RHEOLOGY OF FIBRE REINFORCED FINE-GRAINED HIGH PERFORMANCE CONCRETE FOR THIN-WALLED ELEMENTS - EFFECT OF TYPE AND CONTENT OF STEEL FIBRES

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ABSTRACT

Concretes for thin-walled shell structures have to provide both high strength and flowability. Both can be achieved by reinforcing high strength fine-grained concretes with high contents of steel fibres. However, steel fibres can have a significant effect on the flowability and, as a result, the yield stress and viscosity of the fresh concrete.

The present investigations show the effect of increased fibre contents on the rheological parameters yield stress and viscosity of high strength fine-grained concrete. These parameters were determined by using a rheometer. The suitability of fine-grained concretes for filling thin-walled formwork while maintaining flowability was determined by the time-dependent flow distance in an L-box model formwork. It was shown that there is a critical fibre content beyond which both the yield stress and the viscosity increase strongly. This affects the form filling ability of the concrete containing fibres.

Keywords: rheology, fibres, shell structures, form filling ability

INTRODUCTION

Manufacturing thin-walled, geometrically curved surface structures (shells) with concrete presents a challenge. Therefore, the basic principles of light construction with concrete are to be developed in a current DFG priority programme. The challenge in manufacturing such shells lies mainly in the fact that they should have thin-walled cross sections below 100 mm.

In order to achieve efficient concrete shell structures it is necessary to increase their tensile capacity. Due to the high requirements with respect to the dimensional accuracy of reinforcement arrangement, the reinforcement steel bars used for conventional concrete elements are inappropriate for efficient manufacture. Such precise reinforcement positioning would rise the amount of work and therefore costs of the concrete structure. In the case of very thin-walled shells with $d < 100$ mm it is increasingly difficult to maintain the minimum level of concrete cover. As a consequence, it is evident that the arising tensile forces should be absorbed by steel fibre reinforcement. Reinforcement with short fibres offers the additional advantage to increase the delicate appearance, variety of shape and robustness of shell structures.

The usual fibre content in steel fibre concretes ranges currently from about 1.0 to 2.5 vol.% [1], [2]. With such fibre contents tensile strengths of about 5 MPa are achieved [3]. In the case of thin-walled shell structures, it is crucial to increase the fibre content and thus the tensile capacity. Otherwise high fibre contents affect the concrete flow properties. To guarantee completely formwork filling it is important to have exact knowledge of the rheological properties (yield stress, viscosity) of such concretes containing high fibre contents. It is conceivable that the concrete should exhibit high flowability (expressed as low yield stress and viscosity) in order to fill the formwork completely in an appropriate period of time. To prevent sedimentation of the steel fibres, however, both parameters should not fall below critical values.

Many authors report that the addition of fibres to concretes decreases workability by increasing both yield stress and viscosity [4-7]. This is more pronounced for higher fibre contents and higher aspect ratios l_f/d_f (ratios between fibre length and fibre diameter). Also factors such as water/cement ratio and the content of aggregate play a major part [6], [8]. In particular, the combination of aggregate particles with fibres affects the packing density of the mixture which, in turn, has an effect on flowability [9]. Depending on the composition of the concrete matrix, a critical fibre content exists above which the concrete is no longer workable and fibre agglomerations and clusters occur [1], [9]. In contrast, Kuder et al. [8] observed that flowability initially improved with the addition of fibres, but decreased again after reaching a critical fibre content. According to the authors, this is due to an increased structural breakdown caused by the fibres during the mixing process before the fibres - in case of higher contents - interlock and cause both the yield stress and the viscosity to increase further.

Martinie et al. [9] introduced the so-called total relative packing fraction; a result of the ratio between volume fraction and dense packing fraction of fibres and sand, equation (1).

$$\textit{Total relative packing fraction}: rel\,\phi \;=\; \frac{\phi_f \cdot l_f}{\alpha_m \cdot d_f} + \frac{\phi_s}{\phi_{sm}} \;=\; \frac{\phi_f}{\phi_{fm}} + \frac{\phi_s}{\phi_{sm}} \tag{1}$$

Here ϕ_f is the volumetric fibre content, l_f/d_f the aspect ratio of the fibres and ϕ_s and ϕ_{sm} the volume fraction and the dense packing fraction of sand, respectively. The factor α_m is determined from the product of l_f/d_f and ϕ_{fm}, the dense packing fraction of the fibres [9]. The authors were able to show that the relative yield stress (ratio between the yield stress of concrete containing fibres and concrete without fibres) correlates with the total relative packing fraction $rel\,\phi$ (see Fig. 1).

Figure 1. Relative yield stress as a function of the total relative packing fraction [9]
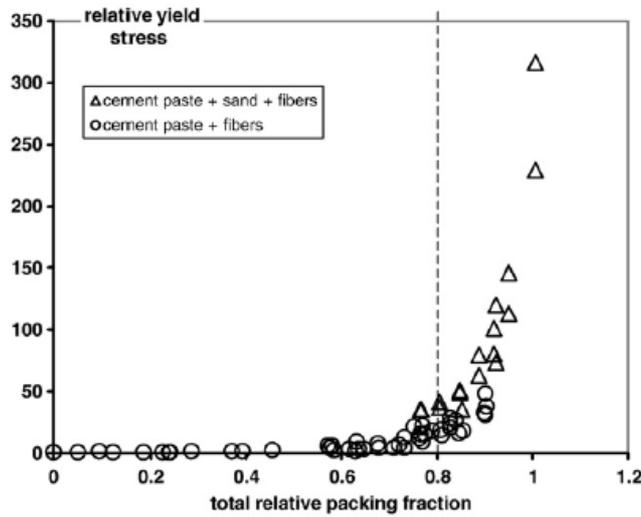
The factors which determine yield stress and workability are thus the content and the aspect ratio of fibres (fibre factor $\phi_f \cdot l_f/d_f$) as well as the volume fraction of the sand. If the yield stress after the addition of fibres is to stay in the same order of magnitude as that of concrete without fibres, $rel\,\phi$ should be ≤ 0.8, cf. Fig. 1. If $rel\,\phi$ is above 0.8, the yield stress will increase disproportionately. Values close to 1.0 will even lead to agglomerations and clusters of fibres [9].

If thus a maximum value $rel\,\phi$ of 0.8 is required, the following equation can be used for the determination of a maximum fibre content $(\phi_f)_{max}$ on the basis of equation (1).

$$(\phi_f)_{max} \;=\; \frac{\left(0.8 - \dfrac{\phi_s}{\phi_{sm}}\right) \cdot \alpha_m \cdot d_f}{l_f} \cdot 100 \;=\; \left(0.8 - \frac{\phi_s}{\phi_{sm}}\right) \cdot \phi_{fm} \;\; [vol.\%] \tag{2}$$

The aim of the present investigations was to determine the effect of fibre content and fibre type on the rheological parameters yield stress and viscosity as well as the form filling ability of high strength fine-grained concrete. The form filling ability of the fresh concretes containing fibres was investigated in an L-box model formwork whose cross-

sectional dimensions were those of a thin-walled shell. Based on the above mentioned approach by Martinie et al. [9], it was to be clarified whether a critical fibre content actually exists beyond which form filling ability is affected adversely.

INVESTIGATIONS

To investigate the effect of increased steel fibre contents on the rheological parameters yield stress and viscosity, 3, 4, 5, 6, 7 and 10 vol.% steel fibres were added to a basic fine-grained concrete without steel fibres. The concrete without steel fibres contained 220 kg/m³ cement of strength class 42.5 R. Furthermore, 350 kg/m³ ground granulated blast-furnace slag, 100 kg/m³ silica fume with a mean particle size of 0.15 µm as well as 485 kg/m³ ground limestone were used. 936 kg/m³ quartz sand with a maximum particle size of 0.5 mm were added. 14 kg/m³ superplasticizer based on polycarboxylate ether was used to fluidify the mix with a water/binder ratio of 0.17. The water content was 186 kg/m³. The compressive strength determined after 50 d for cylinders with d/h = 100/200 mm was 130 MPa (without heat treatment).

Due to the addition of fibres the components were adjusted keeping the ratio between the cement and further solids of the concrete constant. The total water content of the concretes remained constant. Two different steel fibres were used. The diameters and length of fibre 1 were 0.19 mm and 6 mm, respectively. Fibre 2 had the same diameter as fibre 1, but a length of 9 mm. The aspect ratios l_f/d_f of fibre 1 and fibre 2 were 32 and 47, respectively. To determine the packing density of sand and fibres, 5 kg of each material were placed in a cylindrical container with dimensions of d/h = 160/320 mm according to de Larrard [10]. Firstly, the material was loosely filled into the cylinder. A steel piston of the same diameter and a height of 120 mm was used as a load. In the next step, each container was vibrated for a period of 60 s at a frequency of 60 Hz. This was repeated until the volume of the material did not reduce further, i.e. the largest possible compression was achieved. The packing density was calculated from ratio of the mass to the product of the volume and density of material.

The concretes were produced in an intensive mixer to obtain a high degree of homogenisation of the fresh concrete. In a first step, the dry materials were homogenised together with the steel fibres. Homogenisation of the fibres with the dry materials permits better dispersion than scattering the fibres into the flowable concrete - even in case of high fibre contents. Moreover, the mixing time is also reduced [11]. In a next step, water and 40 % of the superplasticizer were added while the mixing tool was operating at a low speed. The remaining superplasticizer was added after mixing for 2 minutes. The mixing time after water addition totalled 3.5 min.

For the measurement of yield stress and plastic viscosity the 4C-Rheometer was used [12]. At the end of the mixing process, the concrete was filled into an Abrams cone positioned on a sand-blasted glass plate. Immediately after the filling process (6 min after the addition of water) the cone was automatically lifted at a speed 0.07 m/s. The time dependent flow curve was recorded by a camera (see Fig. 2). Then, the flow curve

was compared with numerically simulated flow curves and, based on these results, both the yield stress and the plastic viscosity were determined [12].

The form filling ability of concretes containing fibre 1 was examined in an L-box model formwork (Fig. 3). For this purpose, 3.6 L concrete were filled into the vertical section of the formwork. Directly after this, a metal sheet separating the vertical from the horizontal section was lifted at a speed of 0.2 m/s letting the concrete flow through the horizontal section. The flow distance in the fully closed horizontal section was recorded photographically.

| Figure 2. Rheometer	Figure 3. L-box model formwork (dimensions in mm)
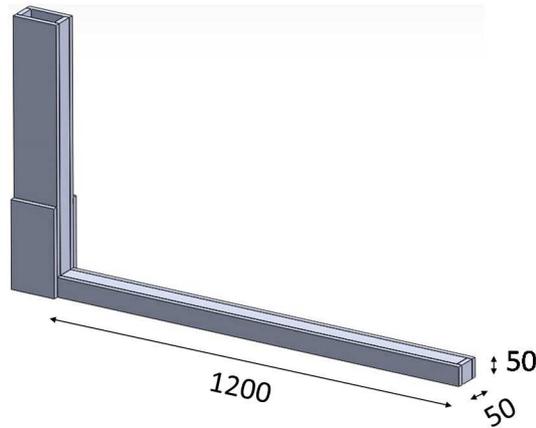
RESULTS AND DISCUSSION

The yield stress and plastic viscosity parameters of fine-grained concrete without fibres determined by rheometer were 11 Pa and 42 Pa·s, respectively. The slump flow of the concrete was at 745 mm. On the addition of the shorter fibre 1 with an aspect ratio of 32, the flowability improved up to a fibre content of 5 vol.% (Fig. 4, left). The plastic viscosity was reduced by half to 21 Pa·s. The yield stress remained almost constant, which correlates again with a slight slump flow increase of 50 mm. Once a fibre content of 6 vol.% was exceeded, both the yield stress and the plastic viscosity increased disproportionately. At the same time, the slump flow decreased below 500 mm. No formation of fibre clusters was observed if fibre 1 was used up to a fibre content of 10 vol.%. Fig. 4 additionally shows the total relative packing fraction $rel\,\phi$ calculated according to equation (1) based on experimentally determined results for the parameters $\alpha_m = 8.5$ for fibre 1 and the dense packing fraction of sand $\phi_{sm} = 63.9$ %. In the case of concrete without fibres $rel\,\phi$ was 0.55 and increased up to 0.73 in the case of a fibre content (fibre 1) of 6 vol.% (Fig. 4, left). As already reported by Martinie et al. [9] a disproportionate increase of yield stress occurs if $rel\,\phi > 0.8$. Besides yield stress the viscosity increases rapidly at this critical fibre content. Consequently, the model according to [9] is also valid for the prediction of maximum

fibre content with regard to viscosity. In the case of fibre 1 (l_f/d_f = 32), the maximum fibre content $(\phi_f)_{max}$ calculated according to equation (2) was 8.2 vol.%.

Figure 4. Yield stress and plastic viscosity parameters for aspect ratios of fibres l_f/d_f = 32 (left) and l_f/d_f = 47 (right) in dependence of fibre content and rel φ
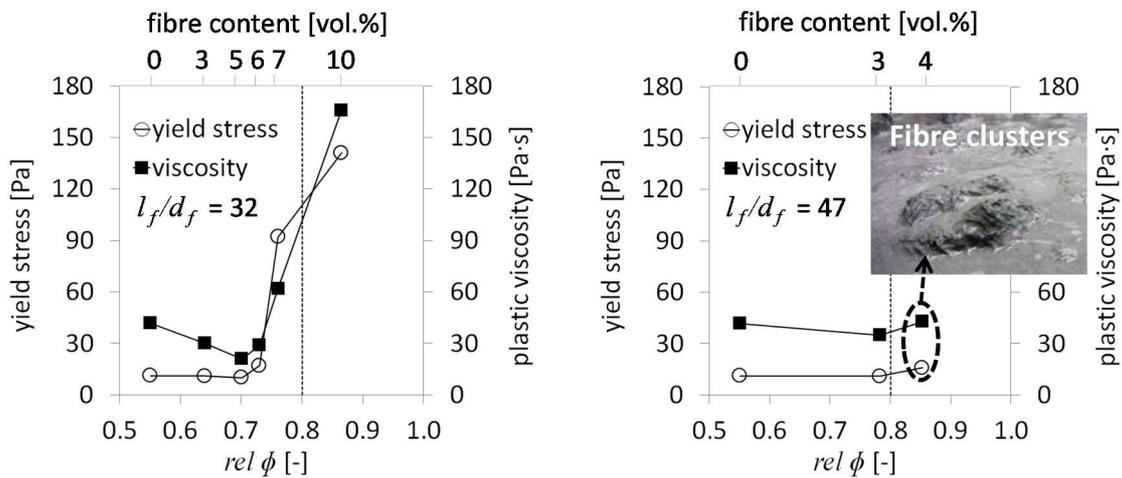
The fact that up to a critical fibre content workability is apparently improved agrees with the results of Kuder et al. [8]. The addition of fibres clearly seems to cause higher structural breakdown due to higher shear thus decreasing the rheological parameters. It is also conceivable that fibres promote the formation of a secondary structure of the binder/sand suspension which results in easier shearing of material. Once *rel φ* was above 0.8, the fibres interfere with each other and a disproportionate increase of yield stress and viscosity occurred.

If fibre 2 was used - only 3 mm longer with an aspect ratio of 47 and an experimentally determined parameter α_m = 5.6 - the critical value of *rel φ* = 0.8 was already achieved for a fibre content of 3.3 vol.% (Fig. 4, right). At a fibre content of 4 vol.% *rel φ* was 0.85. Even though only a slight increase in terms of yield stress and viscosity could be observed if compared with concrete without fibres it contained a high concentration of fibre clusters (Fig. 4, right). As a result, this concrete is no longer suitable for practical application. The large number of fibre clusters also explains the only moderate increase in the rheological parameters since the remaining matrix contained a lower fibre content in comparison to the calculated 4 vol.%. Thus the concrete still exhibited on the whole an apparently good flowability. Fig. 5 shows the time-dependent flow distances in the L-box model formwork for concrete containing fibre 1. Concrete without fibres required 40 s to flow to the end of the horizontal section (flow distance 1200 mm). This was thus considered as a reference time for formwork filling. As shown in Fig. 5, fine-grained concretes showed an improved form filling ability up to a fibre content of 6 vol.%. The time until reaching a flow distance of 1200 mm decreased by more than half (to 16 s) in the case of a fibre content of 5 vol.%. Again, an increased fibre content is related to an improved form filling ability. On the one hand, this is due to an increased density of the concrete containing fibres and, as a consequence, an increased hydrostatic pressure in the vertical section of the model formwork and, on

the other hand, it is due to a decreased viscosity. Thus, this concrete can fill the horizontal section faster. Only in the case of 10 vol.% the flow time was close to 4 min (Fig. 5).

Figure 5. Flow distance in L-box model formwork vs. time in dependence of fibre content and rel φ of fibre 1 (l_f/d_f = 32)
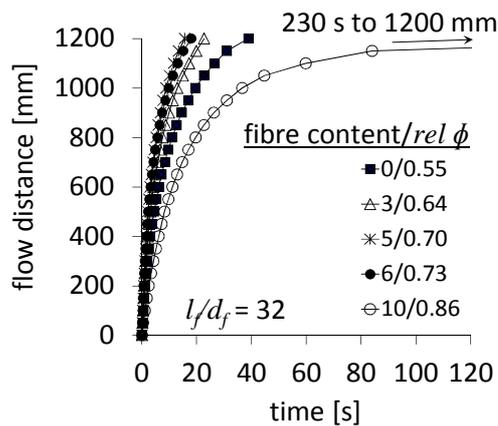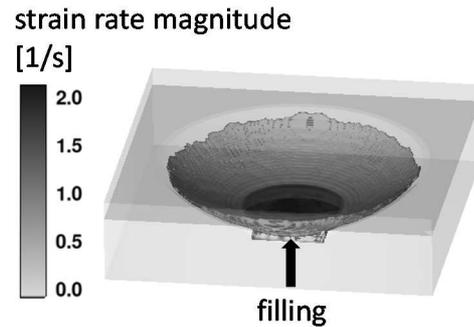
Figure 6. Simulation of the filling process (filling from the lowest point) of a shell, where d = 50 mm with CFD

The significantly higher values of yield stress and viscosity outweigh the effect of increased concrete density with 10 vol.% fibres; very slow filling of the formwork is the result. Thus, the form filling ability of this concrete has to be classified as not acceptable. If a threshold value of *rel φ* ≤ 0.8 is assumed, the model according to Martinie et al. [9] based on equation (2) can thus be used to predict the maximum fibre content with respect to its form filling abilities. In further investigations it is planned to characterize the form filling ability of these concretes in curved non-planar, freely formed shell geometries using computational fluid dynamics (CFD) simulations, see e.g. Fig. 6.

CONCLUSIONS

The presented investigations have shown the effect of fibre content and fibre type on the rheological parameters yield stress and viscosity. Knowledge of these parameters is essential, particularly for the efficient production of curved shell structures with cross sections < 100 mm. Consequently, the form filling ability of concretes containing fibres was investigated in an L-box model formwork. The results show that yield stress and viscosity remain constant or even reduce if shorter fibres up to a fibre content of 6 vol.% were used. Higher contents led to a disproportionate increase of both parameters. This behaviour was also observed for the form filling ability of the concretes where fibre contents up to 6 vol.% led to faster flowing as compared to concrete without fibres. In contrast, concrete reinforced with 10 vol.% fibres was not suitable for filling the formwork of thin-walled construction elements. The use of

longer fibres - only 3 mm longer, but the same diameter – already led to fibre clusters at a fibre content of 4 vol.% and was thus not suitable for practical application. For the prediction of the maximum fibre content with respect to rheological parameters and form filling abilities, it was possible to adopt an existing model which considers both packing density of fibres and sand. With this, it is now possible to optimise concretes with high fibre contents to guarantee high tensile strengths and, at the same time, achieve favourable workability properties. The investigations were carried out within the DFG priority programme 1542 „Concrete light. Future concrete structures using bionic, mathematical and engineering form-finding principles".

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