NOVEL BI-COMPONENT FIBERS FOR THE MECHANICAL REINFORCEMENT OF CONCRETE

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ABSTRACT

The reinforcement of concrete with fibers can be an economical alternative to conventional steel bar reinforcement in many cases. For many years, steel fibers have been the first choice be-cause of their high tensile strength and high elastic modulus. Low modulus fibers, such as poly-olefin based fibers generally are thought to be less suitable for this purpose.

However, co-extrusion processes nowadays allow the economic production of novel bi-component fibers. Polyolefin based fibers with high tensile strength and elastic modulus were successfully applied to enhance the mechanical properties of concrete. The effects of an introduction of nanoparticles and other additives into the fiber polymers and the structuring of the fiber surface on the fiber pull-out characteristics and the bending behavior of concrete are presented.

The performance of bi-component fiber reinforced concrete is studied in 4-point bending and square slab tests where ductile post-peak behavior of such fiber reinforced concrete is achieved, making these fibers interesting for the applications in pre-cast elements, industrial floors and earth quake protecting systems.

KEYWORDS

Fiber; bi-component fiber; concrete; fiber pull-out.

INTRODUCTION

The tensile strength of concrete is lower than its compressive strength by a factor of approximately ten. The failure occurs in a relatively brittle manner. Concrete therefore needs to be reinforced when bearing tensile or shear forces. Safety considerations are often at the forefront. A concrete component when exceeding the maximal load should not break in an abrupt manner, but firstly absorb a certain amount of energy. This is conventionally achieved by reinforcing the concrete with steel bars or meshes. The type of reinforcement is planned in detail and then the reinforcements are applied in cost intensive way (mostly by hand).

For low reinforcement levels, the partial or even complete replacement of such conventional reinforcement by fibers is an advantageous alternative. Because of their high elastic modulus and their relatively high strength, steel fibers generally are used for this purpose.

However, steel fibers also have disadvantages. They may corrode which leads to a loss of strength and also results in unattractive rust traces on the concrete surface. Because of their high stiffness they further entail the danger of injury or material abrasion (concrete mixer, pump) or even damage. As a result of their rigidity they also may have poor dosing and mixing properties leading to high scatter of the material properties due to non-uniform fiber distribution. Large dosing weights arise as a result of the high density, which shows up in the material and transport costs. Other fiber types, such as glass fibers, have decisive disadvantages, for example a limited alkali resistance.

On one hand the fibers need to have a relatively large tensile strength, and on the other hand need to have a high bonding strength with the concrete. In the case of loading, the static friction on the complete surface of the fiber is to remain effective, so that the fiber is uniformly pulled out and a lot of failure energy is

absorbed. The use of polymer fibers offers an alternative. Inexpensive fiber types may be manufactured on the basis of polyolefins (polypropylene, polyethylene) or other thermoplastics. Whilst one achieves with these types of fibers notable tensile strengths in the range of steel, the modulus of elasticity and the bonding strength to concrete is generally low.
It is shown that modern co-extrusion production techniques (Cho, 2000; Kikutani, 1996; Zhao, 2003) and an adequate material selection may help to improve the fiber properties, so that polyolefin based bi-component fibers successfully can be applied in concrete applications.

FIBER PRODUCTION

The polymer fibers presented here are produced according to the standard method for filament production. The raw material (polymer) is molten and then pressed (extruded) through a nozzle, wherein each fiber is pressed out through a separate bore. Bi-component fibers are manufactured by two extruders. The molten polymers are passed through spin-packs with two separate material inflows, so that when leaving the spinnerettes they join together forming a fiber consisting of a core and a sheath (surrounding the core completely).
During the subsequent stretching process, the filaments run through suitable heat sources (ovens) in a non-contact manner in one or more process stages. The degree of stretching (drawing process after spinning) must be selected as high as possible. In order to reach high strength values with a low elongation at break and a high modulus of elasticity the raw polymers must have a low melt flow rate (MFR) and a narrow molecular weight distribution. The MFR is a measure for the viscosity and is defined as the mass flow through a defined nozzle at a certain temperature and pressure load.
However, highly stretched fibers with a diameter of 0.15 to 2 mm tend to split open in the longitudinal direction (fibrillate) under mechanical loading, which can lead to poor bonding between cement matrix and fibers. In order to counteract the fibrillation one operates with polymers which have different viscosities after reaching the melting point. The sheath polymer hence may be selected to be less viscous (higher MFR) than the core polymer. Polymers with a higher MFR and a broader molecular weight distribution have a significantly beneficial behavior during the stretching process. This means that fibers manufactured of such polymers may be drawn to a higher extent and the not completely exhausted sheath may prevent fibrillation..
The manufacturing of the fiber has the advantage that the different polymers can be optimized for different purposes. The sheath polymer may be chosen with respect to the workability and the bonding strength between the fiber and concrete. The core polymer may be optimized independently thereof with regard to a high tensile strength and a small elongation at break. By this way, one may not only achieve fibers with very new, improved characteristics, but also reduce the costs, since it is not the complete fiber which must consist of an expensive polymer. It is possible applying the expensive components to a lesser extent, for example only in the sheath.
The sheath polymer may be optimized to the desired bonding to the cement matrix by way of chemical modification or the incorporation of functional groups on the surface (Li, 1996) or by way of embossing. The continuously and homogeneously stretched fiber is then provided with a structure at a later stage by way of a mechanical embossing. The polymer is simultaneously laterally displaced and grooves and hills are formed which positively influence the bond strength upon pull-out.

MATERIALS AND TEST METHODS

Different fiber types, mono-filaments as well as bi-component fibers were tested in pull-out tests. Ten fibers of the same composition were embedded at a length of 20 mm in a self consolidating mortar (mortar M in table 2) and then pulled-out. The test arrangement is described in more detail in (Kaufmann, 2007).
The fibers consisted either of polypropylene (PP) or high density polyethylene (HDPE) as the base polymer. Bi-component but also uniform filaments were tested. Some fibers contained nano-sized fillers (Jordan, 2005) and other additives in order to increase the modulus of elasticity and the hardness of the surface. A chemical bond by hydration reaction of these particles with the cement matrix is not expected as the particles in the fibers generally are covered by a thin non-reactive polymer film. The fiber surface was structured by mechanical embossment in some cases to improve the bonding between the fibers and the cementitious

matrix. Three different forms of surface structures, named x, y, and z were applied. The fiber compositions and properties are given in Table 1.

The mechanical reinforcement effect of these fibers in concrete was tested applying a four point bending test on large concrete prisms (specimen dimensions 700x150x150 mm^3, span 600 mm) according to the DBV-test guidelines (Marti, 1999; Merkblatt Stahlfaserbeton, 2001). Concrete type A (table 2) was used in these tests. Fiber volume was 0.5 vol.-% (except for steel fibers where a dosage of 25 kg/m^3 was applied).

Furthermore a slab-test on rectangular slabs (600x600x100 mm3, support 500x500 mm^2) according to Swiss standard (Swiss standard SIA 162, 1999) was conducted. Concrete type B (table 2) was used. Fiber volume was 1 vol.-% for all fiber types. The displacement was measured by means of a displacement transducer located at the center of the specimens opposite to the load bearing side.

RESULTS

Fiber-matrix bond

The efficiency of fiber reinforcement in view of an increase of strength and ductility depends on different important factors such as fiber length, fiber orientation and fiber-matrix bond. These parameters are not independent.

The effect of different fiber compositions on the fiber pull-out behavior is plotted in figure 1. As seen, the bond between the uniform fiber 0 and the cement matrix is rather poor. A bond strength (maximum pull-out load divided by embedded fiber surface (= 2π·radius·embedded length)) of just 0.45 N/mm^2 was observed. However this fiber maintains this maximal load level for a relatively large displacement.

The addition of nanoparticles and other additives to this fiber polymer significantly increases the bond strength reaching almost the double value (0.93 N/mm^2) of the standard fiber (compare 0 with A_0). The bond strength can be further improved significantly by applying a structure on the surface of the filaments (fiber A_x). This structuring leading to grooves and swells leads to an improved embedding and increases the friction upon pulling the fiber out of the mortar. The stronger this structuring is, the better is the observed bond. A bond strength of up to 3.17 N/mm^2 was observed for fiber B_z. This is more than seven times the original value of a standard polyolefin fiber.

Comparing fiber C_x (bi-component) with A_x (uniform) also shows the advantage of the bi-component architecture and a proper raw material selection preventing splitting of the fiber upon pull-out. The positive effect of the nanoparticle and additive addition to the sheath polymer is demonstrated when comparing fiber C_x (no nanoparticles/additives) with fiber B_x. The effect of the additives, making the surface harder and the poisson contraction smaller, is especially effective in combination with a surface structuring of the fiber. These measures allow reaching the fiber strength (rupture of fiber B_z) at an embedded length of 20 mm only.

Concrete performance with bi-component fibers

4-point bending test (DBV-test) on prisms

The performance of concrete A (with a maximum aggregate diameter of 32 mm) reinforced with 0.5 vol.-% (approx. 4.5 kg/m^3) of fibers in a four point bending test (DBV-test) is plotted in figure 2. For comparison the results with a commercially available macro-synthetic polyolefin-based fiber (fiber D) and a macro-PVA fiber (fiber E) as well as a standard hooked steel fiber (fiber F, dosage 25 kg/m^3) are also provided. Until the first crack the performance of the fiber reinforced concrete is hardly influenced by the fibers but only depends on the concrete quality. The bending strength however seems to be slightly higher for the bi-component fibers along with the PVA-fibers. This however may be a secondary effect, as a mechanical bridging of initial cracks can not be expected at the applied relatively low fiber dosages. It may result from certain shrinkage crack control induced by the excellent bond to the cement matrix, probably also at early ages.

After the first crack a sudden load drop is observed until the fibers start bridging the cracks and bearing load. The very high elastic modulus of the steel fibers is advantageous at this stage. When displacement increases, the anchorage of the bi-component becomes effective and the supported load even increases again until a displacement of about 2 mm. The fiber with the best bond to the cement matrix (fiber B_z) also shows the best composite performance. Energy adsorption (as seen by the area under the curve) was almost the double of that of the fibers C, D, E or F. Despite the excellent mechanical values of the PVA-fiber, its performance in the concrete was modest.

Square slab test

In mining or flooring applications the load typically is occurring at one certain position. This is also the case in impact situations. This arrangement is very well reflected in a square slab test where the load is applied at the center of a square plate. In this case, the performance of fiber reinforced concrete is astonishing. Some results obtained with a self compacting concrete B with a reinforcement of 1 vol.-% of fibers is shown in figure 3. The workability in all mixtures was comparable.

An excellent post-peak behavior is observed for the concrete reinforced with 1 vol.-% of bi-component fibers. The first crack occurs at much lower load (almost half of the load achieved with fiber reinforcement) and is perfectly bridged by the fibers. This large energy absorption results in a significant safety potential in practical applications, giving the necessary time to put measures into effect before a structure collapses.

Practical application and field test

Even the best fibers are of no use if homogenous distribution is not achieved in the concrete. If the fibers are incorporated into the concrete in a somewhat loose manner, such as blown in or scattered in heaps, then nests of fibers are often formed, into which the concrete does not completely penetrate. These accumulations of fibers worsen the strength and the regularity of the concrete.

A surprisingly effective solution was found in wrapping a few thousand fibers as a bundle, with a water-soluble plastic film, and then cutting off sections or bundles. Upon dissolving the enveloping film, a rapid distribution of the fibers in the concrete results as the fibers primarily were arranged parallel which supports dispersion. With this method it was possible to add high fiber volumes (up to 2 vol.-%) to the concrete without any problem.

Testing of these novel fibers was conducted under realistic on-site conditions. For instance some shotcrete applications were tested (figure 4). Interesting was the fact that the measured fiber rebound was relatively low (<15%) compared with the one for steel fibers typically reaching 20-25%. Hence the excellent fiber matrix bond also increases the adhesion of the fibers in the fresh concrete and helps to save costs as less fibers is lost in such applications.

CONCLUSIONS

Novel co-extrusion techniques were applied to develop a bi-component (core/sheath type) fiber for the mechanical reinforcement of concrete. This special architecture allows an individual optimization of core material and sheath polymer according to their main tasks: high elastic modulus and tensile strength for the core and a good bond to the concrete for the sheath.

A good fiber matrix bond is crucial for an effective usage of the tensile strength of a fiber. Different measures have shown to increase the bond strength significantly. Especially effective were the bi-component architecture of the fiber with a proper polymer selection avoiding fiber splitting under load, the surface structuring and the application of additives in the sheath.

Mechanical testing of bi-component fiber reinforced concrete showed very good performance in four point bending tests. Excellent post-peak behavior was observed in slab tests. The maximum load (post-peak) was almost double as high as the first crack load when using 1 vol.-% of the newly developed fibers.

This result makes these patented bi-component fibers prone for different applications in mining, flooring, earth quake and impact protection.

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Table 1 – Composition and properties of the fibers.

fiber	composition	core/sheath ratio	surface structure	density [g/cm^3]	diameter [μm]	cut length [mm]	strength [MPa]	elast. mod. [GPa]
0	HDPE/PP	uniform	none	0.92	500	50	532	8.7
A_0	HDPE/PP + additives	uniform	none	1	500	50	496	8.9
A_x	+ nanoparticles (A-N)		x				441	6.4
B_0	core = PP_1	70 / 30	none	0.92	500	50	625	10.4
B_x	sheath = PP_2 + (A-N)		x				524	8.7
B_y			y				524	8.9
B_z			z				502	8.8
C_0	core = PP_1	70 / 30	none	0.91	500	50	598	8.4
C_x	sheath = PP_2		x				506	8.6
D*)	polyolefin	uniform	embossed	0.90-0.92	n.a.	48	550	6
E*)	PVA	uniform	none	1.3	660	30	800	29
F*)	steel	uniform	none / hooked	7.8	1000	50	1100	210

*) data acc. to supplier

Table 2 – Concrete mix design.

	cement [kg/m^3]	fines [kg/m^3]	sand/gravel (mm) in [kg/m^3]					water [kg/m^3]	HRWRA PCE-based [kg/m^3]
			0/1	1/4	4/8	8/16	8/32		
concrete A	260 (C1)	60 (F1)	465.6	291	174.6	446.2	562.6	160	3.2
concrete B	386 (C2)	233 (F2)	1539			0	0	193	9
mortar M	365.4	267 (F1)	682.7	754.5	0	0	0	222	7.3

F1: fly ash
C1: CEM I 42.5 N
F2: blend (limestone + microfine cement)
C2: CEM I 52.5 R

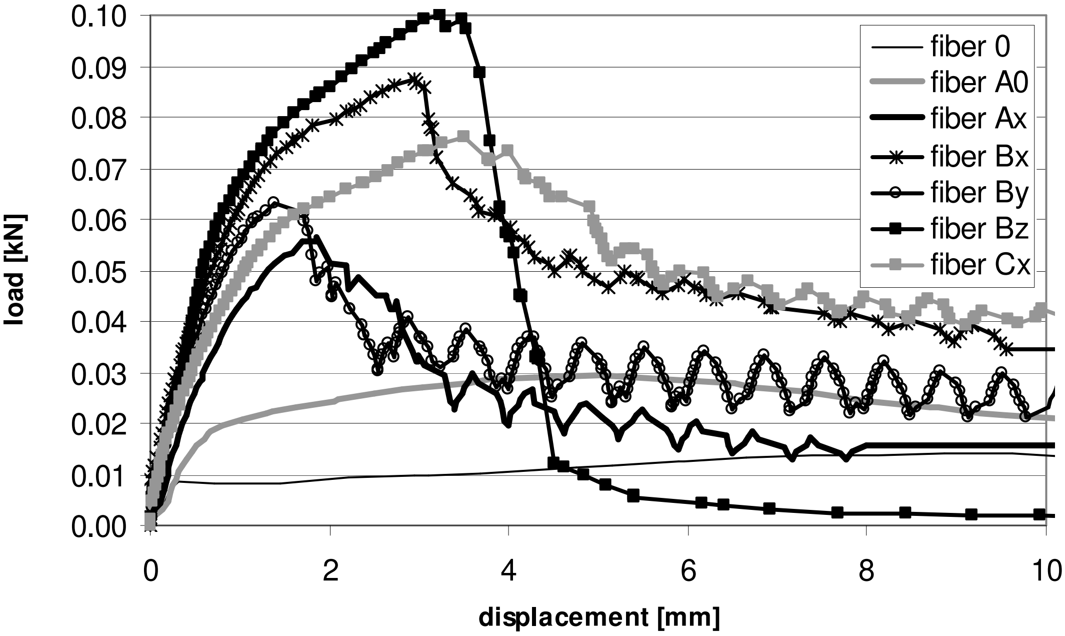

Figure 1 – Fiber pull-out characteristics (fibers embedded in mortar M at a length of 20 mm).

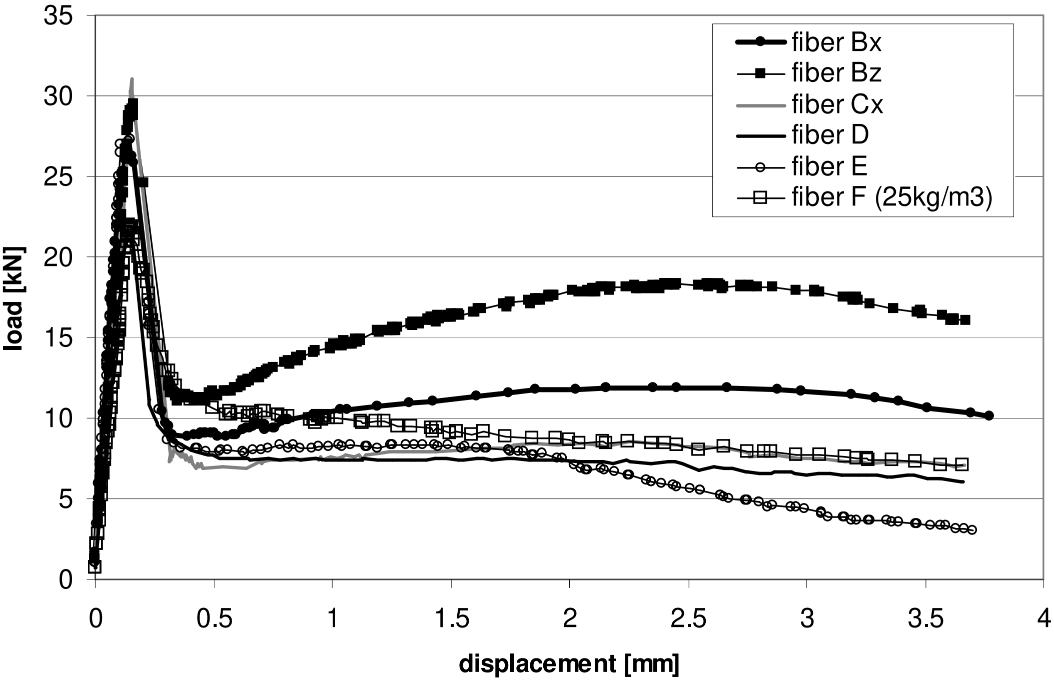

Figure 2 – Test result of DBV-test (4pt. bending, prisms 700x150x150 mm3, span 600 mm) of concrete A reinforced with 0.5 Vol.-% of fibers (approx. 4.5 kg/m^3; steel fiber F was mixed at 25 kg/m^3).

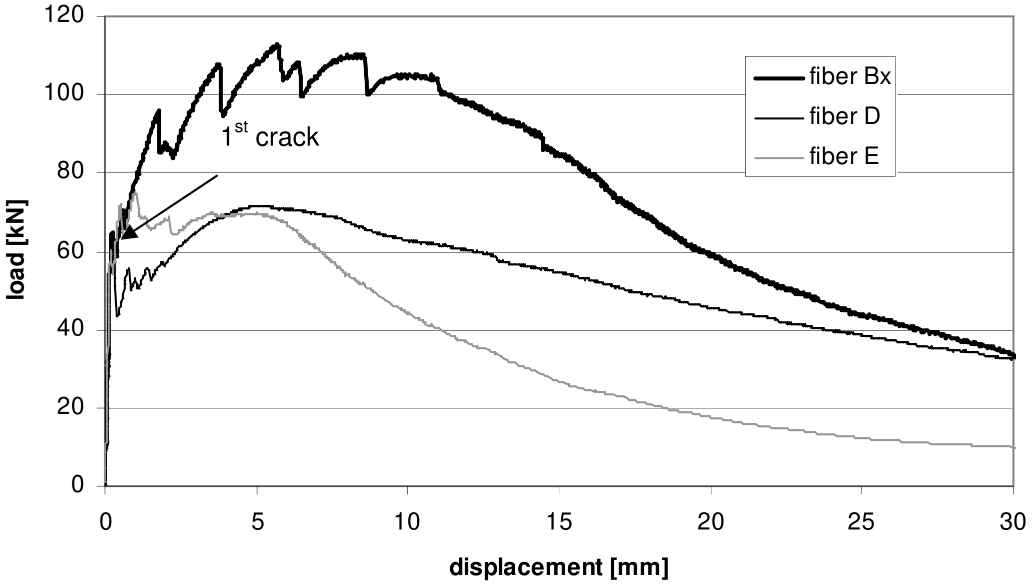

Figure 3 – Test result of slab-test (square plate bending, 600x600x100 mm^3, support 500x500 mm^2) of concrete B (self compacting) reinforced with 1.0 Vol.-% of fibers.

Figure 4 – Testing under field conditions: shotcrete application with bi-component fibers.