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High performance composites in spun-cast elements

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Abstract

Spin-casting is an effective fabrication method to produce concrete poles, masts or pipes. Through the centrifugal process the concrete is compacted and the desired shape, mostly round or ellipsoidal, is obtained. The concrete generally has to be reinforced with steel bars which are susceptible to corrosion. Furthermore, the placement of the reinforcement is time consuming and hence expensive and leads to rather thick and heavy structural elements. The application of short-fiber reinforced cement pastes or mortar is a suitable alternative.

Special requirements regarding workability and strength have to be considered. An optimization of the cement matrix was achieved with a blend of microfine cement and ordinary Portland cement, improving the rheological properties of the fresh mixture and resulting in a dense cement matrix with excellent mechanical properties. Reinforcement with different kinds of short-fibers of carbon and polyvinylalcohol (PVA) was studied.

Flow properties of the fiber reinforced cement composite were optimized with regard to the centrifugal process by applying a newly developed cone-consistency test. The mechanical properties of conventionally cast specimens and of centrifuged prototypes were determined and their durability was verified. Workable, high strength, ductile and durable fiber reinforced composites were obtained in spin-cast elements.

Keywords: Fiber reinforcement; Blended cement; Consistency; Mechanical strength; Microfine cement; Spin-casting; Carbon fiber; PVA fiber

1. Introduction

Cementitious materials are known to be quasi-brittle, with low strength and strain capacity under tension. A steel reinforcement is usually necessary in order to use cementitious materials and concrete as a construction material. Poles, masts, pipes, pillars and other building elements may be produced of steel bar-reinforced concrete by applying a spun-cast method [1]. The specially designed steel bar reinforcement is placed into a mould, the concrete is poured over it and then the mould is closed and rotated around its symmetry axis. The reinforcement of the concrete in such elements with steel bars is time consuming and expensive, susceptible to corrosion and leads to relatively thick and heavy structural elements. The substitution of the steel bars with high performance short-fibers may allow thinner, lighter and less expensive elements.

The fiber reinforced cementitious composite (FRCC) material must show very high strength in flexure and tension and must have a specific workability. It also has to acquire sufficient green body strength to prevent disintegration. The aim of the presented project was to reach a flexural strength of at least 25 MPa without using steel fibers.

A prerequisite for the development of FRCC is an appropriate, optimized cement matrix [2]. The matrix should combine properties such as low porosity and excellent mechanical properties. A high packing density of particles can be obtained by combining two or more binder components with different size distributions [3]. This can be achieved by the addition of microfine cement to ordinary Portland cement. The rheological properties of the fresh mixture improve and very low water/binder ratios are possible, resulting in a dense material with high strength [4].

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Short, high performance fibers are added to increase the bending and tensile strength as well as the ductility of this cement matrix. Usage of steel fibers is not ideal for an application in spun-cast elements. Owing to their high density, fiber segregation occurs during the centrifugation. Furthermore, they bear a corrosion risk which may lead to esthetically unattractive surfaces and some injury potential. Other high performance fibers made of carbon [5] or polyvinylalcohol (PVA) [6,7] are used instead.

From the processing point of view, a good workability of the fresh cementitious composite and good fiber dispersion are very important. Fibers generally tend to stiffen the mix. The problem of obtaining good fiber dispersion and consistency becomes more pronounced for very low water/binder ratios ($w/b < 0.25$). During the centrifugation process, the fiber composite should flow well in order to reach a homogeneous material distribution, but it has to stop moving after centrifugation and reach sufficient green body strength. A thixotropic behavior of the fresh composite is advantageous. During the spinning process shear forces will lower the viscosity of such material and simplify distribution while after spinning the viscosity will increase again, holding it at its place.

2. Experimental program and test methods

2.1. Design of the cement matrix

The development of a high strength fiber reinforced cementitious composite for application in a spin-casting process implies the optimization of the matrix. For this purpose, the influence of different pozzolanic additives (fly ash, microsilica), latent hydraulic components (microfine cement) or inert (limestone filler) additions to Portland cement on the bending strength of fiber reinforced pastes was tested. In this study, mostly a blend of microfine cement (based on blast furnace slag) with ordinary Portland cement (CEM I 42.5 N – similar to ASTM C150 type I) was used. Fig. 1 shows the typical non-spherical shape of the microfine cement. The particle size distributions of the cements are plotted in Fig. 2. Their chemical compositions are given in Table 1. Pastes were prepared using an EN 196-1 [8] type mortar mixer. 20 mass% of Portland cement was replaced by different additives. A polycarboxylate type superplasticizer (solid content 32%) at a dosage of 2 mass% of binder was added. Additionally, a latex dispersion based on styrene and butadiene (2 mass% of binder, 51% solid content) was used to improve the dispersion capacity of the carbon fibers. The water/binder ratio was 0.22. The time of mixing was 3 min at 62.5 rpm according to EN 196-3 [8]. Different fiber types (carbon, polyvinylalcohol (PVA) and polypropylene (PP)) were tested as mechanical reinforcement of the cement paste [9,10]. The fiber properties are given in Table 2. The fibers were added to the fresh pastes and then mixed for an additional 2 min in the same mixer.

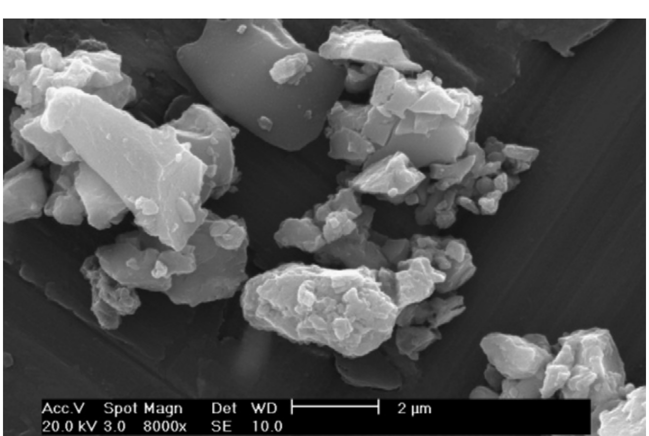

Fig. 1. ESEM micrograph of typical microfine cement particles.

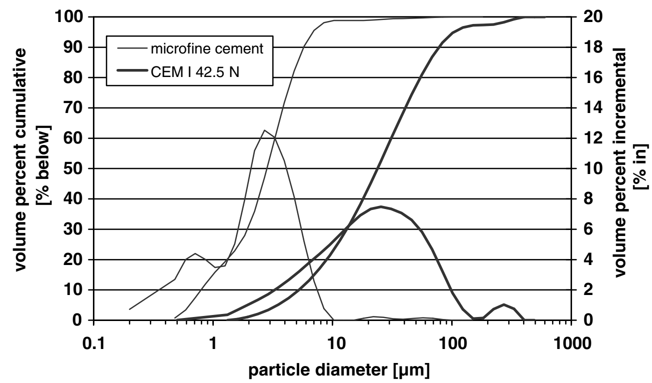

Fig. 2. Particle size distributions of the binder components.

Flow properties of the FRCC were optimized with regard to the centrifugation process. The characterization of the consistency of fiber reinforced composites with standard methods is difficult. The workability therefore was analyzed applying a new method [11]. The measurement arrangement of this cone-consistency test is shown in Fig. 3. A conical measuring bob is moved at a constant velocity into a hollow cone filled with the fresh mixture. The loading rate was adjusted to 0.5 mm/s with an accuracy of 0.01 mm. The resulting force is measured as a function of the displacement of the measuring bob by means of a force gauge with an accuracy of 1%.

In order to evaluate the strength properties, nine conventionally cast prisms ($25 \times 25 \times 100\ mm^3$) were produced for each mix. Bending strength was determined using a 3 point bending test. The span was 80 mm. The displacement was measured with a displacement gauge at the center of the bottom of the specimen. The conventionally cast prisms were stored in water (20 °C) until testing.

2.2. Spin-casting under laboratory conditions

In a first test series, spun-cast pipes with an outer diameter of 180 mm were produced by means of a laboratory production setup (Fig. 4). The length of these specimens

Table 1
Chemical composition of the binder (X-ray fluorescence, loss of ignition according to EN 196-2 [8])

	CaO (mass%)	MgO (mass%)	SiO_2 (mass%)	Al_2O_3 (mass%)	Fe_2O_3 (mass%)	Na_2O (mass%)	K_2O (mass%)	SO_3 (mass%)	L.O.I. (mass%)
Cement (CEM I 42.5 N)	62.8	2.0	19.9	5.4	2.8	0.13	1.0	2.8	2.5
Microfine cement	45.3	8.1	32.6	9.9	0.6	0.3	0.4	2.6	1.5

Table 2
Fiber properties

Material	Young's modulus (GPa)	Tensile strength (GPa)	Elongation at failure (%)	Density (g/cm^3)	Diameter (μm)	Length (mm)
Carbon (PAN)[a]	228	3.8	1.5	1.81	7.2	6.4
PVA-1	40	1.6	6.0	1.3	40	6 12
PVA-2	29	1.0	3.5	1.3	200	6
PP	8.5–12.5	0.35–0.5	8–10	0.91	$35 \times 250 \times 600$[b]	6

[a] Based on polyacrylonitril.
[b] Rectangular cross section.

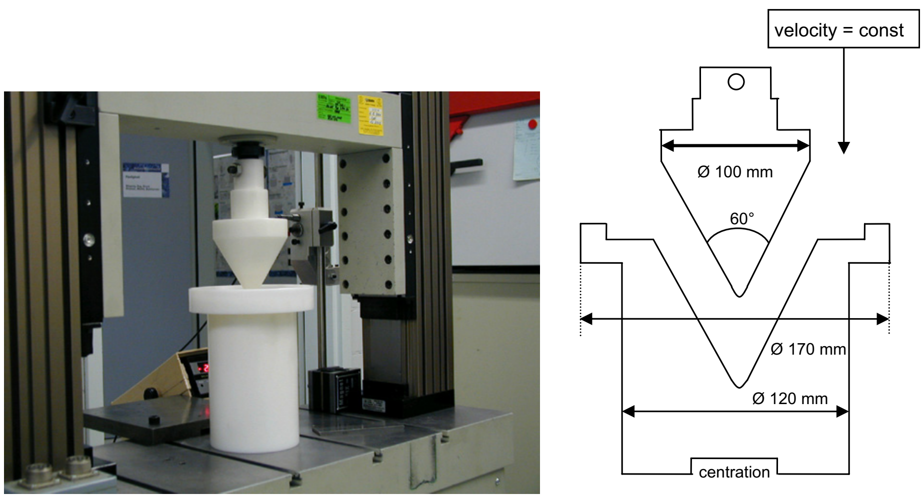

Fig. 3. Test arrangement for the evaluation of the cone-consistency.

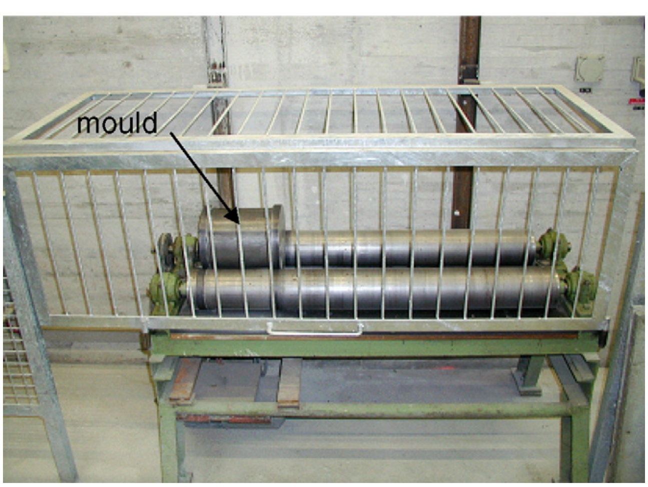

Fig. 4. Laboratory centrifugation setup with mould.

was also 180 mm and the wall thickness was 25 mm. The rotation speed of the mould was 669 rounds per minute (rpm) resulting in an acceleration of 45 g at the outer and 32 g at the inner radius of the pipes.

Different mix designs as shown in Table 4 were examined. Carbon (with different amount of latex dispersion), two types of PVA, and PP fibers were tested. The water/binder ratio for the carbon fiber composites was increased (from 0.155 to 0.2) in order to obtain a sufficient workability.

In order to evaluate the strength properties, 24 prisms ($15 \times 15 \times 80$ mm^3) were cut parallel to the rotation axis after seven days from the centrifuged pipes. It was not possible to cut larger specimens due to the limited wall thickness of the spun-cast pipes. The specimens were tested in a three point bending test arrangement. The span was 45 mm for these specimens. The outer surface of the specimen (outer pipe surface) was used as the tension face. The displacement was measured by a displacement gauge at the center of the bottom of the specimen. The prisms were stored in water (20 °C) until testing at an age of 28 days.

Table 3
Seven day and 28-day bending strength of moist-cured conventionally cast prisms (microfine cement 25 mass%, 2.5% superplasticizer, 4.5 vol% PVA fiber)

Mix nr.	Bending strength (MPa)	
	7 day	28 day
M1A	32.1 ± 4.0	30.5 ± 3.5
M1B[a]	31.8 ± 4.0	30.0 ± 3.0

[a] Polycarboxylate type II, same dosage.

2.3. Fabrication of prototypes under real process conditions

Based on these experiences, spun-cast short-fiber reinforced pipes (length 2 m, outer diameter 200 mm, inner diameter 150 mm) were produced under industrial process conditions (see Fig. 5). Production was carried out on a fabrication line of the producer SACAC AG, Switzerland. Different mix designs as shown in Table 5 were chosen. Taking the results from the laboratory tests into account, carbon fibers were used just in small quantities. The binder composition and the PVA (PVA-1) fiber content were kept constant. Water/binder ratio, the rotation speed and the carbon fiber dosage were varied. The rotation speed of the driving wheel was between 741 and 918 rpm, which results in the accelerations listed in Table 5. The accelerations are proportional to the square of the rotation speed, and hence at higher speed not only higher accelerations but also steeper gradients result through the pipe diameter. The dosage of PVA fibers was kept constant at 4.5 vol%, but the length of the fibers was varied. In mixture M12 a sand content of 50 mass% was added.

From each of the centrifuged pipes, 24 specimens ($15 \times 15 \times 80$ mm^3) were cut and their bending strengths were determined. The cutting of the spun-cast specimens was done after a seven day water immersion of the pipes. These specimens then were stored at a constant relative humidity of 70% (20 °C) until testing at 28 days. These storage conditions were chosen in order to simulate realistic curing conditions in industrial fabrication. Bending strength was determined using a three point bending test. The span was 45 mm and the displacement was measured with a displacement gauge at the center of the bottom of the specimen.

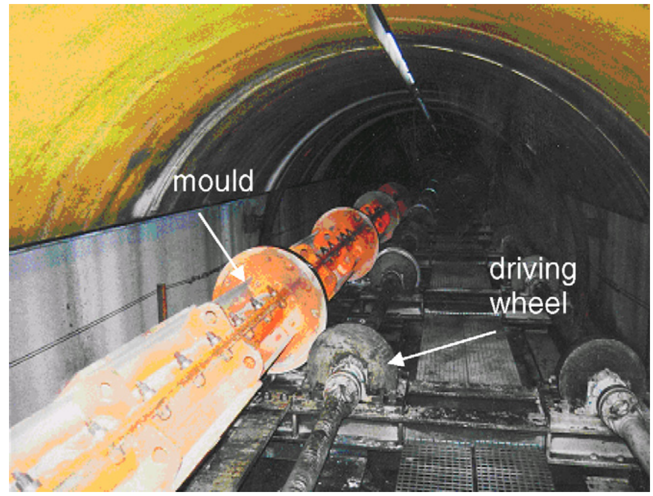

Fig. 5. Centrifugation setup in the fabrication line.

The bending strength at 28 days was also tested on three sections of centrifuged pipes (seven day water immersion, then 20 °C/70%RH). A bending test arrangement with a span of 600 mm was chosen (Fig. 6). The supports consisted of three half rings with a diameter which was 5 mm larger than the outer diameter of the pipes. The space between the supports and the pipes was filled with a thick paper to allow a smooth force introduction. The pipe specimens had a total length of 650 mm, a diameter of 200 mm and a wall thickness of 25 mm. The bending strength was calculated as:

$$\sigma = \frac{s \cdot F \cdot R}{(R^4 - r^4)\pi} \quad (1)$$

where s is the span length (mm); F is the force at failure (N); R is the outer and r the inner diameter (mm) of the pipe. The shear span to depth ratio of the pipe is 1.5, so that the assumption of pure bending is approximate.

The durability of the centrifuged specimens was also tested. Pipe sections 200 mm in length and diameter were submitted to freeze-thaw cycles. At each cycle, the speci-

Table 4
Mix designs and centrifugation parameters for the centrifuged specimens (laboratory)

Batch	Cement (CEM I 42.5 N) (mass%)	Microfine cement (mass%)	w/b	Superplasticizer mass%/binder	Carbon fiber (vol%)	PVA fiber (vol%)	PP fiber (vol%)	Latex dispersion (mass%)
L1	80	20	0.2	2.5	2	0	0	2
L2	80	20	0.25	2.5	2	0	0	2
L3	80	20	0.2	2.5	2	0	0	15
L4	80	20	0.2	2.5	2	0	0	20
L5	80	20	0.155	2.5	0	5.0 (PVA-1, 6 mm)	0	0
L6	80	20	0.155	2.5	0	4.5 (PVA-1, 12 mm)	0	0
L7	80	20	0.16	2.5	0.5	4.5 (PVA-1, 6 mm)	0	0
L8	80	20	0.15	2.5	0	5.5 (PVA-2, 6 mm)	0	0
L9	80	20	0.15	2.5	0.5	5.0 (PVA-2, 6 mm)	0	0
L10	80	20	0.16	2.5	0	0	6.5	0
L11	80	20	0.16	2.5	0.5	0	6	0

Table 5
Mix design and centrifugation parameters for the centrifuged pipes

Batch	Cement (CEM I 42.5 N) (mass%)	Microfine cement (mass%)	*w*/*b*	Superplasticizer mass%/binder	PVA fiber (PVA-1) (vol%)	Carbon fiber (vol%)	acceleration a_c Outer/inner (g)
M1	75	25	0.155	2.5	4.5 (6 mm)	0	37/27
M2	75	25	0.17	2.5	4.5 (6 mm)	0	38/28
M3	75	25	0.17	2.5	4.5 (6 mm)	0.5	33/25
M4	75	25	0.155	2.5	4.5 (12 mm)	0	24/19
M5	75	25	0.155	2.5	4.5 (12 mm)	0	24/19
M6	75	25	0.16	2.5	4.5 (6 mm)	0.5	34/26
M8	75	25	0.155	2.5	4.5 (6 mm)	0	33/25
M10[a]	75	25	0.151	2.5	4.5 (6 mm)	0	24/19
M12[b]	75	25	0.16	2.5	1.5 (6 mm)	0	24/19

[a] Polycarboxylate type II.
[b] Sand 0–3 mm, relation 1:1 to binder.

Fig. 6. Arrangement of three point bending test of pipes with displacement measurement.

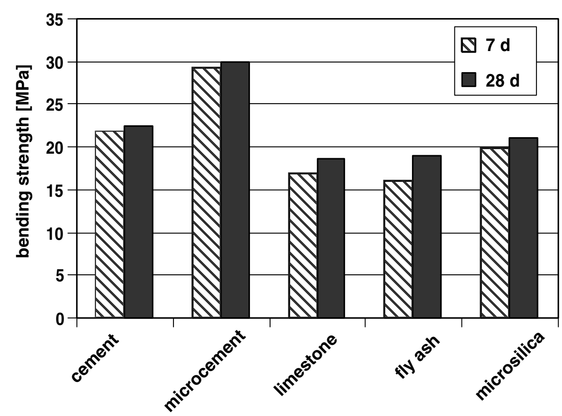

Fig. 7. Influence of different additives on the bending strengths of carbon fiber reinforced composites (prisms $25 \times 25 \times 100$ mm^3, three point bending, span 80 mm).

mens first were immersed for 2 h in water at 20 °C. Then the water was removed and the temperature was lowered at a rate of 0.75 °C/h. The specimens then were kept at −25 °C for 4.5 h. After that the water (20 °C) was allowed to flow into the climate chamber to heat it again. Reference specimens were left immersed in water without temperature cycling. After 40, 80 and 140 cycles, each time 12 specimens ($15 \times 15 \times 80$ mm^3) were cut from both the frozen and reference pipes and their bending strengths were determined.

3. Results

3.1. Influence of the cement matrix on the bending strength

The development of a high strength fiber reinforced cementitious composite implies the optimization of the matrix and the fiber–matrix interface. This can be achieved through a densification of the cement paste. The influence of different binder systems on the bending strength of carbon fiber reinforced (2 vol%) composites is presented in Fig. 7.

The addition of microfine cement significantly increased the bending strength of these composites. Meanwhile, the addition of fly ash, limestone filler or microsilica did not have a positive effect. In the case of microsilica, the unexpected result may result from an insufficient dispersion of the particles. As only pastes were studied, the shear forces generated during mixing might have been much smaller than the inter-particle forces, so that particle agglomerations and hence a reduction of the pozzolanic and the packing effects of microsilica resulted. Somewhat better performance for microsilica and fly ash was obtained at higher ages, but the matrix seems to be too dense for an efficient pozzolanic reaction.

Similar results were obtained for other fiber types as well. Portland cement blended with microfine cement was hence used as a standard matrix.

3.2. Consistency of fiber reinforced composites

A typical result of cone-consistency test is plotted in Fig. 8. The force and the displacement of the measuring bob are plotted. The homogeneity and the variation of the wall thickness of the centrifuged prototypes were compared with the result of the cone-consistency test. In this way, a criterion for good centrifugability can be defined. This criterion depends on the centrifugal acceleration

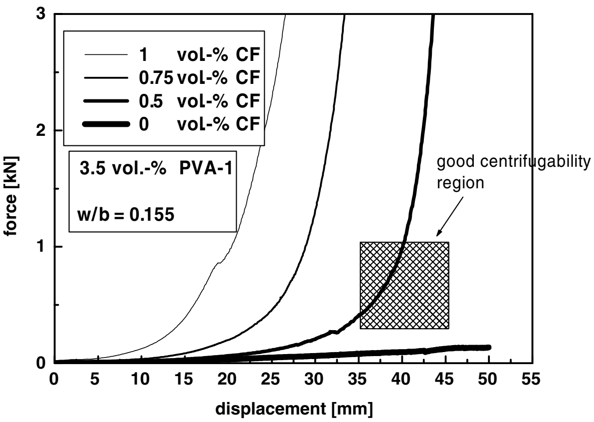

Fig. 8. Effect of the addition of carbon fibers on the workability of the composite (cone-consistency).

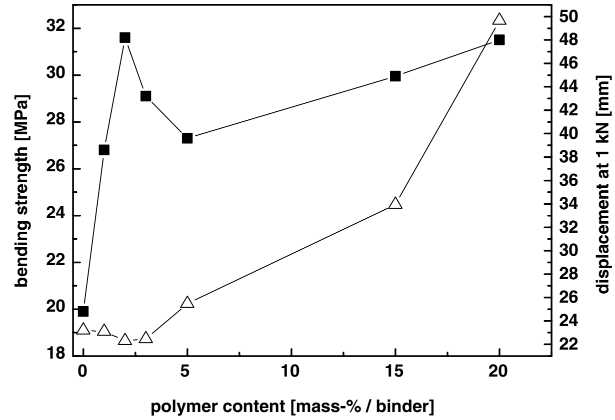

Fig. 9. Influence of latex content on the bending strength and the workability of carbon fiber (2 vol%) reinforced composites ($w/b = 0.2$, 80% CEM I 42.5 N, 20% microfine cement, 3% superplasticizer).

applied during spin-casting. For instance, at a centrifugal acceleration of 30 g, it was found that the force–displacement curve must cross the region 0.2 < force (kN) < 1 and 35 < displacement (mm) < 45 (Fig. 8). When the force–displacement curve missed this region to the left side (e.g. higher forces), the consistency is too stiff, and a large variation in wall thickness resulted in elements formed in the spin casting process. On the other hand, when the curve missed this region to the right, the mix was too fluid. Fiber segregation may occur and the green body strength after centrifugation is so low that disintegration is possible. Furthermore, for elements with small diameters it is often necessary to overfill the mould, which is not possible when the mix is too fluid.

In Fig. 8, the results of cone-consistency tests for a PVA (PVA-1) and carbon hybrid fiber reinforced composite are plotted. Even small carbon fiber contents decreased the fluidity drastically and the requirement for good centrifugability was not fulfilled. The reason for the poor workability of the carbon fibers is their large surface area (fiber diameter is only 7 μm) and the relatively poor wetability of carbon. At the same time, the pure PVA (3.5 vol%) fiber composite was too fluid to be used.

3.3. Improvement of the properties of carbon fiber reinforced composites through latex addition

The workability of carbon fiber reinforced composites may be improved through the addition of a latex dispersion based on styrene and butadiene (51% solid content). The effect of different latex dosages on the cone-consistency result (displacement at a force of 1 kN) and the bending strength of carbon fiber (2 vol%) reinforced pastes (80% CEM I 42.5 N, 20% microfine cement, 3% superplasticizer) is plotted in Fig. 9. Taking the water content of the latex suspension into account, the water/binder ratio was kept constant ($w/b = 0.2$). At dosages above 5%, the latex dispersion has a positive effect on the fluidity. The criterion for good centrifugability for these carbon fiber reinforced composites is only reached at high latex dosages of more than 15%.

The bending strength shows an optimum of about 32 MPa at a medium latex dosage of 2–3%. At higher dosages, the strength first decreases slightly. At dosages higher than 15%, a further strength gain is observed. An explanation for this behavior may be given as follows: At lower content, the latex suspension may increase workability and improve the matrix–fiber bond, owing to film formation. At higher content, the latex could disturb the hydration process of the matrix [12]. The particles may become covered by a latex film which hinders the diffusion and the precipitation of the ions. This leads to a strength loss despite a better workability. At much higher dosages, the latex itself is responsible for the strength development and a partly polymer bonded composite results. However, both strength and workability can be improved with high latex contents, but the economical considerations favor the optimum at medium latex contents. With fibers other than carbon fibers, only minor positive effects of latex dispersions on the bending strength and workability were observed.

3.4. Properties of PVA fiber reinforced composites

Despite the good mechanical performance obtained with carbon fibers, the poor workability limits their application in spun-cast elements. A further disadvantage of the carbon fiber reinforced composites is their very brittle failure behavior. An alternative is the application of high performance PVA fibers at higher dosages. For the application of this fiber type in cementitious materials, fiber properties like strength and elastic modulus have been improved continuously. A good affinity to the cementitious matrix is provided by free OH groups. The properties of the PVA fibers used in the presented work are given in Table 2. The effect of different dosages on the cone-consistency of PVA (PVA-1) fiber reinforced composites is shown in Fig. 10. The

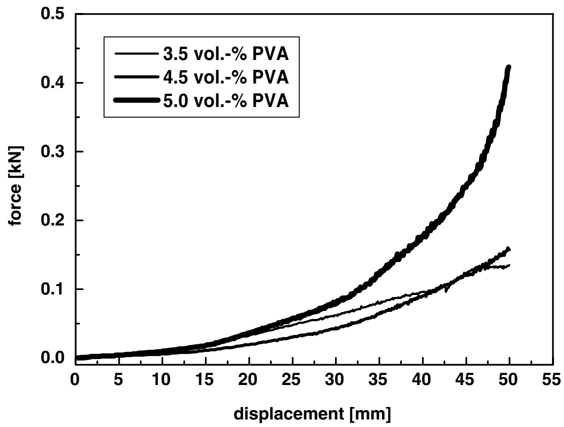

Fig. 10. Influence of the PVA fiber dosage (PVA-1) on the cone-consistency ($w/b = 0.155$, 75% CEM I 42.5 N, 25% microfine cement, 2.5% superplasticizer).

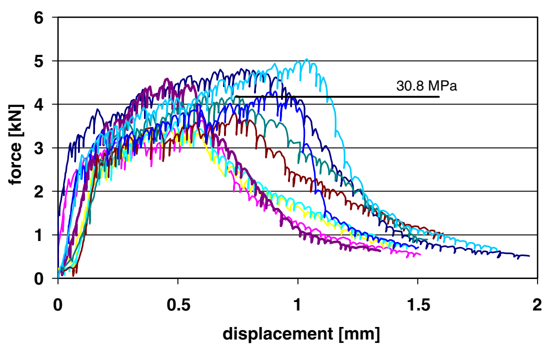

Fig. 11. Force–displacement curves of nine specimen of the same mix in three point bending test (mix 1 A, conventionally cast prisms $25 \times 25 \times 100\ mm^3$).

influence of the fiber content on the workability is moderate, even at very low water/binder ratios.

The mechanical properties of PVA fiber reinforced composites (PVA-1) were determined on conventionally cast prisms ($25 \times 25 \times 100\ mm^3$). As an example, the bending strength of two PVA composites (composition as given in Table 5, mix 1) are given in Table 3. The corresponding force displacement curves for mix 1 A as plotted in Fig. 11 reveal a very high strength and ductile behavior of this composite mixture. The somewhat zigzagging appearance of the force–displacement curve (also in Fig. 14) may be caused by debonding of load-carrying fibers, but over-pronounced by a limited accuracy of the displacement measurement (and hence of the load feedback).

3.5. Laboratory spun-cast specimens

The density of carbon ($1.8\ g/cm^3$) or polymer fibers ($1.3\ g/cm^3$ for PVA, $0.9\ g/cm^3$ for PP) is much lower than the density of the cement paste. Hence segregation effects may occur (Fig. 12). The force that drives the fibers to move towards the inner surface of the pipe wall is the buoyancy caused by the difference in the density. It is proportional to the volume of a fiber and the acceleration force. Friction, with the viscosity of the cement paste as the important parameter, opposes this movement. The friction increases with increasing fiber surface. Hence segregation can be reduced through the selection of fibers with a higher aspect ratio. While PVA-2 fibers were even driven out of the pipe wall (batch L8, aspect ratio = 30), the PVA-1 fibers (batch L5, aspect ratio = 150) remained well distributed within the pipe after centrifugation. Despite the even higher aspect ratio of the carbon fibers, some segregation was observed (batch L1, Fig. 12). The water content of the pastes containing carbon fibers is much higher than the water demand of the pure cement paste. While the pure pastes might be mixed with a water/binder ratio of 0.15 it was necessary to increase it to 0.2 in order to obtain sufficient workability. This leads to a reduction of the viscosity of the cement matrix and a reduced friction and hence fiber segregation. When the carbon fibers segregate, the excess water also moves inward, forming a sponge like layer consisting of carbon fibers and very high water content paste at the inside of the pipe.

Fiber segregation also may be reduced by increasing the viscosity of the composites or by a reduction of the rotation speed. These parameters are not independent, as the workability must be high enough to be able to produce spun-cast elements with uniform wall thicknesses. Segregation also may be hindered through the addition of a latex dispersion, which serves to glue the cement particles and the fibers together.

Segregation of the fibers significantly influences the bending strength. The bending strength measured on cut specimens ($15 \times 15 \times 80\ mm^3$) is plotted in Fig. 13. Compared to the conventionally cast specimens the bending

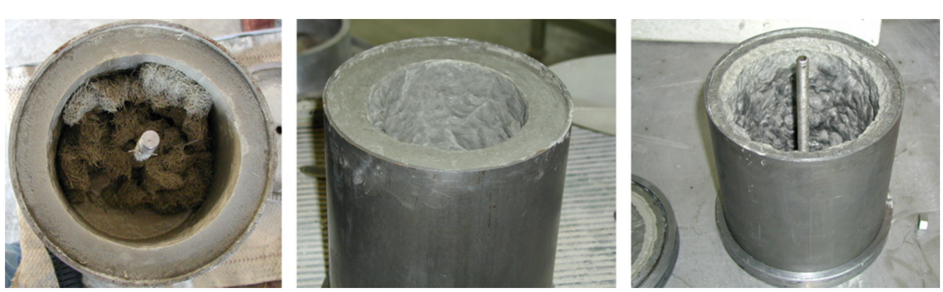

Fig. 12. Fiber segregation effects after centrifugation (laboratory setup) left: L8 (PVA-2), middle: L5 (PVA-1), right: L1 (carbon).

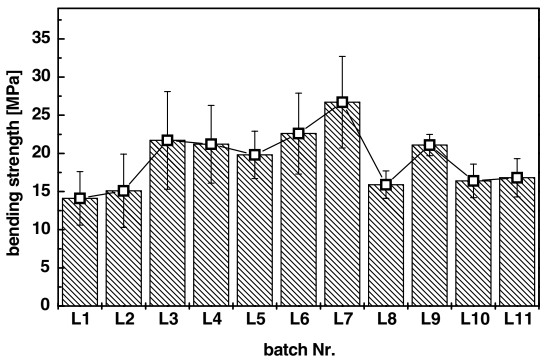

Fig. 13. Bending strengths of prisms (cut from pipes fabricated with centrifugation technique, laboratory setup, $15 \times 15 \times 80$ mm^3, three point, span 45 mm).

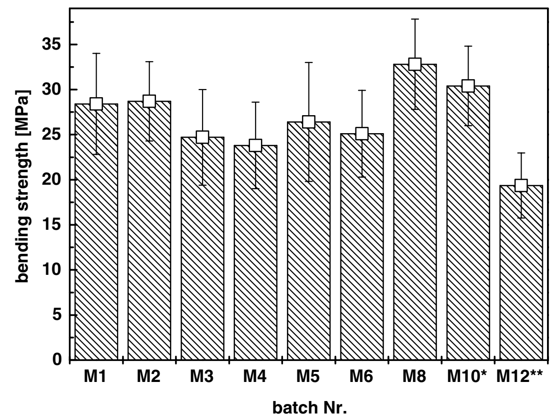

Fig. 15. Bending strengths of prisms (cut from pipes fabricated with centrifugation technique, $15 \times 15 \times 80$ mm^3, three point, span 45 mm).

strength of spun-cast specimens is generally lower. Batches L1, L2, L8, L10 and L11 all show fiber segregation and low bending strength. The addition of small amounts of much finer carbon fibers leads to less segregation and, because of the excellent mechanical properties of the carbon fibers, to higher bending strengths (L7 compared with L5 and L9 compared with L8), except when using PP-fibers (L10 compared to L11). The mechanical properties of the PP fibers might be insufficient to reinforce the already high strength cement matrix. A positive influence of the fiber length can be observed comparing L6 with L5 (despite the lower fiber content of L6). On the other hand, the fiber length reduces workability leading to a higher standard deviation. A higher latex content positively influences the bending strength of carbon fiber reinforced spun-cast composites, as seen comparing L3 and L4 to L1 and L2.

3.6. Spun-cast prototypes produced under real process conditions

Very ductile performance of the cut specimens is observed (Fig. 14). The resulting strengths are shown in Fig. 15. Compared to the laboratory test, generally higher bending strengths are obtained which is mostly due to an improved fiber selection.

Lower accelerations and acceleration gradients resulting from lower rotation speed do not lead to significantly worse test results. Neither, the addition of carbon fibers, which have much better mechanical properties than the PVA fibers, nor the increase of the fiber length of the PVA fibers, lead to an increase in the bending strength of the composites. This is probably due to a poorer workability and hence an increase of inhomogeneity. The best results were obtained with a very low water/binder ratio (0.155) and short PVA fibers.

The bending strength of pipes was also tested. Three pipes of each batch were tested in a three point arrangement as described above. The results are given in Fig. 16. A typical force–displacement curve is shown in Fig. 17. Inhomogeneous fiber distribution and local defects, as observed in microscopic analysis of cross sections, and a size effect may be the reason for a poorer performance compared to the cut specimens. Force gradients, deformations of the mould and low (or high) plasticity may lead to some inhomogeneity of the centrifuged fiber reinforced composite.

The displacement measurement shows a very ductile behavior in the three point bending test. Fiber pull-out

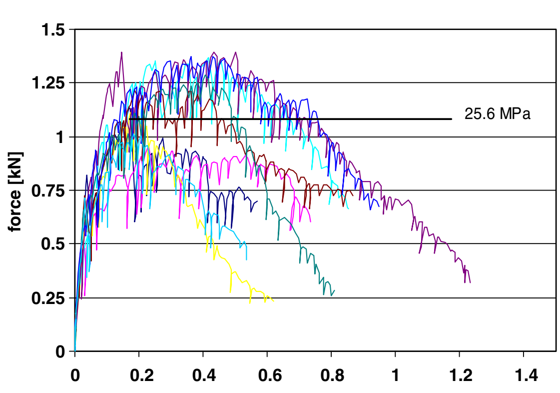

Fig. 14. Force–displacement curves of nine individual specimens of M1 cut from spun-cast pipes ($15 \times 15 \times 80$ mm^3, three point, span 45 mm).

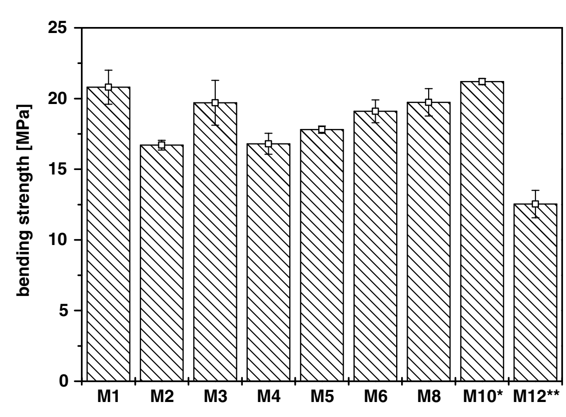

Fig. 16. Bending strengths (3 point bending) of pipes fabricated with the centrifugation technique.

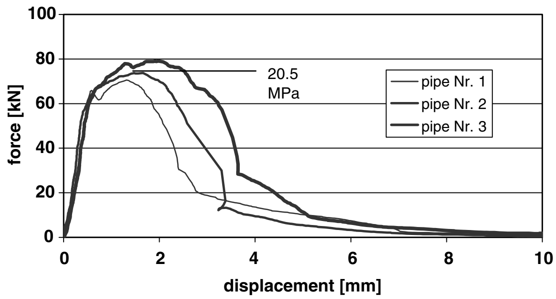

Fig. 17. Force–displacement curves (three point bending) of three individual pipes of the same mix fabricated with the centrifugation technique (mix M1).

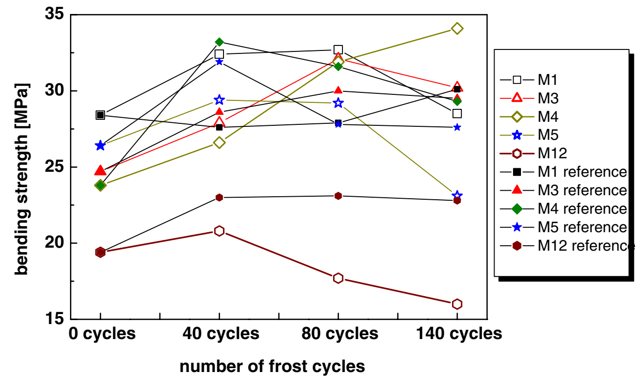

Fig. 18. Frost resistance of centrifuged pipes (cut specimens $15 \times 15 \times 80\ mm^3$, three point bending, span 45 mm).

and post peak strengthening with multiple cracking was observed.

3.7. Durability of spun-cast fiber reinforced composites

The results for the bending strength after different numbers of frost cycles are given in Table 6 and plotted in Fig. 18. The frost resistance generally is very good, despite the very low air-void content after centrifugation (<0.3 vol%, determined microscopically on hardened material). The mixture containing sand shows a somewhat poorer behavior with a significant strength loss after 140 cycles. For some pipes, the strength even increases after 40 frost cycles compared to the reference specimens, which were stored under water only. This may be explained with an internal curing during the frost cycles initiated by micro-ice lens water pumping [13]. Batch number four even shows a continuous improvement of bending strength with increasing number of frost cycles. The long PVA fibers and the low water/binder ratio seem to become more important. Internal microstructural damage caused by self desiccation and early age shrinkage may be healed partly through internal curing initiated by the water pumping into the dense matrix during the frost cycles.

4. Summary

The presented work describes the development of fiber reinforced composites in order to replace conventional steel bar reinforced concrete in spun-cast elements. A dense high strength matrix based on Portland cement blended with microfine cement allowed optimization of strength and rheological parameters of the composites. No special curing or mixing techniques were necessary to achieve a very high strength of over 30 MPa in bending.

A new method, the cone-consistency test, was applied to characterize and optimize the consistency of fiber reinforced composites. A conical measuring bob is moved with constant velocity into a hollow cone containing the freshly mixed composite. The resulting force is recorded as function of the displacement. Comparing the obtained data with data from on-site testing a criterion for mixtures suitable for the spun casting process was developed.

The influence of different fibers (type, dimensions) and of different dosage of a latex dispersion on the workability and strength of the composites with respect to the spin-casting process could be characterized.

The bending strength of carbon and PVA fiber reinforced composites of conventionally cast specimens and of spun-cast prototype pipes were tested. The fabrication of very ductile, high strength and durable composites under real production conditions was possible.

Acknowledgements

This paper presents some results of a three-year research project on the application of fiber reinforced high

Table 6
Bending strengths of cut prisms ($15 \times 15 \times 80$ mm) of centrifuged pipes after frost resistance test

Batch	28 Days (MPa)	40 Cycles (MPa)	40 Cycles reference (MPa)	80 Cycles (MPa)	80 Cycles reference (MPa)	140 Cycles (MPa)	140 Cycles reference (MPa)
M1	28.4 ± 5.6	32.4 ± 4.9	27.6 ± 2.4	32.7 ± 3.2	27.9 ± 3.4	28.5 ± 3.1	30.1 ± 6.4
M2	28.7 ± 4.4	22.6 ± 5.3	28.7 ± 4.7	27.0 ± 3.9	32.5 ± 5.0	28.7 ± 4.4	27.9 ± 3.7
M3	24.7 ± 5.3	27.9 ± 2.7	28.6 ± 4.7	32.1 ± 5.0	30.0 ± 5.0	30.2 ± 4.7	29.5 ± 5.1
M4	23.8 ± 4.8	26.6 ± 4.9	33.2 ± 3.8	31.9 ± 4.5	31.6 ± 6.3	34.1 ± 6.9	29.3 ± 7.3
M5	26.4 ± 6.6	29.4 ± 5.0	31.9 ± 5.2	29.2 ± 5.0	27.8 ± 4.8	23.1 ± 6.1	27.6 ± 6.9
M6	25.1 ± 4.8	29.6 ± 7.3	27.4 ± 3.7	n.a.	n.a.	24.2 ± 4.5	27.4 ± 3.7
M8	32.8 ± 5.0	29.7 ± 3.4	33.0 ± 6.1	26.2 ± 6.1	27.6 ± 6.3	26.5 ± 7.4	27.0 ± 4.9
M10	30.4 ± 4.4	28.4 ± 2.9	30.4 ± 4.2	28.0 ± 3.3	27.9 ± 3.4	29.6 ± 4.1	28.5 ± 4.0
M12	19.4 ± 3.6	20.8 ± 2.0	23.0 ± 6.8	17.7 ± 1.5	23.1 ± 6.4	16.0 ± 2.5	22.8 ± 1.4

performance composites in spin-casting fabrication. The project was supported by the Swiss commission for technology and innovation (KTI/CTI) and SACAC AG, Lenzburg, Switzerland. Special thanks go to K. Moser, G. Terrasi and G. Bättig for their continuous support.

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