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Kovács Imre

BEHAVIOUR OF STEEL FIBRE REINFORCED CONCRETE SLABS IN BENDING

ABSTRACT

Presented paper deals with an experimental study on the structural behaviour of steel-fibre reinforced concrete slabs in bending affected by the fibre orientation. Experimental parameters were the concrete mix (two types of mixture were used, noted by FRC-1 and FRC-2), the fibre content (75 kg/m^3 and 150 kg/m^3 Dramix® ZP 305 hooked-end steel fibres were applied) and the privilege fibre orientation. Crack patterns, failure loads, as well as load–deflection relationships were registered.

INTRODUCTION

Steel fibre reinforced concrete (SFRC) improves properties such as toughness, ductility, fatigue and impact resistance. SFRC is especially applied for concreting road and industrial floor slabs, airfield runways, pavements, refractory materials and other concrete products. Many publications cover basic research on SFRC as a special concrete with characteristics different from those of the conventional concrete [1][2][3][4][5]. However, few results are available concerning the behaviour of SFRC in structural reinforced concrete members [6][7][8][9]. Tests were carried out for investigating the punching strength of prestressed SFRC flat slab [10] as well. As previous tests showed, steel fibre reinforcement is not effective to improve the moment capacity of reinforced concrete members. Though, fibres may have significant effect on shear resistance of reinforced concrete beams and slabs (punching shear). Application of fibres may reduce the amount of stirrups and congestion of reinforcement in high shear regions. Fibres do not only increase shear capacity but also provide substantial post-peak resistance and ductility in shear. However, application of steel-fibre reinforcement in concrete flat slabs are constrained by the available design method. For this reason a new test method and test set-up were developed to study the structural behaviour of steel fibre reinforced concrete slab elements.

EXPERIMENTAL PROGRAM

Test specimens and experimental variables

The experimental program concerned of 4 steel fibre reinforced concrete slab elements with the geometry of 600×600×50 mm. Geometry was chosen so that the behaviour of slab in bending should be a two-way type ($\ell_x = \ell_y = 600$ mm). Slab span to depth ratio was 12 ($\ell_x/d = 600$ mm / 50 mm = 12).

Steel fibre reinforcement was the product of the well known BEKAERT industry, namely the Dramix® ZP 305 hooked-end steel fibre. Since the purpose of the experiment was to study the structural performance of concrete slabs effected by steel fibres and their orientation, two relatively high dosage of fibre were applied. 75 kg/m³ and 150 kg/m³ fibre content were used which are more or less respectively equivalent to 1.0 V% (78,5 kg/ m³) and 2.0 V% (157 kg/ m³) of fibre content.

Due to the quadratic shape of slab specimens only one privilege fibre orientation has been introduced by the use of a pocket vibrator at casting.

Slabs made of a concrete type noted by FRC-1 ($\text{FRC-1}^{75}_{\text{ZP 305}}$ and $\text{FRC-1}^{150}_{\text{ZP 305}}$) and FRC-2 ($\text{FRC-2}^{75}_{\text{ZP 305}}$ and $\text{FRC-2}^{150}_{\text{ZP 305}}$) and manufactured in the laboratory of the Department of Reinforced Concrete Structures, Budapest University of Technology.

Experimental parameters containing the date of casting and testing are summarised in Table. 6.1.

Table 1: Experimental parameters of steel fibre reinforced concrete slabs

	No.	Concrete type	Fibre type	Fibre content [kg/m³]	Date of casting	Date of testing	Age at testing [day]
1	S-1	FRC-1	Dramix ZP 305	75	05.11.99	06.02.02	821
2	S-2			150	08.12.99	08.02.02	790
3	S-3	FRC-2		75	05.11.99	07.02.02	822
4	S-4			150	08.12.99	08.02.02	790

Concrete compositions

According to the experimental variables and constants four types of concrete compositions were designed for the bending tests of steel fibre reinforced concrete slabs.

They are classified into two main groups signed by FRC-1 and FRC-2. As Table 2 indicates concrete composition FRC-2 was mixed with higher cement content and lower water to cement ratio related to mix FRC-1.

The mixtures contain only fine aggregates. Two washed and classified fine aggregate fractions were used, 0-4 mm sandy-gravel and 4-8 mm gravel fractions. The maximum aggregate diameter, therefore, was 8 mm.

The concrete mixes made of pure Hungarian Portland Cement CEM I. 52.5 (550 pc).

The well-known BEKAERT products called Dramix® hooked-ends fibres were applied as fibre reinforcement for all mixes. Their geometrical and mechanical properties are summarised in Table 3. Subscripts of concrete mix notations indicate the type of fibre Dramix® ZP 305, the superscript the fibre content in weight.

The proper workability was obtained by the addition of superplasticizer in order to reduce the water to cement ratio in case of batches containing higher steel fibre content. The superplasticizer used was SIKAMENT-10 HBR.

Table 2: Concrete composition of slab specimens given in dry material [kg/m³]

	Notation of mix	Fine aggregates		Cement	Super-plasticizer	Water to cement ratio	Fibre Content
		0-4 mm	4-8 Mm				
1	$\text{FRC-1}^{75}_{\text{ZP 305}}$	1056	829	330	5,952	0.512	75
2	$\text{FRC-1}^{150}_{\text{ZP 305}}$	1056	829	330	8.571	0.512	150
3	$\text{FRC-2}^{75}_{\text{ZP 305}}$	958	752	500	9.048	0.372	75
4	$\text{FRC-2}^{150}_{\text{ZP 305}}$	958	752	500	10.476	0.372	150

Table 3: Used type of fibre and its mechanical properties

Notation	Material type	Configuration	Aspect ratio $l_f/\varnothing_f$	Density kg/m³	Strength MPa	Elastic modulus GPa
Dramix®ZP 305	Steel		60	7800	1100	200

Concrete compressive strength

6-6 prism (240×100×100 mm) specimens were drilled-out from a slab element made of mixes FRC-1 and FRC-2 in order to study the effect of fibre orientation on the behaviour of concrete members in compression.

Prismatic specimens (240×100×100 mm) of series FRC-1 and FRC-2 were tested by a displacement controlled Instron type testing machine with the capacity of 500 kN. Speed of cross-head (0.2 mm/min.) was chosen so that the displacement controlled test fulfil the international requirements and standards.

Mean strengths of the six prism specimens are summarised in Table 4 and in Figure 3. Sign I. and II. indicates the orientation of fibres related to the axis of the applied load. In case of sign II. the applied load was parallel with the main fibre orientation while in case of I. it was perpendicular to that.

Table 4: Concrete compressive strength measured on 240×100×100 mm prisms

No.	Notation of mix	f_{cm} (mean of 6 prisms) [MPa]	$f_{cm(I,II)}$ (mean of 12 prisms) [MPa]	Age [day]
1	FRC-1 $^{75}_{ZP\ 305-I}$	41.42	39.10	28
	FRC-1 $^{75}_{ZP\ 305-II}$	36.77		28
	FRC-1 $^{150}_{ZP\ 305-I}$	34.55	33.48	28
	FRC-1 $^{150}_{ZP\ 305-II}$	32.40		28
2	FRC-2 $^{75}_{ZP\ 305-I}$	44.02	44.04	28
	FRC-2 $^{75}_{ZP\ 305-II}$	44.05		28
	FRC-2 $^{150}_{ZP\ 305-I}$	37.94	36.80	28
	FRC-2 $^{150}_{ZP\ 305-II}$	35.65		28

Test setup and experimental procedure

Due to the lack of standardised tests on two-way concrete slabs, a new test method was developed determining the structural performances of the elements in bending shown in Photo 1 and Photo 2. The most simple test arrangement and test method was performed. Steel fibre reinforced concrete slab elements were loaded at their central points. Slabs were simply supported on a rigid steel frames formed by a steel girder I120 (MSZ 500, A38) lying on the passive cross-head of the testing machine. Tests were conducted under displacement control using an Instron type servo-hydraulic testing machine with the capacity of 500 kN. Feed-back signals based on the measurements of two LVDTs placed on the passive cross-head.

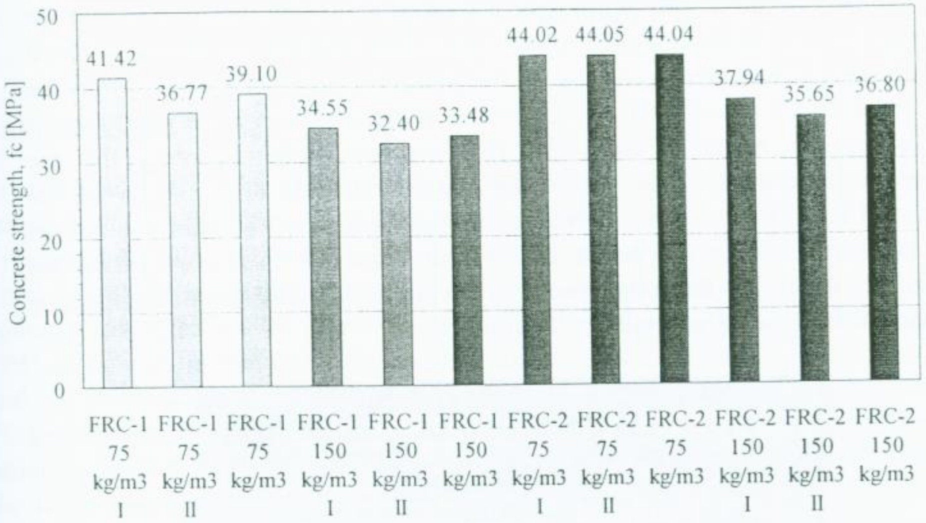

Figure 3: Concrete compressive strengths measured on 240×100×100 mm prisms

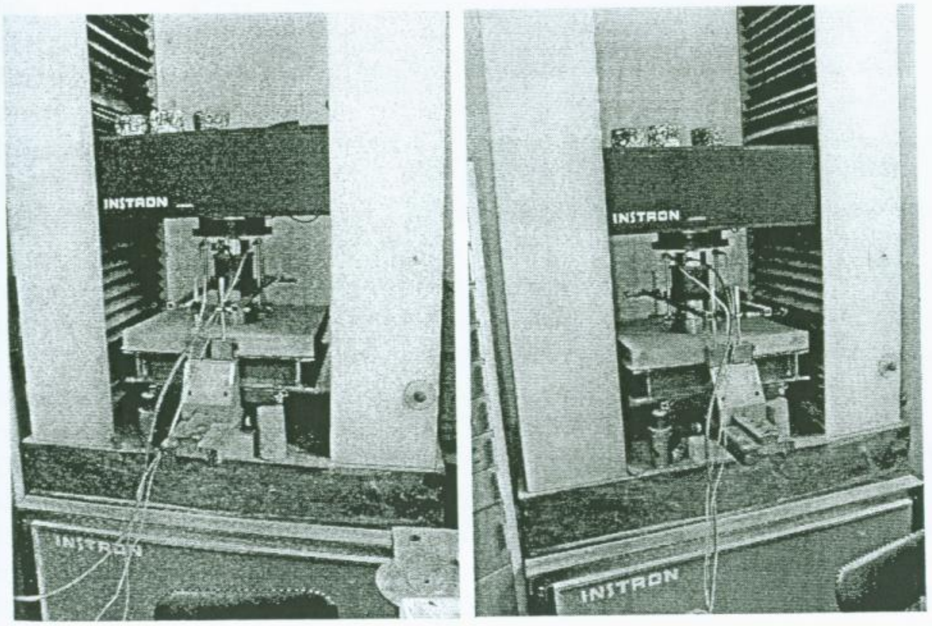

Photo 1: Testing machine and test set-up for bending of steel fibre reinforced concrete slabs

LVDTs directly measured the displacement of SFRC slabs at the third points of their span in one direction. Slabs were placed on the frame support so that the privilege fibre orientation should always be in one direction as shown in Photo 2. Load was determined according to the measuring of the load-cell with the capacity of 20 kN placed between the central point of slabs and the active cross-head of Instron. Speed of cross-head (0.2 mm/min.) was chosen so that the displacement controlled test fulfils the Japan standards [11]. To avoid the damage of test set-up, the maximum measured deflection of the third point of the span was around 8 mm and hence, it was limited in ℓ/75. Tests were performed in the laboratory of the Department of Building Materials and Engineering Geology at Budapest University of Technology.

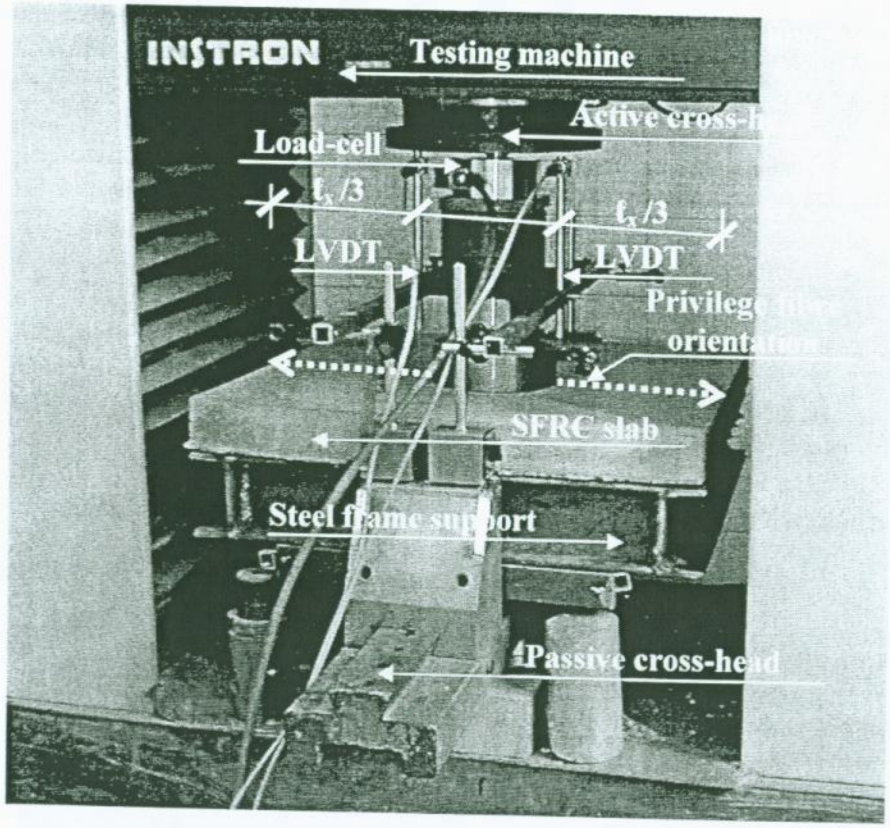

Photo 2: Test set-up and test arrangement of bending test of steel fibre reinforced concrete slabs

EXPERIMENTAL RESULTS

Failure loads

Cracking loads (F_{cr}) and failure loads (F_u) as well as increment of cracking and failure loads of steel fibre reinforced concrete slabs are summarised in Table 5. Cracking as well as failure loads were determined according to the measured Load vs. deflection relationships. Increments are explained as a function of fibre content (150 kg/m^3 vs. 75 kg/m^3) and as a function of concrete type (FRC-2 vs. FRC-1) as well. In the first case cracking load of slab S-2 (FRC-1, 150 kg/m^3) and S-4 (FRC-2, 150kg/m^3) are related to the cracking load of slab S-1 (FRC-1, 75 kg/m^3) and S-3 (FRC-2, 75 kg/m^3), respectively. In the last two columns failure load of S-3 (FRC-2, 75 kg/m^3) and S-4 (FRC-2, 150 kg/m^3) are related to the failure load of slab S-1 (FRC-1, 75 kg/m^3) and S-2 (FRC-1, 150 kg/m^3), respectively. As results indicate significant increment in cracking load can be obtained by applying 150 kg/m^3 ZP 305 hooked-end steel fibres related to slabs containing 75 kg/m^3 ZP 305 hooked-end steel fibres. However, cracking load of slabs were not significantly effected by the type of concrete. When the fibre content was 75 kg/m^3, 10.15 kN (S-1) and 11.13 kN (S-3) cracking load obtained for slabs made of concrete type FRC-1 and FRC-2, respectively. Otherwise, 17.46 kN (S-2, FRC-1) and 21.06 kN (S-4, FRC-2) jack force yield to cracking on the slabs applying 150 kg/m^3 steel fibres. Hence, more or less the same increment in cracking load was obtained by the increase of fibre content in case of FRC-1 (72 %) and FRC-2 (89 %) as well. In contrast with the significant increment in cracking load by the increase of fibre content, the change of concrete type from FRC-1 to FRC-2 did not notably effected the cracking load applying the same fibre content. When 75 kg/m^3 fibres were used 10 % (S-3, FRC-2), when 150 kg/m^3 fibres were used 21 % (S-4, FRC-2) increment in cracking load obtained related to slab S-1 (FRC-1) and S-2 (FRC-1), respectively.

Obviously, that failure load increased applying 150 kg/m^3 steel fibres related to slab containing 75 kg/m^3 steel fibres. By the use of 150 kg/m^3 fibre content 13 % (S-2, FRC-1, $F_u = 32.46$ kN) and 25 % (S-4, FRC-2, $F_u = 40.51$ kN) increment in failure load was achieved, respectively related to slabs S-1 (FRC-1, $F_u =$ 28.73 kN) and S-3 (FRC-2, $F_u = 32.23$ kN), containing 75 kg/m^3 steel fibres. Moreover, by the change of concrete type from FRC-1 to FRC-2, 12 % (S-3, FRC-2, 75 kg/m^3) and 25 % (S-4, FRC-2, 150 kg/m^3) increment was obtained related to slabs S-1 (FRC-1, 75 kg/m^3) and S-2 (FRC-1, 150 kg/m^3), respectively.

Table 5: Cracking load and failure load of steel fibre reinforced concrete slabs made of concrete type FRC-1 and FRC-2 applying 75 kg/m^3 and 150 kg/m^3 ZP 305 Dramix® hooked-end steel fibres

	No.	Concrete type	F_{cr} [kN]	F_u [kN]	A*	B*	C*	D*
1	S-1	FRC-$1^{75}{}_{ZP\,305}$	10.15	28.73	100 %	100 %	100 %	100 %
2	S-2	FRC-$1^{150}{}_{ZP\,305}$	17.46	32.46	172 %	100 %	113 %	100 %
3	S-3	FRC-$2^{75}{}_{ZP\,305}$	11.13	32.23	100 %	110 %	100 %	112 %
4	S-4	FRC-$2^{150}{}_{ZP\,305}$	21.06	40.51	189 %	121 %	125 %	125 %

A*) Increment in cracking load 150 kg/m^3 fibre content vs. 75 kg/m^3 fibre content

B*) Increment in cracking load concrete mix FRC-2 vs. concrete mix FRC-1

C*) Increment in failure load 75 kg/m^3 fibre content vs. 150 kg/m^3 fibre content

D*) Increment in failure load concrete mix FRC-1 vs. concrete mix FRC-2

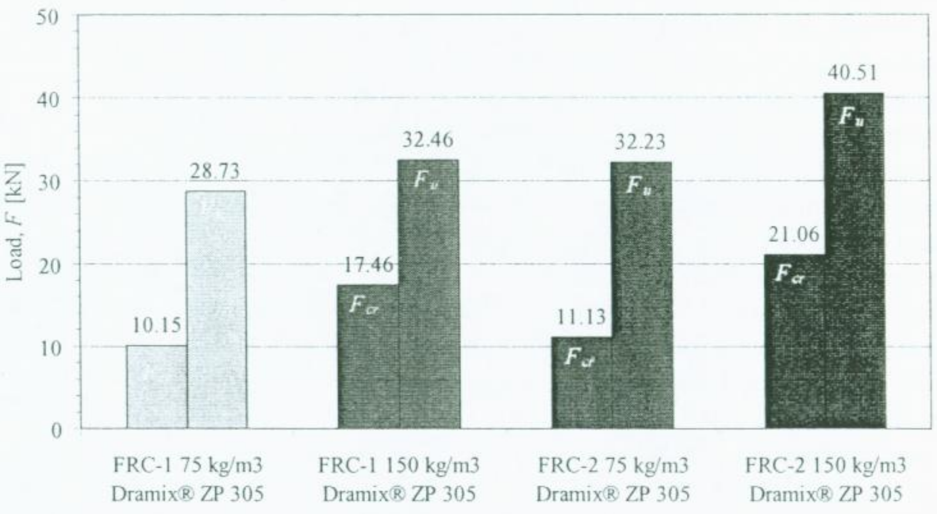

Figure 4: Cracking load and failure load of steel fibre reinforced concrete slabs made of concrete type FRC-1 and FRC-2 applying 75 kg/m^3 and 150 kg/m^3 ZP 305 Dramix® hooked-end steel fibres

Load vs. deflection relationship

Similarly to Table 5, the corresponding deflections measured at cracking loads and failure loads, as well as their increments as a function of the fibre content and the concrete compositions are summarised in Table 6. and in Figure 5. Load vs. deflection relationship and their measuring process of steel fibre reinforced concrete slabs are also presented in Figures 6-9.

As results indicate, deflections corresponding to the cracking load as well as to failure load of steel fibre reinforced slabs increased applying 150 kg/m^3 ZP 305 hooked-end steel fibres related to slabs containing 75 kg/m^3 ZP 305 hooked-end steel fibres. However, deflection measured at cracking not significantly effected by the type of concrete. When the fibre content was 75 kg/m^3, 0.82 mm (S-1) and 1.10 mm (S-3) deflection obtained for slabs made of concrete type FRC-1 and FRC-2, respectively. Otherwise, 1.48 mm (S-2, FRC-1) and 1.83 mm (S-4, FRC-2) deflection was measured on the slabs applying 150 kg/m^3 steel fibres. Hence, more or less the same increment in deflection obtained by the increase of fibre content in case of FRC-1 (80 %) and FRC-2 (66 %) as well.

In contrast to the notable increment in deflection measured at cracking by the increase of fibre content, the change of concrete type from FRC-1 to FRC-2 did not significantly effect the deflection applying the same fibre content. When 75 kg/m^3 fibres were applied 34 % (S-3, FRC-2), when 150 kg/m^3 fibres were used 24 % (S-4, FRC-2) increment in deflection obtained related to slab S-1 (FRC-1) and S-2 (FRC-1), respectively.

Deflection at failure load also increased applying 150 kg/m^3 steel fibres related to slab containing 75 kg/m^3 steel fibres. By the use of 150 kg/m^3 fibre content 44 % (S-2, FRC-1, a_{Fu} = 5.03 mm) and 21 % (S-4, FRC-2, a_{Fu} = 4.33 mm) increment in deflection at failure load was measured, related to slabs S-1 (FRC-1, a_{Fu} = 3.49 mm) and S-3 (FRC-2, a_{Fu} = 3.57 mm), containing 75 kg/m^3 steel fibres, respectively.

Moreover, by the change of concrete type from FRC-1 to FRC-2, 2 % (S-3, FRC-2, 75 kg/m^3) and 21 % (S-4, FRC-2, 150 kg/m^3) increment was obtained related to slabs S-1 (FRC-1, 75 kg/m^3) and S-2 (FRC-1, 150 kg/m^3), respectively.

Figure 6-9. also indicate, that 150 kg/m^3 Dramix® ZP 305 hooked-end steel fibres resulted more smooth load vs. deflection relationships. Due to this relatively high fibre dosage, the fibre reinforcement did not slip, and hence advantageous post-cracking hardening behaviour can be obtained. However, better elastic-plastic behaviour was obtained by the use of concrete mix FRC-2.

Table 6: Measured deflections at cracking load and at failure load of steel fibre reinforced concrete slabs made of concrete type FRC-1 and FRC-2 applying 75 kg/m^3 and 150 kg/m^3 Dramix® ZP 305 hooked-end steel fibres

No.		Concrete type	a_{Fcr} [mm]	a_{Fu} [mm]	A*	B*	C*	D*
1	S-1	FRC-$1^{75}_{ZP\ 305}$	0.82	3.49	100 %	100 %	100 %	100 %
2	S-2	FRC-$1^{150}_{ZP\ 305}$	1.48	5.03	180 %	100 %	144 %	100 %
3	S-3	FRC-$2^{75}_{ZP\ 305}$	1.10	3.57	100 %	134 %	100 %	102 %
4	S-4	FRC-$2^{150}_{ZP\ 305}$	1.83	4.33	166 %	124 %	121 %	121 %

A*) Increment in deflection at cracking load 150 kg/m^3 fibre content vs 75 kg/m^3 fibre content

B*) Increment in deflection at cracking load concrete mix FRC-2 vs. concrete mix FRC-1

C*) Increment in deflection at failure load 75 kg/m^3 fibre content vs 150 kg/m^3 fibre content

D*) Increment in deflection at failure load concrete mix FRC-1 vs. concrete mix FRC-2

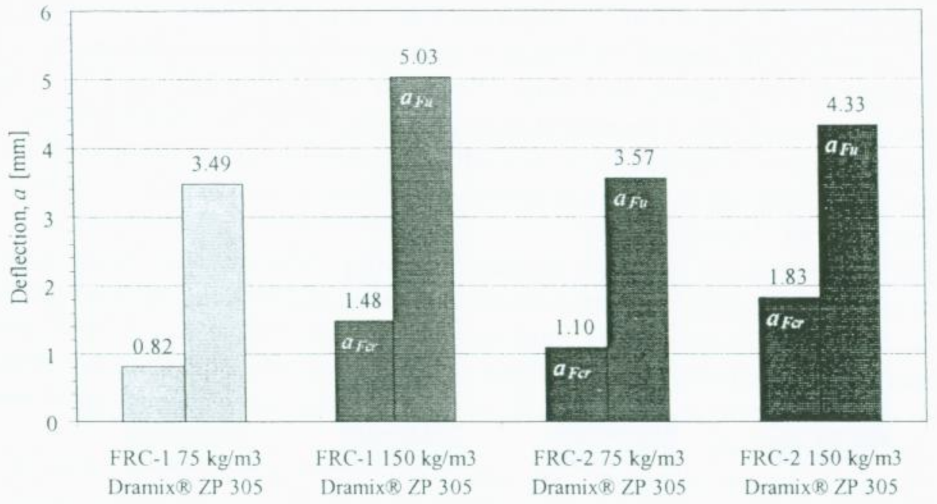

Figure 5: Measured deflections at cracking load and at failure load of steel fibre reinforced concrete slabs made of concrete type FRC-1 and FRC-2 applying 75 kg/m^3 and 150 kg/m^3 Dramix® ZP 305 hooked-end steel fibres

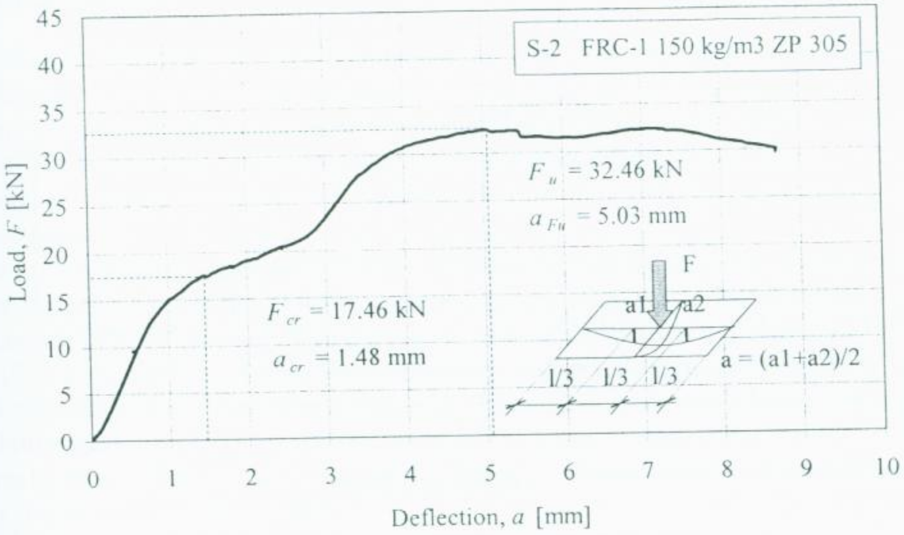

Figure 6: Load vs. deflection relationship of steel fibre reinforced concrete slab made of concrete mix FRC-1, applying 75 kg/m^3 Dramix® ZP 305 hooked-end steel fibres, noted by S-1

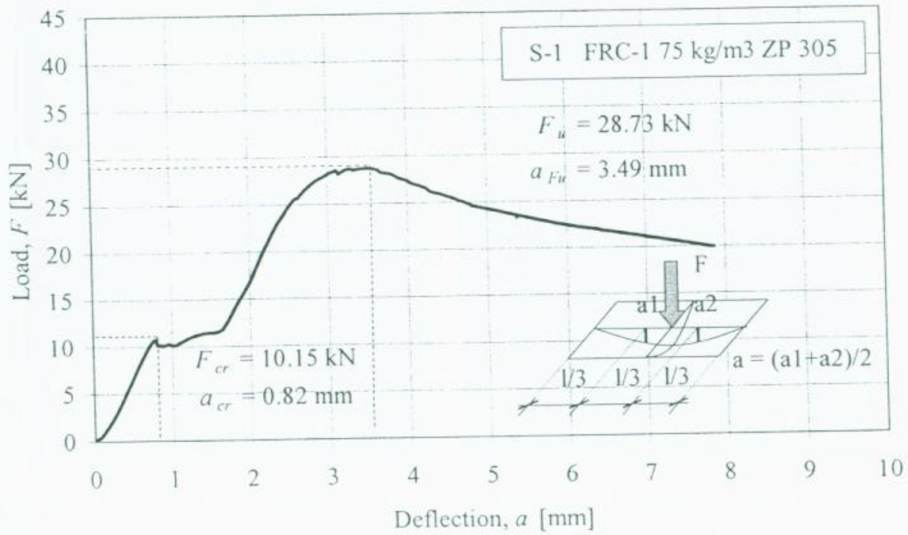

Figure 7: Load vs. deflection relationship of steel fibre reinforced concrete slab made of concrete mix FRC-1, applying 150 kg/m^3 Dramix® ZP 305 hooked-end steel fibres, noted by S-2

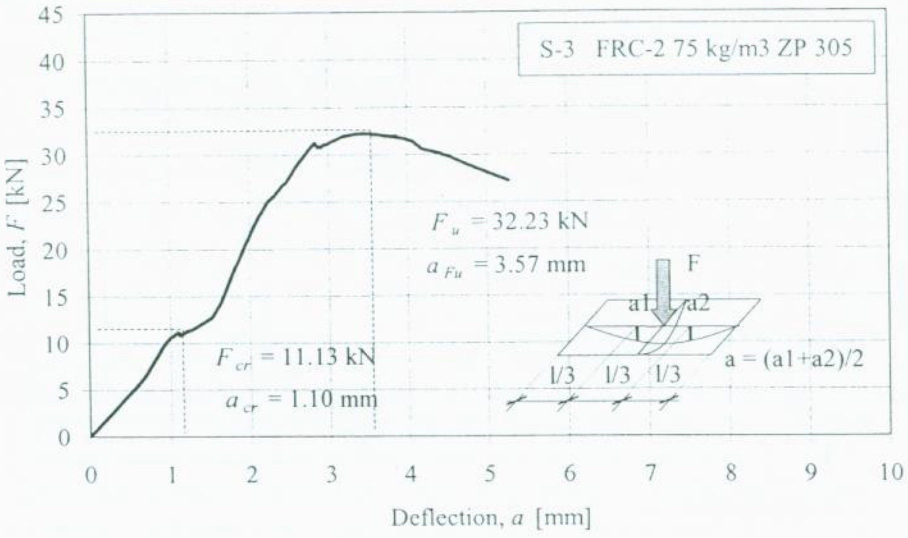

Figure 8: Load vs. deflection relationship of steel fibre reinforced concrete slab made of concrete mix FRC-2, applying 75 kg/m^3 Dramix® ZP 305 hooked-end steel fibres, noted by S-3

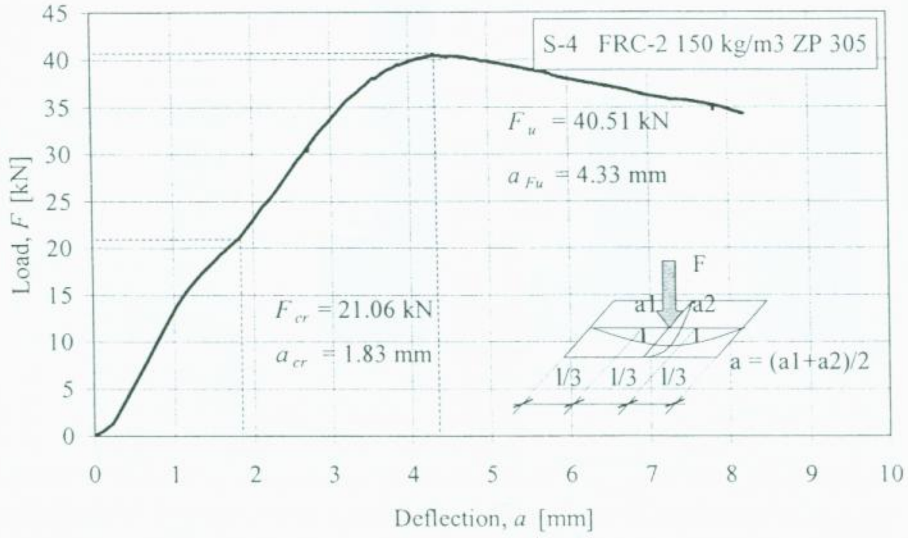

Figure 9: Load vs. deflection relationship of steel fibre reinforced concrete slab made of concrete mix FRC-2, applying 150 kg/m^3 Dramix® ZP 305 hooked-end steel fibres, noted by S-4

Crack pattern

After the bending tests of steel fibre reinforced concrete slabs, crack pattern effected by the main fibre orientation was analysed.

Failure lines of slabs can be seen in Photo 3. Photos were made after the bending tests, therefore they represent deformation states at different load levels. Failure loads as well as the schematic representation of the main fibre orientations are also presented on the photos.

As photos indicate, direction of crack propagation was more or less parallel with the main fibre orientation. However, crack propagation was effected by the used concrete mix and applied fibre content as well. In the case of concrete mix FRC-2 (S-3, S-4), applying higher cement content, less cracks appeared on the surface of slabs than in the case of concrete mix FRC-1 (S-1, S-2), considering the same fibre content. In case of both concrete type, 75 kg/m^3 fibre content resulted more cracks than 150 kg/m^3 fibre content. Further, the mean crack widths decreased by the increase of fibre content.

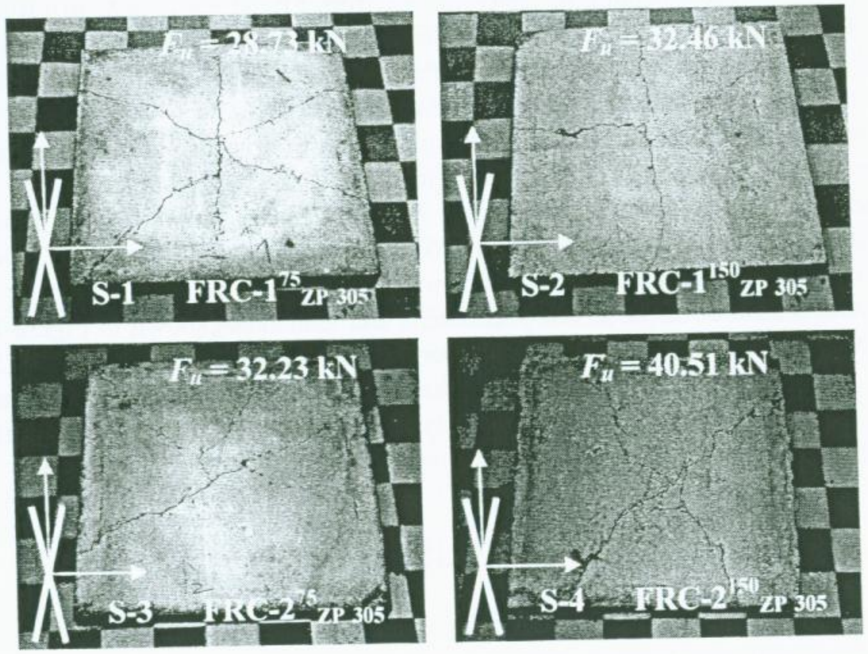

Photo 3: Crack pattern of steel fibre reinforced concrete slabs

Effect of concrete strength on the structural performance of steel-fibre reinforced concrete slabs

Cracking load as well as failure load of steel fibre reinforced concrete slabs as a function of concrete strength measured on 240×100×100 prims (f_c), the Dramix® ZP 305 hooked-end steel fibre content (75 kg/m^3 and 150 kg/m^3) and the concrete compositions (FRC-1 and FRC-2) are represented in Figure 10 and Figure 11. Dotted and normal lines indicate cracking load and failure load on both diagrams, respectively. Vertical dotted lines indicate the steel-fibre reinforced concrete slabs, S-1, S-2, S-3 and S-4, respectively.

Diagrams indicate that structural performance of steel-fibre reinforced concrete slabs strongly depend on the steel fibre content and on the concrete composition as well. However, the tendencies of cracking or failure load effected by the fibre content and concrete compositions are not proportional to the compressive strength as shown in Figure 10 and in Figure 11.

Considering the same steel fibre content, 75 kg/m^3 or 150 kg/m^3, Figure 10 indicate that cracking as well as failure load increased by the increase of cement content, i.e. by the changing of concrete mix from FRC-1 (S-1, S-2) to FRC-2 (S-3, S-4). When 150 kg/m^3 steel fibres were applied in case of slab S-2 and S-4, 9.90% increment in concrete strength resulted 21% and 25% increment in cracking load and failure load, respectively. Otherwise, 12.6% increment in concrete strength yield to 10% and 12% increment in cracking and failure load by the use of 75 kg/m^3 steel fibres related to slab S-1 and S-3, respectively.

Further, for both concrete compositions, 75 kg/m^3 fibre content resulted lower cracking or failure load related to mixes containing 150 kg/m^3 steel fibres, even if the concrete strength increased as shown in Figure 11.

The main reason of the observed phenomena and tendencies shown in Figure 10 and in Figure 11 may lie in the higher porosity of concrete mix containing 150 kg/m^3 steel fibre. However, despite of the lower concrete strength of mixtures made with 150 kg/m^3 steel fibre, this large fibre dosage increased both the cracking and failure load as well, related to the mixtures containing 75 kg/m^3.

CONCLUSIONS

Based on the experimental observations related to the structural behaviour of steel-fibre reinforced concrete slabs in bending, the following conclusions can be made:

A) *New test method* as well as *test set-up* were developed for bending test of two-way type fibre reinforced concrete slabs.

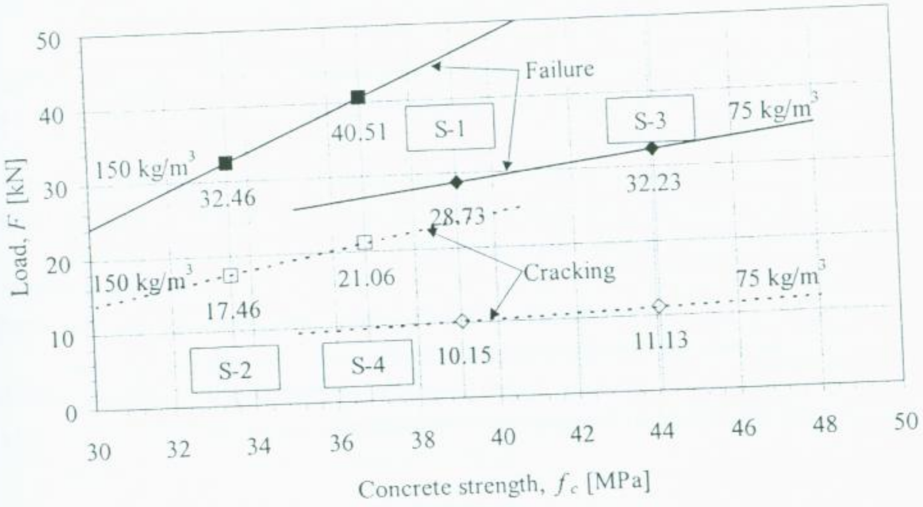

Figure 10: Cracking load as well as failure load of steel fibre reinforced concrete slabs as a function of the concrete strength and Dramix® ZP 305 hooked-end steel fibre content. Dotted lines and continuous lines indicate the cracking load and failure load, respectively.

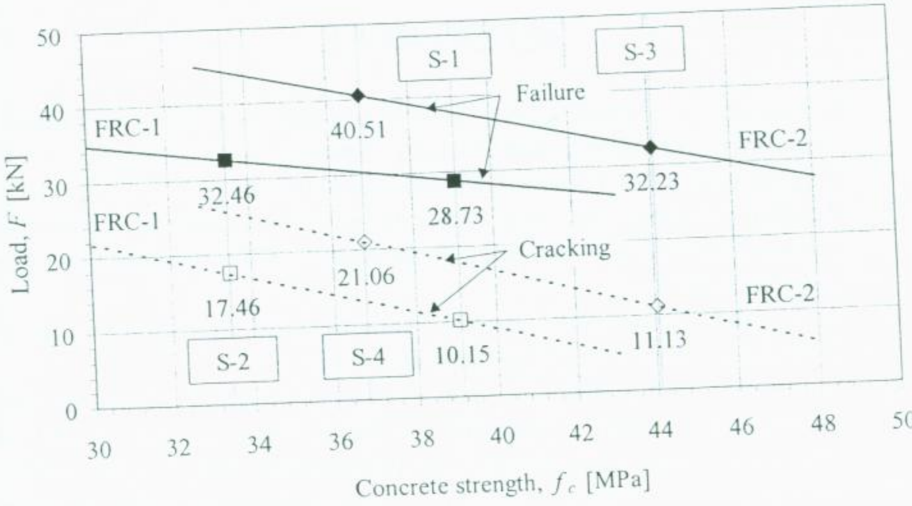

Figure 11: Cracking load as well as failure load of steel fibre reinforced concrete slabs as a function of the concrete strength and the concrete compositions (FRC-1 and FRC-2). Dotted lines and continuous lines indicate the cracking load and failure load, respectively.

B) *Cracking load* of steel-fibre reinforced concrete slabs are strongly effected by the applied fibre content and the used concrete type as summarised in Table 5.

C) *Failure load* of steel-fibre reinforced concrete slabs are also strongly effected by the applied fibre content and the used concrete type as summarised in Table 5.

D) *Deflection measured at cracking load* of steel-fibre reinforced concrete slabs are strongly effected by the applied fibre content and the used concrete type as summarised in Table 6.

E) *Deflection measured at failure load* of steel-fibre reinforced concrete slabs are strongly effected by the applied fibre content and the used concrete type as summarised in Table 6.

F) *Significant post cracking behaviour* was observed after cracking which was proportional to the applied fibre content.

ACKNOWLEDGEMENT

Author wish to thank for the financial support by the Hungarian Research Foundation (OTKA) Grants Nr. T025647 and Nr. F025621.

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