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The experimental investigation of the mechanical properties of steel fibre-reinforced concrete according to different testing standards

A. Ryabchikov*, M. Kiviste, S.-M. Udras, M. Lindpere, A. Vassiljev and N. Korb

Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Chair of Rural Building and Water Management, Kreutzwaldi 1, EE51006 Tartu, Estonia
*Correspondence: alexander.ryabchikov@emu.ee.

Abstract. Steel fibre-reinforced concrete (SFRC) is widely applied in the construction of civil infrastructure projects, including the following: industrial floors, slabs, walls, and foundations. The application of steel fibres in the reinforcement of concrete remarkably improves the post-cracking behaviour of such concrete. In order to estimate this property, the energy involved in absorption is measured by using several valid testing standards: EVS-EN 14651:2005, EVS-EN 14488-5:2006, and ASTM C1550-12a. The objective of this study was to carry out a comparable analysis of the results that have been obtained using previously-mentioned standards and to be able to find a more reliable method for the determination of the fracture toughness of SFRC specimens. Experiments were carried out in accordance with the chosen standards. It was concluded that procedure involved in the ASTM standard provides a smaller variability of results with better levels of repeatability, therefore a smaller volume of specimens can be tested in one series in order to achieve reliable results.

Key words: SFRC, steel fibres, flexural strength, energy absorption capacity.

INTRODUCTION

SFRC has advantages over traditionally reinforced and pre-stressed concrete structures (Altun et al., 2007; Kiviste et al., 2019) in terms of its use in civil engineering projects. Steel fibres can be added to a concrete mix in order to make it an integral part of any fresh concrete laying. Although research on SFRC has been rather active during the past decade, there is still a need for evidence-based information on certain mechanical properties that are involved in SFRC. Abbass et al. (2018) found that the addition of different content levels and lengths of steel fibres with increasing water-to-cement ratios tended to cause an increase of about 10–25% in the compressive strength of concrete and about 31–47% in its direct tensile strength. An increase in steel fibre content from 0.5% to 1.5% (per volume of concrete) increased flexural strength from 3% to 124% for steel fibre with a smaller aspect ratio of 65, whereas for a higher aspect ratio of 80, a 140% increase in flexural strength was observed when compared to concrete without any steel fibre additives. Han et al. (2019) found that the length of the steel fibres has a greater effect on the mechanical properties of SFRC than does the maximum size of any coarse aggregate being used.

When it comes to designing SFRC elements it is important to know flexural strength and post-cracking behaviour, which can be estimated by measuring the energy absorption capacity of test specimens (Salehian et al., 2014; Abbass et al., 2018). Changes in concrete compressive strength and flexural tensile strength are quite small at a steel fibre level that is below 3% of the volume of the concrete and are not of any significance when it comes to design purposes (Ryabchikov et al., 2015; Dong & Shi, 2020).

The post-cracking behaviour of SFRC depends upon the type of steel fibres being used, plus the aspect ratio and its distribution within the volume of concrete. Several European standards (EVS-EN 14651:2005; EVS-EN 14488-5:2006) and an American standard (ASTM C1550-12a) have been developed for determining the flexural toughness of SFRC using different specimen types (beams, square slabs, or round panels). Flexural toughness is defined as the energy that is absorbed during the three-point bending of the beam and this equals the area that is under a load-deflection curve (Köksal et al., 2013).

From knowing the area that is under the load-deflection curve it is possible to determine an equivalent flexural strength (f_e) according to Japanese Standard JSCE-SF4. This is defined as the stress, which corresponds to the average load value over the area of the load deflection curve. The equivalent flexural strength can be directly used in designing SFRC elements.

The objective of this study was to review, compare, and analyse the flexural behaviour, flexural toughness, and failure modes of SFRC test specimens using the aforementioned European and American standards in order to be able to highlight their advantages and disadvantages.

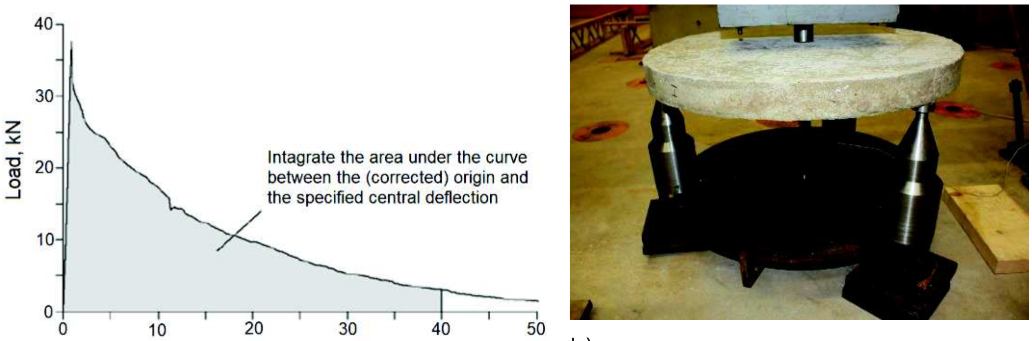
SFRC test specimens were prepared and tested according to two European standards and one American standard, under which different loading configurations have been applied. According to the EVS-EN 14651:2005 standard, the notched prisms with dimensions of 150×150×600 mm were tested using a scheme that involved three-point bending. According to the EVS-EN 14488-5:2006 standard, steel fibre square slabs with dimensions of 600×600×100 mm were continuously supported on each side and were centrally loaded. Under the American standard, ASTM C1550-12a, round slabs with a diameter of 800 mm and a thickness of 75 mm were pivot-supported at three points and centrally loaded until they fractured. The results were analysed and conclusions were drawn up.

MATERIALS AND METHODS

Experiments with SFRC have been carried out according to three standards, where various forms of specimen shape (beams, square slabs, and round panels) have been used. Specimens were prepared and treated as prescribed in the applicable standards.

Experiments with round panels

The flexural toughness of SFRC was determined according to the ASTM C1550-12a standard, for which round panels have to be tested. Toughness is defined as the energy that is absorbed by the specimen which is equivalent to the area that is under the load-deflection curve between the onset of loading and a specified central deflection point (Fig. 1, a). Two series of experiments were carried out with round panels. The ingredients of the concrete and data for the specimens are presented in Table 1.



a) b)

Figure 1. Integrating the area under the load-net deflection curve (a) to obtain the energy absorption levels (ASTM C1550-12a), and photo (b) showing the loading of a round plate specimen (Vassiljev, 2013).

Round panels with a nominal diameter of 800 mm were placed on three pivot supports for the bending test (Fig. 1, b). The failure mode for three symmetrically arranged support pivots (Fig. 2) results in low variability levels in the energy that is absorbed by a set of panels up to a specified central deflection point. The nominal thickness of a panel is 75 mm, which strongly influences the panel's performance and has to be measured very accurately. The actual diameter of a specimen should be within the range of 790–810 mm and at a thickness of 70–90 mm. If the actual dimensions of a specimen are different from the nominal dimensions that have been given here then the peak load should be corrected accordingly.

Table 1. The ingredients of a round panel specimen (Vassiljev, 2013; Udras, 2016)

	Series 1	Series 2
Cement CEM II/B-M(T-L) 52.5N, kg m^{-3}	400	-
Cement CEM-I 42.5N, kg m^{-3}	-	383
Sand 0–8, kg m^{-3}	1,000	592 (0–5)
Gravel 4–12, kg m^{-3}	800	1,110 (8–16)
Superplasticiser, % of cement mass	0.67	-
Water, kg m^{-3}	190	230
Water-cement ratio		0.6
Steel fibres HE 1/60, kg m^{-3}	48	-
Steel fibres HE 1/50, kg m^{-3}	-	70
Strength class of concrete	C45/55	
Average diameter, mm	798 ± 5	798 ± 5
Average thickness, mm	75 ± 1	75 ± 1

Panels were loaded with the hydraulic cylinder, a Lukas LZM 25/200, the deflections were measured with the Ahlborn Almemo FWA050T displacement sensor, and the experimental data were recorded using the Ahlborn Almemo 5690-2 data recorder. The experimental data were further processed on a personal computer.

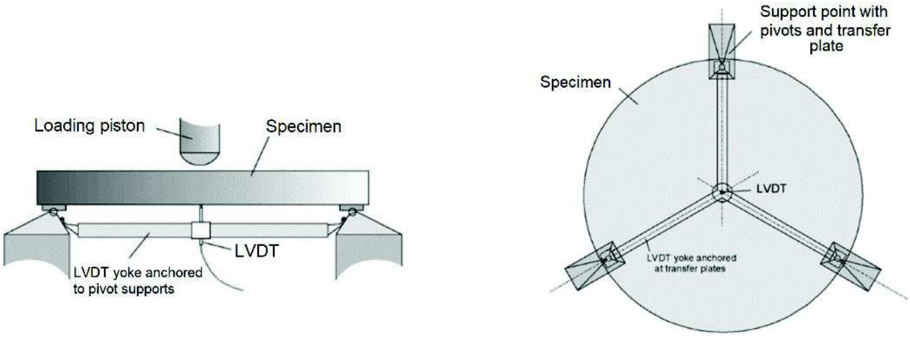


Figure 2. Schematic for loading up a round plate specimen (ASTM C1550-12a).

The corrected energy absorption level is calculated for deflection values of 5 mm, 10 mm, 20 mm, and 40 mm according to the formula presented in standard:

$$W = W'\left(\frac{t_0}{t}\right)^{\beta}\left(\frac{d_0}{d}\right), \tag{1}$$

where W' is the measured energy absorption level, J; t is the measured average thickness, mm; t_0 is the nominal thickness of 75 mm; d is the measured average diameter, mm; d_0 is the nominal diameter of 800 mm, $\beta = 2.0 - (\delta - 0.5)/80$; and δ – the specified central deflection at which the capacity to absorb energy is measured, in mm.

Experiments with the slabs

The energy absorption capacity of fibre-reinforced slab specimens was determined in accordance with the European standard, EVS-EN 14488-5:2006. A square slab is continuously supported along its edges and is loaded at the centre. The load-deflection curve was recorded and the test was continued until a deflection of at least 30 mm was achieved at the slab's mid-span. Five square slabs were cast with dimensions of 600×600×100 mm (Fig. 3, a). Hooked-end steel fibres, HE 75/35, with a dosage of 35 kg m^{-3} were used for reinforcing the concrete. The ingredients of the concrete specimens are presented in Table 2.

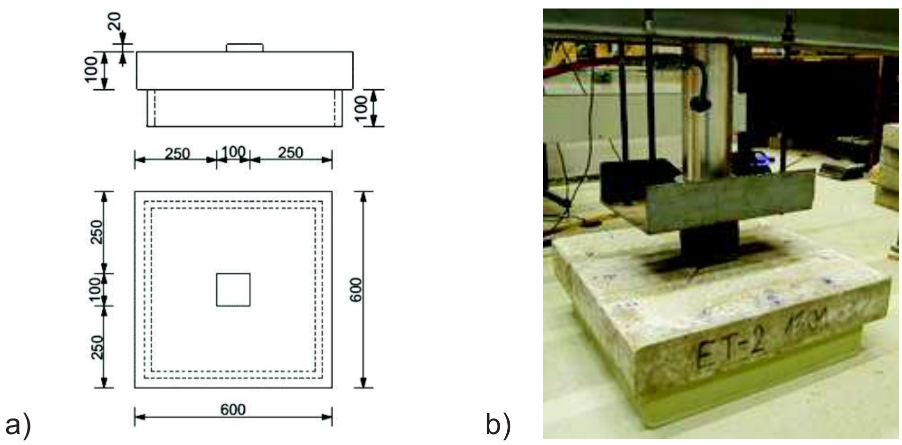


Figure 3. Schematic (a) and photo (b) for the loading configuration of a rectangular slab specimen (Lindpere, 2016).

A square rigid frame support (with a thickness of 20 ± 1 mm and internal dimensions of 500 ± 2 mm) was produced so that it could support the slab (Fig. 3, a). Slabs were loaded with the hydraulic cylinder, a Lukas LZM 25/200 (Fig. 3, b), with deflections being measured with an Ahlborn Almemo FWA050T displacement sensor, and test results being recorded with an Ahlborn Almemo 5690-2 data recorder.

The energy absorption capacity was calculated as the area under the load-deflection curve between a deflection of zero and 25 mm.

Table 2. The ingredients of a round panel specimen (Lindpere, 2016)

Cement CEM II/B-M(T-L) 52.5R, kg m^{-3}	325
Sand 0-8, kg m^{-3}	1,036
Gravel 4-16, kg m^{-3}	865
Water, kg m^{-3}	180
Steel fibres, kg m^{-3}	35
Strength class of concrete	C25/30
Average length of edge, mm	600.9 ± 0.8
Average thickness, mm	101.4 ± 0.3

Experiments with the beams

Experiments with beams were carried out in accordance with the EN 14651:2005+A1:2007 standard. The measurements for the specimens were 150×150×600 mm. An Instron 3369 universal testing machine with a capacity of 50 kN was applied for the implementation of the three-point bending loading test (Figs 4, a, 4, b). The specimens were loaded at the start of the process so that the deflection increased at a constant rate of 0.08 mm min^{-1}. The deflection rate from a value of 0.13 mm was adjusted to a constant rate of 0.21 mm min^{-1}. The test was stopped at a deflection point of 5 mm. Deflections were measured by means of a video extensometer with an accuracy level of 0.001 mm at the mid-span of a beam.

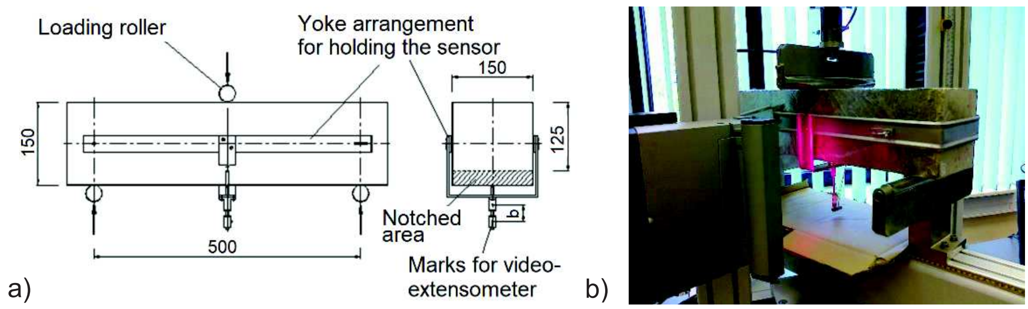


Figure 4. Schematic (a) and photo (b) showing the loading of a beam specimen (Ryabchikov et al., 2015).

The yoke arrangement was used for mounting the displacement transducer of a video extensometer and ensuring the accurate measurement of the mid-span deflections, excluding any effects that may have been due to the seating or twisting of the test beam on its supports. Two series of tests were carried out with dosages of 25 kg m^{-3} and 35 kg m^{-3}. Crimped steel fibres SAVEX 1/50 were used for reinforcement. Specimens were notched at the mid-span of the beam's tensile zone. The width of the notch was 5 mm or less and the height of the fracture section was at 125 ± 1 mm (Fig. 4, a).

The limit of proportionality (LOP) f_L and residual flexural strength f_i, corresponding to deflections of 0.47, 1.32, 2.17, and 3.02 mm, were calculated according to the formulas given in the EN 14651:2005+A1:2007 standard.

The equivalent flexural strength $f_{e,3}$ and $R_{e,3}$ values were obtained according to the code of the Japanese Society of Civil Engineers – JSCE-SF4. The equivalent flexural strength $f_{e,3}$ is determined from the area below the load-deflection curve until the measured deflection becomes $1\ 150^{-1}$ of the specimen's span (Fig. 5). The further toughness of the SFRC can be estimated by the equivalent flexural ratio $R_{e,3} = f_{e,3} f_L^{-1}$ – the higher the value of $R_{e,3}$, the higher is the expectation in terms of the beam's load-bearing capacity and toughness. The equivalent flexural strength is calculated at a deflection of 3.33 mm using the formula (2):

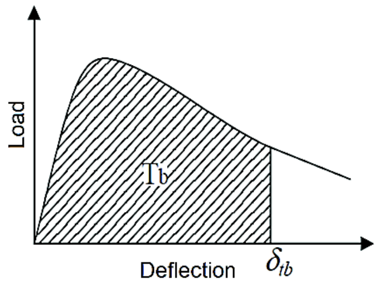


Figure 5. Area T_b for calculating flexural toughness (JSCE-SF4).

$$f_{e,3} = \frac{T_b l}{3.33 b h^2}, \quad (2)$$

where T_b is the area below the load-deflection curve; l is the span length; b is the width of the specimen; and h is the height of the fracture section.

RESULTS AND DISCUSSION

The main objective of the study was to provide a review and to carry a comparative analysis of methods for the determination of the residual flexural strength and energy absorption capacity of fibre-reinforced concrete. Experiments were carried out in accordance with two European standards and one ASTM standard. All three standards prescribe the use of different specimen shapes: beams, square slabs, and round panels.

An experimental diagram representing the dependence of the central deflection of a round concrete panel with steel fibres HE 1/60 (48 kg m^{-3}) on the load is presented in Fig. 6, and a version with steel fibres HE 1/50 (70 kg m^{-3}) is shown in Fig. 7.

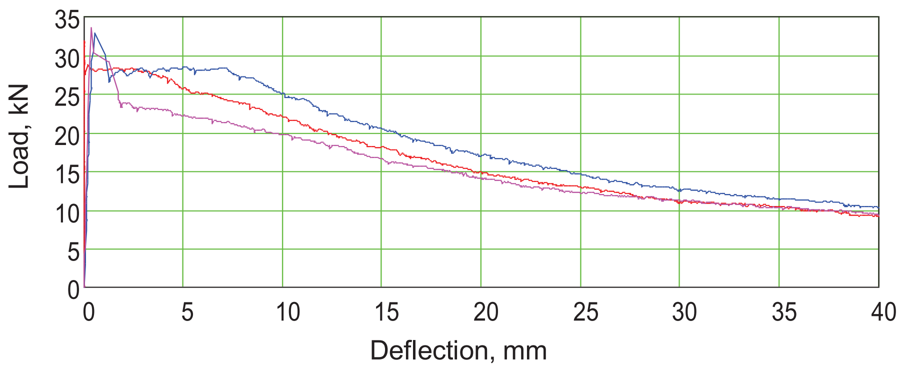


Figure 6. The load-deflection curve of a round concrete panel (strength class C45/55) containing steel fibres HE 1/60 with a dosage of 48 kg m^{-3} (Udras, 2016).

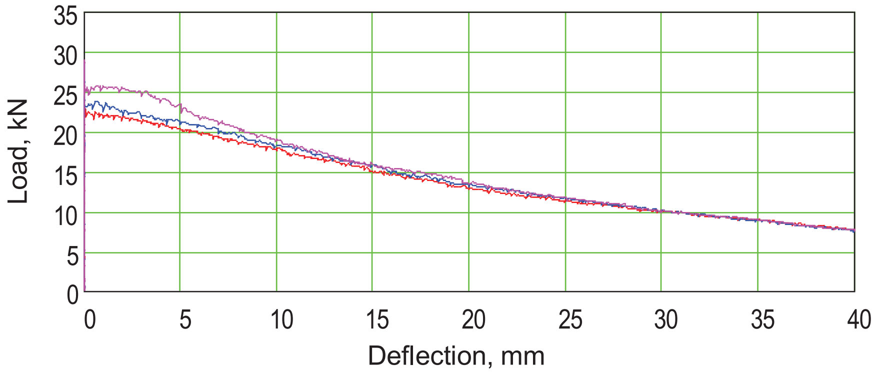


Figure 7. The load-deflection curve of a round concrete panel (strength class C25/30) containing steel fibres HE 1/50 with a dosage of 70 kg m^{-3} (Vassiljev, 2013).

The calculated average peak load and absorbed energy at the certain central deflections for a round panel for both series of experiments are summarised in Table 3.

Table 3. Peak load (kN) and energy absorption (J) at the central deflections of a round panel

	Series 1 (Udras, 2016)	Series 2 (Vassiljev, 2013)
Peak load	32.90 ± 5.50	27.19 ± 2.33
5 mm	133.36 ± 19.56	116.01 ± 5.03
10 mm	253.86 ± 61.48	216.42 ± 6.41
20 mm	439.51 ± 115.28	374.17 ± 6.13
40 mm	681.06 ± 167.12	582.61 ± 5.36

Three panels were tested in each test series. The differences between the series were in terms of dosage and in the strength class of the concrete, which mainly affects the peak load value. It can be seen in Figs 6 and 7 that the fluctuation of load deflection curves is higher in the case of a lower fibre dosage.

This was affected by the uneven distribution of fibres in the section fracture and by the difference in the aspect ratio of the fibres.

The load-deflection curves of tested square concrete slabs with measurements of 600×600×100 mm and containing steel fibres of the HE 75/50 type with a dosage of 35 kg m^{-3} are presented in Fig. 8. The average peak load was 53.9 ± 8.7 kN and the absorbed energy at 25 mm of central deflection was 571 ± 99 J, respectively (Lindpere, 2016). Fig. 8 shows that the peak values within one series of experiments fluctuated within a fairly high range. The peak load is higher than load at first crack and it caused by the amount of fibres bridging the cracks, what is different specimen by specimen. The reason for such behaviour is the chaotic nature of the fibre dispersion and orientation, which was very sensitive to the moulding procedure (Laranjeira, 2010).

Two series of experiments with beams were carried out. The first series was with a dosage of 25 kg m^{-3} and the second series was at 35 kg m^{-3}. All specimens were notched according to the testing standard, EVS-EN 14651:2005+A1:2007. The load-deflection curve of beams that contained steel fibres of the SAVEX 1/50 type with a dosage of 35 kg m^{-3} is presented in Fig. 9. The experimental results are su mmarised in Table 4.

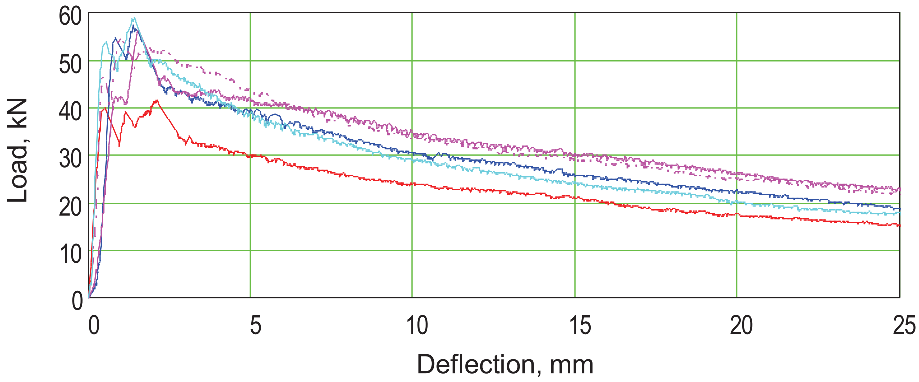


Figure 8. The load-deflection curve of a square concrete slab (600×600×100 mm) containing steel fibres HE 75/50 with a dosage of 35 kg m^{-3} (Lindpere, 2016).

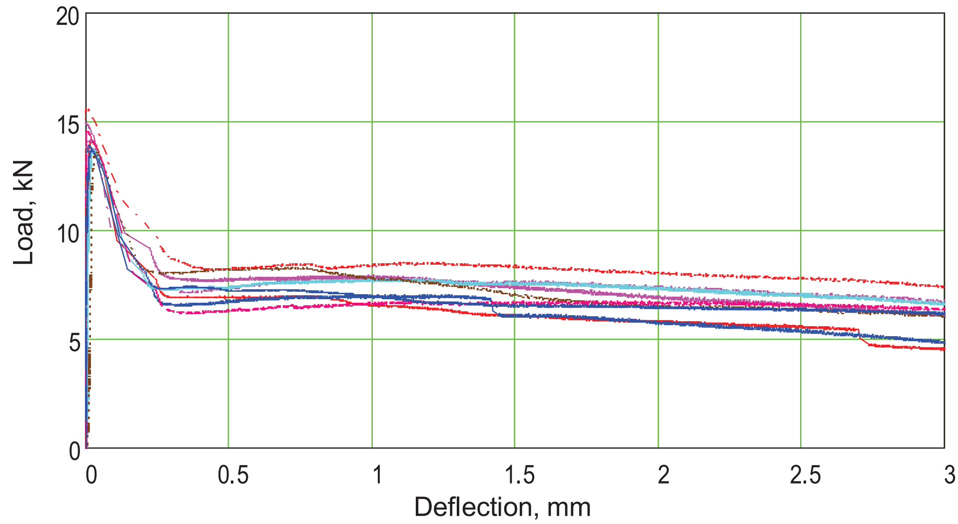


Figure 9. The load-deflection curve of concrete beams (150×150×600 mm) which contain steel fibres of the SAVEX 1/50 type with a dosage of 35 kg m^{-3} (Korb, 2008).

The fluctuation of the area below the load-deflection curve within one series of experiments is significantly high. In the case of the beam at least twelve specimens had to be tested to obtain reliable results. A lower residual flexural strength and higher deviation was observed in the case of a lower dosage of fibres (Table 4).

Table 4. The dimensions of specimens and the results from testing the beams (Korb, 2008).

	Dimensions of the section area (mm)		LOP (MPa)	Residual flexural strength (MPa)		Equivalent flexural strength	
	Height	Width	f_L	$f_{0.47}$	$f_{3.02}$	$f_{e,3}$ (MPa)	$R_{e,3}$ (%)
Series 1	125 ± 1	156 ± 1	4.30 ± 0.13	2.20±0.44	1.78±0.35	2.18±0.37	51 ± 8
Series 2	125 ± 1	154 ± 1	4.47 ± 0.13	2.35±0.16	1.94±0.16	2.30±0.15	51 ± 2

The major advantage of the round panel test when compared to the square panel test is the formation of three cracked lines (Fig. 10, a). The large dimension was formed of the cracked area (containing three cracks of a length of 400 mm and a depth of 75 mm), which ensured a certain level of consistency and stability in the experimental results that were obtained (Ciancio et al., 2014). The same tendency was observed in our experiments. When comparing the load-deflection curves of the round panels (Fig. 7) and those of the square slabs (Fig. 8), a higher fluctuation can be seen in the experimental data for the squared slabs. The loading configuration of the round panel is statically determined and the loading configuration of the square slab is statically undetermined. Therefore the crack patterns on the square slabs at the point of failure are different for each tested specimen (Fig. 10, b); therefore the section area and the number of 'working' fibres is different every time, which directly affects the absorption capacity of the specimen and the mode of its failure (Salehian et al., 2014).

a) 

b) 

Figure 10. Fracture mode for a round panel (a) (Udras, 2016) and for a square slab (b) (Ciancio et al., 2014).

The flexural toughness characterises the structural parameter rather than a material property, and this is dependent upon the dimensions of the sample (Ciancio et al., 2014).

In the case of the beam specimens it is difficult to ensure the uniform distribution of fibres across the entire volume. Therefore, there is a high level of fluctuation in residual flexural strength (Table 4), since a large number of tests should be carried out in order to obtain reliable results. Experiments have demonstrated that the results are more uniform with fibre dosages that start at 30 kg m^{-3} (Korb, 2008).

CONCLUSIONS

The flexural test which covered three shapes (beams, square slabs, and round panels) of steel fibre reinforced specimens according to the recommendations specified in three standards (two European standards and one ASTM) were all carried out and the following conclusions were found:

1. In comparison with the European standard, the experimental results that were obtained by applying the ASTM standard provided a smaller variability in the test results, which means better repeatability, and a greater fracture surface with more fibres. This, in turn, decreased the influence of any uneven distribution of fibres. Therefore less

test specimens were required in order to achieve a reliable result. This meant also that the fracture surface of specimens was measured more accurately.

2. The advantage of a round panel test when compared to a square panel test was the formation of three cracked lines. Therefore a large cracked area was formed, which ensured a greater degree of consistency and stability in terms of the experimental results that were obtained.

3. The application of round panels eliminated the sawing of a notch that was required to prepare the beam specimens. Notched specimens always had only one cracked line at the point of failure, meaning also a smaller cracked area. This, in turn, resulted in a larger variability in the test results.

4. The crack pattern in the square panels at the point of failure was found to be different for each tested specimen. Therefore the section area and the number of 'working' fibres were found to vary somewhat, which in turn directly affected the absorption capacity of the specimen.

5. The limitation in terms of applying the ASTM standard consists of a requirement for preparing a test specimen of relatively large dimensions, which weighs approximately 100 kg.

6. The fibre dosage of 30 kg (or more) per cubic metre of concrete resulted in more uniform residual flexural test results.

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