Improvement of Serviceability and Strength of Textile Reinforced Concrete by using Short Fibres*

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Summary: Nowadays, thin-walled load bearing structures can be realised using textile reinforced concrete (BRAMESHUBER and RILEM TC 201-TRC [1]). The required tensile strength is achieved by embedding several layers of textile. By means of the laminating technique the number of textile layers that can be included into the concrete could be increased. To further increase the first crack stress and the ductility as well as to optimize the crack development, fine grained concrete mixes with short fibres can be used. By a schematic stress-strain curve the demands on short fibres are defined. Within the scope of this study, short fibres made of glass, carbon, aramid and polyvinyl alcohol are investigated in terms of their ability to fit these requirements. On the basis of these results, the development of hybrid fibre mixes to achieve the best mechanical properties is described. Additionally, a conventional FRC with one fibre type is introduced. Finally, the fresh and hardened concrete properties as well as the influence of short fibres on the load bearing behaviour of textile reinforced concrete are discussed.

1 Introduction

Similar to steel reinforced concrete textile reinforced concrete is able to carry high tensile loads by the use of high strength alkali resistant (AR) glass textiles. However, textile reinforced concrete exhibits a crack formation phase with high strains which is disadvantageous at the verification of serviceability. Furthermore, fine grained concrete and glass, considered individually, show a brittle fracture behaviour. Therefore, recent developments of fine grained concretes focus on higher first crack strengths and a more ductile behaviour. This shall be achieved by the addition of short fibres.

Fig. 1 schematically depicts the behaviour of conventional textile reinforced concrete. After the first crack of the matrix (part I), tensile specimens feature a crack formation phase with

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small increases in load and high strains (part IIa). Having been completely transferred to the textile, the load is increased until the textile fails (part IIb) [2].

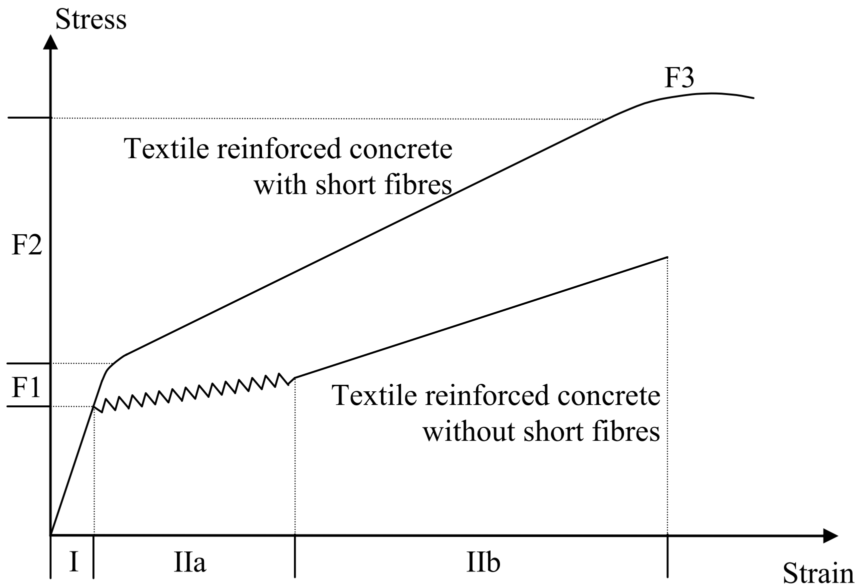

Fig. 1: Schematic stress-strain behaviour of textile reinforced concrete with and without short fibres.

Likewise Fig. 1 schematically shows the target stress-strain curve of textile reinforced concrete with additional short fibre reinforcement. The first part F1 describes the contribution of the short fibres to a higher first crack load of the concrete. Part F2 is characterized by a strain hardening behaviour with initial crack formation. During the phase of crack formation the short fibres help to bridge the cracks and improve the crack pattern. The stiffness and the load level as compared to that of mere textile reinforced concrete may be increased by the effective increase in the reinforcement ratio. The transition F2/F3 describes the maximum contribution of the short fibres. As soon as the initial bond of the fibres changes into a friction bond or the short fibres break the load-bearing capacity of the short fibres is reduced and the stiffness decreases. The short fibres are pulled out and the gradient of the stress-strain curve approaches the original load bearing behaviour of the textiles. In previous investigations [3] it turned out, however, that before the transition from F2 to F3 a failure of the glass textile occurs when high-strength short fibres with a good matrix bond are used. In this case, the addition of short fibres leads to an increased load level covering the entire gradient of the stress-strain curve.

It was the aim to supplement the conventional load bearing behaviour of textile reinforced concrete by the two parts F1 and F2. As both these parts place different demands on short fibres, the combination of fibres of different materials, sizes and shapes with different functions seems advantageous. Micro-fibres are capable of increasing the first crack stress of the concrete by reducing and delaying the micro-crack formation. After the formation of a first macro-crack the macro-fibres may allow a further increase in load bridging the cracks [4]. Both fibre types provide reinforcement at different fracture levels and may complement each other. The present paper describes the development of hybrid fibre concretes that improve the load bearing behaviour in each of the presented parts of the stress-strain curve. Additionally, a single fibre concrete with better workability and the fresh and hardened concrete properties are presented.

2 Materials and specimens

Basically, fine grained concretes for textile reinforced concrete feature a very flowable consistency which is made possible by limiting the maximum grain size to 0.6 mm, a high binder content as well as different pozzolanic additives and superplasticizers. The fine grained concrete mix PZ-0708-01 is the standard mix in the Collaborative Research Centre 532 and is based on a mix developed by BRAMESHUBER Et Al. [5]. This mix has very good fresh and hardened concrete properties and serves as reference. However, because of the high water demand of most fibre types it is suitable for fibre concretes to only a limited extend. To investigate the influence of short fibres on the load-bearing behaviour of textile reinforced concrete a new mix FC was developed. In this mix the binder content was further increased to yield a better workability and the content of silica fume was increased to improve the contact area between fibre and matrix. The mix proportions of the reference mix PZ-0708-01 and the mix FC are shown in Table 1.

Table 1: Mix proportions of fine grained concretes PZ-0708-01 and FC

Mix proportions	Unit	PZ-0708-01	FC
Cement CEM I 52.5 N	kg/m³	490	700
Fly ash		175	150
Silica fume		35	150
Water		280	400
Quartz powder		500	218
Sand		714	384
Superplasticizer	% by mass of binder content	0.7	0.75
Binder content	kg/m³	700	1000
w/b ratio	-	0.4	0.4

As a result of previous examinations [6], the number of short fibre types to be examined could be reduced considerably. A survey of the fibres applied here is given in Table 2. As textile reinforcement, a 1200 tex bi-directional alkali resistant glass textile with a cross sectional area of 71.65 mm^2/m in the longitudinal direction was applied (see Fig. 2A).

Table 2: Applied short fibres and properties

Fibre	Material	Dimensions L	Dimensions D	Type	Young's modulus	Tensile Strength	Density
		mm	µm		N/mm²	N/mm²	g/cm³
A	Aramid	20	12	Integral	73,000	3,400	1.39
G1	Glass	6	20	Water dispersible	72,000	1,700	2.68
G2	Glass	12	20	Integral	72,000	1,700	2.68
G3	Glass	6	20	Integral	72,000	1,700	2.68
C	Carbon	3	7	Water dispersible	238,000	3,950	1.79
P	PVA[1)]	8	40	Water dispersible	42,000	1,600	1.30

[1)] Polyvinyl alcohol

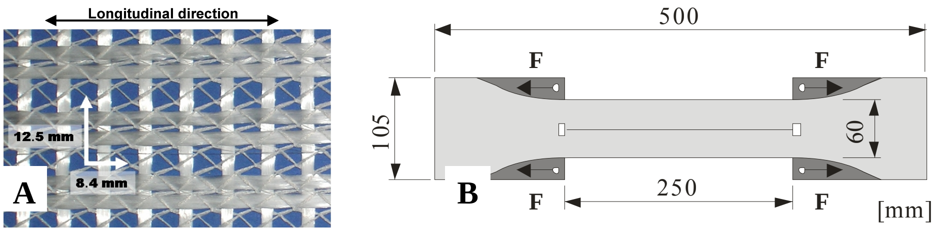

Fig. 2: A) Applied AR glass textile manufactured at the Institut für Textiltechnik, RWTH Aachen University, Germany. B) Dumbbell tensile specimen with dimensions.

Within the framework of this investigation tensile tests were conducted on dumbbell specimens (see Fig. 2B) with a cross sectional area of either 10 x 60 mm^2 and a length of 500 mm or with a cross sectional area of 10 x 100 mm^2 and a length of 1000 mm. 3-point-bending tests were carried out on flat prisms with the dimensions of 40 x 20 x 160 mm^3 and a span of 100 mm.

All mixes were mixed in a mortar mixer for five minutes. For the mixes containing short fibres, the short fibres were stirred in during a mixing break. All tensile specimens were produced horizontally. For the specimens produced without textiles, the mixes containing short fibres were cast into the formwork and properly screeded. Specimens containing textiles were produced with the so-called laminating technique. Here, layers of fine-grained concrete and textile are alternately rolled into the formwork until the requested amount of layers is reached. Two layers of textile were used for the specimens examined here which corresponds to a reinforcement content of 143 mm²/m (V_f = 1,4 %) in the cross section. All test specimens were cured at a temperature of 20 °C and a relative humidity of 95 % for 24 hours. Afterwards, the tensile specimens were sealed and stored for 26 days at 20 °C. One day before testing, the specimens were prepared and stored at 20 °C and 65 % RH. The flat prisms were stored under water until testing. The tensile tests were carried out on a universal testing machine controlled by cross-head displacement at a rate of 0.5 mm/min. The uniaxial load was applied in the waist shaped area of the test specimens. The force was measured by a load cell and the elongation by one inductive gauge on each side.

3 First crack strength

To investigate the influence of different short fibre types on the first crack strength four short fibre mixes consisting of the basic mix FC and the respective short fibre type were tested. Fibre types G2 and G3 were not considered in this first study because of preliminary bending tests in which water dispersible glass fibres led to much better results concerning first crack strength. With the exception of the carbon fibres, a fibre content of 2 % by volume was chosen for comparison. For reasons of workability, the carbon fibre content had to be reduced. A content of about 0.6 % by volume was determined in preliminary tests and results in a workability comparable to that of the 2 % mixes. Tensile specimens without textile were produced of all short fibre concretes. One stress-strain curve of each fibre type is exemplarily shown in Fig. 3. Additionally, a stress-strain curve of a specimen with only two layers of AR glass textile serves as reference curve. According to Jesse [2] it can be assumed that two layers of AR glass textile do not increase the first crack load of the concrete.

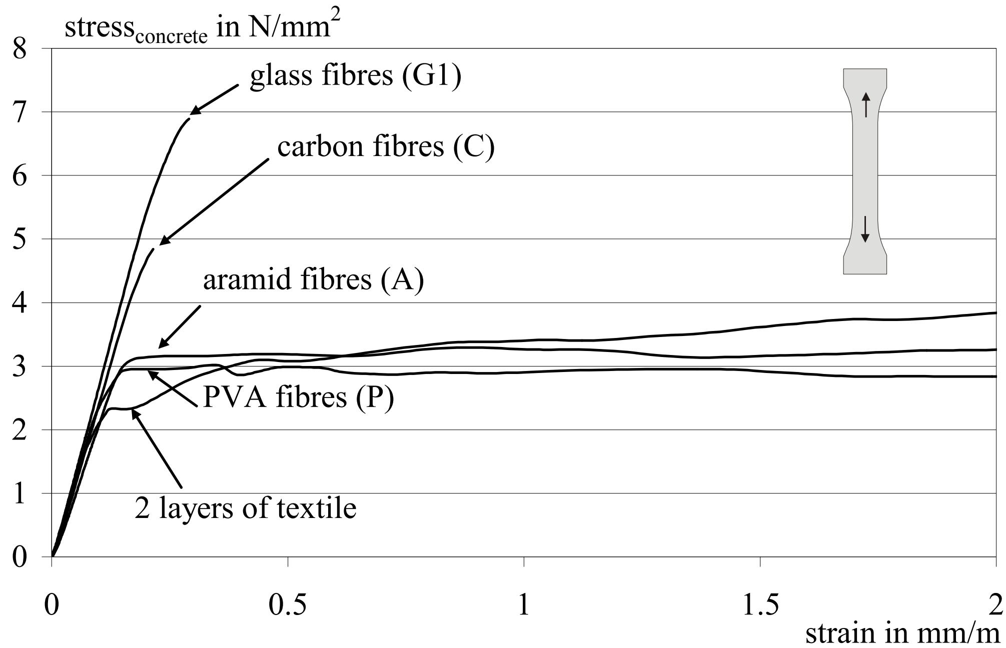

Fig. 3: First crack stresses of specimens with different short fibre types

If only the increase of the first crack load is desired this goal can be achieved just by adding short fibres. Whereas the addition of aramid and PVA fibres leads only to a minor rise, the first crack load is considerably increased by the addition of carbon and water dispersible glass fibres.

4 Post-cracking behaviour

With regard to the combination of short fibres, in this section short fibres shall be considered which are activated after the first crack and feature good crack-bridging properties. Based on the target tensile load bearing behaviour shown in Fig. 1, at first the requirements on these short fibres are defined:

- Maintenance of the load level after the first crack

  The short fibres presented in section 3 increase the first crack load. This places high demands on the fibre-matrix bond of the crack-bridging fibres. The fibres must be capable of absorbing the increased energy set free at the crack without an unstable load decrease occurring in the tensile test. This calls for a high tensile strength, a high stiffness and a good bond to the matrix.
- Formation of a fine crack pattern

  At the simultaneous application of textiles and short fibres a tension stiffening behaviour of the total system is normally ensured by the textile. The wrong fibre selection may, however, especially at high first crack loads lead to a coarse crack pattern with large crack spacings and crack widths. Therefore, the fibres used must feature a good crack-bridging effect. To this end a high stiffness to minimize the crack widths and a good bond to the matrix to minimize the crack spacings are necessary.
- Stiffness of the total system

  The combination of textiles and short fibres may lead to an altogether stiffer stress-strain behaviour because of the increased reinforcement ratio. This requires a good initial bond between matrix and fibre (see Part F2, Fig. 1). It is important as well that the short fibres feature a subcritical fibre length. They shall not suddenly fail but be pulled out of the matrix when the initial bond fails.

It results from the requirements mentioned that the crack-bridging fibres must feature a high tensile strength, a high Young`s modulus as well as a sufficient bond to the matrix. Therefore, aramid fibres (A), long integral glass fibres (G2) and due to their high ductility PVA fibres (P) were selected to be further investigated in terms of their crack-bridging behaviour. With regard to the proposed combination of short fibres the micro fibres (C) and (G1) were not considered here. To assess the post-cracking behaviour of the respective fibre concretes the stress-deflection curves of flat prisms were determined in a preliminary test. The volume content of the fibres amounts to 2 % by vol. The results are depicted in Fig. 4. It is obvious that the aramid fibres are superior to the glass - and PVA fibres regarding their strain hardening and fibre pull-out behaviour. Moreover, the aramid fibres which are provided with an alkali-resistant coating have a relatively low water demand. Hence, first of all the aramid fibres are further investigated for the application as crack-bridging fibres.

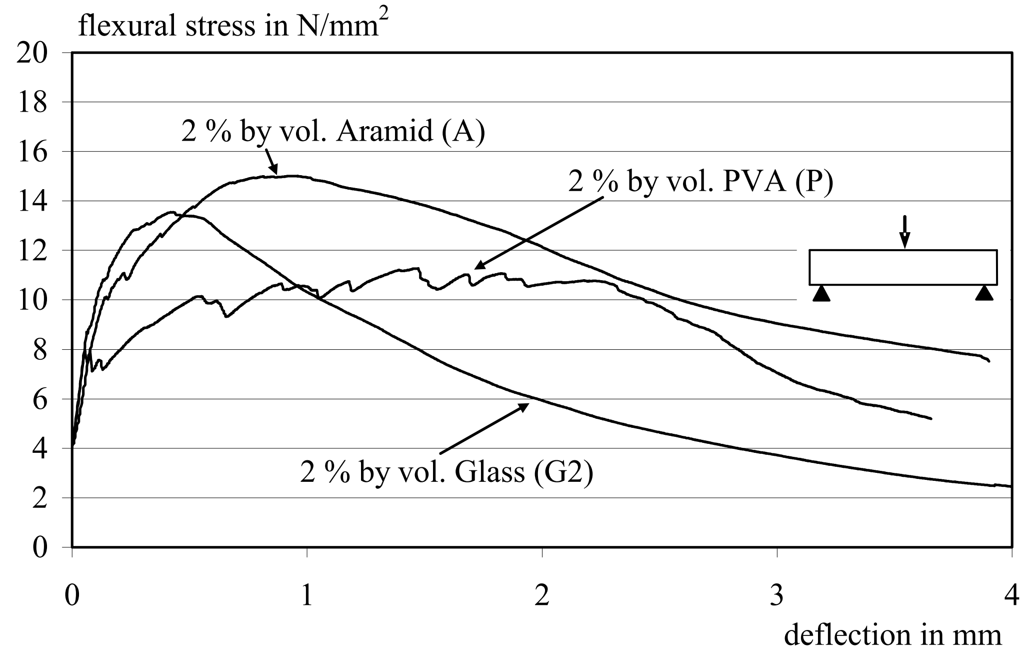

Fig. 4: Post-cracking behaviour of prisms with different macro fibres in bending tests.

5 Combination of short fibres

According to the results in chapter 3, the 3 mm carbon fibres as well as the 6 mm water dispersible glass fibres were chosen for an increase in the first crack strength. For bridging the macro-cracks the aramid fibres seem most suitable. The result are two short fibre combinations consisting of glass and aramid fibres as well as of carbon and aramid fibres which will be closer examined in the following regarding their fibre volume contents.

When combining short fibres the effects on the workability of the concrete mix has to be taken into account. In consideration of the common water demand, the different fibre types have to be applied in minor quantities each compared to fibre volumes in concretes with only one fibre type. As the short fibres shall be applied mainly in building members under tensile stress, above all the uniaxial tensile strength depending on the fibre content must be clarified. For the glass and carbon fibres uniaxial tensile tests were therefore carried out on the tensile specimens described in chapter 2 with varying fibre content. For carbon fibres the fibre content was increased by 0.3 % by vol. For water dispersible glass fibres increase rates of 0.5 % by vol. were chosen because of their slightly better workability. In Fig. 5 the average tensile strengths of the fibre concretes are illustrated for the different fibre contents. Per data point three specimens were tested. At both fibre types the selected fibre quantities always entailed an abrupt failure of the specimens after the formation of the first crack. Hence, the displayed strengths can be regarded as first crack load of the concrete. In the case of the carbon fibres, it turned out that already very small added quantities lead to a significant increase in the first crack load. Larger quantities lead to no significant increases in the crack load because of the growing deterioration of the mix workability and the resulting trapped air. Therefore and with regard to the common water demand, the optimum carbon fibre content was chosen to be 0.5 % by vol. which turned out to be a good compromise between workability and strength. This behaviour was not exhibited by the glass fibres. The crack loads of the concrete grew proportionately to the added fibre quantity. As the glass fibres compared to the carbon fibres feature a decisively lower water demand, larger added quantities have a minor influence on the workability and homogeneity of the concrete. Therefore, a content of 1.5 % by vol. was specified for the glass fibres. With the chosen fibre contents the specific surface and thus the water demand of both fibre types are nearly the same.

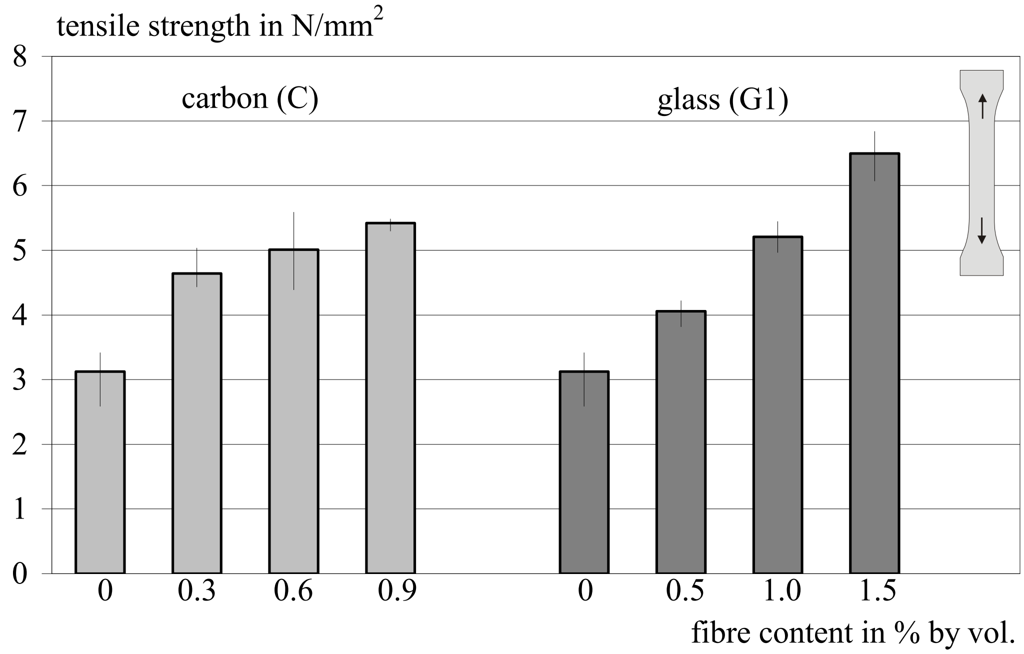

Fig. 5: Influence of carbon and glass fibre content on the concrete tensile strength.

The fractions of aramid fibres have not been investigated systematically so far. In a first step, the fibre contents were chosen considering the workability of the concrete and static requirements. Former investigations [3] showed that the combination of only carbon fibres and textiles furnishes no satisfactory results as the carbon fibres fail in a brittle way at the crack of the matrix and are unable to bridge cracks. For this reason a higher aramid fibre content of 2 % by vol. seemed necessary. Contrary to the carbon fibres, the combination of glass fibres and textiles furnished better results in [3] as the glass fibres have also crack-bridging abilities. However, the specimens featured a reduced stiffness after the first crack of the matrix. Altogether, an aramid content of 1 % by vol. was regarded as being sufficient to support the strain hardening behaviour. The interaction between crack-bridging fibres and textiles will be part of future investigations. Thus, the previous considerations result in the following short fibre mixes: FC-0.5C-2A, consisting of 0.5 % by vol. of carbon fibres (C) and 2 % by vol. of aramid fibres (A) as well as FC-1.5G-1A, consisting of 1.5 % by vol. of glass fibres (G1) and 1 % by vol. of aramid fibres (A).

The approaches mentioned above aimed at the optimisation of the tensile load bearing behaviour of textile reinforced concrete by using combinations of short fibres with different properties. The presented short fibre combinations feature the best properties in terms of first crack strength and ductility within this investigation. However, due to their high fibre volume these mixes are not flowable and can only be used with the laminating technique. Hence, for reduced demands on the load bearing behaviour the flowable mix FC-3G containing 3 % by vol. of integral glass fibres (G3) with a length of 6 mm was developed. This standard glass fibre type has a relatively low water demand and allows a good workability of the concrete. It can both increase the first crack strength and act as a crack-bridging fibre.

6 Tensile load bearing behaviour of textile reinforced concrete

Fig. 6 shows the tensile stress-strain curves of textile reinforced concrete with two layers of AR glass and the short fibre mixes FC-0.5C-2A, FC-1.5G-1A and FC-3G. Additionally, there are the reference curves of the mixes PZ-0708-01 and FC with only two layers textile without short fibres. Basically, it is shown that the addition of short fibres fulfils the target phrased in section 1. The three presented short fibre concretes lead to a significant increase in the first crack load and to a uniform load transfer to the textile. The formation of finer crack patterns, which are illustrated in Fig. 7 can also be recognized by the undisturbed gradient of the stress-strain curves. A finer crack pattern may also entail higher ultimate strains compared to textile reinforced concretes without short fibres. As implied in section 1, the textile fails before the effect of the short fibres is reduced by loss of bond. Compared to the results of Fig. 5, in the case of the carbon fibre mix FC-0.5C-2A the first crack load is further increased by the interaction with the aramid fibres and the glass textile and thus slightly exceeds the first crack load of the mix FC-1.5G-1A. Hence, the interaction of carbon and aramid fibres seems to be more advantageous regarding the first crack load than the combination of glass and aramid. Although the glass fibre type G3 is not as effective in the micro scale as the water dispersible glass fibres in mix FC-1.5G-1A the first crack load can rise to the same level when using a higher volume.

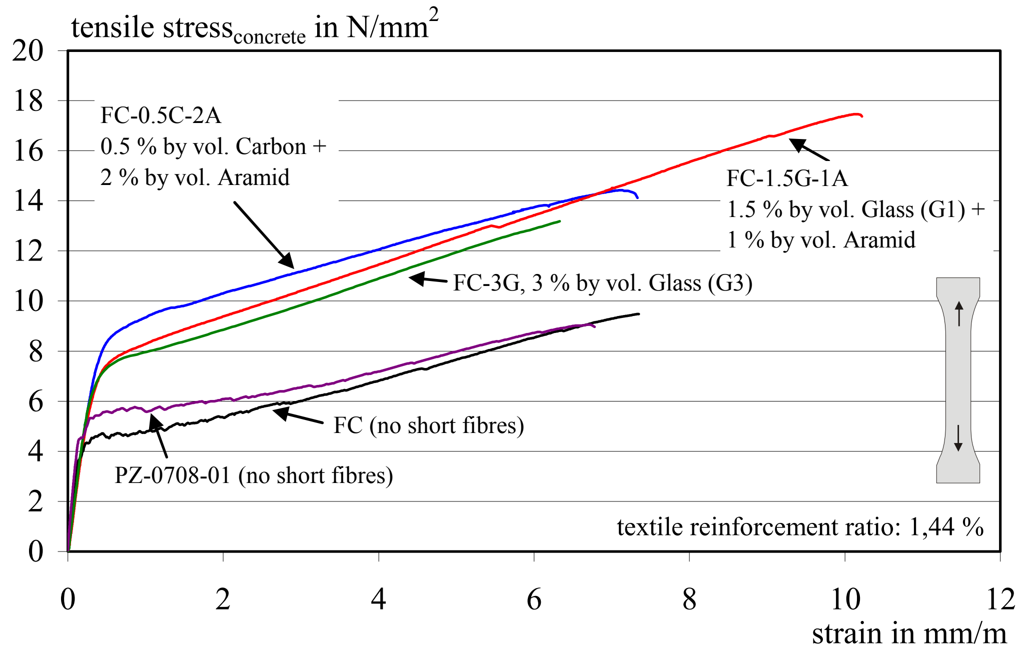

Fig. 6: Stress-strain behaviour of textile reinforced concrete with and without short fibres.

Concerning crack development the best results were achieved with mixes FC-3G and FC-1.5G-1A (see Fig. 7). If the two fibre combinations are compared the combination of glass and aramid fibres allows higher ultimate strains and leads to a finer crack pattern. Furthermore, this mix features a better workability than mix FC-0.5C-2A. Because of the only minor difference at the first crack load, the mix FC-1.5G-1A seems to be better suited for the application in textile reinforced concrete.

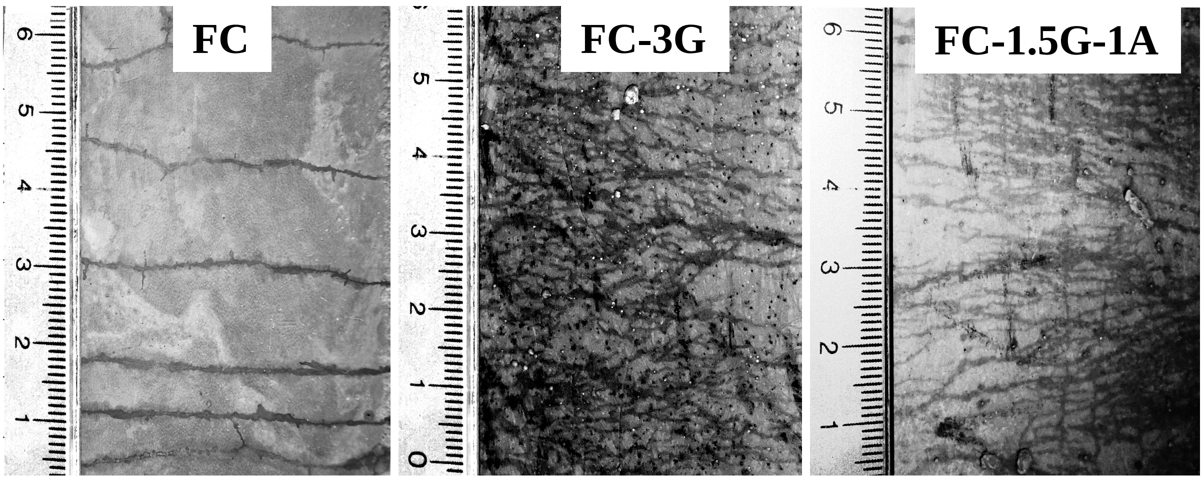

Fig. 7: crack patterns of textile reinforced concrete without short fibres (FC) and with fibre concretes FC-3G and FC-1.5G-1A

7 Fresh and hardened concrete properties

The developed fibre concretes generally differ from the conventional fine grained concretes being used for textile reinforced concrete. This affects the hardened concrete properties as well as the fresh concrete properties in particular. Generally, the workability is affected due to the high water demand of most short fibres. A production of textile reinforced concrete elements using the casting method is possible only to a limited extend. In case of the mix FC-1.5G-1A only the laminating technique can be applied. On the other side the tensile load bearing behaviour of textile reinforced concrete could be considerably improved with the presented short fibres mixes. The mechanisms of action of textiles and short fibres generally complement each other. Therefore, recent developments aim at fibre concretes with good workability and a high load carrying capacity. The fresh and hardened concrete properties of the plain concretes FC and PZ-0708-01 as well as the fibre concretes FC-1.5G-1A and FC-3G are compiled in Table 3.

Table 3: Properties of the plain concretes PZ-0708-01 and FC and the fibre concretes FC-3G und FC-1.5G-1A

Concrete properties		Unit	PZ-0708-01	FC	FC-3G	FC-1.5G-1A
Density		kg/m^3	2188	2219	2036	1974
Air content		% by vol.	2.2	0.8	2.0	3.8
Slump flow		mm	300	161	-	-
Spread (mortar)		mm	-	-	240	177
Compressive strength	7d	N/mm^2	66.4	67.1	67.0	75.0
	28d		86.5	91.1	97.9	93.2
Flexural strength	7d	N/mm^2	9.2	9.5	14.6	25.0
	28d		12.5	13.0	17.9	23.6
Young's modulus	28d	N/mm^2	33000	25400	23000	24600
Fracture energy		N/m	66.6	30.5	3525.2	7321.4
Characteristic length		mm	109.0	54.3	4112.9	12605.1

8 Summary

The present paper describes the improvement potential of the tensile load bearing behaviour of textile reinforced concrete by adding short fibres and short fibre combinations. In a first step, the general tensile behaviour of textile reinforced concrete with short fibres is described by a schematical stress-strain curve. Three parts are introduced: the increased first crack stress (F1), the strain hardening (F2) and the loss of initial bond of the short fibres (F3). In order to improve the first crack stress and the strain-hardening behaviour short fibre types and volumes were determined for each part. The highest increase of the first crack stress could be obtained with water dispersible glass fibres (6 mm) or carbon fibres (3 mm). For both fibre types optimized fibre volumes with regard to strength and workability were determined. To improve the post-cracking behaviour aramid fibres were selected. On the basis of the findings obtained, two combinations of short fibres were developed to combine the advantages of the respective fibre types. As a result, the first crack stress could be improved by about 40 %. Furthermore, the load transfer from the concrete to the textile is more ductile with all presented fibre mixes, which also results in finer crack patterns. As a result of the increased multiple crack formation, the short fibres were also still efficient in the areas of high strains. This can lead to higher loads and higher ultimate strains. The results demonstrate that the positive properties of the short fibres can be combined. In addition to the hybrid fibre concretes a fibre concrete with only one fibre type was developed. This concrete has a slightly lower performance but a better workability. Finally fresh and hardened concrete properties of all mixes were presented.

9 References

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