EXPERIMENTAL BEHAVIOR OF MESH REINFORCED SHOTCRETE AND STEEL FIBER REINFORCED SHOTCRETE PANELS.

Joaquim António Oliveira de Barros

ABSTRACT

The existent experimental data reveal that the steel fiber reinforcement improves the energy absorption capacity, the fatigue and impact strength and the cracking behavior of the cement based materials. These material benefits increase the structural ductility, safety and durability.

Apart from these material-structural enhancements, the applications made by the steel fiber reinforced shotcrete (*SFRS*), like the tunnel linings, have proven that *SFRS* can provide a viable technical, economical and practical alternative to conventional mesh reinforced shotcrete. The loss of concrete and the construction time decrease when using *SFRS* technology.

In order to compare the behavior of the conventional mesh reinforced shotcrete and *SFRS* it is current to carry out experimental tests on panels of these materials. In this article, the tests performed on panels of concrete reinforced with wire mesh and on panels reinforced with three different percentages of hooked-ends steel fibers (25, 30 and 35 kg/m^3 of fibers) are discribed. All the panels were manufactured by shotcrete technology in the site plant of the Alqueva dam (Portugal). The main results are presented and analyzed.

Keywords: Ductility, Flexural panel test, Rebound, Shotcrete, Steel fibers, Toughness

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1 - INTRODUCTION

Steel fiber reinforced shotcrete (*SFRS*) is a cement-based material containing discontinuous discrete steel fibers that is pneumatically projected at high velocity onto a surface (ACI 506 1984, ACI 506.2 1990). Existing shotcrete equipment has been used to apply *SFRS* with little or no modifications (ACI 506.R 1990, Vandewalle 1991). The *SFRS* can be placed by the dry or wet process. Several factors influence the selection of the applying process, such as: equipment costs, experience of the Contractor, time to place, space at application site for the equipment, dust, skill requirements, rebound, material and energy consumption, material properties required (Vandewalle 1991).

Shotcrete reinforced with wire mesh has been successfully replaced by *SFRS* because the time to place and the rebounded material are decreased, the rupture mode can be more ductile, the safety is increased and the material properties are improved (Morgan and Mowat 1982, Holmgren 1983).

The material properties most improved by fiber reinforcement are the following: ductility, toughness, flexural strength, impact resistance and fatigue resistance (ACI 544.1R 1982, ACI 506 1984, Balaguru and Shah 1992). These material enhancements have turned attractive the use of *SFRS* in several applications namely: mine and tunnel lining, rock slope stabilization, shell structures, refractory lining, dam construction, repair of surfaces and fire protection coatings (ACI 506 1984, Morgan and McAskill 1984, Burgun and Guillebon 1987, Vandewalle 1991, Balaguru and Shah 1992).

The toughness and the ductility are related to the material energy absorption capacity. Since this property is the most benefited by fiber reinforcement, several tests have been proposed to measure this property (ACI 544.2R 1989). For *SFRS* to be applied in underground constructions, a panel flexural test was also proposed (EFNARC 1993). This test simulates one of the most current failure modes that can occur in these applications (Holmgren 1983).

In the present work the flexural tests carried out with shotcrete panels reinforced with wire mesh and reinforced with steel fibers are described. The results obtained are discussed.

2 - CHARACTERISTICS OF THE PANELS

The panels were fabricated by the Contractor, in the site plant of the Alqueva dam, at Alentejo, Portugal, by shotcreting in vertical position against wood molds. The panel’s reinforcement and the date of panel’s fabrication are included in Table 1. These data were given by the Contractor.

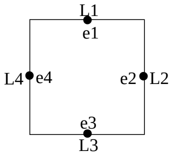
Table 1 - Characteristics of the panels supplied by the Contractor.

Panel reinforcement	Nº of panels	Manufacture date
25 kg/m^3 of fibers	4	1997/07/28
30 kg/m^3 of fibers	4	1997/07/28
35 kg/m^3 of fibers	3	1997/07/28
Wire mesh	4	1997/07/29

The fibrous panels were reinforced with hooked-ends ZP30/.50 (length of 30 mm and diameter of 0.5 mm) Dramix steel fibers (Bekaert 1991). According to the Contractor, the manufacturing, the curing and the transport conditions from the Alqueva dam to the Laboratory of Minho University have followed the recommendations of the ACI Committee 506 (1984, 1990). After arrived at the Laboratory, the panels remained in the natural environment of the Laboratory (65% RH and 20ºC) until three days before testing.

According to the recommendations of the European Federation of National Associations of Specialist Contractors and Material Suppliers for the Construction Industry (EFNARC, 1993), the panels must have 600x600x100 mm dimensions (Figure 2). The main characteristics of the panels, measured in laboratory, are presented in Table 2. The panel edges are designated by L1, L2, L3 and L4, and the panel thickness evaluated at midside of the panel edges are denominated by e1, e2, e3 and e4.

Table 2 - Panel characteristics measured in Laboratory.

Panel	Panel reference	Weight (Kg)	Dimensions (mm) 							
			L1	L2	L3	L4	e1	e2	e3	e4
25 Kg/m^3 of fibers	P25 - 1	88.8	591	604	599	604	110	112	114	116
	P25 - 2	95.2	604	600	593	599	114	120	119	115
	P25 - 3	87.9	604	604	610	602	110	110	108	110
	P25 - 4	87.8	605	606	610	605	109	105	110	105
30 Kg/m^3 of fibers	P30 - 1	83.3	602	607	606	605	103	105	104	102
	P30 - 2	93.8	602	604	604	605	122	119	108	121
	P30 - 3	99.9	598	606	600	604	110	109	112	115
	P30 - 4	84.0	601	603	604	606	105	105	105	105
35 Kg/m^3 of fibers	P35 - 1	91.3	602	602	602	595	115	115	113	114
	P35 - 2	101.0	603	604	604	603	128	125	123	132
	P35 - 3	102.5	605	610	609	605	123	122	125	123
Wire mesh	Pwm - 1	102.0	602	598	600	598	129	125	122	124
	Pwm - 2	97.0	603	599	601	602	117	118	118	121
	Pwm - 3	92.8	603	603	600	603	114	113	114	112
	Pwm - 4	87.0	596	607	600	601	102	106	110	106

The surface of the panels turned over to the nozzleman presented geometric irregularities of dimension less than 10 mm. According to the EFNARC (1993), the rough surface of the panel shall be the one supported in the test rig. In order to guarantee a correct support of the panel, these surfaces were capped by a mortar with sand:cement ratio of 3:1.

Analyzing the data in Table 2 it can be conclude that the dimensions of the edges of the panels meet approximately the recommended values. However, the thickness of the panels is always higher than the recommended value, due to the surface layer applied for capping.

The reinforcement used in one series of panels was a mesh of 100 × 100 mm with wires of three millimeters in diameter. After tests, it was verified that the wire mesh was located between 20 to 30 mm from the rear panel surface, i.e., the surface facing the mold.

The panels were immersed in potable water for at least three days before testing. The panels were taken from the water and remained in the natural environment of the Laboratory one day before testing.

3 - EQUIPMENT AND TEST PROCEDURES

The energy absorption capacity can be evaluated from the relationship between the load and the displacement at panel center, until a given displacement. According to the EFNARC (1993), this displacement is 25 mm, which is well above the displacement corresponding to the peak load. After peak load a structural softening occurs, where the load bearing capacity decreases with increasing the displacement. In order to perform stable tests in materials with strain softening (Hordijk 1991), the test rig must has enough rigidity and the equipment should be servo-controlled. This equipment is not available in most of Laboratories because it is very expensive. However, with some appropriate procedures, stable tests can be carried out with conventional equipment. In the present work the tests were performed with a conventional equipment. The accuracy of the results is suficient for the objectives of this research work.

Figure 1 shows the structure supporting the test set up. It consists of HEB 200 steel profiles, setting up a frame which offers reaction to the actuator. The contour of a panel is supported on thick steel cylinders which are placed in UNP 100 steel profiles supported on the main frame, as it is schematically represented in Figure 2. A center point load was applied through a contact surface of 100 × 100 mm.

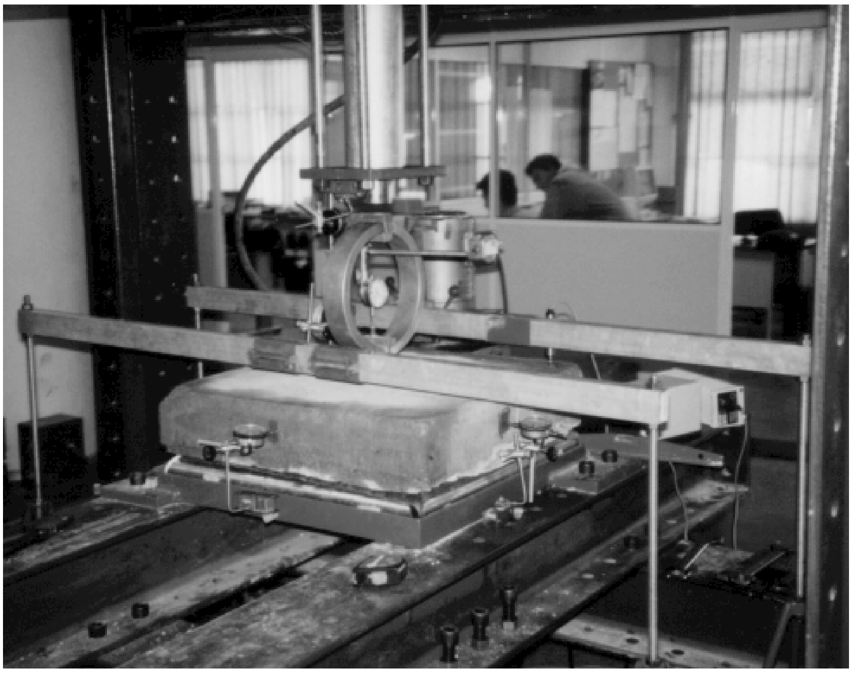


Figure 1 - Set-up for the panel test.

The load was supplied by a hydraulic actuator. The rate of deflection recommended by EFNARC is 1.5 mm/minute. In order to fit this rate of deflection, a displacement transducer was attached to the piston of the actuator. The rate of deflection was adjusted according to the rate of deflection read in this transducer, even when structural softening had occured. The load was measured by a load ring with a maximum capacity of 100 kN. The displacement at center of the panel was measured using a transducer attached to a frame fixed to the exterior of the supporting structure, in order to avoid the inclusion of extraneous displacements (see Figure 1).

If the actuator is not perfectly orthogonal to the panel, horizontal component of forces can be introduced during a test. These forces dissipate uncounted energy. To control the occurrence of the horizontal component of forces, in-plane movement of the panel middle surface was measured with displacement transducers applied at panel vertical faces (see Figure 1). In all tests the in-plane movement of the panel middle surface was approximately symmetric. Therefore, it was not introduced horizontal forces of significant value. The displacements obtained in these transducers are due to the expansibility of the cracked concrete layers. This expansibility is significant because in the bottom surface it was attained a crack opening of 20 to 30 mm, at the end of a test. The measurements were registered every five seconds.

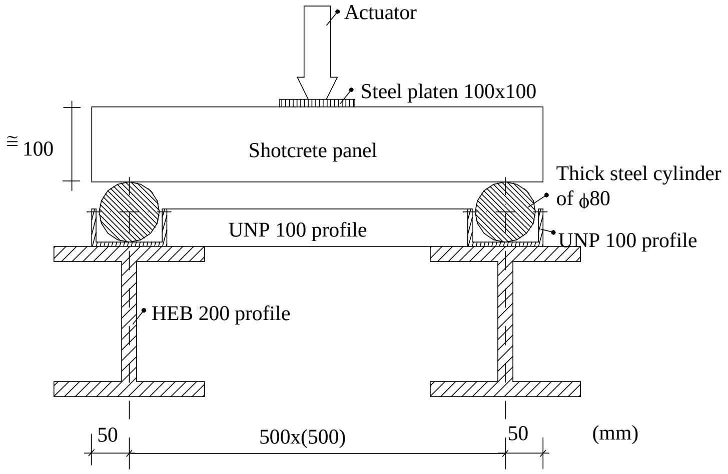


Figure 2 - Schematic representation of the panel support structure.

4 - TEST RESULTS AND DISCUSSION

The relationship between the load and the displacement at panel center and the relationship between the energy and the displacement at panel center are shown in Figure 3 for the series of panels tested. The energy was evaluated from the following expression:

$$E_\delta = \sum_{i=1}^{n_\delta} \frac{F_{i+1} + F_i}{2} \left(\delta_{i+1} - \delta_i \right) \tag{1}$$

where E_δ is the energy dissipated until δ displacement value, n_δ is the number of scan readings until this displacement, F_{i+1} and F_i are the forces at the scan numbers *i+1* and *i*, and δ_{i+1}, δ_i are the corresponding displacements.

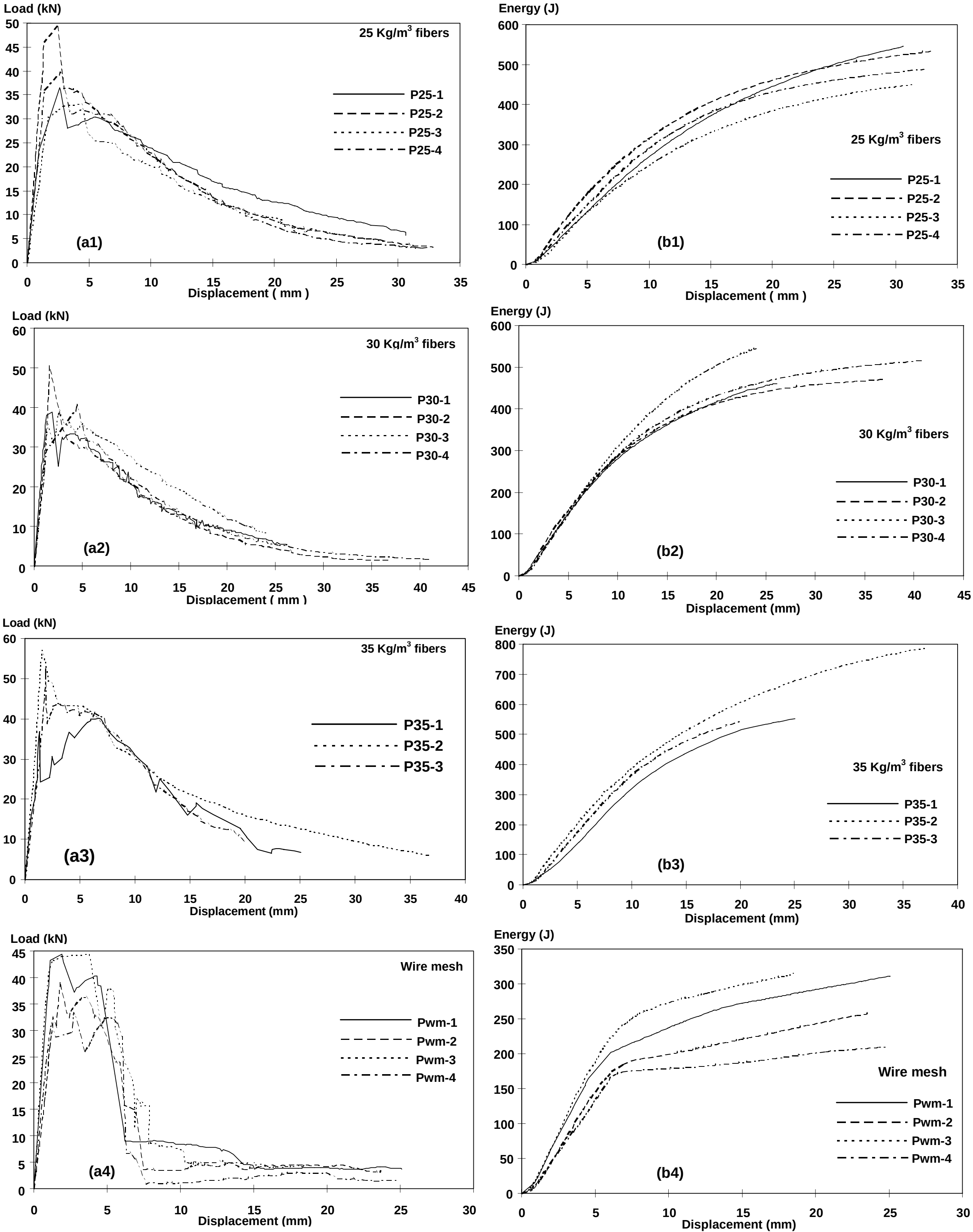


Figure 3 - Load-displacement relationship for the series of panels reinforced with 25 (a1), 30 (a2) and 35 Kg/m^3 (a3) of fibers and with wire mesh (a4). Energy-displacement relationship for the series of panels reinforced with 25 (b1), 30 (b2) and 35 Kg/m^3 (b3) of fibers and with wire mesh (b4).

Table 3 includes the load bearing capacity of the panels and the average load bearing capacity of the series of panels. It is noted that the load bearing capacity of the panels increases with the fiber content. The load bearing capacity of the panels reinforced with the minimum fiber content (25 Kg/m^3) is quite near the load bearing capacity of the panels reinforced with wire mesh.

Table 3 - Panel load bearing capacity and average load bearing capacity of the series of panels.

Panels reinforced with	Reference	Load bearing capacity, $F_{\max}$ (kN)	Average load bearing capacity, $\overline{F}_{\max}$ (kN)
25 Kg / m^3 of fibers	P25 - 1	36.3	39.5 (s=6.1)$^{(1)}$
	P25 - 2	49.3	
	P25 - 3	32.8	
	P25 - 4	39.7	
30 Kg / m^3 of fibers	P30 - 1	38.5	42.0 (s=4.8) $^{(1)}$
	P30 - 2	50.1	
	P30 - 3	38.8	
	P30 - 4	40.4	
35 Kg / m^3 of fibers	P35 - 1	39.9	50.8 (s=7.8) $^{(1)}$
	P35 - 2	57.1	
	P35 - 3	55.5	
Wire mesh	Pwm - 1	44.1	39.9 (s=4.7) $^{(1)}$
	Pwm - 2	38.7	
	Pwm - 3	44.1	
	Pwm - 4	32.7	

(1) Standard deviation

In several research works it has been shown that rebound of fibers is higher than rebound of matrix, resulting in a lower fiber content in the composite in place. Fiber retention between 40% to 70% have been reported (Parker and al. 1975, Ryan 1975, Rose et al. 1981). If an average fiber retention value of 55% in the panels tested is admitted, the effective fiber content in panels reinforced with 25 Kg/m^3 of fibers (before gunning) will be 13.7 Kg/m^3, which is slightly higher than the steel content of the panels reinforced with wire mesh (11 Kg/m^3). The relationship between $\left(\overline{F}^{\,f}_{\max} - \overline{F}^{\,wm}_{\max}\right) \big/ \overline{F}^{\,f}_{\max} \times 100$ and the fiber content is represented in Figure 4, where $\overline{F}^{\,f}_{\max}$ and $\overline{F}^{\,wm}_{\max}$ are the average load bearing capacity of the series of fibrous panels and the series of panels reinforced with wire mesh, respectively.

The energy dissipated until the displacement of 15, 20, 25 and 30 mm is included in Table 4. According to the EFNARC (1993), the energy shall be evaluated until the displacement of 25 mm. In panels failed before this displacement is attained, the EFNARC document recommends that the energy dissipated until failure shall be also evaluated. Therefore, Table 4 includes also a column with the energy dissipated until panel failure. From the results in Table 4 it can be pointed out that, the energy dissipated increases with the fiber content. The relationship between $\left(\overline{E}^{\,f} - \overline{E}^{\,wm}\right) \big/ \overline{E}^{\,f} \times 100$ and the fiber content is represented in Figure 5, where $\overline{E}^{\,f}$ and $\overline{E}^{\,wm}$ are the energy dissipated until the displacement of 25 mm of the series of fibrous panels and the series of panels reinforced with wire mesh, respectively. It can be conclude that with the increment of fiber content the increase of the energy absorption capacity is more significant than the increase of the load bearing capacity.

Table 4 - Energy absorption capacity until the displacement of 15, 20, 25, 30 mm and until panel failure.

		Energy until the displacement of					
Panels reinforced with	Panel reference	15 mm (J)	20 mm (J)	25 mm (J)	Average (J)	30 mm (J)	Failure (J)
25 Kg / m^3 of fibers	P25 - 1	372	445	500	470 (s=32)$^{(1)}$	541	-
	P25 - 2	406	462	497		523	-
	P25 - 3	330	385	421		446	-
	P25 - 4	380	432	461		482	-
30 Kg / m^3 of fibers	P30 - 1	362	416	456	478 (s=41) $^{(1)}$	460	-
	P30 - 2	366	414	442		459	-
	P30 - 3	425	504	547		547	547
	P30 - 4	377	432	467		489	-
35 Kg / m^3 of fibers	P35 - 1	436	514	552	591 (s=62) $^{(1)}$	552	552
	P35 - 3	513	606	678		734	-
	P35 - 4	478	543	543		543	543
Wire mesh	Pwm - 1	272	292	311	273 (s=43) $^{(1)}$	311	311
	Pwm - 2	221	243	258		258	258
	Pwm - 3	299	314	314		314	314
	Pwm - 4	188	202	210		210	210

(1) - Standard deviation

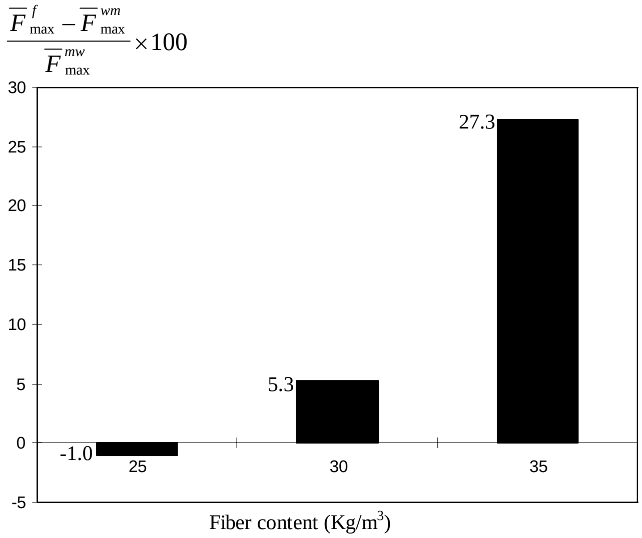


Figure 4 - Comparison of the average load bearing capacity between fibrous panel series ($\overline{F}^{f}_{\max}$) and panel series reinforced with wire mesh ($\overline{F}^{wm}_{\max}$).

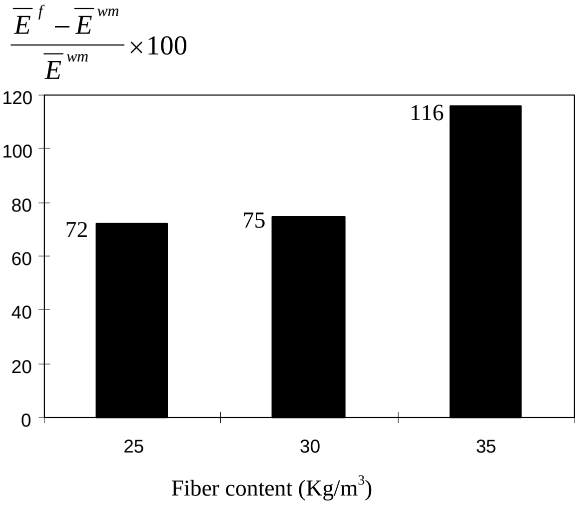


Figure 5 - Comparison of the energy absorption capacity until the displacement of 25 mm between fibrous panel series ($\overline{E}^{f}_{\max}$) and panel series reinforced with wire mesh ($\overline{E}^{wm}_{\max}$).

During the test, the panel support conditions are changed. Until cracking, a panel is continuously supported in its contour. After cracks have crossed the panel supporting edges, the panel is supported only on small segments near the cracks, and the remainder panel contour is lifted up. Therefore, the panel structural behavior after macrocracking is dependent on the changes occured in the panel supporting conditions. If the number of cracks crossing the panel supporting edges increases, the effective dimension of the panel supports is also increased, and, consequently, a high residual load carrying capacity should be expected. Since the number of cracks increases with the fiber content (Barros 1995, Barros and Figueiras 1997), the load bearing capacity and the energy absorption capacity after cracking increase with the fiber content. These benefits are higher in structures of higher hiperstaticity, because a better stress redistribution is capable of a more diffuse crack pattern, which is proportional to fiber content.

Figure 6 shows typical crack patterns developed in the panel series.

5 - CONCLUSIONS

In this research work, flexural tests on panels reinforced with wire mesh ($A_{sx} = A_{sy} = 71$ mm^2/m equivalent to 11 Kg/m^3 of steel) and on panels reinforced with 25, 30 and 35 Kg/m^3 of hooked-ends Dramix ZP30/.50 steel fibers were carried out. The panels were manufactured using the shotcrete technology. Certain procedures were followed to ensure stable tests with conventional equipment. The relationship between the load (F) and the displacement at the center of the panel (δ) was obtained. After cracking it was verified that the load carrying capacity increases with the fiber content. The peak load of the series of panels reinforced with 35 Kg/m^3 of fibers is 27% higher than the peak load of the panels reinforced with wire mesh. The peak load of the panels reinforced with 25 Kg/m^3 of fibers is quite near that of the panels reinforced with wire mesh. More significant improvements were observed in the energy absorption capacity. This property was obtained from the $F - \delta$ relationship, being the area under this curve until a given deflection (25 mm according to the EFNARC document). For the panels reinforced with 35 Kg/m^3 of fibers the energy absorption capacity was 116% higher than the one obtained for the panels reinforced with wire mesh.

6 - ACKNOWLEDGMENTS

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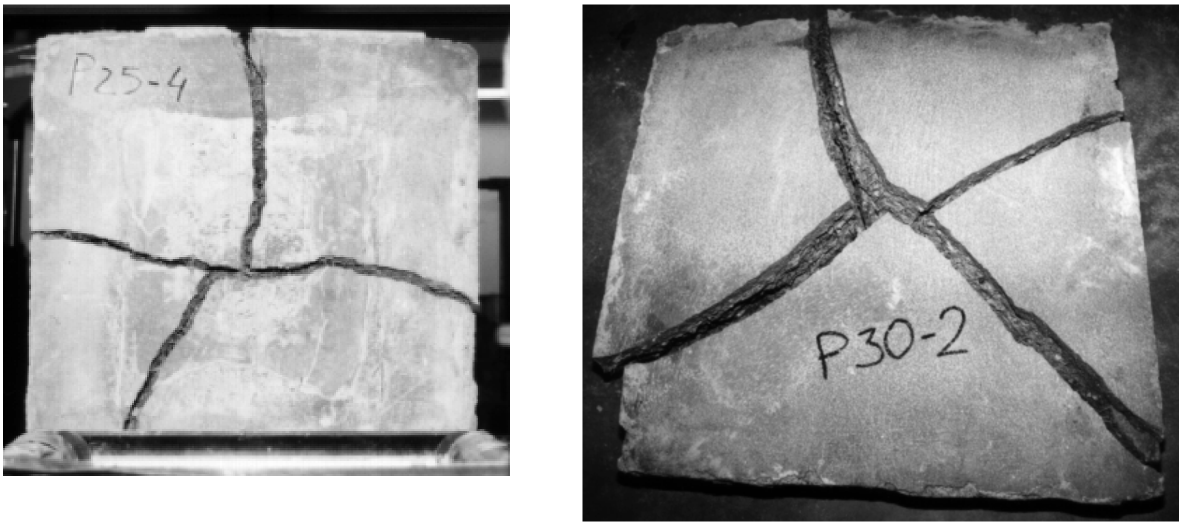
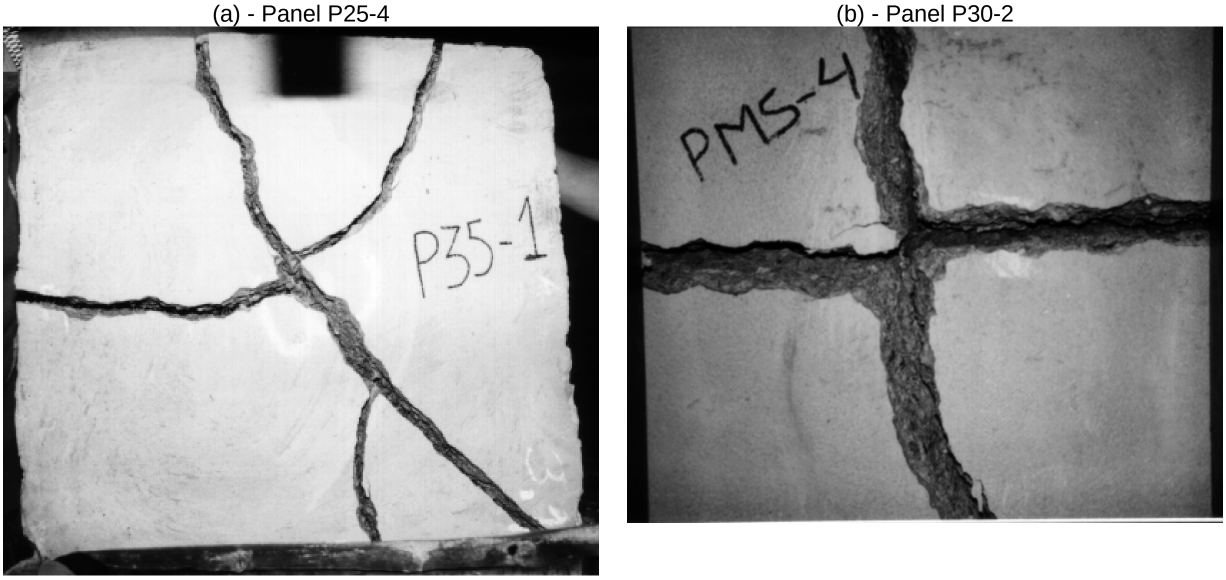


(a) - Panel P25-4 (b) - Panel P30-2



(c) - Panel P35-1 (d) - Panel Pwm-4

Figure 6 - Typical crack patterns of series of panels reinforced with 25 (a), 30 (b), 35 (c) Kg/m^3 of fibers, and with wire mesh (d).

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