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Compressive stress–strain relationship of steel fibre-reinforced concrete at early age

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Abstract

This article presents some comparative results from a continuing study of the properties of steel fibre-reinforced concrete/shotcrete (SFRC/S) at early age. The overall aim of the investigation is to develop the SFRC for applications in tunnels and in other underground constructions. The impact and bending properties both for beams and for panels of SFRC have been analysed in extensive experiments, but the compressive behaviour of SFRC/S, especially at early ages, has been disregarded. In this article, the effect of steel fibres in influencing the compressive strength, the duration for the peak load and the energy absorption under uniaxial compressive loading at the early ages has been studied. The results of experimental investigations on the behaviour of SFRC and plain concrete under compressive load at early ages are presented. The parameters of the study were: fibre content, age of concrete and energy absorption.

Keywords: Steel fibre; Concrete; Compression; Stress–strain relationship; Early age

1. Introduction

The mechanical properties of concrete/shotcrete can be improved by the addition of steel fibres. The toughness of steel fibre-reinforced concrete/shotcrete (SFRC/S) can be measured by different test methods, such as the beam test and the panel test. While most methods give an indication of the flexural energy, the compressive test is considered to be better-suited to observe the behavior of SFRC for underground construction at an early age, because in many cases SFRC/S in tunnels is mainly subjected to compression [1–3].

Several investigations of beam and panel bending tests have demonstrated that the addition of steel fibres in concrete/shotcrete can enhance greatly the ductility and toughness not only after 28 days, but also at early ages.

Many researchers hold the view that steel fibres do not have a significant influence on the compressive behavior of concrete/shotcrete due to the small volume of fibres in concrete/shotcrete mix [1,4]. This opinion is correct for SFRC/S at the age of 28 days. In many cases, SFRC/S in tunnel is subjected to compression; the tunnel is loaded at the highest degree during the first advance rounds after spraying, and therefore, most failures occur at early ages. The investigation of compressive behavior of SFRC at early age shows some different and very interesting results. In order to evaluate the development of stress/strain ($\sigma-\varepsilon$) properties in compression, experimental investigations have been carried out on laboratory SFRC as well as on dry-mix SFRS at a tunnel site. The measurements were performed at about 9 h and continued up to 81 h. Due to the inherent variability of samples obtained on-site (i.e., the variation of w/c ratio), the trends were not as clear as those of the laboratory cubes.

This study demonstrated that the use of fibre reinforcement in concrete/shotcrete can greatly enhance the compressive ductility, toughness and energy absorption at early ages.

2. Experiments

The mix design of SFRC plate was as follows: tunnel cement (OPC): 450 kg/m^3, aggregate (sand 0–8 mm): 1770

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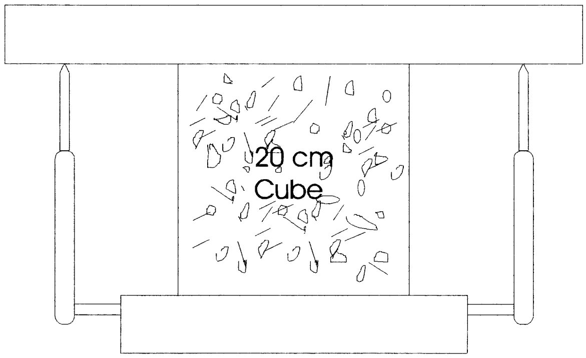

Fig. 1. Set-up for load-versus-displacement test.

kg/m^3, superplasticiser: 1% of cement, water cement/ratio: 0.45. The steel fibre contents for compressive strength tests were 20, 40 and 60 kg/m^3; fibre content for stress/strain tests at compression was 60 kg/m^3, fibre length of 30 mm, diameter of 0.5 mm. The hooked end fibre has an aspect ratio of 60.

For the following reasons, the compressive test describes the state of tunnel concrete more closely than the well-known bending beam and plate tests:

- In many cases, the tunnel shell is subjected mainly to compressive load.
- The properties of steel fibre-reinforced concrete and shotcrete at early age have great significance for load-bearing capacity and serviceability of a tunnel shell.

The cube specimens for compression strength were load-controlled and tested at the ages of 8, 10, 18, 36, 48 and 72 h. Specimens for load-versus-displacement responses were deformation-controlled and tested when the cubes were 9- and 81-h old. The experiments were performed on 200-mm cube prisms. According to German guidelines [5], the loading rate for the compression strength was 0.5 N/mm^2 per second. To investigate the fibre influence on the concrete behavior under compressive load and on the differential compressive ductility between green and hardened concrete, the cubes of SFRC were tested under a deformation rate of 1 mm/min. Each result is an average of three specimens. Fig. 1 illustrates the test set-up for the load-versus-displacement experiment.

3. Results

3.1. Fibre influence on the compressive strength

The addition of steel fibres aids in converting the properties of brittle concrete to a ductile material, generally improving the compressive strength of green concrete; but the improvement in strength does not always increase with a larger dosage of fibres. The average results of compressive strength are presented in Table 1.

It shows that the best values of compressive strength of SFRC after 8 and 10 h were achieved with a fibre content of 40 kg/m^3. Perhaps due to the higher air content with fibres in the specimen, a fibre volume of 60 kg/m^3 does not further enhance the compressive strength. For the hardened concrete, 30 h after the mix, the fibres have no significant influence on the compressive strength of concrete [7]. Fig. 2 shows the fibre distribution in a cube after the test.

Despite not having the highest compressive strength, SFRC 60 demonstrated the best ductility under compressive load at 8 and 10 h:

- the compressive load increase continued after visible crack-opening on the specimen surface.
- after achieving the maximum strength, the load of SFRC was sustained over some minutes, while the load of other concrete samples without fibres fell down quickly from the maximum value.

The two experimental results are very useful for the application of SFRC in tunnelling.

3.2. Fibre influence on the stress/strain behavior in compression

3.2.1. Failure and fibre reinforcing mechanisms

Figs. 3 and 4 qualitatively show the failure patterns in the specimen from shear (oblique cracks) to splitting (vertical cracks). Concrete can be considered as a highly heterogeneous material because of its composite structure. The fibres embedded in the matrix affect the stress and strain fields, enhancing stress redistribution and reducing strain localisation. Furthermore, the fibres bridge micro-cracks in concrete/shotcrete. Experimental investigations have shown that if the degree of utilisation (actual stress/

Table 1
Development of compressive strength of concrete and SFRC

	Comprehensive strength (N/mm^2)					
Age of concrete (h)	8	10	18	30	48	72
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 for abbreviations.

Fig. 2. Steel fibre distribution in the cube of SFRC after the test of compression strength.

compressive strength) is above 60%, the micro-cracks begin to grow to macro-cracks [3,7–9].

Some articles have reported that the rupture of the SFRS cubes occurs mostly with cracks parallel to the loading direction, and after the peak load, the prisms have been squashed or pressed out of shape. However, according to the specimens' geometry, the failure mode of compressed concrete specimens can be considered as resulting from local tensile mechanisms, or from a combination of tensile and shear mechanisms [10] (Figs. 2 and 3). In fact, from the failure patterns of cubes shown in Figs. 2–4, a part of the cracks (h_2) are parallel to the loading direction, where h_2 depends on the height h of the specimen and its cross-section.

For SFRS, the fibre distribution is mainly two-dimensional and the main compression loads occur parallel to fibre orientation (in tunnel linings) [Figs. 3(a) and 4(a)]. In that case, fibres can only improve the pre- and post-crack behaviours in the zones of h_1 and h_3 (oblique shear failure). In the zone of h_2 (splitting failure), the fibres do not influence the post-crack behavior of SFRS. The fibre-reinforcing efficiency depends on the length of h_2. With the increasing of h_2, the fibre-reinforcing efficiency will be decreased (Fig. 4).

Because of the mainly three-dimensional fibre distribution of SFRC [Figs. 3(b) and 4(b)], steel fibres can not only affect the crack behavior in the zones of h_1 and h_3, but also in the zone of h_2. The post-crack behavior

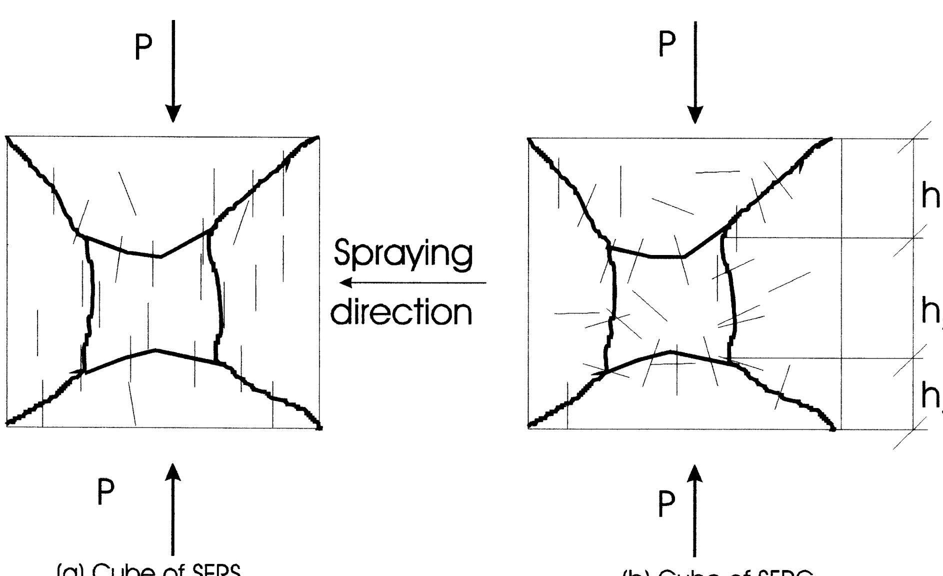

Fig. 3. Failure and fibre reinforcing mechanisms of uniaxially compressed cubes.

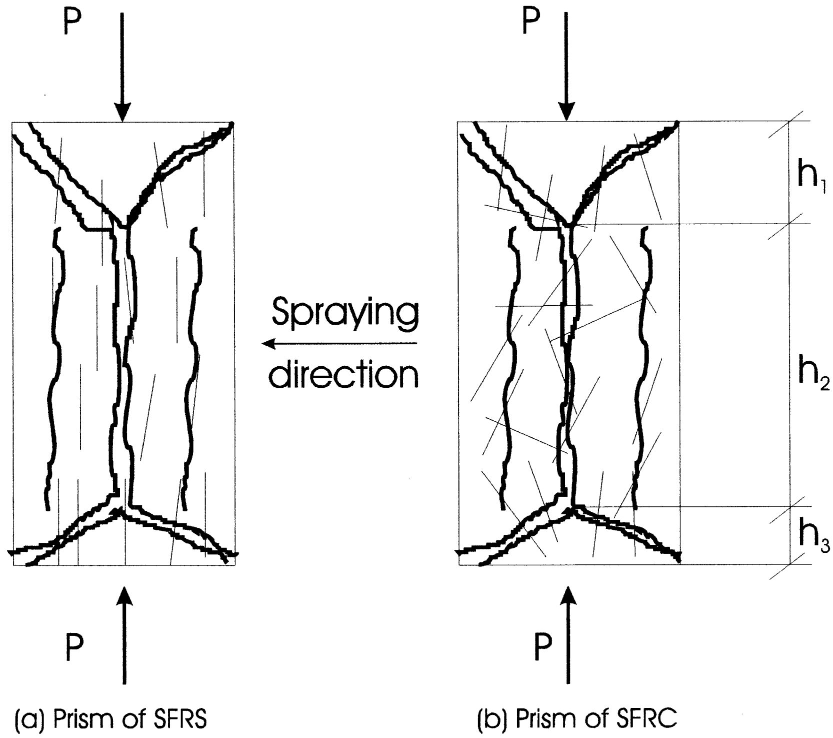

Fig. 4. Failure and fibre reinforcing mechanisms of uniaxially compressed prisms.

illustrated in Figs. 3 and 4 may be interpreted as a function of the number of fibres bridging the fractured crack surfaces [4].

3.2.2. Fibre influence on the load-carrying capacity at compression

At early age, fibres can influence greatly the duration and the load-carrying capacity at the peak load and in the range from 95% of the peak load to the peak load. The average results at the peak load and for the range of 95% of peak load at the age of 9 h are given in Table 2, which indicate the significant increase of the duration at the peak load of SFRC. After the peak load, the curves of plain concrete and SFRC descend in a similar manner.

For hardened concrete at the age of 81 h, influence of steel fibre on the peak load is very different to that at early ages. The average results at the peak load and in the range of 95% of peak load at the age of 81 h are given in Table 3, which indicate that in hardened concrete fibres have no effect on the duration at peak load and on its 95% range. Compared to Table 2, SFRC shows a better ductility after the peak load than plain concrete.

3.2.3. Energy-absorption capacity at compression

When the opening energy of micro-cracks in a specimen becomes strong enough, the micro-cracks link up to form one or more macro-cracks. Fig. 5 illustrates the fibre effect on stress/strain properties of the green concrete under a compressive force. At early age, fibres have a strong influence not only on the post-crack, but also on the pre-crack behavior of green concrete at compression. For the same strain, SFRC could sustain more stress both before and after the peak load [6].

The energy absorption per unit volume under compression was determined as the area under the stress (σ)/strain (ε) curve (Fig. 5), the value can be calculated [11] using Eq. (1)

$$E = \int_0^{\varepsilon} \sigma \, d\varepsilon. \quad (1)$$

The average results of energy absorption per unit volume at the age of 9 h are given in Table 4.

E_{p9} is the energy absorption up to the peak load after 9 h and E_{t9} is the total energy absorption up to the strain of

Table 2
Average values of duration at the peak load and at the range of 95% peak load at the age of 9 h

Range of the load	Peak load	95% of the peak load
Duration of SFRC 60 (s)	14	57
Duration of plain concrete (s)	6	29

Table 3
Average values of duration at the peak load and at the range of 95% peak load at the age of 81 h

Range of the load	Peak load	95% of the peak load
Duration of SFRC 60 (s)	1	42
Duration of plain concrete (s)	1	41

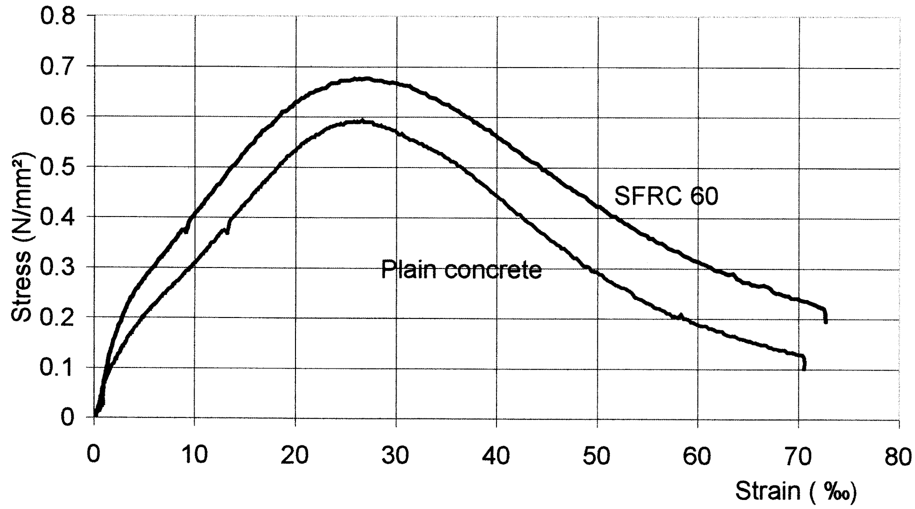

Fig. 5. Comparison of the stress–strain curves for plain concrete and SFRC with 60 kg/m^3 fibres at the age of 9 h.

6% after 9 h. Table 4 shows the significant enhancement of energy absorption before and after the peak load at early age:

- The increase of energy absorption until peak load amounts to 47.7%.
- The enhancement of total energy absorption up to the strain of 6% is 30.67%.

Fig. 6 shows the different performances of SFRC and plain concrete at the age of 81 h. The two curves have similar gradient before the peak stress. It shows the fibres do not have much influence on the long-term behavior of hardened concrete before the peak load. The significant improvement in the energy absorption and in the ductility at uniaxial compression is found only after the peak load, compared to Fig. 5.

The average results of energy absorption per unity in volume at the age of 81 h are given in Table 5.

E_{p81} is the energy absorption up to the peak load after 81 h and $E_{t81}$is the total energy absorption up to the strain of 4% after 81 h. Table 5 shows the significant enhancement of energy absorption especially after the peak load for hardened concrete:

- In contrast to the behavior at 9 h, the increase of energy absorption before peak load amounts to only 16%.
- The enhancement of total energy absorption up to the strain of 4% comes to 41.4%.

Table 4
Average values of energy absorption at the age of 9 h

Material	E_{p9}	E_{t9}
Plain concrete	9.26	22.4
SFRC 60	13.68	29.27

4. Discussion

The properties of concrete/shotcrete under uniaxial compressive load at early age are very complex and dependent on several parameters. Previous results have shown that the failure occurs in a localised zone as a shear or cleavage fracture. The failure mode of concrete specimens can be considered as resulting from local tensile mechanisms, or from a combination of tensile and shear mechanisms. The structural response depends on the characteristic dimension and on the boundary conditions [9].

It is worth noting that the properties of SFRC/S at early age are very important for tunnelling and other underground construction. Some results in the literature have shown that distribution of steel fibres is two-dimensional in SFRS. But our investigations [7,12,13] have indicated that for SFRS the fibre distribution can be only defined as "mainly" two-dimensional due to the unevenness of different aggregate, technology and other building site factors. It means that:

1. The steel fibres are not precisely distributed in one plane in shotcrete and can partly influence the vertical splitting cracks too (Figs. 3 and 4). For the safety of the structure, this partial effect of fibres on the vertical cracks can be neglected.
2. The mainly two-dimensionally distributed steel fibres in shotcrete can affect the oblique shear cracks greatly.

Investigations have shown that the steel fibres distribute mainly three-dimensionally in SFRC. It means that the steel fibres can reinforce both oblique cracks and vertical cracks (Figs. 2–4), especially, bridging of fractured vertical crack surfaces of specimens is more distinct than SFRS. That is an important point of distinction between SFRC and SFRS.

The fibre effect on failure mechanisms and the structure response appear to be related not only to the age of concrete but also to the different construction method

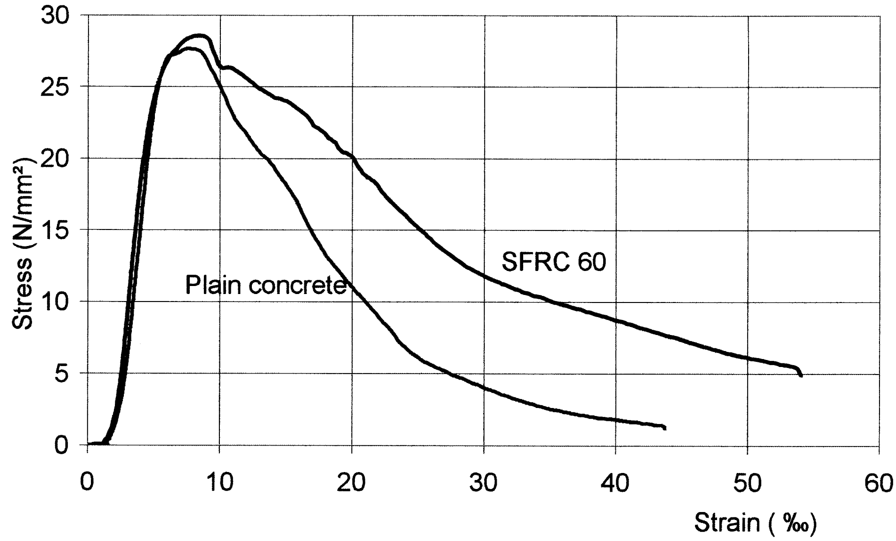

Fig. 6. Comparison of the stress–strain curves for plain concrete and SFRC with 60 kg/m^3 fibres at the age of 81 h.

(shotcrete or cast in place concrete) and to the dimension of the tested specimens.

At early age, the steel fibres can increase the duration of peak load and of the range of 95% for peak load. It is very useful for tunnelling due to the following three reasons:

1. The tunnel shell is loaded from early age.
2. It indicates the higher deformation behavior of SFRC at the peak load.
3. For the same load degree at a time interval, because of the quickly hardened concrete/shotcrete matrix, the degree of utilisation decreased very promptly at early age [9]. In this sense, the steel fibres can enhance the safety of the structure at early age.

In addition to improving the duration before and after peak load, another important aspect of SFRC/S is the increased energy absorption at uniaxial compression. For the same strain, SFRC could sustain more stress both before and after the peak load at early age. The fibre-reinforcing efficiency is increased to some extent, because of enhanced fibre–concrete matrix interfacial bond strength [14].

5. Conclusions

The above mentioned investigations allow the two different fibre influences to be distinguished for green concrete and for hardened concrete. The experimental and analytical results of this study have led to the following conclusions:

1. For SFRS, the mainly two-dimensionally distributed steel fibres can reinforce the shear failure (oblique cracks) significantly.
2. For SFRC, the mainly three-dimensionally distributed steel fibres can reinforce both the shear failure (oblique cracks) and the splitting failure (vertical cracks) greatly.
3. At early age, compared to plain concrete, steel fibres can increase the duration of peak load of the green concrete under the compressive load significantly.
4. In the long-term, for hardened concrete, steel fibres have no influence on the duration at peak load.
5. At early age, steel fibres enhance the energy absorption and the ductility of the concrete under the compressive load not only for post-crack, but also before the peak load.
6. In the long-term, steel fibres enhance the energy absorption and the ductility of the hardened concrete at compression mainly after the peak load.

Table 5
Average values of energy absorption at the age of 81 h

Material	E_{p81}	E_{t91}
Plain concrete	106	396
SFRC 60	123	560

6. Notation

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.

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