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Comparative study of steel fibre-reinforced concrete and steel mesh-reinforced concrete at early ages in panel tests

Yining Ding*, Wolfgang Kusterle

Institute of Building Materials and Material Testing, University of Innsbruck, Technikerstr. 13, A-6020 Innsbruck, Austria

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Abstract

Recently it has become more and more common to replace steel reinforcement with steel-fibre reinforced concrete/shotcrete in underground constructions. It is therefore of great importance to compare the behaviour of steel-fibre reinforced concrete and conventional steel-reinforced concrete. In cases of shotcrete at the tunnel face, it is important to obtain a fast stabilizing effect. To avoid damage to the shotcrete caused by blasting or drilling for bolts, it is also important to obtain high early strength. Compared to the actual strength, the tunnel shell is loaded to the highest degree during the first advance rounds after spraying, and therefore most failures occur at early ages. To evaluate the development of punching shear and flexural ductility for panels, experimental investigations were preformed on laboratory concrete in accordance with EFNARC. The measurements were taken at the earliest age of the specimen possible, about 10 h, and continued up to 48 h.

Keywords: Fibre-reinforced concrete; Steel fibre; Steel mesh; Early age; Panel test

1. Introduction

Although the fibre influence on concrete/shotcrete at later ages is well known, at present, there are few research results comparing the properties of steel fibre-reinforced concrete (SFRC) with various fibre contents and steel-reinforced concrete (SRC), especially at ages of 10 h to 2 days. For shotcrete it is important to obtain high early strength [1]. At the laboratory of the Institute of Building Materials and Material Testing, University of Innsbruck, preliminary tests on fibre-reinforced concrete with a shotcrete mix design and on conventional steel mesh-reinforced concrete at early age has been performed. In the consideration of shotcrete rebound, a finer grading curve compared to base mix of shotcrete was used. Experimental investigations were performed on laboratory concrete in accordance with EFNARC [2].

The position of the steel mesh and the steel area ratio in the panel is important. For these tests, the steel mesh was placed centrally. While it could more ideally be positioned in the tension face, it is more common in underground support for the bars/meshes to be pinned directly to the excavated face [3,4]. Often, steel reinforcement with steel area ratio of minimal percentage is used.

This study demonstrated that the use of fibre reinforcement in concrete/shotcrete can greatly enhance the punching shear capacity, flexural ductility, toughness, and therefore possibly replace the conventional steel mesh reinforcement.

2. Testing

The mix design of SFRC plate was as follows: tunnel cement (ordinary Portland cement) 450 kg/m^3, aggregate (sand 0–8 mm) 1,770 kg/m^3, superplasticizer 1%, water cement ratio 0.45. The steel fibre contents were from 20, 40, and 60 kg/m^3, with a fibre length of 30 mm and diameter of 0.5 mm. The hooked end fibre has an aspect ratio of 60. According to the Austrian Guideline [5], the steel area ratio of the mesh (CQS, diameter 6 mm, distance 100 mm, μ = 0.19%) corresponds to the minimum percentage for slab reinforcement. The weight of the steel mesh of a panel is 0.714 kg, just as much as the fibre weight in an SFRC panel with fibre content of 20 kg/m^3.

To investigate the toughness behaviour and the energy absorption of steel fibre-reinforced concrete/shotcrete, well-known beam and slab tests have been developed. Equivalent flexural experiments for beams have been investigated. Because of the following reasons, the panel test was regarded as better for examining the material properties than the beam test.

* Corresponding author. Tel.: +43-512-507-6628; fax: +43-512-507-2902.

E-mail address: Ding.yining@uibk.ac.at (Y. Ding)

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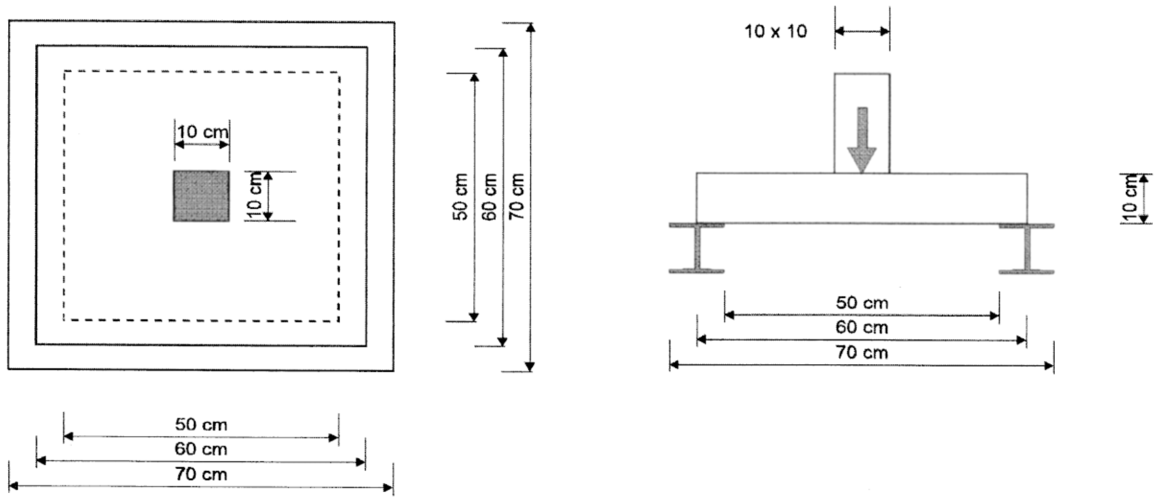

Fig. 1. Set-up for plate test.

1. A beam is a statically determinate system and will be subjected to bending in the longitudinal length direction only.
2. A plate is a statically indeterminate system and will be subjected to bending in two directions (*x* and *y*). A statically indeterminate system allows additive stress redistribution in another direction after the first peak-load.
3. A slab is considered to represent more realistically the two-directional bending of thin shotcrete shell structures in tunnelling and mining than the beam.

A test panel of 600 × 600 × 100 mm was supported on its four edges by a rigid metallic frame and centre point load applied through a contact surface of 100 × 100 mm (Fig. 1). The rate of deformation at the midpoint was 1.5 mm per min.

The load-deformation curve (Fig. 2) was recorded to a specified deflection of 25 mm at midpoint of the panel. From the load-deformation curve a second curve is drawn, giving the absorbed energy as a function of the plate deflection.

2. Results

The criterion for the evaluation of the material toughness of panel test is the energy absorption class (Table 1) [2].

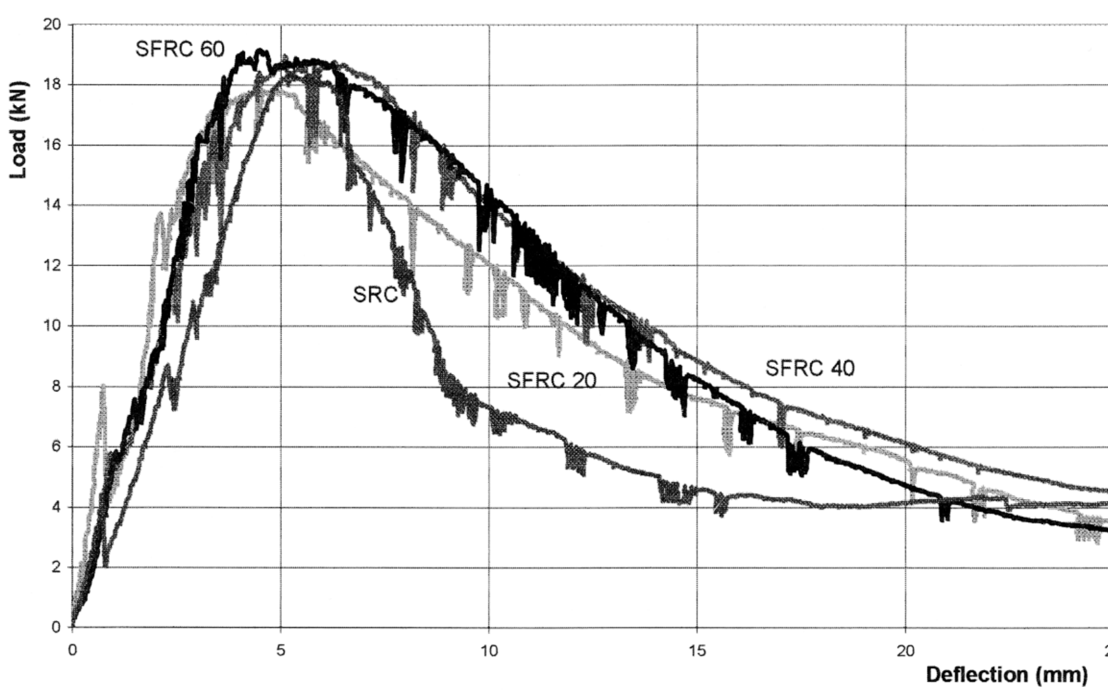

Fig. 2. Comparison of the load-deflection curves for SFRC and SRC at the age of 10 h.

Table 1
Energy absorption requirements

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

2.1. Behaviour at the age of 10 h

Fig. 2 shows the load-deflection curves to compare the effects of SFRC with different fibre content and SRC with centrally placed steel mesh at the age of 10 h. As mentioned earlier, the weight of the steel mesh is the same as the fibre weight with fibre content of 20 kg/m^3 in an SFRC panel. However, the ductility and the energy absorption of SRC are lower than those of SFRC 20 (Fig. 2). The load-deflection graph illustrated in Fig. 2 is typical for a panel test and it differs substantially from the beam test [6], because the beam is only subjected in one direction (longitudinal direction). The slab acting in two directions exhibits much larger increases in load-carrying capacity after first crack. This experiment shows that:

1. Because of the stress redistribution in the second direction after the first peak-load, the plate of SFRC 20 behaved in a more stable manner after the first crack than a beam [6] with the same fibre content.
2. The plate of SFRC 20 can absorb more energy than the plate of SRC with steel mesh of the same weight.
3. The ductility and energy absorption of SFRC 40 are equivalent or better than those of SFRC 60.

Figs. 3, 4, 5, and 6 show the comparisons of the effects of SFRC with different fibre content and SFC at the ages of 18, 30, and 48 h.

2.2. Behaviour at the age of 18 h

Compared to Fig. 2, SRC shows the much better post-crack behaviour than SFRC 40 and SFRC 60, up to a deflection of about 7 mm. It can be seen that:

1. After the peak load, the load-carrying capacity of SRC fell faster than that of SFRC 40, SFRC 60, and indicates a very unstable zone.
2. In the unstable zone, SFRC 40 and SFRC 60 show better load-carrying capacity than SRC.
3. The ductility and energy absorption of SFRC 60 are better than those of SFRC 40.
4. In contrast to the behaviour at 10 h, the plate of SRC with the same weight of steel mesh can absorb more energy due to the more hardened concrete matrix than SFRC 20 or SFRC 40.

2.3. Behaviour at the age of 30 h

From Fig. 4 it can be seen that:

1. The ductility of SFRC 40 is almost the same as that of SFRC 60.
2. The ductility and energy absorption of SFRC 40 and SFRC 60 are better than those of SRC.
3. Similar to the behaviour at 18 h, the plate of SRC with the same weight of steel mesh can absorb more energy than the SFRC 20 plate.

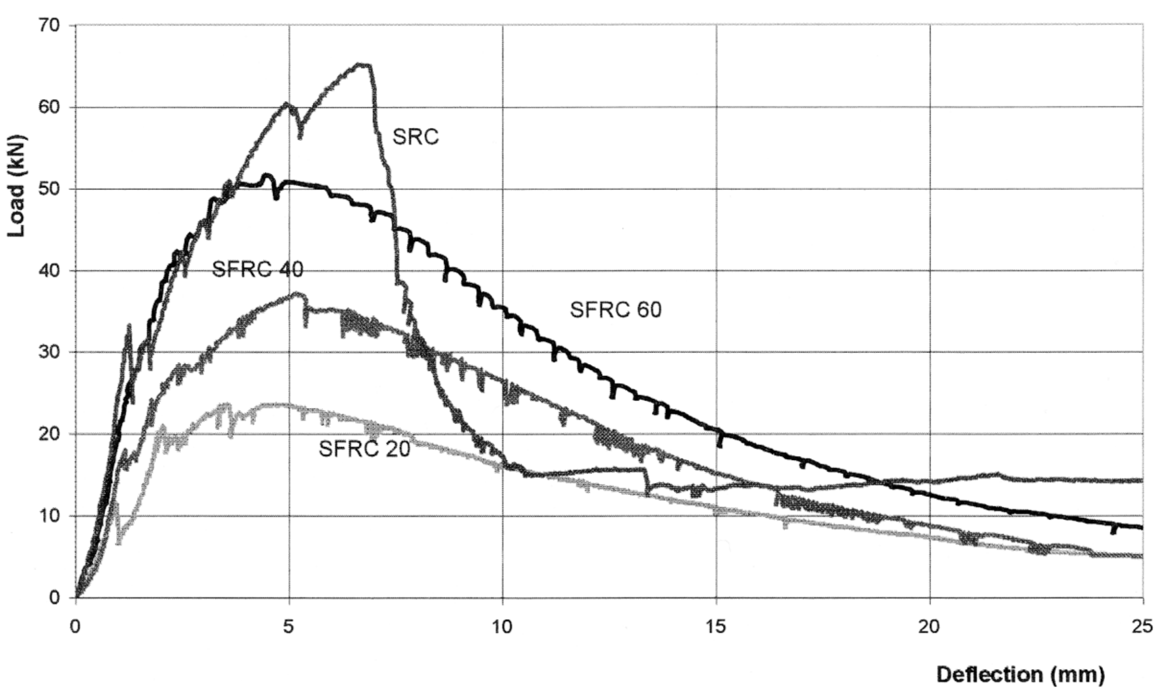

Fig. 3. Comparison of the load-deflection curves for SFRC and SRC at the age of 18 h.

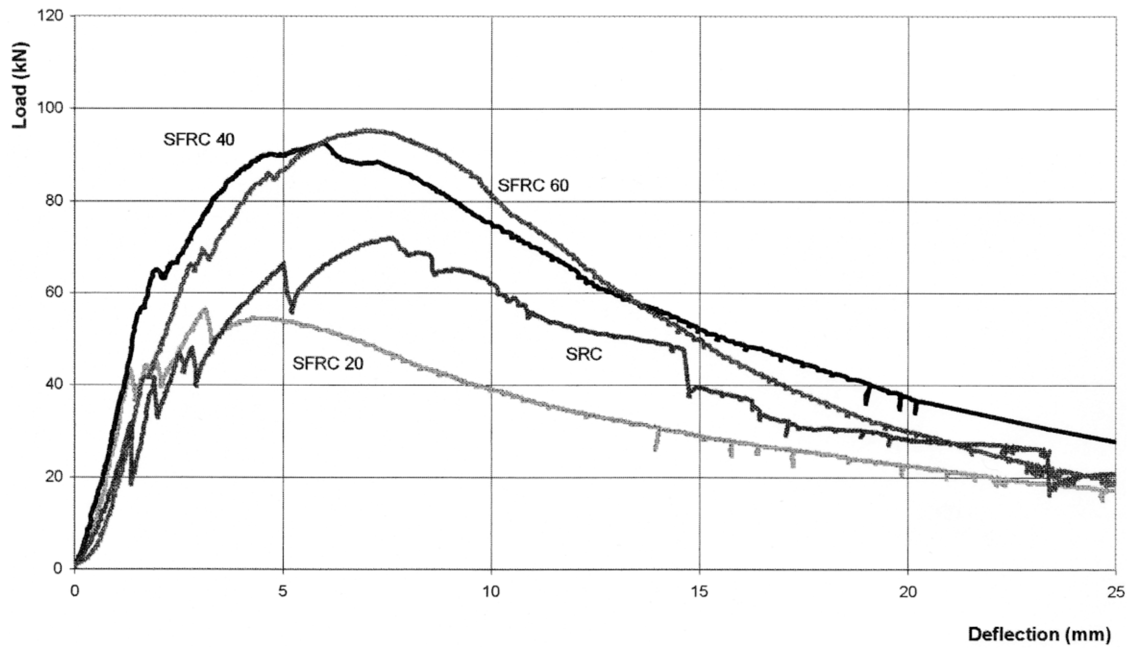

Fig. 4. Comparison of the load-deflection curves for SFRC and SRC at the age of 30 h.

The concrete matrix at 30 h is much stronger than at 10 h and the bond and the friction stress between the steel mesh and the concrete matrix are greater, thus that the SRC panel can behave better than SFRC 20 over the entire deflection zone.

2.4. Behaviour at the age of 48 h

Figs. 5 and 6 show that:

1. In contrast with Fig. 4, there are clear differences of ductility and energy absorption between SFRC 40 and SFRC 60.
2. The energy absorption of SRC is slightly better than that of SFRC 40.
3. Only the ductility and energy absorption of SFRC 60 are better than those of SRC over the entire deflection zone.

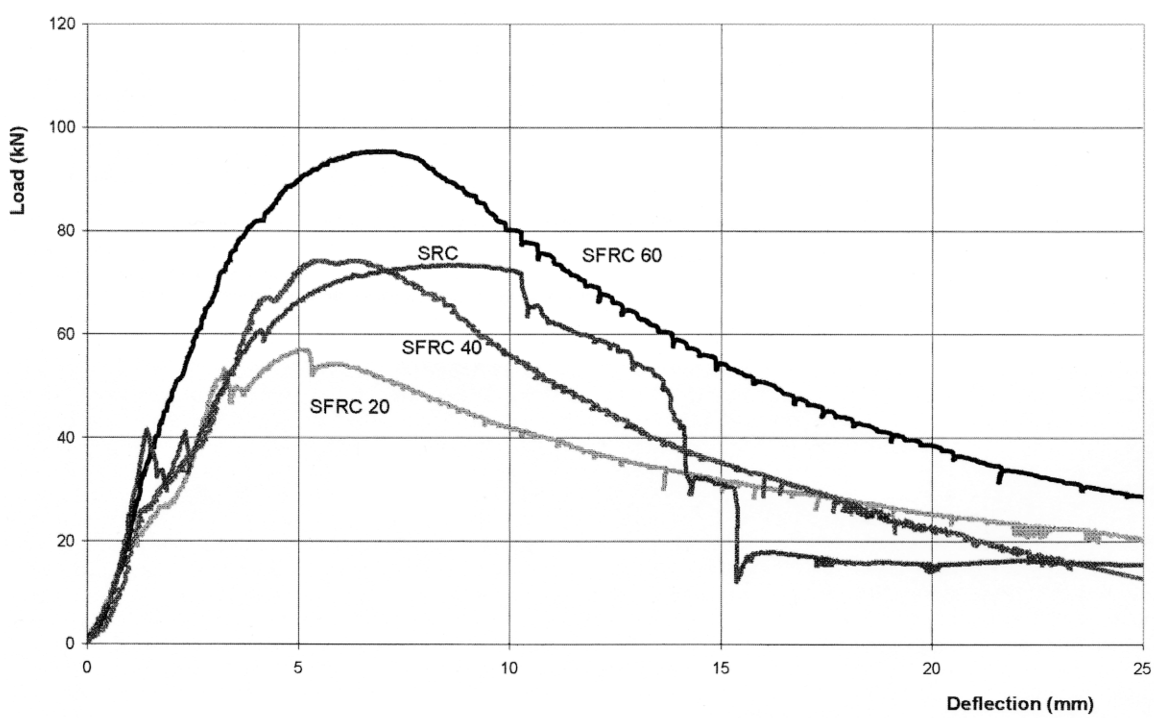

Fig. 5. Comparison of the load-deflection curves for SFRC and SRC at the age of 48 h.

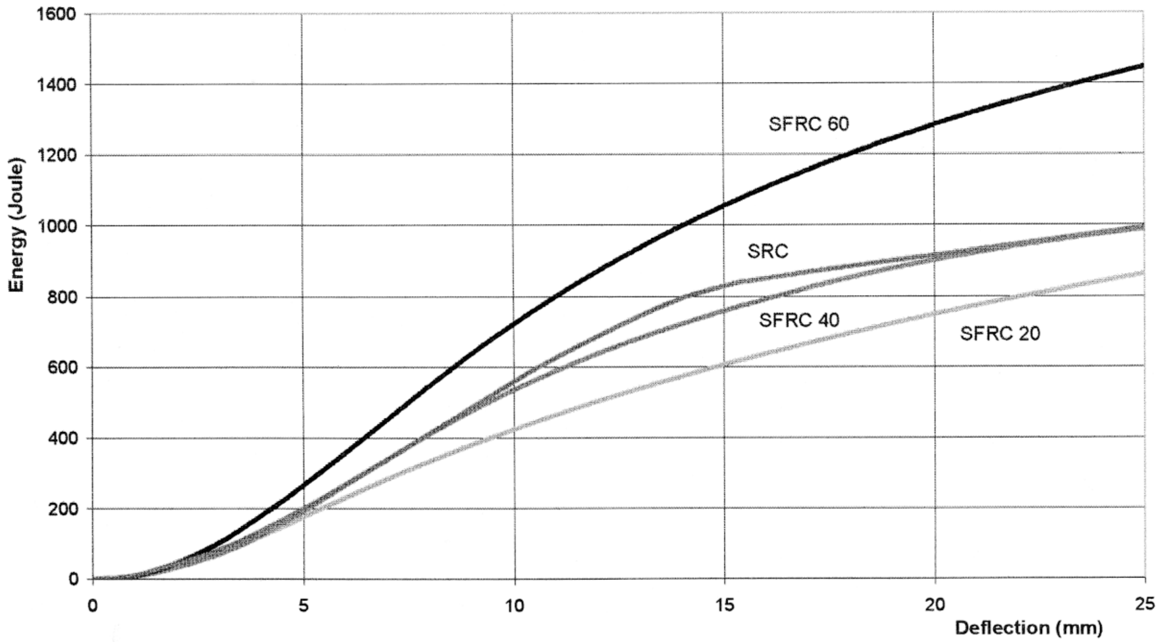

Fig. 6. Comparison of the energy absorption curves for SFRC and SRC at the age of 48 h.

The results of the average values are presented in Table 2. Compared to Table 1, Table 2 shows that:

- SFRC 20 achieved class a (500 J) at the deflection of 15 mm and exceeded class b (700 J) on the deflection of 20 and 25 mm at the age of 30 h.
- SFRC 40, SFRC 60, and SRC exceeded class c at 30 h at a deflection of 25 mm.
- Comparison made at the different concrete ages indicate that only the ductility and the energy absorption of SFRC 60 exceeded those of SRC from 10 to 48 h.

Generally, the requirements of energy absorption values in Table 1 are not too high and they could be achieved or exceeded by SFRC with a low-fibre content of 20 kg/m^3.

To compare the investigations of panel test, flexural strength and energy absorption of beam test, and compressive strength, the results of compressive strength and flexural strength have been summarised in Tables 3 and 4.

The addition of steel fibres aids in converting the brittle properties of concrete into a ductile material, and increases compressive strength of green concrete. However, no significant trend of improving compressive strength at an early age was found [6].

The results of equivalent flexural strength and energy absorption of beams according to the German Guideline [7] are presented in Table 4.

Table 2
Comparison of the energy absorption of panel test for SFRC and SRC

	E (10 mm)	*E* (15 mm)	*E* (20 mm)	*E* (25 mm)
PLF2010	135.50	181.50	214.00	235.50
PLF2018	212.00	299.00	355.00	393.33
PLF2030	446.67	615.67	740.67	831.67
PLF2048	415.67	594.67	725.67	827.67
PLF4010	159.00	218.33	255.00	279.33
PLF4018	276.00	385.00	451.33	493.00
PLF4030	711.33	**1034.67**	**1269.33**	**1444.00**
PLF4048	530.33	783.67	953.33	**1067.00**
PLF6010	145.67	201.67	236.00	258.33
PLF6018	401.00	545.67	632.33	686.00
PLF6030	732.00	**1042.00**	**1238.50**	**1368.00**
PLF6048	712.00	**1039.00**	**1262.00**	**1416.67**
PLM10	108.00	133.33	154.67	171.67
PLM18	421.00	562.00	652.00	731.00
PLM30	534.33	824.67	**1001.67**	**1115.33**
PLM48	578.33	857.00	990.67	**1080.67**

See Notation section in text for abbreviations. Bold indicates values higher than class c in Table 1.

Table 3
Development of compressive strength of concrete and fibre-reinforced concrete

	Compressive strength (N/mm^2)					
	8 h	10 h	18 h	30 h	48 h	72 h
Concrete without fibre	1.86	4.03	13.89	25.87	32.56	36.06
SFRC 20	2.35	5.11	18.63	26.33	32.65	37.52
SFRC 40	2.5	5.08	15.5	23.5	32.44	37.13
SFRC 60	1.8	3.8	15	25	33.3	37

See Notation section in text for abbreviations.

Table 4
Comparison of the test results of SFRC beams with different fibre contents and SRC

Fibre content (kg/m^3)	Age of concrete (h)	β_{BZ} (N/mm^2)	D^f_{BZ2} (kN mm)	equ β_{BZ2} (N/mm^2)	D^f_{BZ3} (kN mm)	equ β_{BZ3} (N/mm^2)	D_{BZ} (kN mm)
SFRC 20	10	0.39	0.45	0.16	2.33	0.14	2.71
SFRC 20	18	2.13	2.54	0.90	16.14	0.95	18.77
SFRC 20	30	3.92	5.54	1.97	29.32	1.74	33.54
SFRC 20	48	4.36	6.74	2.40	39.83	2.36	44.93
SFRC 40	10	0.65	1.11	0.40	7.80	0.46	8.47
SFRC 40	18	3.35	7.35	2.52	46.50	2.76	50.29
SFRC 40	30	3.52	8.04	2.86	45.69	2.71	49.69
SFRC 40	48	6.30	14.75	5.25	82.43	4.88	89.91
SFRC 60	10	0.77	2.12	0.75	10.73	0.64	11.53
SFRC 60	18	2.75	6.97	2.48	39.81	2.43	42.88
SFRC 60	30	3.96	9.03	3.21	50.14	2.97	54.77
SFRC 60	48	4.12	12.06	4.29	68.59	4.08	73.59
SRC	10	0.54	2.50	0.89	14.23	0.84	14.79
SRC	18	1.79	6.45	2.29	32.38	1.92	34.28
SRC	30	3.68	10.89	3.87	85.71	5.08	89.97
SRC	48	4.26	11.49	4.08	86.28	5.11	91.38

See Notation section in text for abbreviations.

3. Discussion

There is a clear difference between aboveground construction and underground construction. Due to well-established design standards in building aboveground, it is safe enough only to evaluate the behaviour at 28 days. For underground construction, however, the investigation at a single point of the concrete age is not sufficient for assessing factors of safety, because the load-deformation condition and the concrete behaviour may develop very quickly at early age. It is necessary to investigate the development of the behaviour for both SFRC and SRC over a period of time, and this development may have statistical significance at early age.

Fig. 7 shows the failure mode of the steel mesh-reinforced panel at the age of 10 h after the test. The SRC panels failed in punching shear modes. As mentioned earlier, due to the in situ condition in tunnelling, the steel reinforcement corresponds to the minimal percentage of the slab reinforcement, which is without shear reinforcement. Moreover, the friction and bond stress between the steel mesh and the green concrete matrix are too low, so that it can not offer the shear-resistant effect.

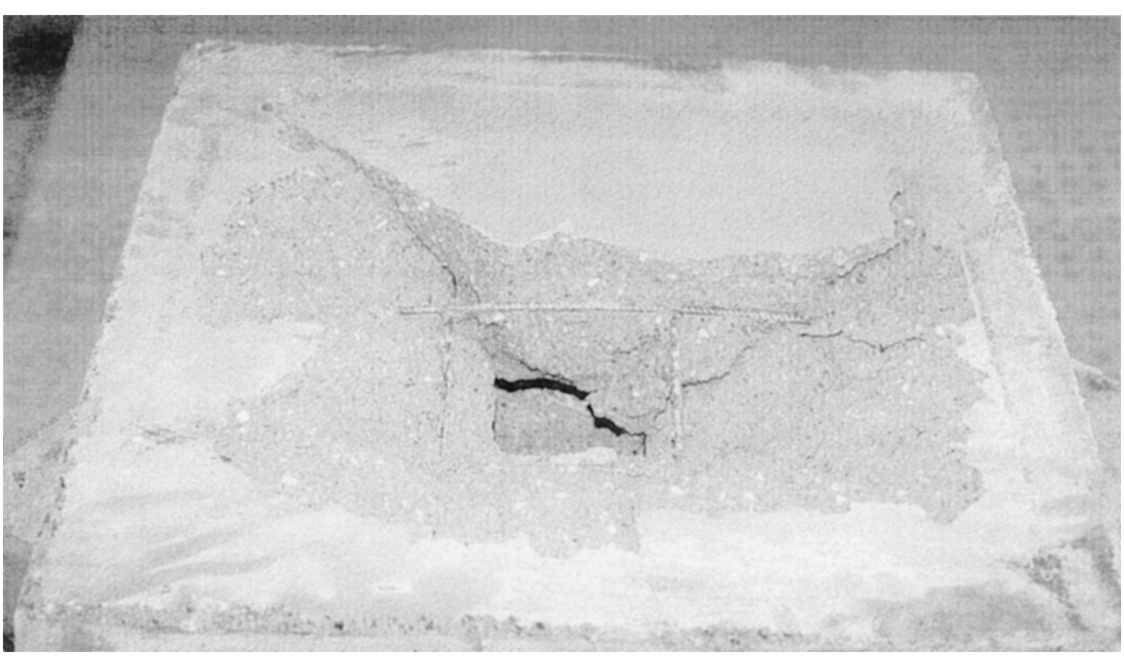

Fig. 7. Failure pattern of SRC after the plate test at 10 h.

With an increase of concrete maturity, the hardened concrete and the stronger friction and bond function between steel mesh and concrete matrix could carry more punching shear stress than that at 10 h. Therefore, the SRC panels failed mainly in punching shear modes and showed some evidence of flexural failure modes at the ages of 18, 30, and 48 h [6].

Fig. 8 shows the failure pattern and crack formation at the underside of the steel fibre-reinforced plate at the age of 30 h. In contrast to the failure pattern of SRC, the SFRC panels failed mainly in flexural modes with some punching shear. As the load increased, the underside of the panels developed a series of cracks radiating outward to the edges from the centrally loaded area. The failure is caused dominantly by the damage from the radial cracks. The panel is stable in the postcrack region of the load-deflection curve.

The mode of failure changed from punching shear to flexure. This means that:

1. Steel fibres, which are regularly distributed two- or three-dimensionally in the panel, can work partly as shear reinforcement. Therefore fibre reinforcement greatly increases the shear capacity.
2. The ductility is also enhanced greatly by the addition of fibres.

4. Conclusions

Many panels were tested to investigate the different influences of steel fibre and steel mesh on the concrete/shotcrete at early age, when: (1) the fibre had a length of 30 mm, diameter of 0.5 mm, and aspect ratio of 60; and (2) the steel mesh corresponding to minimum panel reinforcement was centrally placed. The experimental and analytical results of this study have led to the following conclusions:

1. The fibre reinforcement enhances the punching shear capacity greatly.
2. The punching shear as the cause for failure in conventional steel-reinforced concrete/shotcrete panels changes to flexural failure of steel fibre-reinforced concrete/shotcrete panels when the fibre content exceeds 20 kg/m^3.
3. SFRC 40 has considerably higher ductility and energy absorption than does SFRC 20. The fibre reinforcement enhances flexure capacity significantly, but the energy absorption of SFRC 40 is higher than that of SFRC 60 at 10 to 30 h. It means that fibre content of 40 kg/m^3 may be a possible economical point for the dosage zone from 40 to 60 kg/m^3 [8].
4. SFRC 20 has higher energy absorption at the age of 10 h than does SRC, but lower than that of SRC after

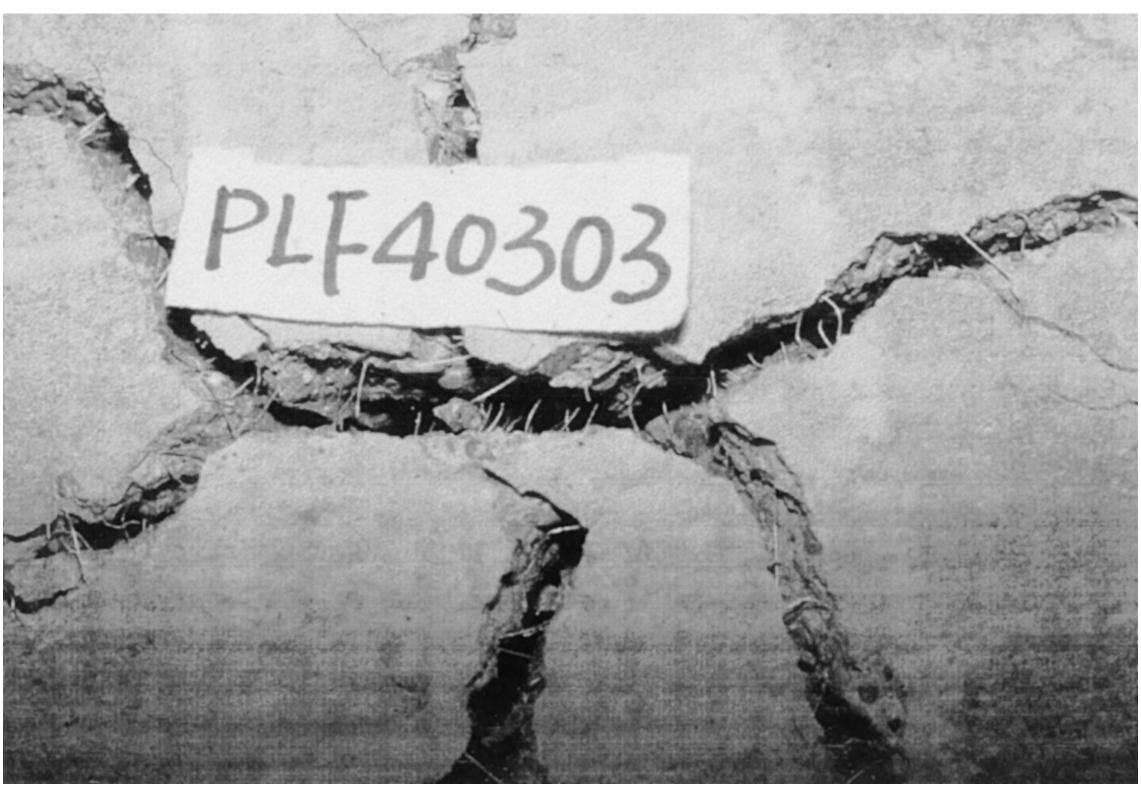

Fig. 8. Failure pattern of SFRC after the plate test at 30 h.

18 h. This points to an important phenomenon: steel fibres have more influence on the green concrete than on hardened concrete [8].

5. Only SFRC with fibre content of 60 kg/m^3 can replace SRC with centrally placed steel mesh of minimal steel area ratio. In this case, the steel weight of SFRC 60 per panel is three times greater than SRC.

5. Notation

μ: steel area ratio

E (10 mm): energy absorption (J) at the deflection of 10 mm

E (15 mm): energy absorption (J) at the deflection of 15 mm

E (20 mm): energy absorption (J) at the deflection of 20 mm

E (25 mm): energy absorption (J) at the deflection of 25 mm

D_{BZ}: energy absorption (kN mm) of the fibre-reinforced concrete beam (before and after the first crack) [7]

D^f_{BZ2}: energy absorption of steel fibre-reinforced concrete beam by $\delta_2 = \delta_1 + 0.65$ (mm) [7]

D^f_{BZ3}: energy absorption of steel fibre-reinforced concrete beam by $\delta_3 = \delta_1 + 3.15$ (mm) [7]

β_{BZ}: flexural tensile strength of beam [7]

equ β_{BZ2}: equivalent flexural tensile strength (MPa) of beam by δ_2 [7]

equ β_{BZ3}: equivalent flexural tensile strength (MPa) of beam by δ_3 [7]

SFRC *X*: steel fibre-reinforced concrete with fibre content of *X* kg/m^3; for example, SFRC 60: steel fibre-reinforced concrete with fibre content of 60 kg/m^3

PLF *XY*: fibre-reinforced plate with fibre content of *X* kg/m^3 at the age of *Y* hours; for example, PLF 2010: plate with fibre content of 20 kg/m^3 at the age of 10 h

PLM *Y*: steel mesh-reinforced plate at the age of *Y* h; for example, PLM 18: steel mesh-reinforced panel at the age of 18 h.

SRC *Y*: steel bars-reinforced beams at the age of *Y* h; for example, PLM 18: steel mesh-reinforced panel at the age of 18 h

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