SP-251—1

Improvement of Serviceability and Strength of Textile-Reinforced Concrete Elements with Short Fiber Mixes

by M. Hinzen and W. Brameshuber

Synopsis: Nowadays, thin-walled load bearing structures can be realized using textile-reinforced concrete (Brameshuber and RILEM TC 201-TRC, 2006). 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 strength and the ductility and to optimize the crack development, fine-grained concrete mixtures with short fibers can be used. By simultaneously using different types of short fibers, the positive properties of each fiber may be combined. By a schematic stress-strain curve, the demands on short-fiber mixtures are defined. Within the scope of this study, short fibers made of glass, carbon, aramid, and polyvinyl alcohol are investigated in terms of their ability to fit these requirements. Furthermore, examinations to determine the fiber types and fiber volumes are presented. Finally, two hybrid fiber-reinforced concretes are introduced. On the basis of stress-strain curves of textile-reinforced concrete, the advantages of these fiber mixtures are discussed.

Keywords: ductility; fine-grained concrete; first crack strength; short fibers; textile-reinforced concrete

Marcus Hinzen, born in 1978, study of civil engineering at RWTH Aachen University, Germany, since August 2005 research assistant at the Institute of Building Materials Research (ibac) of RWTH Aachen University, Germany

Wolfgang Brameshuber, born in 1956, study of civil engineering, Technical University of Karlsruhe, PhD of engineering at the faculty of Civil Engineering, Technical University of Karlsruhe, 10 years of practical experiences, BUNG consultant, Heidelberg, director of the main laboratory at Bilfinger Berger, since 1999 holder of the chair of Building Materials Science at RWTH Aachen University and director of the Institute of Building Materials Research (ibac) of RWTH Aachen University.

CHAPTER 1 - INTRODUCTION

In this paper the main focus is directed on an improved tensile behavior of textile reinforced concrete concerning strength and serviceability. It is the aim to improve the behavior of textile reinforced concrete precisely in the area of the crack formation in terms of an increased first crack strength and a more ductile behavior which means to achieve a distinct multiple cracking with smaller crack widths. The increase in strength and the improved ductility shall be achieved by the use of a ductile fiber reinforced fine grained concrete mix.

The positive properties of steel, glass or polypropylene fibers for the application in concrete have often been emphasized in the literature (Banthia and Soleimani 2005; Butler et al. 2006; Markovic et al. 2003). The more special types of short fibers as carbon (Banthia, 1994; Deng 2005), aramid and polyvinyl alcohol (PVA) (Li et al. 2001; Saito et al. 2003) and especially the interaction of short fibers with glass textiles have so far been considered to a lesser extent. Moreover, due to the special properties of the fine grained concrete mixes developed within the scope of the Collaborative Research Center 532 “Textile reinforced concrete”, a re-examination of all fiber types was necessary.

In previous examinations, an increase in the tensile strength of the fine grained concrete as well as a more ductile behavior after the first crack of the matrix due to single short fiber types could be verified (Hinzen and Brameshuber 2006, 2007). The present paper deals with the combination of short fibers and the interaction with the glass textile of the textile reinforced concrete. At first, the general tensile load bearing behavior of textile reinforced concrete with additional short fiber reinforcement is schematically depicted. After specification of the short fiber requirements, different fiber types are assessed regarding their suitability and suitable volume contents are determined experimentally. Finally, the improved bearing behavior of the textile reinforced concrete is presented for two fiber combinations.

CHAPTER 2 – TARGET TENSILE LOAD BEARING BEHAVIOR

It is the target of the investigations to increase the first crack load of the textile reinforced concrete and to render the process of the crack formation more ductile. Fig. 2.1 schematically depicts the behavior of conventional textile reinforced concrete. After the first crack of the matrix (part I), tensile specimens feature a crack formation phase with 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). Likewise Fig 2.1 schematically shows the target stress-strain curve of textile reinforced concrete with additional short fiber reinforcement. The first part F1 describes the contribution of the short fibers to a higher first crack load of the concrete. Part F2 is characterized by a strain hardening behavior with initial crack formation. During the phase of crack formation the short fibers 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 fibers. As soon as the initial bond of the fibers changes into a friction bond or the short fibers break the load-bearing capacity of the short fibers is reduced and the stiffness decreases. The short fibers are pulled out and the gradient of the stress-strain curve approaches the original load bearing behavior of the textiles. In previous investigations (Hinzen and Brameshuber 2007) it turned out, however, that before the transition from F2 to F3 a failure of the glass textile occurs when high-strength short fibers with a good matrix bond are used. In this case, the addition of short fibers leads to an increased load level covering the entire gradient of the stress-strain curve.

It is the aim to supplement the conventional load bearing behavior of textile reinforced concrete by the two parts I and II. As both these parts place different demands on short fibers, the combination of fibers of different materials, sizes and shapes with different functions seems advantageous. In many cases, micro-fibers are combined with macro-fibers. Both fiber types provide reinforcement at different fracture levels and may complement each other. Micro-fibers 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-fibers may allow a further increase in load bridging the cracks (Banthia, and Soleimani 2005; Lawler et al. 2002). Hence, the interaction between micro-fibers and macro-fibers mostly leads to an improvement of strength and ductility. Therefore, in a first step different investigations are reverted to in order to obtain suitable short fiber types and volumes for each of the presented parts of the stress-strain curve.

CHAPTER 3 – EXPERIMENTAL PROGRAM

3.1 – Materials, mixes and specimens

The fine grained concrete mix used for the short fiber reinforced concrete is based on a standard mix developed in the Collaborative Research Center 532 (Brameshuber and Brockmann 2001). Basically, the mixes feature a very flowable consistency which is made possible by limiting the maximum grain size to 0.6 mm ($2.362 \cdot 10^{-2}$ in.), a high binder content as well as different pozzolanic additives and superplasticizers. In the basic mix applied here, 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 fiber and matrix. The mix proportions of the basic mix FC without fibers are shown in Table 3.1.

As a result of previous examinations (Hinzen and Brameshuber 2006), the number of short fiber types to be examined could be reduced considerably. In preliminary bending tests it became obvious that carbon fibers can very effectively be applied to increase the first crack load. Furthermore, water dispersible glass fibers led to considerable improvements in terms of first crack strength and crack development. In the range of crack bridging short fibers, PVA fibers are promising due to their good chemical bond to the matrix and relatively high tensile strength. Additionally, aramid and non-water dispersible glass fibers were included to the examinations. A survey of the fibers applied here is given in Table 3.2. As textile reinforcement, a bi-directional alkali resistant glass textile with a cross sectional area of 71.65 mm^2/m (4.724 in.^{2}/ft) in the longitudinal direction was applied (see Fig. 3.1A).

Within the framework of this investigation tensile tests were conducted on dumbbell specimens (see Fig. 3.1B) with a cross sectional area of 10 x 60 mm^2 (0.394 x 2.362 in.^{2}) and a length of 500 mm (19.685 in.). However, for the tensile load bearing behavior in Fig. 5.2, similar specimens with a cross sectional area of 10 x 100 mm^2 (0.394 x 3.94 in.^{2}) and a length of 1000 mm (39.37 in.) had to be applied. 3-point-bending tests were carried out on flat prisms with the dimensions of 40 x 20 x 160 mm^3 (1.574 x 0.787 x 6.299 in.^{3}) and a span of 100 mm (3.94 in.).

3.2 – Production and execution of the test

All mixes were mixed in a mortar mixer for five minutes. For the mixes containing short fibers, the short fibers were stirred in during a mixing break. All tensile specimens were produced horizontally. For the specimens produced without textiles, the mixes containing short fibers 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 (9.448 in.^{2}/ft) in the cross section. All test specimens were cured at a temperature of 20°C (68°F) and a relative humidity of 95 % for 24 hours. Afterwards, the tensile specimens were sealed and stored for 26 days at 20°C (68°F). One day before testing, the specimens were prepared and stored at 20°C (68°F) 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 ($1.969 \cdot 10^{-2}$ in./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.

CHAPTER 4 – SELECTION OF FIBER TYPES

4.1 – First crack strength

To investigate the influence of different short fiber types on the first crack strength four short fiber mixes consisting of the basic mix and the respective short fiber type were tested. With the exception of the carbon fibers, a fiber content of 2 % by volume was chosen for comparison. For reasons of workability, the carbon fiber 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 were produced of all short fiber concretes. One stress-strain curve of each fiber type is exemplarily shown in Fig. 4.1. When evaluating the first crack load it can be assumed that two layers of AR-glass textile do not increase the first crack load of the concrete (Jesse, 2004). Therefore, an additional stress-strain curve for a specimen with only two layers of AR-glass serves as reference curve.

As the tensile specimens were manufactured with the laminating technique described above, the surface structures of the specimens on the formwork side are not identical to those on the casting side. This may lead to irregular shrinkage deformations which were also observed by Jesse, 2004. Therefore, the specimens were not perfectly straight before the test which resulted in a reduction of the absolute first crack strengths. This influence of the different manufacturing techniques will be subject of further investigations.

If only the increase of the first crack load is desired this goal can be achieved just by adding short fibers. Whereas the addition of aramid and PVA fibers leads only to a minor rise, the first crack load is considerably increased by the addition of carbon and water dispersible glass fibers. The carbon fibers used are available in different lengths. Fibers with a length of 12 mm (0.472 in.) proved to be unsuited. To find out which carbon fiber length had the best strength-improving properties, bending tests on flat prisms (40 x 20 x 160 mm^3) (1.574 x 0.787 x 6.299 in.^{3}) were conducted. In doing so 3 mm (0.118 in.) as well as 6 mm (0.236 in.) long carbon fibers in different fiber contents were examined. To document the effects on the workability, the spread of the fresh concretes was determined additionally. The results are depicted in Fig 4.2. The diagram comprises the flexural strength as well as the workability as functions of the fiber volume for both fiber lengths. It becomes obvious that the flexural strength can not be increased as of a fiber content of 0.6 % by vol. The reason is the decreasing workability and the inherent higher introduction of air into the matrix. Furthermore, it becomes evident that, at a slightly better workability, the 3 mm (0.118 in.) long carbon fibers tend to lead to higher strengths. The tests served to select the carbon fiber length considering workability and strength. Up to now water dispersible glass fibers were only used at a length of 6 mm (0.236 in.). Examinations regarding the influence of the glass fiber length will be carried out shortly.

4.2 – Post-cracking behavior

With regard to the combination of short fibers, in this chapter short fibers shall be considered which are activated after the first crack and feature good crack-bridging properties. Based on the target tensile load bearing behavior shown in Fig 2.1, at first the requirements on these short fibers are phrased:

- **Maintenance of the load level after the first crack**
  The short fibers presented in chapter 3.1 increase the first crack load. This places high demands on the fiber-matrix bond of the crack-bridging fibers. The fibers 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 fibers a tension stiffening behavior of the total system is normally ensured by the textile. The wrong fiber selection may, however, especially at high first crack loads lead to a coarse crack pattern with large crack spacings and crack widths. Therefore, the fibers 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 fibers may lead to an altogether stiffer stress-strain behavior because of the increased reinforcement ratio. This requires a good initial bond between matrix and fiber (see Part II, Fig 2.1). It is important as well that the short fibers feature a subcritical fiber 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 short fibers must feature a high stiffness, a high Young`s modulus as well as a sufficient bond to the matrix. Therefore, of all short fiber types hitherto examined, the selection is restricted to aramid fibers (A), non-water-dispersible glass fibers (G2) and PVA fibers (P). Steel fibers are not intended for the application in textile reinforced concrete. To assess the post-cracking behavior of the respective fiber concretes the stress-deflection curves of flat prisms were determined in a preliminary test. The volume content of the fibers amounts to 2 % by vol. The results are depicted in Fig. 4.3. It is obvious that the aramid fibers are superior to the glass - and PVA fibers regarding their strain hardening and fiber pull-out behavior. Moreover, the aramid fibers which are provided with an alkali-resistant coating have a relatively low water demand. Hence, first of all the aramid fibers are further investigated for the application as crack-bridging fibers. Investigations with PVA fibers will be carried out in the near future.

CHAPTER 5 – COMBINATION OF SHORT FIBERS

For an increase in the first crack strength the 3 mm (0.118 in.) carbon fibers as well as the water dispersible glass fibers were chosen in chapter 4.1. For bridging the macro-cracks the aramid fibers seem most suitable. The result are two short fiber combinations consisting of glass and aramid fibers as well as of carbon and aramid fibers which will be closer examined in the following regarding their fiber volume contents.

When combining short fibers the effects on the workability of the concrete mix has to be taken into account. In consideration of the common water demand, the different fiber types have to be applied in minor quantities each compared to fiber volumes in concretes with only one fiber type. As the short fibers shall be applied mainly in building members under tensile stress, above all the uniaxial tensile strength depending on the fiber content must be clarified. For the glass and carbon fibers uniaxial tensile tests were therefore carried out on the tensile specimens described in chapter 3.1 with varying fiber content. For carbon fibers the fiber content was increased by 0.3 % by vol. For water dispersible glass fibers increase rates of 0.5 % by vol. were chosen because of the slightly better workability. In Fig 5.1 the average tensile strengths of the fiber concretes are illustrated for the different fiber contents. Per data point three specimens were tested. At both fiber types the selected fiber 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 fibers, the results were similar to Fig. 4.2. 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, with regard to the common water demand, the carbon fiber content was reduced to 0.5 % by vol. which turned out to be a good compromise between workability and strength. This behavior was not exhibited by the glass fibers. The crack loads of the concrete grew proportionately to the added fiber quantity. As the glass fibers compared to the carbon fibers 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 fibers. With the chosen fiber contents the specific surface and thus the water demand of both fiber types are nearly the same.

The fractions of aramid fibers have not been investigated systematically so far. In a first step, the fiber contents were chosen considering the workability of the concrete and static requirements. Former investigations (Hinzen and Brameshuber 2007) showed that the combination of only carbon fibers and textiles furnishes no satisfactory results as the carbon fibers fail in a brittle way at the crack of the matrix and are unable to bridge cracks. To improve the crack-bridging behavior a content of 2 % by vol. was specified for the combination with carbon fibers. Contrary to the carbon fibers, the combination of glass fibers and textiles furnished better results. 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 behavior.

Thus, the previous considerations result in the following short fiber mixes: FC-0.5C-2A, consisting of 0.5 % by vol. carbon fibers and 2 % by vol. aramid fibers as well as FC-1.5G-1A, consisting of 1.5 % by vol. glass fibers and 1 % by vol. aramid fibers. The compositions of both mixes are compiled in Table 5.1. Fig 5.2 shows the tensile stress-strain curves of textile reinforced concrete with two layers of AR-glass and the respective short fiber mix. Additionally, there is a reference curve with only two layers textile without short fibers. Basically, it is shown that the addition of short fiber combinations fulfills the target phrased in chapter 2. Both presented short fiber concretes lead to a significant increase in the first crack load and to a uniform load transfer to the textile. The formation of a finer crack pattern, which can also be recognized by the undisturbed gradient of the stress-strain curve, entails altogether higher ultimate strains compared to the textile reinforced concrete without short fibers. As implied in chapter 2, the textile fails before the effect of the short fibers is reduced by loss of bond.

Compared to the results of Fig. 5.1, in the case of the carbon fiber mix, the first crack load is increased once more by the interaction between the aramid fibers 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 fibers seems to be more advantageous regarding the first crack load. An evaluation of the crack pattern is still pending. Apparently the combination of glass and aramid fibers, however, leads to a better crack formation behavior. In previous investigations the water dispersible glass fibers also yielded the shortest crack spacings of less than 1 mm (Hinzen and Brameshuber 2007). As a result of the better crack formation behavior and the higher ultimate strain as well as 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. Furthermore, it features a slightly better workability. Important fresh and hardened concrete properties of the basic fiber mix FC and the mix FC-1.5G-1A are compiled in Table 5.2.

By regarding former results of specimens with only one fiber type (Hinzen and Brameshuber, 2007) it seems that the positive properties of single fiber types can also be combined at textile reinforced concrete. The mostly high water demand of the fiber concretes, however, significantly reduces the workability. Therefore, the improvement of concrete properties and the loss in workability must always be weighed up against each other. These optimizations and in particular the comparison between single and hybrid fiber reinforcement are subject of current research work.

CHAPTER 6 – SUMMARY

The present paper describes the improvement potential of the tensile load bearing behavior of textile reinforced concrete by adding short fiber combinations. In a first step, the general tensile behavior of textile reinforced concrete with short fibers is described by an schematically 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 fibers (F3). In order to improve the first crack stress and the strain-hardening behavior short fiber types and volumes were determined for each part. The highest increase of the first crack stress could be obtained with water dispersible glass fibers (6 mm / 0.236 in.) or carbon fibers (3 mm / 0.118 in.). For both fiber types optimized fiber volumes with regard to strength and workability were determined. To improve the post-cracking behavior aramid fibers seem most suitable. On the basis of the findings obtained, carbon fibers and glass fibers were each combined with aramid fibers to combine the advantages of the respective fiber types. As a result, the first crack stress could be improved by about 40 % with the glass fiber mix and 60 % with the carbon fiber mix. Furthermore, the load transfer from the concrete to the textile is more ductile with both fiber mixes, which also results in finer crack patterns. As a result of the increased multiple crack formation, the short fibers were also still efficient in the areas of high strains. This leads to higher loads and higher ultimate strains. The results demonstrate that the positive properties of the short fibers can be combined. However, due to the limited total fiber content, there will always have to be a distinct adjustment between the improvement potential and the workability of the concrete.

CHAPTER 7 – REFERENCES

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Table 3.1 – Proportions of the basic mixtures FC

Mixture components	**Unit**	**Amount**
Cement CEM I 52.5 N	kg/m^3 *	700
Fly ash		150
Silica fume		150
Water		400
Quartz powder		218
Sand		384
Superplasticizer	% by mass of binder content	0.75
Binder content	kg/m^3	1000
w/*b* ratio	—	0.4

* $1\ kg/m^3 = 6.2426 \cdot 10^{-2}\ lb/ft^3$

Table 3.2 – Short fiber types and properties

Fiber	Type	Dimensions			Young's modulus	Tensile Strength	Density
		L	D	Geometry			
		mm *	µm †		N/mm² ‡		g/cm³ §
A	Aramid	20	12	Straight, strands	73000	3400	1.39
G1	Glass	6	20	Straight, water dispersible	72000	1700	2.68
G2	Glass	12	20	Straight, strands	72000	1700	2.68
C	Carbon	3	7	Straight, water dispersible	238000	3950	1.79
P	PVA ‖	8	40	Straight, water dispersible	42000	1600	1.3

*1 mm = $3.937 \cdot 10^{-2}$ in
†1 µm = $3.937 \cdot 10^{-5}$ in
‡1 N/mm² = 0.14504 ksi
§1 g/cm³ = 62.426 lb/ft³
‖Polyvinyl alcohol

Table 5.1 – Fiber cocktail mixtures

Name	Fine-grained concrete	Fiber material	Content in % by vol.
FC-0.5C-2A	Basic mixture (Table 3.1)	Carbon (C)	0.5
		Aramid (A)	2
FC-1.5G-1A		Glass (G1)	1.5
		Aramid (A)	1

Table 5.2 – Mechanical properties of the basic mixture FC and the short fiber mixture FC-1.5G-1A

Concrete properties		Unit	FC	FC-1.5G-1A
Density		kg/m³ *	2219	1974
Air content		% by vol.	0.8	3.8
Spread (mortar)		mm †	-	177
Compressive strength	7d	N/mm² ‡	67.1	75.0
	28d		91.1	93.2
Flexural strength	7d	N/mm²	9.5	25.0
	28d		13.0	23.6
Young's modulus		N/mm²	25400	24600

*1 kg/m³ = $6.2426 \cdot 10^{-2}$ lb./ft³
†1 mm = $3.937 \cdot 10^{-2}$ in
‡1 N/mm² = 0.14504 ksi

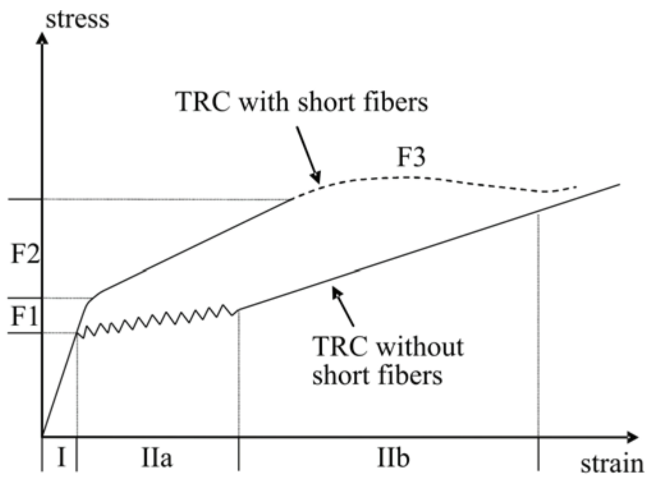

Fig. 2.1 – Schematic stress-strain behavior of textile reinforced concrete with and without short fibers.

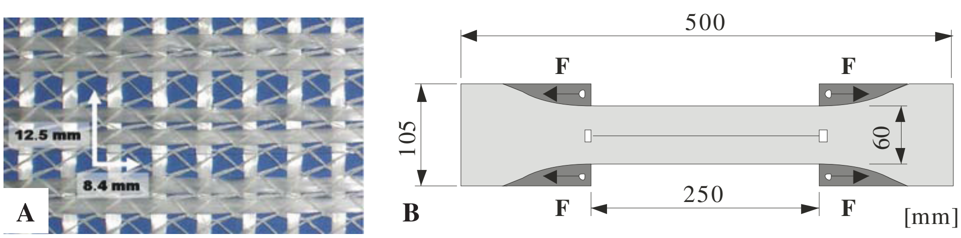

Fig. 3.1 – A) Applied AR-glass fabric manufactured at the Institut für Textiltechnik, RWTH Aachen University, Germany. B) Dumbbell tensile specimen with dimensions. (1 mm = $3.937 \cdot 10^{-2}$ in.)

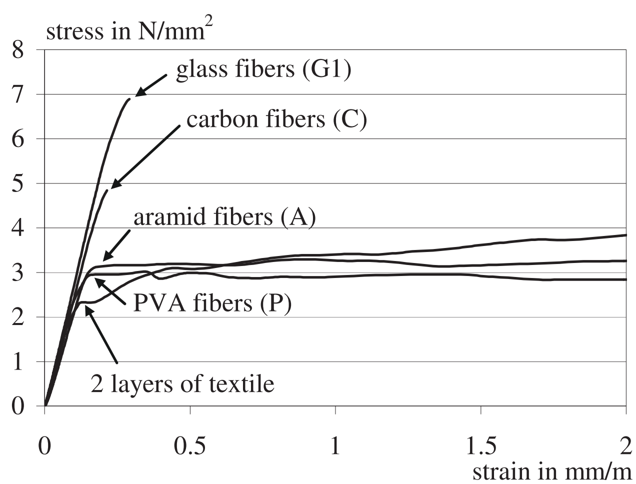

Fig. 4.1 – First crack stresses of specimens with different short fiber types. (1 N/mm^2 = 0.14504 ksi, 1 mm/m = 1 ‰)

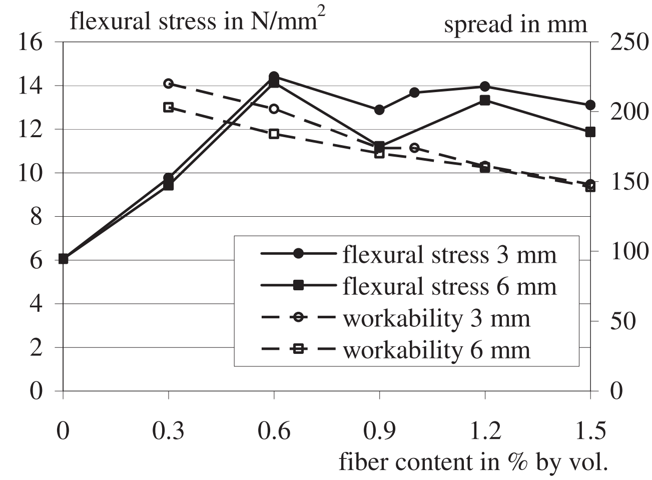

Fig. 4.2 – Influence of fiber content and fiber length on the flexural strength and the workability of concrete containing carbon fibers.
(1 N/mm^2 = 0.14504 ksi, 1 mm = 3.937 · 10^{-2} in.)

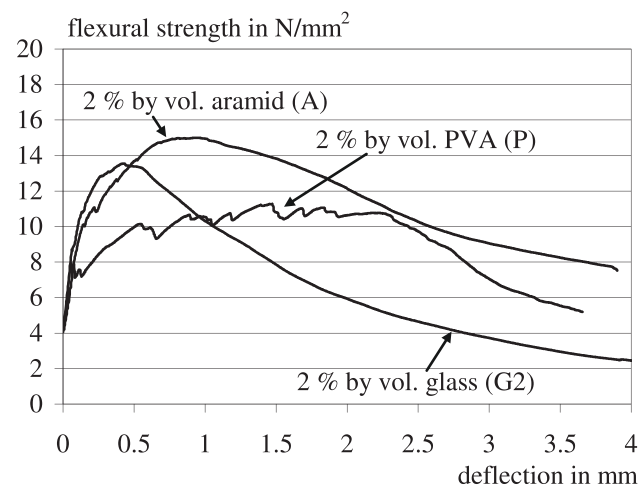

Fig. 4.3 – Post-cracking behavior of flat prisms with different macro fibers in bending tests. (1 N/mm^2 = 0.14504 ksi, 1 mm = 3.937 · 10^{-2} in.)