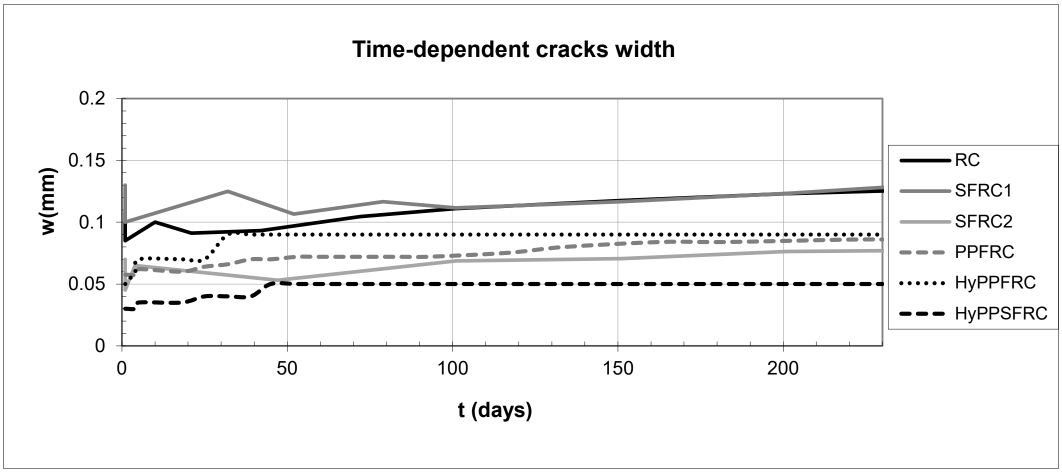

Figure 6: Time-dependent cracks width

Table 3: Final observed cracks width

Concrete type / Cracks width(mm)	RC	SFRC1	SFRC2	PPFRC	HyPPFRC	HyPPSFRC
w (g)	0.13	0.13	0.077	0.086	0.09	0.05

As it was predicted, the cracks in all beams appeared between the level of permanent and service load. At the two reinforced concrete beams (RC), 4 and 6 cracks appeared from the precracking load. At the steel fibre reinforced concrete beams (SFRC1), 2 cracks appeared in each beam, while at the beams from SFRC2, 2 and 1 crack appeared. At the polypropylene fibre reinforced concrete beams (PPFRC), 4 and 5 cracks appeared. At the hybrid polypropylene fibre reinforced concrete beams (HyPPFRC), 2 cracks appeared in each beam. At the hybrid polypropylene steel fibre reinforced concrete beams (HyPPSFRC) 2 and 1 crack appeared.

After removal of the variable load “q”, the cracks width decreased and increased thereafter up to the moment of appearance of new cracks at some of the beams. The mentioned new cracks were with smaller crack width and therefore they decrease the average value of all crack widths. This can be also noticed from the Figure 6 in the first 100 days. After forming of all cracks there is only increase in their width.

From the Figure 6, can be noticed that the instantaneous cracks width at the moment of precracking and after precracking for SFRC1 are bigger than RC, while for SFRC2 and PPFRC are significantly smaller. However, total cracks width of RC and SFRC1 are the same, while the one of SFRC2 is reduced for 40.8% and the one of PPFRC is reduced for 33.8%. For the hybrid fibre reinforced concrete types, it can be noticed that after 50 days the cracks are stabilized since there is no increase in the cracks width. The total cracks width of HyPPFRC is reduced for 30.8%, while the one of HyPPSFRC is reduced for 61.5%.

However, having in mind the complexity of the process of cracking, the randomly oriented fibres in each type of fibre concrete and the low level of stress from the permanent load, which is about 20% from the concrete strength, can be concluded that the fibres significantly decrease the crack widths.

4 CONCLUSIONS

- Long term deflections of the beams subjected to sustained loads in the period of 230 days, for different fibre reinforced concrete types are reduced up to 25% when compared to ordinary concrete RC, with biggest decrease at the hybrid fibre reinforced concrete types.
- The final observed cracks width of the beams subjected to sustained loads in the period of 230 days, for different fibre reinforced concrete types are reduced up to 60% when compared to ordinary concrete RC, with biggest decrease at the hybrid fibre reinforced concrete type HyPPSFRC.

- From the presented results can be noticed that there is reduced ongoing of the fibre pull-out with time.
- The results presented in this paper indicate the positive influence of additional reinforcing of RC beams with different types of fibres on the long term deflections and cracks width and thus ensuring durability and sustainability of concrete structures.
- The reinforcing of the concrete mixes with fibres is mostly effective with certain combination of different types of fibres.

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