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Comparative evaluation of steel mesh, steel fibre and high-performance polypropylene fibre reinforced shotcrete in panel test

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Abstract

In this study, experimental investigations were performed on steel mesh (SM), steel fibre (SF) and high-performance polypropylene fibre (HPPF) reinforced shotcrete (HPPFRS) panels to evaluate performance characteristics such as toughness, flexural ductility, energy absorption and load capacity. The panel tests, in accordance with European specification for sprayed concrete (EFNARC), were made on 18 prismatic specimens having the same mix designs and were cured for 28 days but reinforced with various fibres. In addition, the rebound characteristics of these mixes were determined to compare the actual in situ fibre contents.

Test results show that all reinforcements, including HPPFs that are low-modulus fibres, greatly improved the flexural ductility, toughness, and load-carrying capacity of the brittle matrix. It was seen that there was a positive synergy effect between steel and polypropylene fibre in hybrid fibre usage from a performance point of view. According to results, it can be concluded that a hybrid polypropylene-SF can be used alternatively instead of SM and monosteel fibre as a reinforcement in shotcrete applications to get better efficiency in mechanical properties of composite.

Keywords: Concrete; Composite; Fibre reinforcement; Fracture toughness; Panel test

1. Introduction

Shotcrete can be defined as "Mortar or concrete pneumatically projected at high velocity on to a surface" [1]. Steel-fibre reinforced shotcrete/concrete (SFRS/C) contains discontinuous discrete steel fibres (SFs) as a reinforcement. Since the early 1970s, when the first experimental work was undertaken with SFRS/C, it has been the subject of many field and laboratory studies [2–4] and is the focus of many current investigations [5–7]. In addition, it has been used extensively in most parts of the world for a wide variety of applications including new construction, in the repair and rehabilitation of older and deteriorated structures, in slope stabilization, as retaining walls for large excavations, and for tunnel lining, etc. [8–10]. Especially in underground construction, it has become more common to use SF reinforcement instead of steel-mesh reinforcement. In steel-mesh applications, the installation of steel mesh (SM) can be difficult, time consuming, hazardous and expensive. In addition, lining quality can be poor, i.e., no uniform bond between shotcrete and rock, forming low-quality shadow areas behind the wire, and badly placed reinforcement due to irregular mesh positions, etc. By contrast, fibres eliminate the need for conventional concrete reinforcing steel, welded wire mesh or the chain-link mesh, and this alone results in a significant enhancement of the ease of shotcrete placement. In addition, fibres impart toughness or energy-absorption capability to hardened shotcrete, resulting in improved deformability [11]. Additionally, SF-reinforced shotcrete (SFRS), having high ductility, provides homogeneous fibre reinforcement and strong bond to the surface [8].

It is important to compare the behaviour of SM-reinforced shotcrete (SMRS) with that of SFRS from a performance characteristic point of view. In addition, new materials like synthetic fibres have been also investigated to compare with steel fibre in shotcrete/concrete [12–17].

Synthetic fibres, e.g., high-performance polypropylene fibre (HPPF), which has been used to prevent plastic shrinkage cracks in fresh concrete, can be used at high addition rates to improve hardened concrete properties like toughness, flexural ductility, ultimate load capacity, etc.

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Toughness is the amount of energy that is absorbed before and after fracture. Ductility and high-fracture strains are also important characteristics of fibre-reinforced shotcretes (FRS) because the main reason for incorporating fibres in concrete and shotcrete is to impart ductility to an otherwise brittle material. In addition, fibre reinforcement improves the energy absorption and crack resistance of shotcrete [11]. With an increasing load on the composite, fibres will tend to transfer the additional stress to the matrix through bond stresses until they fail or pull out [18]. In this way, they enable shotcrete to continue to carry load after cracking, the so-called postcracking behaviour [8].

This study shows that the use of HPPF reinforcement in shotcrete, with a sufficient fibre content, can greatly improve flexural ductility, toughness, and ultimate load capacity and, therefore, it can be used with SF reinforcement, especially in tunnel applications.

2. Materials and experimental work

2.1. Materials

2.1.1. Cement

An ordinary Turkish Portland Cement (PC 42.5, corresponding to ASTM Type I) was used for the production of concrete mixtures.

2.1.2. Aggregates

A natural river sand having a particle size between 0 and 1 mm in 13% and a crushed stone having a particle size between 0 and 5 mm in 57% were used as fine aggregates. A sieve analysis of the fine aggregates in shotcrete is shown in Table 1. In addition, the crushed stone having a particle size between 5 and 12 mm was used as coarse aggregate in 30%. Table 2 shows the sieve analysis of the coarse aggregates.

2.1.3. Admixtures

The following admixtures were used in the shotcrete:

– Micro silica (a pozzolanic admixture)
– A high range water reducing admixture
– An accelerating admixture added at the nozzle

Table 1
Sieve analysis of fine aggregates in shotcrete

Sieve number	Cumulative percent passing	
	Fine aggregate (0–1)	Fine aggregate (0–5)
3/8 in. (9.5 mm)	100	100
No. 4 (4.75 mm)	100	95.7
No. 8 (2.36 mm)	98.4	62.7
No. 16 (1.18 mm)	95.3	37.5
No. 30 (600 μm)	87.8	24.8
No. 50 (300 μm)	34.3	2.8
No. 100 (150 μm)	11.3	2.0

Table 2
Sieve analysis of coarse aggregate in shotcrete

Sieve number	Cumulative percent passing
	Coarse aggregate
1 1/2 in. (37.5 mm)	100
1 in. (25.0 mm)	100
3/4 in. (19.0 mm)	100
1/2 in. (12.5 mm)	98.1
3/8 in. (9.5 mm)	64.9
No. 4 (4.75 mm)	2.7
No. 8 (2.36 mm)	0

2.2. Concrete mixtures

Concrete mixes having 0.41 water/cement ratio and 2.5% air content values were prepared and sprayed into moulds.

The concrete mix proportions used in this experimental study are given in Table 3.

2.3. Experimental study

In the design of SMRS, the steel mesh (diameter: 8 mm; intervals: 150 mm; and weight: 23.5 kg/m^3) was used as a reinforcement. In the SFRS panels, the SF contents were 35 and 50 kg/m^3, with a fibre length of 30 mm and a diameter of 0.6 mm. The volume percentages occupied by these fibres were 0.45% and 0.64% of 1 m^3 of shotcrete, respectively. The fibre had flattened ends with a round shaft and had an aspect ratio of 50. In high-performance polypropylene fibre reinforced shotcrete (HPPRS) panels, the fibre contents were 7 and 10 kg/m^3, with a fibre length of 30 mm and a nominal filament diameter of 0.9 mm. The volume percentages occupied by these fibres were 0.78% and 1.1% of 1 m^3 of shotcrete, respectively. In the hybrid panels, the SF and HPPF reinforcement contents were 30 and 5 kg/m^3, corresponding to 0.38% and 0.55% volume percent, respectively.

To investigate the toughness behaviour and the energy absorption of FRS, well-known beam and panel tests have been developed. Panel tests are generally considered to better represent the relative behaviour of different FRSs in linings [15,16]. Panel-based performance assessment is desirable because panels fail through a combination of stress actions that reflect the behaviour of an in situ lining more closely than other mechanical tests [5,16]. In addition,

Table 3
Base concrete mix proportions (kg/m^3)

Materials	Saturated surface dry	Dry
Cement	500	500
Water	205	245
Aggregate		
(F.A.-1)	218	213
(F.A.-2)	906	880
(C.A.)	490	482
Admixture (microsilica)	25	25
High water reducing admixture	10	10
Accelerator added at nozzle	7.0% by mass of cement	

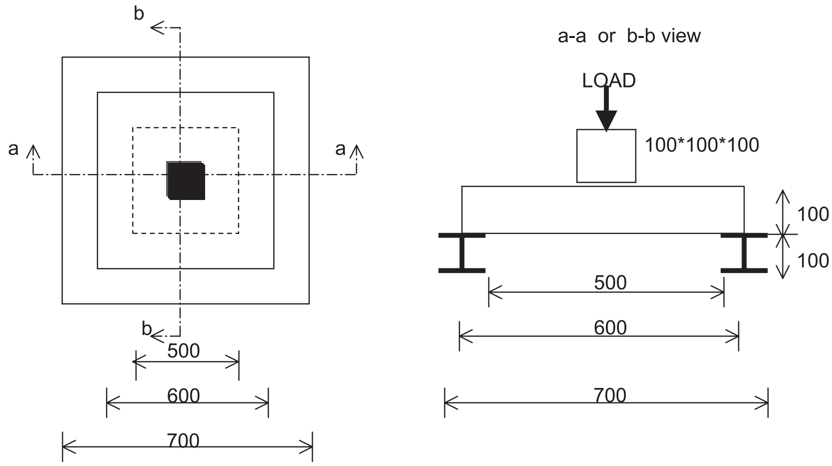

Fig. 1. Set-up for EFNARC Panel Test (dimensions in mm).

according to Bernard [5], although the actual behaviour and load capacity of a continuous lining differs from that of panels tested with simple support conditions, statically determinate and simple support conditions are more suitable for the purpose of routine performance assessment than rigid modes of restraint in panel tests due to ease of calculations. In this study, EFNARC panel test [19], in which square EFNARC panels tested with simple support conditions, was used to provide a relative measure of shotcrete mix performance involving a mode of loading that approximates in situ conditions.

As can be seen from Fig. 1, a test panel of 600 × 600 × 100 mm was simply supported on its four edges by a rigid metallic frame. A centre point load was applied using a 400 kN Universal Testing Machine through a contact surface of 100 × 100 mm. The rate of deformation at the midpoint was nearly 1.5 mm/min. The panels were stored in water for 28 days immediately before testing and kept moist during testing. EFNARC specifies that the prepared panels shall be stored in water for a minimum of 3 days [19].

3. Test results and discussions

The load–deformation curves (Figs. 2 and 3) were obtained as an average of the results of the tests performed on six groups having three panels each: SMRS, SFRS 35 and 50 HPPFRS 7 and 10, and mix of SFRS 30 + HPPRS 5 panels.

Then, the energy–deformation curves (Figs. 4 and 5) were found by integrating the area under these curves, giving the absorbed energy as a function of the panel deflection [19]. The average results for the first-peak load, the maximum load and the energy absorption, in Joules, for a deflection of 25 mm for shotcrete panels can be seen in Table 4.

The criterion for the evaluation of the material toughness of the panel test is the energy absorption class (Table 5; [19]). For tunnel repair jobs, the SNCF (French railway company) specifies energy absorption of 500 J for a deflection of 25 mm [8,20].

As seen from Figs. 2 and 4, and Table 4, the first-peak and ultimate loads of SFRS 50 are the highest loads; but after the

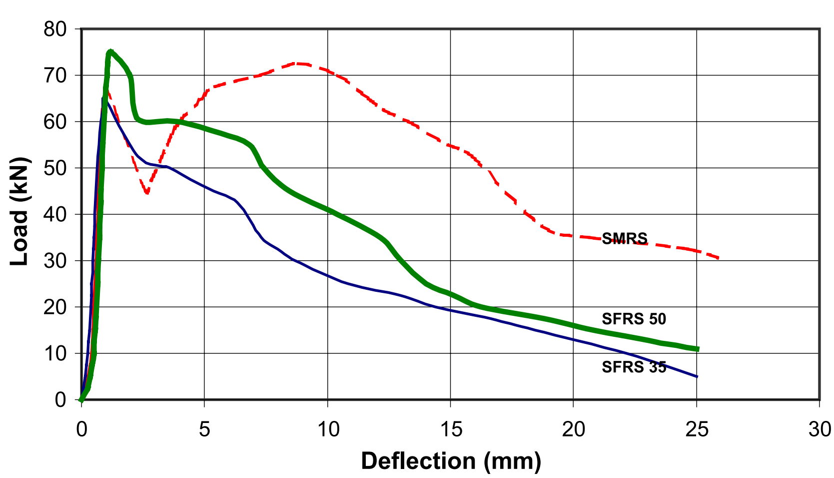

Fig. 2. Comparison of the load–deflection curves for SMRS, SFRS 35 and SFRS 50 panels at the age of 28 days.

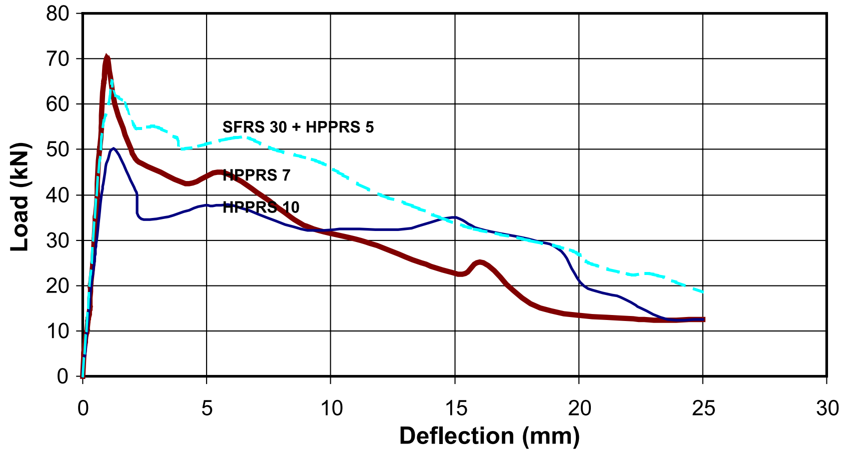

Fig. 3. Comparison of the load–deflection curves for HPPRS 7, HPPRS 10 and mix of SFRS 30 + HPPRS 5 panels at the age of 28 days.

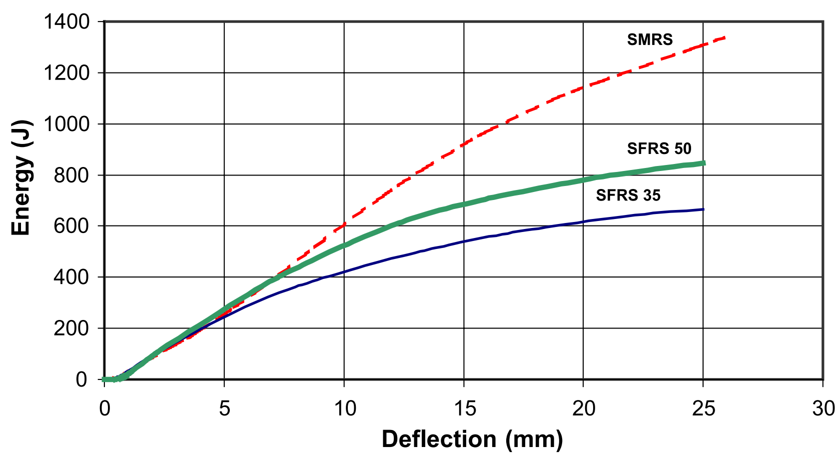

Fig. 4. Comparison of the energy–deflection curves for SMRS, SFRS 35 and SFRS50 panels at the age of 28 days.

peak load, the load-carrying capacity of SFRS 50 drops faster than SMRS and indicates a very unstable zone. On the other hand, in the unstable zone, SMRS shows better load-carrying capacity and energy absorption than others. In addition, for SMRS, after the first-peak load, there is a decrease in load-carrying capacity up to a deflection of 2.5 mm; but after that, the load capacity increases and reaches its ultimate value, which is smaller than that of SFRS 50, at a deflection of 9 mm. However, its energy absorption up to the deflection of 25 mm is 1.5 times that of SFRS 50.

The main reason of SMRS panel having higher energy absorption capacity than SFRS panel is that the bond and the friction stresses between the SM and the shotcrete matrix are much greater than that between the SFs and the shotcrete matrix. The SM has enough bond length that enables it to show strain hardening in the plastic zone after yielding point. In other words, the section of the curve of SMRS panels in the inelastic zone (the section between points of a deflection of 2.5 and 9 mm) shows increases in deformation with increases

Table 4
Comparison of the average values of first-peak load (kN), ultimate load (kN) and energy absorption (J) to a deflection of 25 mm

Types of shotcretes	First-peak load (kN)	Ultimate load (kN)	Energy absorption at 25 mm (J)
SMRS	67.5	72.5	1308
SFRS 35	65.0	65.0	664
SFRS 50	75.0	75.0	846
HPPRS 7	70.0	70.0	716
HPPRS 10	50.0	50.0	751
MIX 35	65.0	65.0	965

Table 5
Energy absorption requirements according to EFNARC

Toughness class	Energy absorption for deflection up to 25 mm (J)
a	500
b	700
c	1000

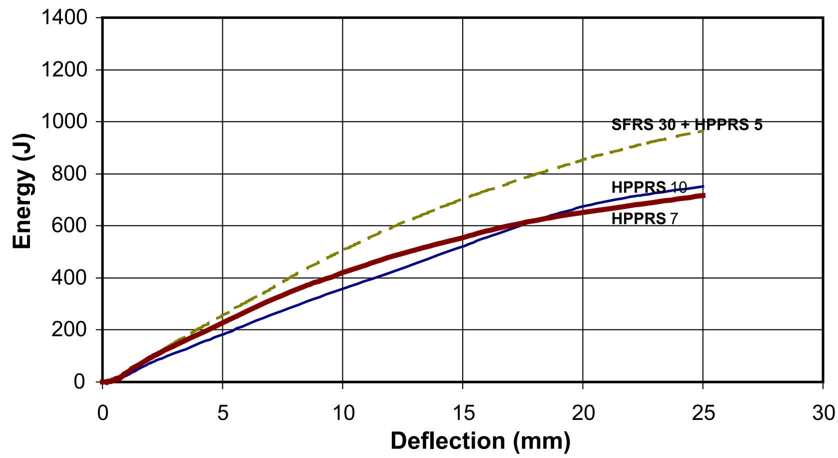

Fig. 5. Comparison of the energy–deflection curves for HPPRS 7, HPPRS 10 and mix of SFRS 30 + HPPRS 5 panels at the age of 28 days.

in load. This event causes the increase of the load-carrying and energy absorption capacities of SMRS panel.

On the other hand, in SFRS panels, after reaching their ultimate loads, there are noted significant decreases in load-carrying capacities. After the first cracking of the matrix, the composite carried the increasing loads by the pullout resistance of the fibres due to the fact that the matrix has very low tensile strength. With an increasing load, the fibres transferred the additional stresses to the matrix through bond stresses, and additional cracking was observed in the matrix because these bond stresses were smaller than the bond strength of the fibres. This process of multiple cracking continued until the accumulated local debonding caused fibre pullout. Slipping off fibres from shotcrete matrix prevents SFs from absorbing the tensile forces present. While the width of the cracks was increasing, they did not show plastic deformation with strain hardening, and this decreased the degree of toughness and ductility of the composite.

Apart from these observations, it can be said that an increase in fibre content for an optimum value enhances the load-carrying and energy absorption capacities for SFRS.

As can be seen from Figs. 3 and 5 and Table 4, the first-peak and ultimate loads of HPPRS 7 are higher than that of the HPPRS 10 and SFRS 30 + HPPRS 5 hybrid panels; but after the peak load, the load-carrying capacity of HPPRS 7 falls significantly, just like that of SFRS 50, and indicates a very unstable zone. On the other hand, in the unstable zone HPPRS 10 shows better load carrying and energy absorption capacity than HPPRS 7. Comparing the HPPRS 7 with HPPRS 10, the energy absorption of HPPRS 10 is slightly greater than that of HPPRS 7. This situation is different than that of the SFRS, where an increase in fibre content increased the ultimate load and energy absorption capacity. In HPPRS, an increase in the fibre content decreased the ultimate load capacity, but the energy absorption did not show much increase. Additionally, the results for HPPRS 7 are better than that of SFRS 35 but slightly inferior to SFRS 50. It should be noted that although the fibre content of HPPRS is lower than that of SFRS 35 and SFRS 50, in mass basis, it is higher in volumetric basis.

In comparison of the HPPRS 5 + SFRS 30 hybrid panels with SFRS 35, it can be seen that their ultimate loads are nearly equal, but the effect of the addition of HPP fibres provides a softening in the load deflection curve. The area under the curve is much larger than that of SFRS 35 and, correspondingly, the ductility and energy absorption up to a deflection of 25 mm of the hybrid mix shotcrete is nearly

Table 6
Comparison of average fibre quantities after shooting for shotcrete mixes

Types	Core weight (A) [g]	Fibre weight (B) [g]	Core volume (E) [cm^3]	Concrete weight (C) [gr]	Fibre content (D) [%]	Fibre amount (F) [kg/m^3]	Fibre rebound (G) [%]
SFRS 35	1745	14.6	785.4	1730.4	0.84	18.6	46.86
SFRS 50	1785	22.2	785.4	1762.8	1.26	28.3	43.40
HPPRS 7	1758	4.8	785.4	1753.2	0.27	6.1	12.86
HPPRS 10	1748	7.0	785.4	1740.9	0.40	9.0	10.30
MIX 35[a]	1755	18.2	785.4	1736.8	1.04	23.2[b]	33.86

C = Concrete weight (g): $C = A - B$.
Calculation of the fibre content (%): $D = (B/C) \times 100$.
Calculation of the actual fibre amount (kg/m^3): $F = B/E$.
Calculation of the fibre rebound (%): For example, for SFRS 35, the theoretical fibre amount is 35 kg/m^3. The actual fibre quantity F = 18.60 kg/m^3 (as shown in the table). The fibre rebound (%): $G = 35 - 18.60/35 = 46.86\%$.

[a] MIX 35 = 5 kg/m^3 HPPF + 30 kg/m^3 SF

[b] 4.1 kg/m^3 HPPF + 19.1 kg/m^3 SF-1 = 23.2 kg/m^3

1.5 times that of SFRS 35. It should be also noted that although the fibre content of the hybrid mix shotcrete is equal to that of SFRS 35 in mass basis, it is higher in volumetric basis.

One of the probable reasons of HPPRS panels showing better performance than SFRS panels is that they have higher fibre content than SFRS panels in volumetric basis; that is, an increase in fibre content for an optimum value increased the load-carrying and energy absorption capacities. In addition, it was observed that although the homogeneously distributed HPP fibres have very low Young's modulus, nearly 3500 MPa, and they are expected to have little effect on crack propagation, they showed better adherence and bond, being geometrically engineered to anchor mechanically with high friction stresses to the shotcrete.

Shotcrete was applied traditionally using dry-mix process in this study. The drawbacks of this process include a dusty shooting environment and excessively high material rebounds, which, in the case of fibrous mixes, consist essentially of coarse aggregates and fibres [21]. Rebound of fibres during shooting of shotcrete mixes at the tunnel site decreases the fibre content in them, causing adverse effects on mechanical and economical properties.

The rebound characteristics of the FRS panels, i.e., their actual in situ fibre contents, were determined according to the following procedure. First, the cores in dimensions of 10×10 cm in diameter and height were taken from the shotcrete panels having dimensions of $50 \times 50 \times 20$ cm. They were weighted and then crushed under a huge load. Subsequently, SF and PP fibres in crushed core specimens were accumulated by magnetism and by hand, and after that, they were weighted. Finally, the fibre content (%), fibre quantity (kg/m^3) in FRS and fibre rebound percent (%) were tabulated (Table 6).

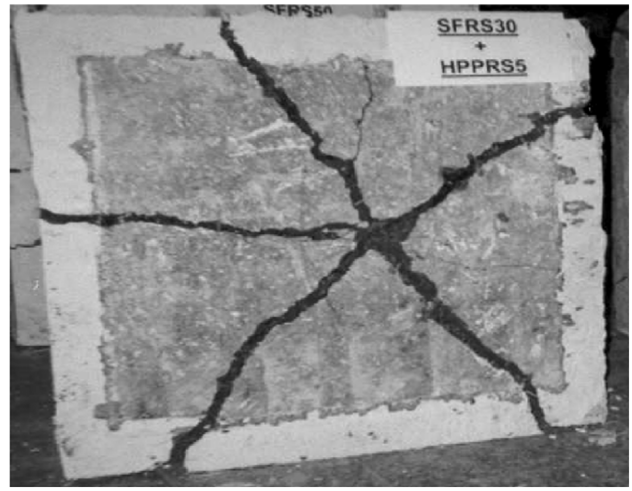

Fig. 7. Failure pattern of the SF30 + HPP 5 after the panel test.

From this table, by comparing the fibre rebound percentages, it can be seen that the rebound percentage of SFs is nearly four times greater than that of HPP fibre. The fibre rebound percentage of hybrid mix is lower than that of SFRS 35 due to the usage of HPPF instead of SF. According to results, confirming other studies [15], HPP fibre usage highly reduces rebound because HPPFs with very low specific gravity, nearly 0.91, are more convenient to mix and to shoot with shotcrete.

Figs. 6, 7 and 8 show the failure mode of the panels. The SMRS panels failed mainly in a punching shear mode and also showed evidence of a flexural failure mode due to the concrete having some tensile strength with strong friction and bond between the SM and concrete matrix, thus increasing the punching shear capacity, relatively in little amount, although not having shear reinforcement. On the other hand, the mix of steel fibre and HPPF panels, and of steel-fibre reinforced shotcrete panels with HPPRS panels failed mainly in a flexural mode with some punching shear. As the load increased, the underside of the panels developed

Fig. 6. Failure pattern of SMRS panel after the panel test.

Fig. 8. Failure pattern of the HPPRS 7 after the panel test.

a series of cracks, radiating outward to the edges from the centrally loaded area. The failure is caused predominantly by the damage from the radial cracks. The fibres that are regularly distributed, mainly two or three, dimensionally in the panel, can work partly as shear reinforcement by increasing the shear capacity with ductility.

Apart from these observations, by comparing Figs. 4 and 5 with Table 5, it can be noted that:

– SMRS achieved Class b (700 J) at a deflection of 8 mm and exceeded Class c (1000 J) at deflections of 17 and 25 mm.
– SFRS 50 achieved Class a (500 J) at a deflection of 8 mm and exceeded Class b (700 J) at deflections of 15 and 25 mm.
– SFRS 35 achieved Class a (500 J) at a deflection of 13 mm and was in the same class at a 25-mm deflection.
– HPPRS 7 achieved Class a (500 J) at a deflection of 12 mm and exceeded Class b (700 J) at deflections of 23 and 25 mm.
– HPPRS 10 achieved Class a (500 J) at a deflection of 14 mm and exceeded Class b (700 J) at deflections of 21 and 25 mm.
– The mix of HPPRS 5 and SFRS 30 achieved Class a (500 J) at a deflection of 10 mm and exceeded Class b (700 J) at deflections of 15 and 25 mm.

4. Conclusions

The experimental investigation was performed on steel mesh, steel fibre, HPPF and a mix of SF + HPPFRS panels to evaluate performance characteristics such as toughness, flexural ductility behaviour, energy absorption and load capacity. In addition, the rebound characteristics of these mixes were determined to compare the fibre amounts after shooting.

As a result of this investigation, the following conclusions are derived:

1. The addition of HPP fibre that is low modulus to the shotcrete enhanced toughness, flexural ductility, energy absorption and load capacity with punching; shear capacity also significantly increased.
2. By comparing the rebound characteristics of the fibres, it can be concluded that using HPP fibre in shotcrete is very advantageous because it does not only cause an increase in performance of shotcrete but also a reduction the loss of fibres due to rebound. Reduction in rebound has also significant financial implications. By increasing the fibre loss reduction (fibres as the most expensive component of the shotcrete mix), HPPFs also improve the economical attractiveness of FRS.
3. An increase in the HPP fibre content from 7 to 10 kg/m^3 did not impart a huge increase in toughness and, in contrast to SF, caused a decrease in first-peak load. Therefore, there may be an optimum value from a performance characteristics point of view for HPPRS nearly at about 7 kg/m^3 fibre content because an excess of fibres may also have adverse effects on strength due to the introduction of additional defects during the processing stage.
4. Comparing the results of HPPRS 7 with SFRS 35, it appears that there may be an optimum point at which it may be possible to use HPP fibre instead of SF.
5. This research shows that there is a positive synergy effect between steel and polypropylene fibre on load carrying capacity, ductility and toughness. Using HPP fibre with steel fibre in FRS greatly enhanced the performance. It can be concluded that hybrid fibre system is more efficient than monofibre system from a performance point of view, if fibres are used in proper amounts.
6. All shotcretes reached the toughness class of a (500 J) at a deflection of 25 mm, which is specified by SNCF [20] for tunnel repair jobs.

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