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Mechanical flexural properties of concrete with melt-extract stainless steel fibres

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Research Paper

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Mechanical flexural properties of concrete with melt-extract stainless steel fibres

An experimental study is performed to evaluate the effect of melt-extract stainless steel fibres on mechanical and flexural properties of concrete. A total of seventy-two specimens are used to determine an optimum fibre dosage and mechanical properties of plain and steel fibre reinforced concrete. Twelve full-scale beam specimens are then exposed to four-point bending tests. The effect of melt-extract stainless steel fibres on flexural behaviour of beams is quantified in this testing. A beam specimen is exposed to four-point bending, after being subjected to 15000 cycles of fatigue load. Pre- and post-fatigue flexural properties of beams with melt-extract steel fibres are compared and discussed.

Key words:

steel fibre reinforced concrete, melt-extract stainless steel fibres, mechanical properties, fatigue test

Prethodno priopćenje

Predrag Blagojević, Nikola Blagojević, Danijel Kukaras, Darko Živković, Aleksandar Šutanovac

Mehanička svojstva pri savijanju betona armiranog vlaknima od nehrđajućeg čelika

Eksperimentalno istraživanje provedeno je kako bi se ispitao utjecaj vlakana od nehrđajućeg čelika na mehanička i savojna svojstva betona. Koristila su se 72 uzorka kako bi se utvrdila optimalna doza vlakana i odredila mehanička svojstva nearmiranog betona te betona ojačanog čeličnim vlaknima. Dvanaest uzoraka greda realnih veličina ispitano je savijanjem u četiri točke. Provedenim ispitivanjem kvantificiran je utjecaj vlakana nehrđajućeg čelika na mehanička svojstva pri savijanju greda. Provedeno je i ispitivanje uzorka grede savijanjem u četiri točke nakon što je na njemu provedeno ispitivanje na zamor s 15000 ciklusa opterećenja. Uspoređena su i analizirana mehanička svojstva pri savijanju greda s čeličnim vlaknima prije i poslije ispitivanja na zamor.

Ključne riječi:

beton ojačan čeličnim vlaknima, vlakna nehrđajućeg čelika, mehanička svojstva, ispitivanje na zamor

Vorherige Mitteilung

Predrag Blagojević, Nikola Blagojević, Danijel Kukaras, Darko Živković, Aleksandar Šutanovac

Mechanische Eigenschaften beim Biegen von Beton, der mit Edelstahlfasern bewehrt ist

Eine experimentelle Studie wurde durchgeführt, um den Einfluss von Edelstahlfasern auf die mechanischen und Biegeeigenschaften von Beton zu untersuchen. 72 Proben wurden verwendet, um die optimale Faserdosis und die mechanischen Eigenschaften von Stahlbeton und Stahlfaserbeton zu bestimmen. Zwölf Proben von Balken realer Größe wurden durch Biegen an vier Punkten getestet. Der Test quantifizierte den Einfluss von Edelstahlfasern auf die mechanischen Eigenschaften von Biegebalken. Ein Vierpunkt-Biegetest wurde auch durchgeführt, nachdem ein Ermüdungstest mit 15.000 Lastzyklen durchgeführt wurde. Die mechanischen Eigenschaften beim Biegen von Stahlfaserträgern vor und nach Ermüdungsprüfungen wurden verglichen und analysiert.

Schlüsselwörter:
Stahlfaserbeton, Edelstahlfasern, mechanische Eigenschaften, Ermüdungsprüfung

1. Introduction

Key mechanical shortcomings of concrete are brittle failure and lack of tensile strength. In everyday practice, these disadvantages are mitigated using steel bars. However, despite the presence of steel bars, cracking of reinforced concrete is unavoidable. Due to the appearance of cracks, the strength and serviceability of reinforced concrete is reduced significantly. In the past few decades, considerable research efforts have been invested in the study of possibilities for using use of steel fibres as an addition or alternative to steel bars [1, 2]. The small size of steel fibres, compared to steel bars, allows for a more homogenous distribution of steel in concrete, preventing or delaying the onset of cracks. Crack arrest and crack bridging mechanisms [1], which develop in steel fibre reinforced concrete (SFRC), were identified as the main mechanisms through which concrete mechanical properties, such as tensile and shear strength, are enhanced. These benefits lead to several improvements in structural performance, including an increase in flexural ductility, greater fatigue strength, higher resistance to impact load, and longer service life [1, 3, 4]. The main disadvantage of SFRC is the inability to control the distribution and orientation of fibres, which can lead to inconsistent structural behaviour [5, 6]. The effect of steel fibres on concrete behaviour largely depends on the fibre volumetric ratio (i.e., the ratio between the steel fibre volume and concrete volume) and fibre shape (e.g., straight, irregular, hook-end), and fibre dimensions. As the fibre volumetric ratio increases, the concrete tensile and flexural strength also increase [7-9]. Several experimental and theoretical investigations have revealed that irregularities in fibre shape, such as curves or hooks, have a positive effect on the flexural and tensile strength of concrete [8, 10-12]. The reason is the higher pull-out strength of these fibres, which is due to mechanical anchorage created by the deformed shape [11]. However, the workability of concrete reduces with an increase in the fibre volumetric ratio, due to the balling of fibres, especially pronounced in hook-end fibres and steel fibres of irregular geometry [7, 10, 13].

Experimental findings on the effects steel fibres have on the compressive strength and elastic modulus are conflicting. Certain studies show that steel fibres decrease compressive strength and elastic modulus [13, 14], while others point to an increase in these concrete properties [15]. Nevertheless, the effect of steel fibres on compressive strength and elastic modulus is not significant.

Steel fibres do not significantly affect the pre-crack behaviour of concrete, i.e. their effect can be seen once the cracks appear [10, 16]. Steel fibres ensure a better diffusion of cracks, and so cracks have a smaller opening and are more evenly spread [17]. When longitudinal (i.e., bar) reinforcement is used together with steel fibres, the strain in longitudinal reinforcement is reduced due to the presence of steel fibres. However, the relative improvement of concrete flexural behaviour caused by steel fibres is decreased [17].

The behaviour of concrete reinforced with melt-extract stainless steel (MESS) fibres is investigated in this paper. MESS fibres are produced by a rotating wheel that spins molten metal into the open air. Hence, fibres have irregular, partially random geometry, as the manufacturing process allows for a certain variability in fibre shape (Figure 1). These fibres are suitable for use in corrosion-prone environments [18, 19], as they are made of stainless steel. Furthermore, these fibres are commonly used in refractory concrete, as they can withstand high temperatures [20]. However, experimental results on the mechanical and structural benefits of using MESS fibres are scarce. The aim of this study is to examine the behaviour of melt-extract stainless steel fibre reinforced concrete (MESSFRC) and to quantify the benefits of adding these fibres to concrete, i.e. to determine their suitability for practical application. Therefore, an experimental study was performed to assess mechanical and structural properties of MESSFRC. Identical plain concrete samples are tested and compared to MESSFRC results. Additionally, a full-scale beam specimen is exposed to low-cycle fatigue, and then tested statically, to examine how fatigue load affects mechanical and structural properties of beams with MESS fibres.

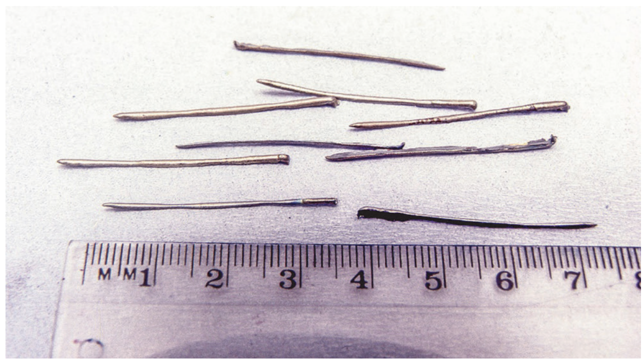

Figure 1. Melt-extract stainless steel fibres.

2. Experimental program

Specimens with different MESS fibre volumetric ratios, varying from 0.75 % to 2.5 %, are tested first, to establish the optimal fibre dosage. Then, mechanical properties, such as elastic modulus, and compressive and tensile strength, are obtained on plain concrete and MESSFRC test specimens. To examine the flexural behaviour of MESSFRC beams, twelve full-scale beams (176 mm x 100 mm x 2000 mm) are exposed to four-point bending and compared to plain concrete specimens. Parts of the four point bending tests presented in this paper have been published in [21] and are repeated here for completeness. A beam specimen was then exposed to low-cycle flexural fatigue loading. After 15000 cycles of fatigue loading, the specimen was tested statically. The goal was to compare pre- and post-fatigue flexural behaviour of MESSFRC beams. A summary of tests, as well as specimen dimensions, quantity, fibre content, and testing age, are presented in Table A1 in the Appendix.

Table 1. A summary of performed tests

Test type	Specimen shape and dimension	Number of specimens	Fibre content [%]	Specimen age
Compression	Cube 100 mm	3	0.75	7 days
		3	1.5	
		3	2	
		3	2.5	
Four-point bending	Prism 100 mm x 100 mm x 500 m	3	0.75	
		3	1.5	
		3	2	
		3	2.5	
Splitting	Cylinder 100 mm x 200 mm	3	0.75	
		3	1.5	
		3	2	
		3	2.5	
Compression	Cube 100 mm	6	0	28 days
		6	1.5	
Four-point bending	Prizma 100 mm x 100 mm x 500 m	6	0	
		6	1.5	
Splitting	Cylinder 100 mm x 200 mm	6	0	
			1.5	
ISO 6784 test to obtain the elastic modulus	Cylinder 100 mm x 200 mm	3	0	
		3	1.5	
Four-point bending of beams without longitudinal reinforcement (B series)	Beam 100 m x 176 mm x 2000 mm	3	0	
		3	1.5	
Four-point bending of beams with longitudinal reinforcement (RB series)		3	0	
		3	1.5	
Post-fatigue four-point beam bending		1	1.5	

2.1. Mixture properties

Mixture proportions by weight are given in Table 2. Maximum diameter of the aggregate was limited to 10 mm. Ordinary Portland Cement was used. Water to cement ratio was 0.4. Fibres were 35 mm long, with an equivalent diameter of 0.64mm and an aspect ratio of 55. The ultimate tensile strength of the fibres was 897 MPa. The aggregate, cement and steel fibres were first mixed for 3 minutes, to prevent balling and uneven distribution. Then, water was added to the mixture and mixed again for 2 minutes. All test specimens, except for twelve full-scale beams, were vibrated on a vibrating table. Due to their large dimensions, beams could not be placed on the vibrating table. Therefore, the beams were carefully vibrated with a poker vibrator, so as not to decrease homogeneity of the mixture. This was achieved firstly by vertically inserting and pulling out the poker vibrator, without dragging the poker vibrator across the beam span and, secondly, by leaning the poker vibrator to the outer surface of the framework, transmitting the vibrations from the framework to concrete. Specimens were demoulded after 24 hours and cured in water for 28 days prior to testing. The exception were the specimens used to obtain optimum fibre dosage, which were tested at 7 days of age.

Table 2. Mixture proportions by weight for 1.5 % volumetric ratio of fibres

	Weight [kg/m^3]	Weight ratio
Portland Cement	750	1
Sand (0 mm - 4 mm)	885	1.18
Coarse aggregate (4 - 10 mm)	645	0.86
Water	300	0.4
Fibres (length = 35 mm. diameter = 0.64 mm)	117	0.156

2.2. Optimum fibre dosage

The first step in the experimental investigation was to determine an optimum dosage of fibres. Volume fraction of the fibres was varied from 0.75 % to 2.5 %. Compressive strength was tested on three 100 mm concrete cubes. Four-point bending and splitting tests were performed to obtain tensile strength of specimens with varying fibre dosage. The dimension of prisms exposed to four-point bending tests was 100 mm x 100 mm x 500 mm, while the span was 410 mm. Cylindrical specimens 200mm in length and 100 mm in diameter, were used in splitting tests. In total, 36 specimens were tested.

2.3. Mechanical properties

Once the optimal fibre dosage was established, new test specimens, containing the optimal fibre dosage, were made and cured for 28 days prior to testing. The dimensions of the test specimens were the same as described in Section 2.2 and can also be found in Table 1.

Compressive strength
The compressive strength was measured on six plain concrete and six MESSFRC specimens.

Concrete tensile strength
The four-point prism bending test and cylinder splitting test were performed to establish the flexural tensile strength of specimens with an optimum fibre dosage. In total, 24 specimens were tested.

Elastic modulus
The modulus of elasticity was calculated from tests on plain concrete and MESSFRC cylinders. The load was applied in accordance with ISO 6784 [22].

2.4. Four-point bending of MESSFRC beams

Twelve four-point bending MESSFRC beam tests, six without longitudinal reinforcement (labelled B) and six with two 8mm bar longitudinal reinforcement (labelled RB) were exposed to four-point bending. Three B-series beams contained MESS fibres, and were labelled B-SF (beams with steel fibres). Beams made of plain concrete were labelled B-PC. Similarly, beams with longitudinal reinforcement only weree labelled RB-PC (i.e. reinforced beams – plain concrete) and beams with longitudinal reinforcement and MESS fibres were labelled RB-SF (i.e. reinforced beams – steel fibres). Dimensions of the beam cross-section was 100mm by 176mm, the length of the beams was 2000m and the total span was 1920mm (Figure 2). The yield stress of the rebar was 460MPa. The concrete cover in RB beams was 14mm. Beams contained no transverse reinforcement. Volume fraction of the fibres was 1.5 % for all specimens. Deflections were measured at mid span of the beam and in the thirds of the beam span. Five strain gauges were placed along the height of both sides of the mid-span cross section (Figure 2). Furthermore, in one specimen of RB-PC and RB-SF series, strain gauges were placed on the longitudinal reinforcement. Beams were loaded hydraulically at the thirds of the beam span (Figure 2). Load application was force controlled, and load was applied at the rate of 10 kN/h in 1 kN increments.

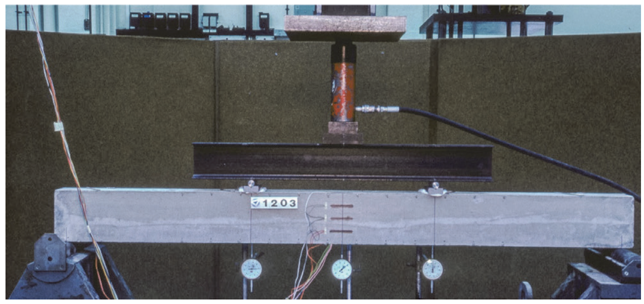

Figure 2. Four-point beam bending set-up

2.5. Post-fatigue flexural tests of MESSFRC beams

One MESSFRC beam specimen, identical to the ones used for static flexural tests (100 mm x 176 mm x 2000 mm, span 1920 mm), was exposed to flexural fatigue loading and then tested statically. The fatigue forces were applied in the thirds of the span with a frequency of 0.5 Hz using a Losenhausen testing machine with a capacity of 100 kN. The lower load level was 2 kN, while the upper limit of the applied forces was 22.5 kN, being approximately 60 % of the experimentally obtained flexural strength. After 15000 cycles, the beam was exposed to a four-point beam bending test, identical to the one described in Section 2.4. Load – Strain and Load – Deflection relations were obtained and compared to the pre-fatigue beam results.

3. Results and discussion

3.1. Optimum fibre dosage

The compressive and tensile strengths of 7 day old specimens with varying fibre volumetric ratio, and with a fitted second degree polynomial function illustrating the trend of the observed data points, are presented in Figure 3. Table 3 shows the mean values and coefficients of variation for these mechanical parameters calculated from three test results for each fibre volumetric ratio. All tested mechanical properties increased with an increase in the fibre volumetric ratio. The increase of the bending and splitting tensile strength was more pronounced than the increase in compressive strength. Compared to specimens with the 0.75 % fibre volumetric ratio, the mean bending and splitting tensile strength increased by 14 % and 66 %, respectively, when the fibre content was 2.5 %, while the compressive strength increased by 3 % only.

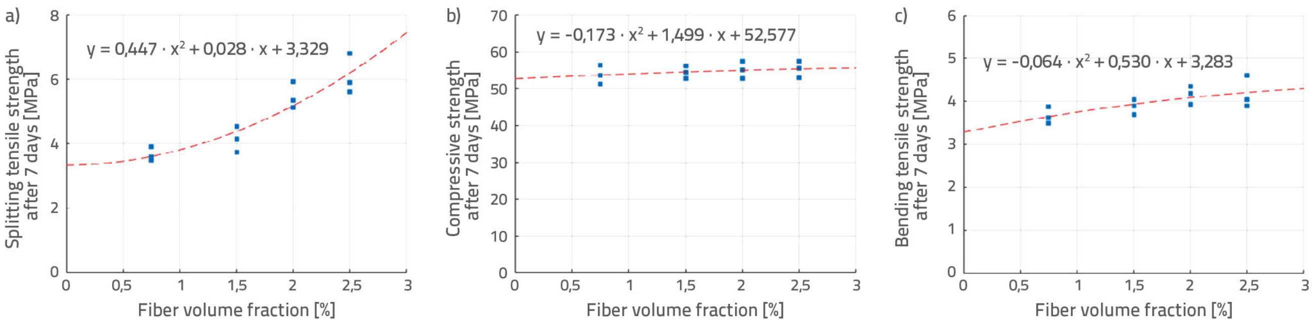

Figure 3. a) Splitting tensile strength; b) compressive strength; c) bending strength for specimens with varying fibre content

Table 3. Mean values and coefficients of variation for mechanical parameters of 7 day old specimens with varying fibre volumetric ratio

Volumetric ratio [%]	**Splitting tensile strength** [MPa]	**Bending tensile strength** [MPa]	**Compressive strength** [MPa]
0.75	3.66 (5.8 %)	3.66 (5.4 %)	53.63 (4.8 %)
1.5	4.14 (9.8 %)	3.87 (4.4 %)	54.34 (3 %)
2	5.46 (7.6 %)	4.16 (5.1 %)	55.01 (4.2 %)
2.5	6.09 (10.2 %)	4.18 (8.9 %)	55.2 (4 %)
*Values in brackets are coefficients of variation			

To quantify the variance of the results, the coefficient of variation (CoV) was calculated for each fibre volumetric ratio from three test results (Table 2). The CoV of compressive strength results was constant for all volumetric ratios, and amounted to around 4 %. The CoV of the splitting tensile strength increased with an increase in the fibre volumetric ratio, from 5.8 % for the 0.75 % of fibres to 10.2 % for the 2.5 % of fibres. The CoV of the bending tensile strength was around 5 % for fibre volumetric ratios ranging from 0.75 %, 2 %, and 8.9 %, for 2.5 % of fibre content.

When the volume fraction of the fibres was above 1.5 %, an extensive balling of fibres was noticed, and the workability of concrete reduced significantly. Therefore, to avoid potential uneven distribution of the fibres in larger specimens, the decision was made to limit the fibre volumetric ratio to 1.5 % in future tests.

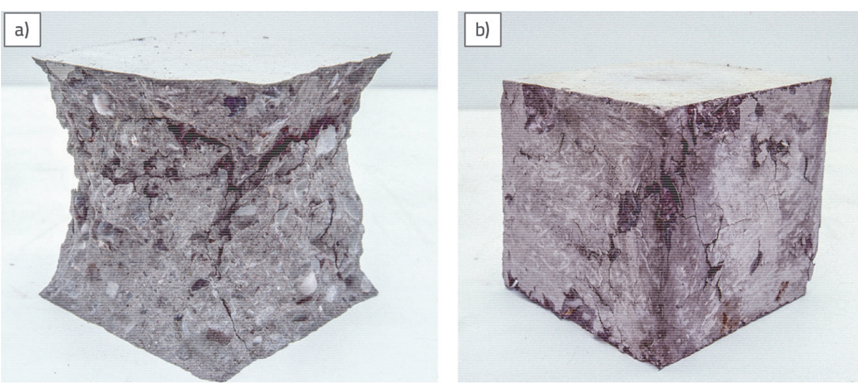

Figure 4. Cube specimens: a) without; b) with MESS fibres after compressive strength testing

3.2. Mechanical properties

Table 4 shows mean values and coefficients of variation of mechanical properties for plain concrete specimens (without fibres) and for specimens with 1.5 % of MESS fibres (with fibres).

3.2.1. Compressive strength

No significant increase in compressive strength was observed with the addition of MESS fibres. However, a difference in the behaviour of specimens at failure was noticed. The presence of MESS fibres prevented the spalling of concrete (Figure 4). This finding is in accordance with [7, 23, 24].

3.2.2. Bending tensile strength

The comparison of tensile strengths of plain and steel fibre reinforced concrete is presented in Table 4. Experimental results show that, due to MESS fibres, an average bending tensile strength of specimens was increased by 33.75 %. Furthermore, an increase in result variation was noticed, i.e. the coefficient of variation increased from 9.7 % for specimens without fibres to 16.7 % for specimens with fibres (Table 4).

3.2.3. Splitting tensile strength

The effect of the addition of MESS fibres on the splitting tensile behaviour of concrete is illustrated in Figure 5. After reaching peak splitting tensile strength, cylinder specimen containing MESS fibres (Figure 5.a) is significantly less cracked than the specimen without MESS fibres (Figure 5.b). The splitting tensile test results show that an addition of MESS fibres results in approx. 45 % increase in splitting tensile strength. The increase in splitting tensile strength is comparable to an increase caused by hook-end fibres at the same volumetric ratio [15]. An increase in the variation of results can be observed with the addition of MESS fibres (Table 4). The coefficient of variation of splitting tensile strength increased from 2.8 % to 10.9 % when MESS fibres were added to the concrete mixture.

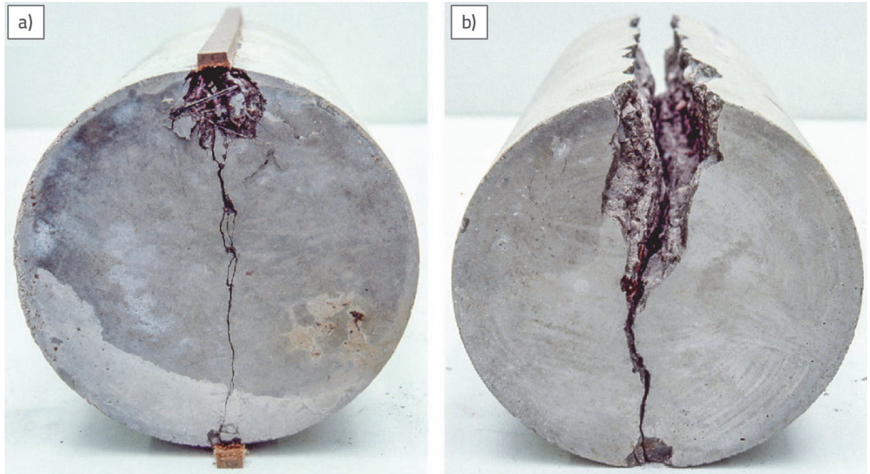

Figure 5. Cylinder specimens with (a) and without (b) MESS fibres after splitting tests

3.2.4. Elastic modulus

The elastic modulus value was obtained as a mean value of three tested specimens. The results are presented in Table 4. The elastic modulus increased by around 10 % due to addition of MESS fibres. The dispersion of results also increased with an addition of fibres, the coefficient of variation increased from 1.3 % in plain concrete specimens, to 4.1 %. However, the overall effect of MESS fibres on the elastic modulus is not significant.

Table 4. Experimentally obtained MESSFRC mechanical properties

Mechanical properties [MPa]	**Without fibres**	**With fibres**
Compressive strength	66.9 (6.4 %)	68.9 (4.2 %)
Bending tensile strength	8.0 (9.7 %)	10.7 (16.5 %)
Splitting tensile strength	4.2 (2.8 %)	6.1 (10.9 %)
Elastic modulus	28320 (1.3 %)	31250 (4.1 %)

*Values in brackets are coefficients of variation of sample values

3.3. Four-point beam bending tests

3.3.1. Beams without longitudinal reinforcement (B series)

The experimentally obtained load-deflection curves for the B series beams are presented in Figure 6a.
An average flexural strength of beams made of MESSFRC (B-SF) was by 70 % higher compared to plain concrete beams (B-PC) (Table 5). Steel fibres bridged the cracks, leading to post-crack displacement capacity in two out of three B-SF specimens. On the contrary, beams without MESS fibres failed as soon as one macro-crack appeared. The load-strain curves are presented in Figure 7. A slight increase was noticed in the variance of compressive and tensile concrete strains of B-SF specimens compared to B-PC specimens (Figure 7). In the range in which strain measurement was possible, the load-strain ratio was linear in both B-PC and B-SF specimens.

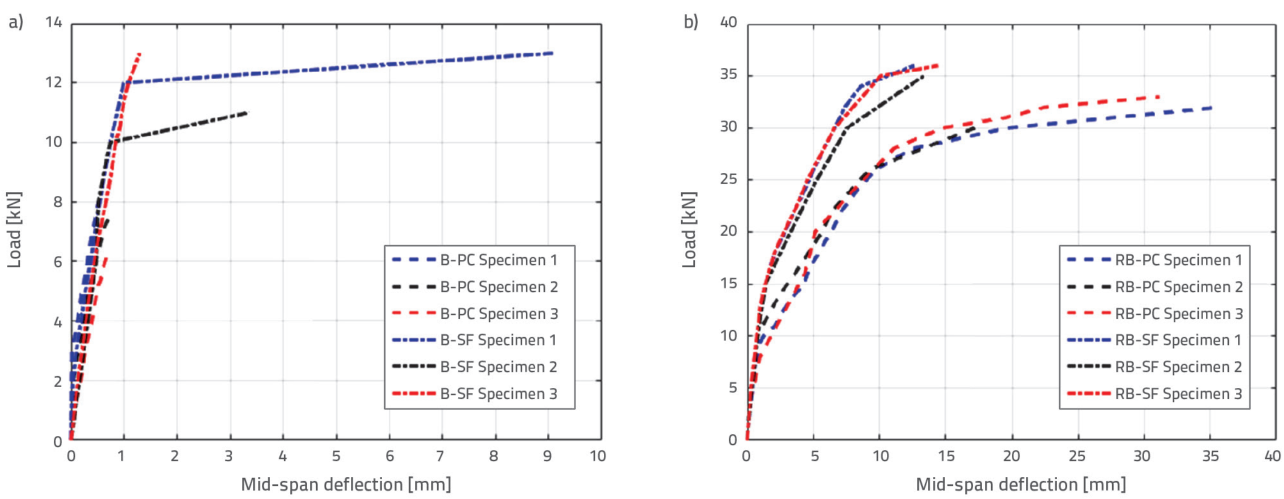

Figure 6. Load-deflection curve in the middle of the beam for: a) beams without reinforcement - series B; b) beams with reinforcement - series RB

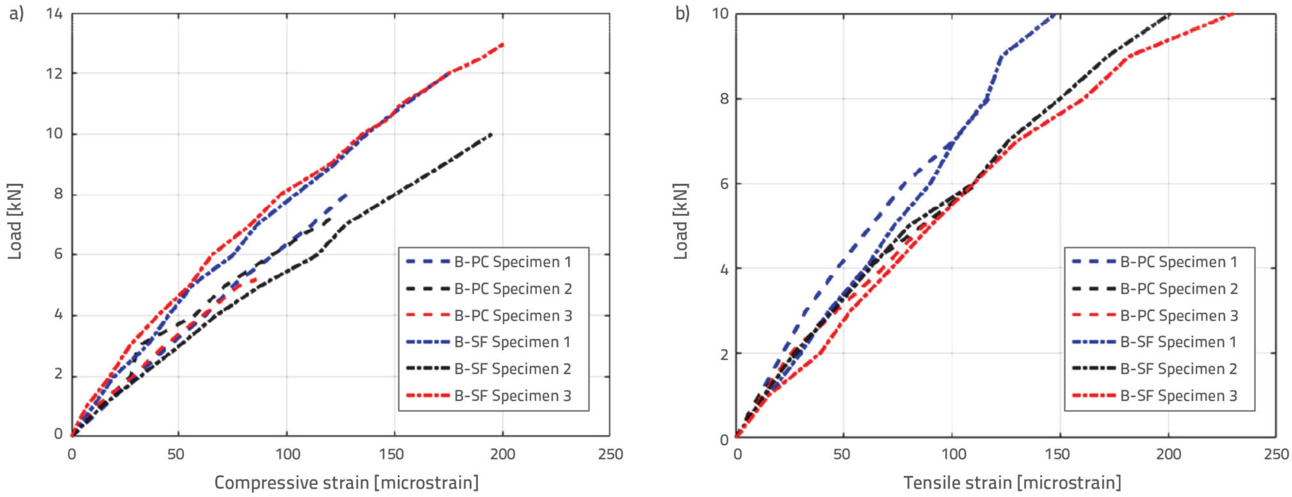

Figure 7. Curves for beams without reinforcement: a) load - compressive deformations; b) load - tensile deformations

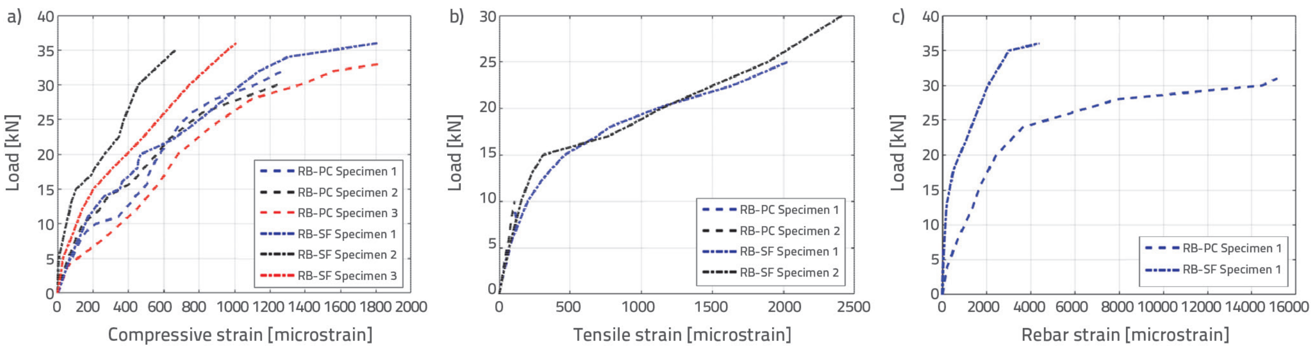

Figure 8. Curves for reinforced beams: a) load - compressive deformations; b) load - tensile deformations; c) load - reinforcement deformations

Table 5. Average first-crack and ultimate strength of B and RB series beams

Strength [kN]	**B-PC**	**B-SF**	**RB-PC**	**RB-SF**
First-crack strength	-	-	12	17.7
Ultimate strength	7.33	12.33	31.7	35.7

3.3.2. Beams with longitudinal reinforcement (RB series)

The load-deflection relation for beams with longitudinal reinforcement is presented in Figure 6.b. Beams with bar reinforcement and steel fibres (RB-SF) had 13 % higher flexural strength compared to beams with bar reinforcement only (RB-PC) (Table 5). The first-crack strength increased by 48 % due to the presence of MESS fibres (Table 5). The findings regarding the peak deflection are somewhat confusing, as it seems that plain concrete samples (RB-PC) had a higher peak deflection than beams with steel fibres (RB-SF). However, this might be a consequence of the force-controlled testing. Namely, displacement-controlled testing might have revealed a plateau or a softening behaviour in the load-deflection relation of RB-SF specimens, which could lead to a larger peak deflection and ductility of the beams with steel fibres.

The concrete compressive strain values of RB-PC were, on an average, slightly larger than the compressive strain values of RB-SF at the same load level (Figure 8a). Since in some cases cracks appeared near the strain gauges, the concrete strain until failure could not be measured. For example, the concrete tensile strain values in RB-PC were measured up to formation of the first macro crack near the strain gauges. In RB-SF specimens the measurement was possible even when the flexural behaviour was nonlinear. Until the first macro cracks appeared, the concrete tensile strains were almost the same for RB-PC and RB-SF beams. The effect of adding MESS fibres to concrete is quite evident in Figure 8c, where the relation between the load and tensile strain of rebars is presented. The rebar strain is significantly lower due to the presence of MESS fibres. As the load level increased, the difference increased as well. At near-failure load (30 kN) of the RB-PC beam, the rebar strain was 1.44 %, while at the same load level the rebar strain in RB-SF beam was 0.2 %. It should be noted that these are the results of only one beam per series. However, the decrease in rebar strain due to presence of steel fibres was also observed by Zhang et al. [17].

3.3.3. Crack patterns and failure modes

Differences between crack patterns and failure modes of plain and MESS fibre reinforced concrete beams are illustrated in figures 9 to 11. Failure modes of beams without rebar – the B series beams – are presented in Figure 9. Beams made of plain concrete (Figure 9a) experienced brittle failure in the mid-third of the span. When the MESS fibres were added, the near-failure behaviour of the beams was ductile in two out of three tested beams. MESS fibres prevented brittle failure of the beam (Figure 9b). In both cases, one macro crack formed and led to failure.

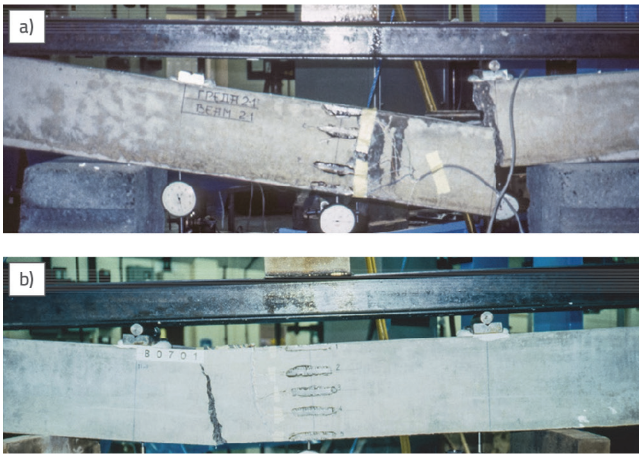

Figure 9. Failure mode of: a) B-PC beams; b) B-SF beams

The crack pattern of beams with longitudinal reinforcement (the RB series), due to a 22.5kN force, is presented in Figure 10. The cracks in plain concrete beams (the RB-PC series) propagated further along the height of the cross-section (Figure 10a), when compared to the beams with MESS fibres (the RB-SF series) for the same load (Figure 10.b). At the force of 22.5 kN, an average horizontal distance between the cracks in the middle third of the span amounted to approximately 10cm for both the RB-PC and the RB-SF beams.

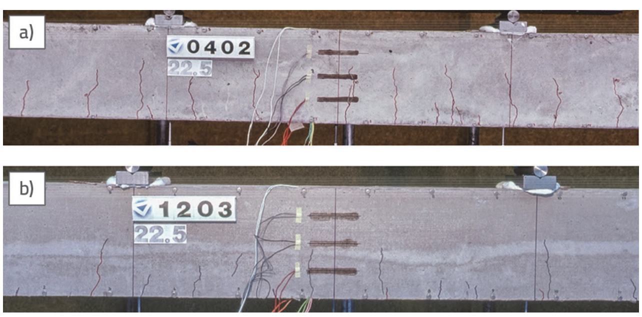

Figure 10. Cracks to a force of 22.5kN: a) RB-PC beams; b) RB-SF beams

Failure modes of RB-PC and RB-SF beams are presented in Figure 11. The beams without MESS fibres failed in a brittle manner, due to shear (Figure 11.a), while beams with MESS fibres exhibited a ductile flexural failure in the mid-span (Figure 11.b). Hence, MESS fibres increased the shear strength of the beam, shifting the failure mode from brittle shear to ductile flexural failure. Furthermore, the cracks in RB-SF beams at failure propagated less along the height of the beam, and are more evenly spread along the beam length. The horizontal crack distance is around 6 cm for RB-SF beams at failure, as opposed to the RB-PC series, where the cracks are higher along the cross-section and are spaced at larger horizontal intervals of 10cm. This further proves that MESS fibres enable a more even distribution of stresses in concrete, increasing the flexural strength.

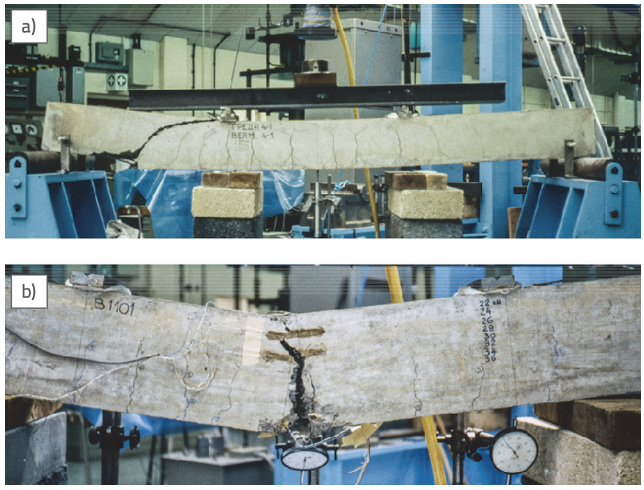

Figure 11. Failure mode of: a) RB-PC beams; b) RB-SF beams

3.4. Post-fatigue loading

The load-strain and load-deflection relations for beams before and after exposure to low-cycle flexural fatigue loading are compared in Figure 12. The maximal fatigue loading level was 22.5 kN, which amounts to around 60 % of beam flexural strength. At this loading level, cracks appear in the middle third of the span, as illustrated in Figure 10 for the case of static loading. Therefore, a drop in beam flexural stiffness is to be expected in the post-fatigue test, because of the cracks caused by fatigue load. The drop in flexural stiffness is observed both in load-strain and load-deflection relations. For example, at the load level of 10kN, the mid-span deflection and compressive and tensile strains in post-fatigue tests are 3 to 4 times larger compared to pre-fatigue tests (Figure 12). However, as the load increases, and cracks start to appear in the pre-fatigue beams, the difference in flexural behaviour caused by fatigue loading decreases. This is best illustrated in the load–deflection diagram (Figure 12c), where the pre- and post-fatigue behaviour is almost the same for the load level in excess of 27kN. The flexural strength did not significantly change due to fatigue loading, in both pre- and post-fatigue tests, i.e. the beam failed at around 36kN. The deflection at maximal load is slightly larger for the post-fatigue specimen, being 16.5 cm instead of 14 cm in pre-fatigue tests.

Hence, due to 15000 cycles of 2/22.5 kN of flexural fatigue loading, the dominant change in flexural behaviour is observed

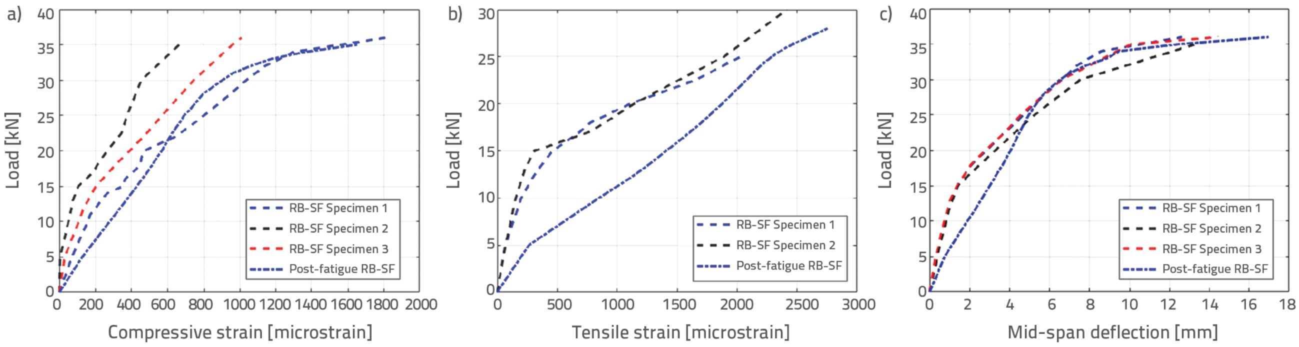

Figure 12. Diagram: a) Load - Compressive Strain; b) Load - Tensile Strain; c) Load - Deflection relation for RB-SF beams exposed to fatigue load

in the linear range, where the beam flexural stiffness decreased 3 to 4 times. The cause of the change is the appearance of cracks due to fatigue load. As cracks start to appear in beam specimens that were not exposed to fatigue, the flexural behaviour between pre- and post-fatigue beams becomes similar.

4. Conclusion

An experimental study is performed to examine the effect of adding melt extract stainless steel fibres to concrete. Melt-extract stainless steel fibres of irregular geometry with an aspect ratio of 55, an equivalent diameter of 0.64 mm, and length of 35 mm, were used in the study. The following conclusions on the effect these fibres have on the mechanical behaviour of concrete can be drawn:

- The balling of fibres was noticed for fibre volumetric ratios larger than 1.5 %, which significantly reduced the workability of concrete. Hence, the volumetric ratio of 1.5 % was adopted.
- Compressive strength and elastic modulus increased by 3 % and 10 %, respectively. The spalling of concrete due to compressive failure was prevented by steel fibres.
- Bending and splitting tensile strength increased by 34 % and 45 %, respectively. Variances among experimental results increased with the addition of fibres.
- Beams without longitudinal reinforcement exhibited a 70 % increase in ultimate flexural strength. In two out of three specimens, fibres prevented brittle failure of the beam, by bridging the macro crack that led to beam failure.
- Beams with longitudinal reinforcement exhibited a 48 % increase in the first-crack strength and 13 % increase in ultimate strength. Load-strain relations showed that steel fibres decreased the compressive and tensile strain values of concrete and, most notably, the strain of longitudinal reinforcement. Crack distance decreased due to presence of steel fibres. Hence, at failure, the crack distance in plain concrete beams was almost twice the crack distance in beams with steel fibres. Beam failure mode changed from brittle shear failure to ductile flexural failure due to addition of steel fibres.
- After 15000 cycles of fatigue load at 2/22.5 kN (5 %/60 % of ultimate beam strength), the flexural stiffness of a beam specimen decreased by approximately 3 to 4 times. The difference between the flexural behaviour of pre- and post-fatigue beams decreased as the load level increased. The ultimate beam strength did not change due to fatigue loading.

Experimental results presented in the paper show that melt-extract stainless steel fibres can significantly improve flexural behaviour of concrete, and can therefore be considered as an interesting alternative to straight or hook-end steel fibres, especially in corrosion-prone or high-temperature environments.

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