Fracture mechanics for SFRC Pavement

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Summary

An extensive experimental research on industrial pavements made of Steel Fibre Reinforced Concrete (SFRC) is presented herein. Seven full scale slabs on grade have been tested. In order to reproduce a Winkler subgrade, the slabs were placed on several steel springs. Structural response of slabs with fibres having different geometries and different volume fractions are compared. A slab in plain concrete and a slab reinforced with a traditional steel welded mesh have been tested as reference specimens. Numerical simulations based on Non Linear Fracture Mechanics (NLFM) have been carried out in order to simulate the slab behaviour. The numerical results predict well the actual behaviour of SFRC slabs on grade and NLFM can be usefully adopted for design purposes because considers well the fibre contribution after cracking of the concrete matrix.

Keywords: Pavements, Fibre Reinforced Concrete, Fibres.

1. Introduction

Slabs on grade represent one of the main applications of Steel Fibre Reinforced Concrete (SFRC). In these structures fibres can totally substitute the conventional reinforcement (rebars or welded mesh) with significant advantages in terms of toughness and strength under static and dynamic loads. Furthermore, fibres can reduce cracking due to thermal or shrinkage effects. The use of fibre reinforcement is often economically convenient with respect to conventional reinforcement due to reduction of labour costs and time to check the correct placement of the reinforcement.

At present there is still a lack of design rules for SFRC structures. As a consequence, engineers usually design slabs on grade by adopting the same rules that are valid for concrete with conventional reinforcement and are based on the elastic behaviour of the slab. However, this approach is not correct since post-cracking behaviour of SFRC is markedly different from concrete with conventional reinforcement. In fact, the post-cracking behaviour of SFRC is a markedly non-linear behaviour and is softening with the volume fraction of fibres often used in practice (V_f=0.3÷0.6%; Fig. 1a); the conventional reinforcement keeps an (almost) linear behaviour (with a lower stiffness with respect to the uncracked stage) until the reinforcement yields (Fig. 1b).

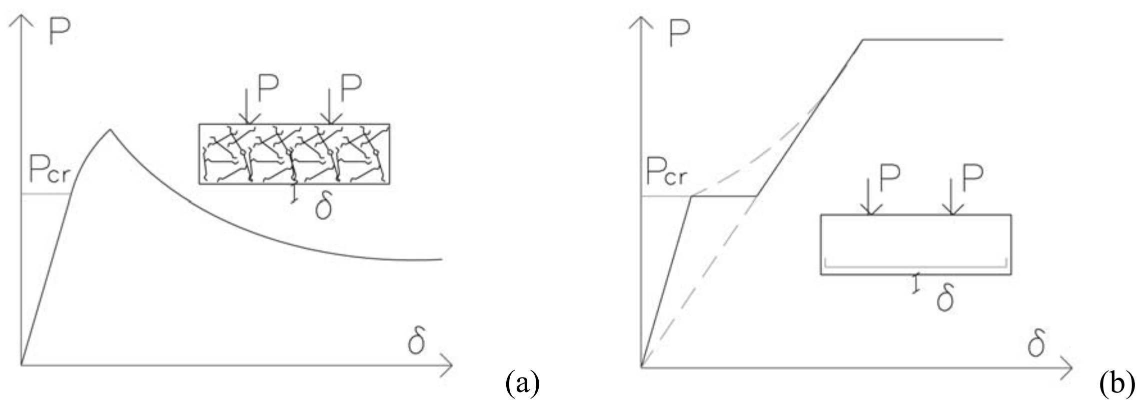


Fig. 1 Typical response of a bending test on a SFRC beam (a) and on a r.c. beam (b).

Therefore, SFRC pavements require new or improved design rules to consider the efficiency of SFRC. Only few results are available in the literature such as the well known slabs tested from Falkner and co-workers [1]. Other interesting experimental results were obtained by Beckett [2] and Kukreja [3] while earlier experimental results from the Authors were published in [4].

In the present paper results of an extensive experimental research program on SFRC slabs on grade are presented. The behaviour of slabs placed on an elastic subgrade is considered herein with regard to both serviceability and ultimate limit states. The slabs are subjected to a single point load in the slab centre.

The experimental tests have been modelled by means by a FE analyses based on Non Linear Fracture Mechanics.

2. Experimental program

The behaviour of slabs on grade was experimentally studied on full-scale specimens: seven slabs having a square geometry with a side of 3 m and a thickness of 0.15 m were tested. The experimental model aims to reproduce a portion of pavement between joints.

A reference slab (P0) was cast without any reinforcement; five slabs were made with concrete reinforced with a different volume fraction of fibres having different geometries. Finally, a slab (P6) reinforced with 8@200x200 mm steel mesh at the bottom layer was also tested (this slab was also reinforced under the load point to avoid punching failure).

Two different types of hooked steel fibers have been adopted in the SFRC (Fig. 2):

- 50/1.0 fibers having a length (l_f) of 50 mm and a diameter (ϕ_f) of 1 mm (aspect ratio= l_f/ϕ_f =50);
- 30/0.6 fibers having a length (l_f) of 30 mm and a diameter (ϕ_f) of 0.6 mm (aspect ratio=50).

Fig. 2 Fiber adopted for casting the slabs.

The slabs were made of a normal strength concrete (C25/30) typical for pavement applications. The slump of the fresh concrete was higher than 150 mm for all the slabs. Table 1 shows the average values of compressive strength ($f_{c,cube}$), measured from cubes having a side of 150 mm and determined at the same day the slabs were tested. The volume fraction of fibres introduced in the slabs is also shown in Table 1 (slab P0 is made of plain concrete).

Table 1 Main results from the slab tests.

Slab	$f_{c,cub}$ (MPa)	50/1.0 ($\%_{vol}$)	30/0.6 ($\%_{vol}$)	Traditional reinforcement	Exp. ultimate load (MPa)	Num. ultimate load (MPa)	Num. Crack. load (MPa)
P0	35.9	-	-		177.0	183.0	46.7
P1	30.4	0.38[(a)]	-		246.2	245.0	44.4
P2		0.38[(b)]			238.6	248.5	46.7
P3	33.1	0.57[(a)]			247.6	227.8	49.5
P4	35.2		0.38		265.0	231.9	50.1
P5	36.1		0.38		258.6	213.9	46.8
P6	34.2	-	-	8@200x200 mm	387.5	-	-

(a) fibre 50.1.0.
(b) fibre 50.1.0B.

The fracture properties of the materials have been determined by four point bending tests on notched beams (150×150×600 mm), according to the Italian Standard [5]. The bending tests were carried out by using a close-loop hydraulic machine (Instron) with the crack opening displacement as feedback control.

In order to reproduce an elastic (Winkler) soil, the slabs were placed on small steel springs (Fig. 3a) that were designed to simulate a typical subgrade for pavements (k=0.08 N/mm^3). The springs were obtained through small steel plates supported along the border (Fig. 3c); each spring was tested in order to verify the design stiffness. The target subgrade stiffness was obtained by placing the springs at a distance of 375 mm in both directions. A thin layer of high-strength mortar was put between the springs and the slab to compensate the out-of plane deformations of the slab due to curling (Fig. 3d).

The load was applied in the centre of the slab by means of a hydraulic jack (Fig. 3b). A 1000 kN load cell was placed under the jack and 6 Linear Variable Differential Transformers (LVDTs) were used to measure the vertical displacements in different locations of the slab (Fig. 3b).

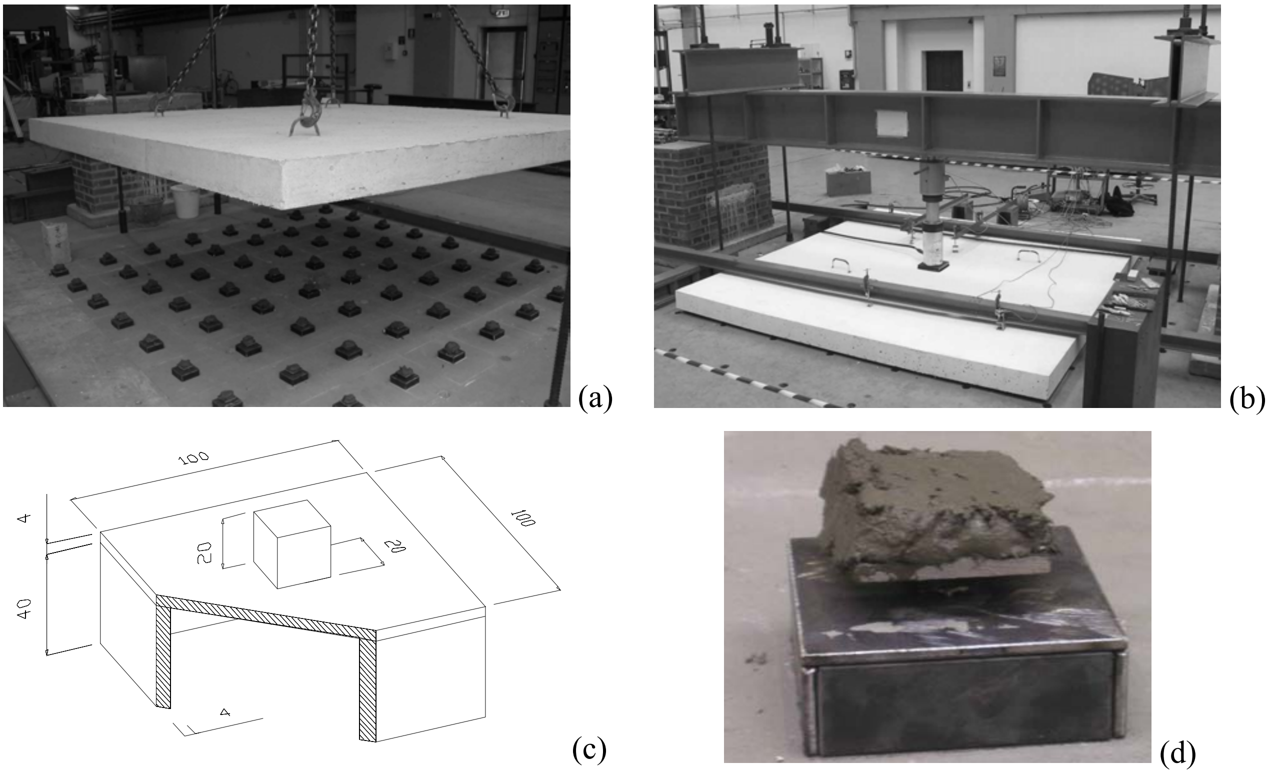


Fig. 3 Spring position simulating the Winkler soil (a), experimental set-up (b), steel spring for simulating the elastic subgrade (c, d).

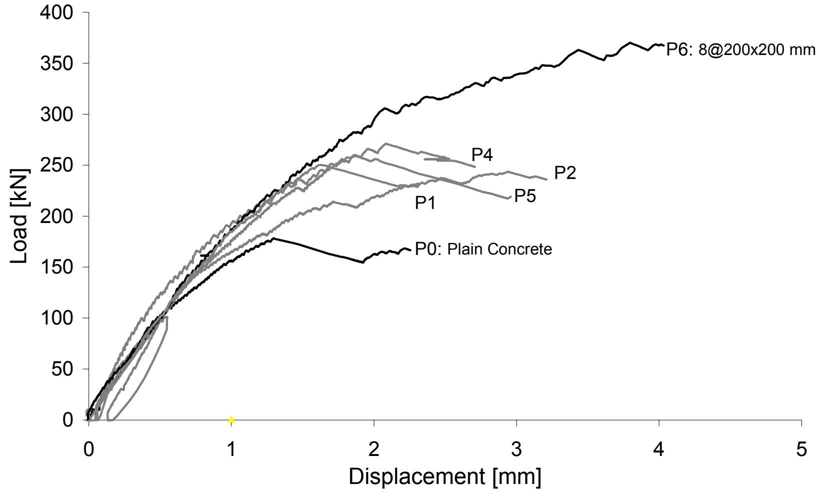
3. Experimental results

The seven slabs were tested up to failure; the ultimate load was conventionally reached when two main cracks developed up to the slab border and a collapse mechanism occurred. Afterwards, the load could still increase because of the subgrade stiffness.

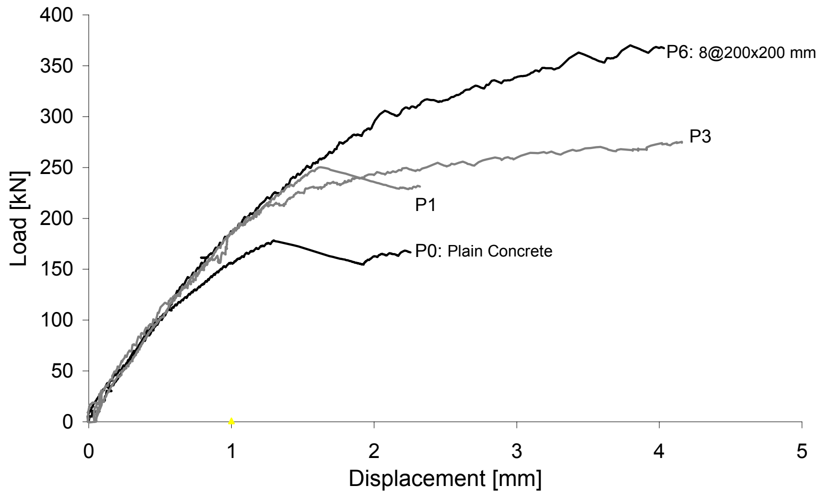
Figure 4 shows the experimental load-displacement (of the slab centre) curves. The results are presented herein by comparing slabs with fibres having the same aspect ratio and different lengths (Fig. 4a) and different contents (Fig. 4b). In all the graphs the curves obtained from slab P0 (without any reinforcement) and slab P6 (with conventional reinforcement) are also plotted. The values of the ultimate loads for each slab are reported in Table 1. Figure 4a shows that slabs with smaller fibres have a lightly higher ultimate load since there is a higher number of these fibres in the cracked section and smaller fibres may be better distributed in the structure. Figure 4b shows that the presence of a higher fibre content does not increase significantly the ultimate load but provide a more stable behaviour after cracking.

Slab P0 without any reinforcement has not only a lower ultimate load but also a more brittle behaviour (the slab fell apart in 4 pieces at ultimate). Slab P6, with conventional reinforcement, has a higher ultimate load since all the reinforcement is concentrated at the bottom layer where the tensile stresses are present in the experiment. Different is the case of slabs in practice where tensile stresses are present even at the top surface while the upper reinforcement can hardly be kept close to the top surface during casting operations.

The final crack pattern evidences the collapse mechanism, similar for slab P0 and all the SFRC slabs, and characterized by two main cracks developed along the median lines (Figs. 5a,b). In the slab with conventional reinforcement many radial cracks are visible; however, the main cracks developed along the diagonal and median lines (Fig. 5c).

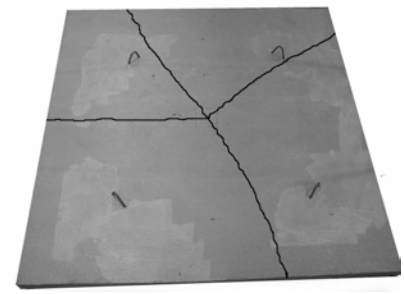


(a)



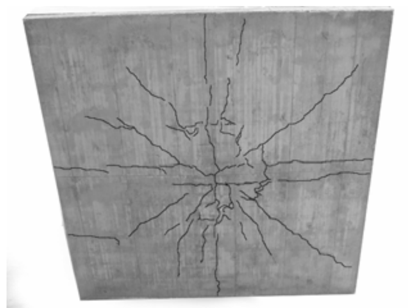
(b)

Fig. 4 Load versus central displacement for fibre with a different geometry (a) and a different fibre content (b).



Slab P0 (a)

Slab P4 (b)



Slab P6 (c)

Fig. 5 Final crack pattern for slabs P0 (a), P4 (b) and P6 (c).

4. Numerical analysis

Since fibres start working after cracking of the concrete matrix, and the material response is no longer linear, SFRC slabs on grade can be better analysed by adopting methods based on Non Linear Fracture Mechanics (NLFM) [6]. This approach allows to simulate the crack development in the slab that is stable because of the stress redistribution along the cracked surfaces. This allows a load increase during crack propagation until a collapse mechanism occurs; the ultimate load may be 4-5 times the first crack load [4]. By doing so, the residual strength of cracked concrete, which is significant for SFRC, is taken into account in the constitutive laws.

The numerical analyses of SFRC slabs on grade can be performed by adopting FE commercial programs that include NLFM based on a discrete crack or a smeared crack approach. The FE program adopted in the present paper was MERLIN [7] that uses discrete cracks and considers the structure as a number of linear elastic subdomains linked by interface elements. The latter simulate the cracks whose position must be known a priori. Interface elements initially connect the subdomains (as rigid links) and start activating (i.e. cracks start opening) when the normal tensile stress at the interface reaches the tensile strength of the material. Afterwards, the crack propagates and cohesive stresses are transmitted between the crack faces according to stress-crack opening (σ-w) laws (which are given in the input for the interface elements). These (σ-w) laws were obtained by performing an inverse analysis [8] from the four-point bending tests on beam specimens.

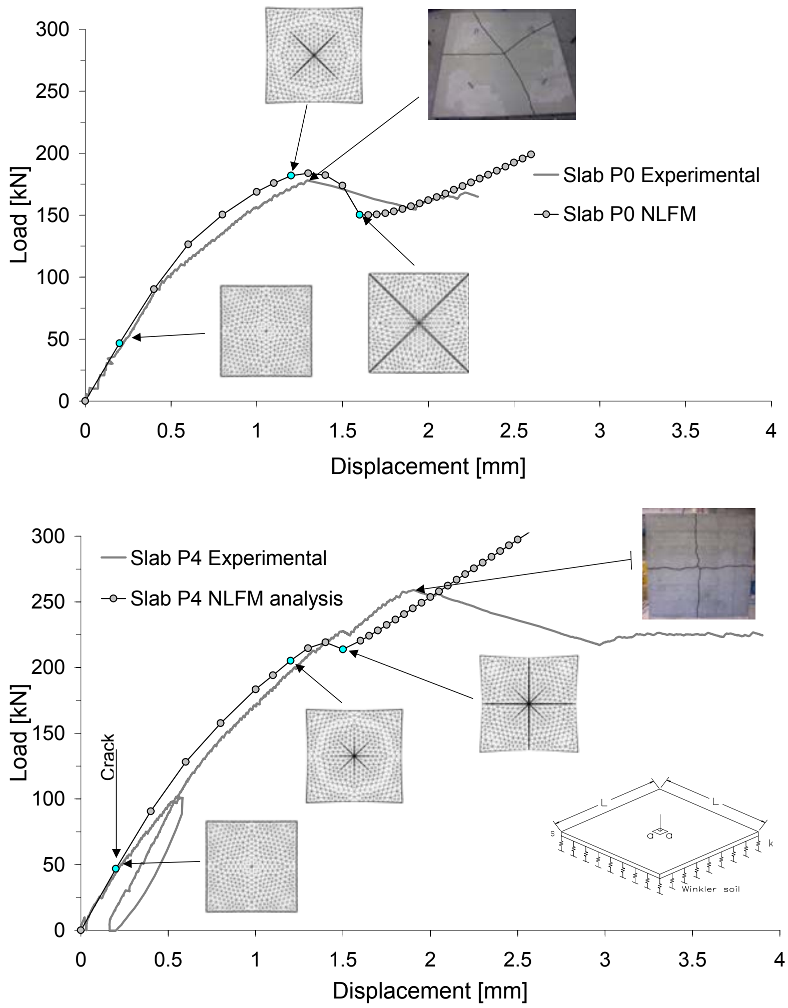


Fig. 5 Comparison of numerical and experimental results for Slab P0 (a) and Slab (P4)

The tensile strength and the elastic moduli were experimentally determined from cylinders (Tab. 1). Table 2 shows the parameters of the post-cracking (softening) law that was approximated as a bilinear law where the initial steeper branch represents the bridging effect of concrete between microcracks and the final long tail represents the fibre links between the crack surfaces. Parameters w_1 and s_1 represents the coordinates of the break point while w_c represents the critical (stress-free) crack opening [6]. Since all the slabs were made with the same concrete composition (but different batches), the first steeper branch was assumed the same for all the slabs.

The comparison between typical numerical and experimental results, as obtained from slabs P0 and P4, is exhibited in Figure 5 where the numerical crack development is also shown. It can be noticed that the numerical NLFM analyses provide a good approximation of the experimental behaviour both for the initial stiffness and for the ultimate load.

The numerical crack development is also shown in Figure 5. It should be observed the similar final crack pattern and the remarkable load increment in the SFRC slab after crack onset that is made possible by the remarkable toughness of SFRC and by the stress redistribution over the cracks.

Table 2 Parameters of the post-cracking law used for the numerical simulation of slabs P0 and P4.

Specimen	Fibre type	Volume fraction ($\%_{vol}$)	f_{ct} (MPa)	s_1 (MPa)	w_1 (mm)	w_c (mm)
P0	-	-	2.7	0.75	0.030	0.27
P4	30/0.6	0.38	2.7	1.2	0.025	8

5. Discussion and conclusion

The paper concern an extensive experimental program on full-scale slabs on grade reinforced with a small volume fraction of steel fibres. Results show that smaller fibres allow to slightly increase the ultimate load and that a higher volume fraction of fibres provides a more stable behaviour of the slab after cracking. Steel fibres allow to avoid the brittle collapse of slab without reinforcement and provide a remarkable slab strength. The latter was lower that the one obtained from the slab with conventional reinforcement (8@200x200 mm steel mesh) that was correctly placed close to the bottom surface of the slab. This may not occur in practice where tensile stresses are also present in the top surface where the welded mesh (or rebars) can hardly stay during concrete placement.

Structural analyses of the slabs based on Non Linear Fracture Mechanics allow to better simulate the actual slab behaviour; by using this method, the load increase during the crack development can be accounted for, until a collapse mechanism occurs. The NLFM approach has been validated by comparing the numerical and the experimental results.

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