Rheology of Carbon Fibre Reinforced Cement-Based Mortar

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Abstract. Carbon fibre reinforced cement based materials (CFRCs) offer the possibility of fabricating "smart" electrically conductive materials. Rheology of the fresh mix is crucial to satisfactory moulding and fresh CFRC conforms to the Bingham model with slight structural breakdown. Both yield stress and plastic viscosity increase with increasing fibre length and volume concentration. Using a modified Viskomat NT, the concentration dependence of CFRC rheology up to 1.5% fibre volume is reported.

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INTRODUCTION

Carbon fibre reinforced cement (CFRC) materials are of technological interest because of the electrical conductivity of the hardened material. This changes in response to deformation and cracking and enables them to be self-monitoring in service ("smart"), with a range of potential applications [1,2]. To realize its potential as a smart material, fresh CFRC must be capable of being shaped, so its rheology is important. A lower limit of carbon fibre content, the percolation threshold (typically 0.3-0.5% by volume), must be exceeded in order to confer the desired electrical properties. An earlier paper [3] confirmed that CFRCs conform to the Bingham model, with slight structural breakdown, and that increasing the fibre length and fibre volume concentration increase both yield stress and plastic viscosity. It established that the Viskomat NT can measure the rheology of CFRCs up to 0.5% fibre volume but that modifications to the measurement system were needed in order to exceed the percolation threshold. This paper reports an investigation of modified impellers for CFRCs at up to 1.5% fibre volume concentration.

EXPERIMENTAL

The materials and procedure were the same as described in [3]. Briefly, CEM I Portland cement, siliceous sand of max particle size 2mm, water-reducing plasticizer at fixed dosage and carbon fibre (SIGRAFIL C® - diameter 7.5 μm) were used in a standard mortar with a sand/cement ratio of 0.5 (by mass). The experimental variables were
(i) water/cement ratios of 0.4, 0.45 and 0.5;
(ii) fibre lengths of 3, 6, 9 and 12 mm; and
(iii) fibre volumes of 0, 0.5, 0.75, 1.0, 1.25 and 1.5% (by volume of sample).

In the Viskomat NT [4], as the cylindrical container (diameter 83 mm) rotates at speed N, mortar flows through the stationary impeller, generating a torque T, which is measured by a transducer. A series of torque and rotational speed readings, recorded by computer, fit a straight line of the form

$$T = g + h\,N \tag{1}$$

where g (Nmm) is related to yield stress (Pa) and h (Nmms) is related to plastic viscosity (Pa s). The standard impeller X (diameter 64 mm) was used in the earlier work [3] and additional impellers Y (diameter 60 mm) and Z (diameter 50 mm) were fabricated in order to extend the measurement range to deal with the stiffer CFRCs expected at higher fibre volume concentration. All three impellers were calibrated by an established procedure, based on the

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Metzner-Otto principle that the mean effective shear rate KN in a mixer is proportional to the rotational speed [5,6], using Newtonian liquids (silicone oil at different temperatures) and power law liquids (aqueous solutions of diutan gum at a single temperature). Using this procedure the Bingham yield stress τ_0 and plastic viscosity μ are given by

$$\tau_0 = (K / G)\, g \tag{2}$$

$$\mu = (1 / G)\, h \tag{3}$$

The values of G and K so obtained follow a trend with impeller size and enable the measurements using all three impellers to be put on a common scale (see Table 1).

TABLE 1. Calibration constants for the standard and modified impellers

Impeller	Diameter mm	K / G	1 / G
X	64	5.18	0.53
Y	60	6.42	0.71
Z	50	9.94	1.22

Mortars were tested using the same protocol as in [3], namely a flow curve ramping up from 0 to 3.33 rev/s and back to 0 over 7 minutes, followed by sequential addition of fibres and retesting up to the highest fibre content, with strict adherence to times of testing to ensure reproducibility. 3.3 rev/s corresponds to a mean effective shear rate, calculated from K above, of about 32, 30 and 27 s^{-1} for impellers X, Y and Z, respectively. The Viskomat NT has a torque cut-out device to prevent overloading above the maximum of 200 Nmm, so different impellers were used in the tests, as appropriate to keep within this limit (Table 2).

RESULTS

Results of two test programmes are presented here. Series A is for up to 0.5% fibre volume and values were converted from the data in [3] using the calibration constants for impeller X. Series B is for fibre volumes 0-1.5%. Table 2 confirms that impeller X is able to test all the CFRCs at 0.5% fibre and shows that it was necessary to use the progressively smaller impellers Y and Z as the mixes got stiffer. The CFRCs at 0.4 water/cement ratio and 1.0% or more fibre were too stiff to test even with the smallest impeller, causing torque overload. Thus the smaller impellers successfully extend the testing range of the instrument.

TABLE 2. Test series B: ability of impellers X, Y and Z to test CFRCs (O denotes too stiff to test).

Water / Cement	0.5				0.45				0.4			
Fibre Length mm	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
0.5% fibre	X	X	X	X	X	X	X	X	X	X	X	X
0.75% fibre	X	X	X	Y	Y	Y	Z	Y	Z	O	Y	O
1.0% fibre	X	X	Y	Z	Z	Z	Z	Z	O	O	O	O
1.25% fibre	Y	Y	Y	Z	Z	O	Z	O	O	O	O	O
1.5% fibre	Y	Z	Y	Z	Z	O	O	O	O	O	O	O

CFRCs at 0 and 0.5% fibre were tested in both series and Figure 1 shows that there is good agreement between the yield stresses obtained in each series but less good agreement for plastic viscosities. The experimental error on plastic viscosity is greater due to the scatter of points on the flow curve and the dashed lines indicate the experimental errors of ± 10% and ± 25% respectively. Additionally, in Series A the 0.5% fibre CFRC was tested last in the sequence, while in Series B it was tested early, and this difference of about 45 minutes in the time from mixing to testing could be enough to cause a systematic bias to higher values in the Series B results. Despite this reservation, it seems reasonable to present the trends in the data obtained from the two series on composite graphs.

Figure 2 summarises all the results from both series, obtained at water/cement ratio 0.5. The impeller used in any particular test can be identified by reference to Table 2.

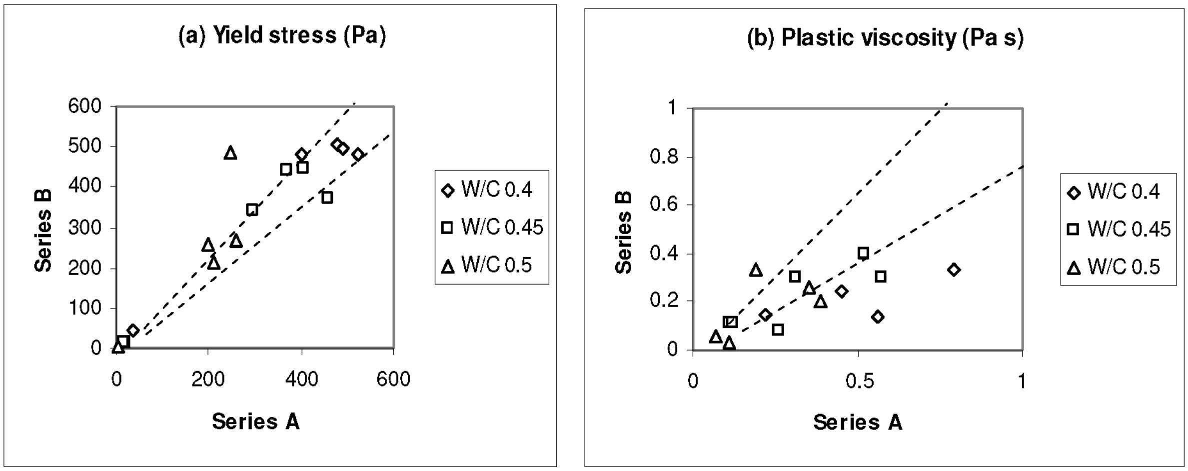

FIGURE 1. Correlation between (a) yield stress and (b) plastic viscosity for Series A and B, using standard impeller X.

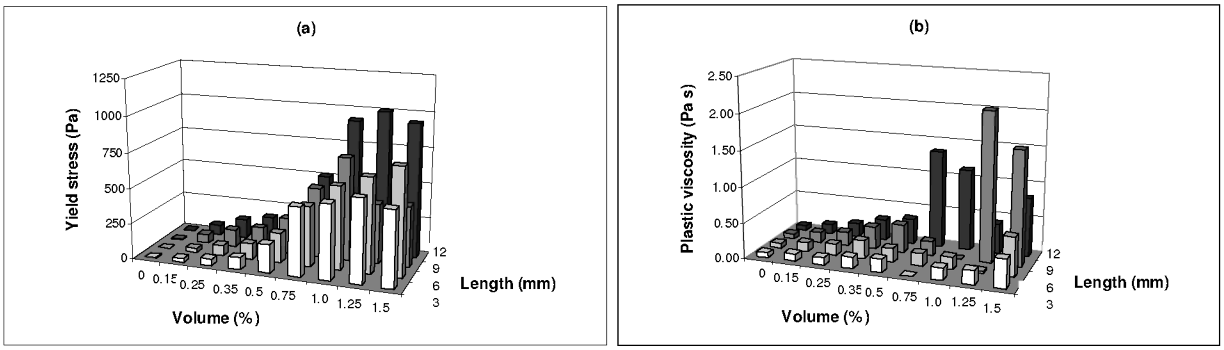

FIGURE 2. Effect of fibre length and volume concentration on (a) yield stress and (b) plastic viscosity of CFRC.

DISCUSSION AND CONCLUSION

The results show that using smaller impellers extends the Viskomat NT's testing capability to fibre volume concentrations well above the percolation threshold. The yield stresses and plastic viscosities without fibres are within the accepted range of values for mortars [5] and increase with increasing fibre length, increasing fibre volume concentration and decreasing water/cement ratio. The results extend the range of data from that previously reported to facilitate the development of practical, mouldable mix formulations for smart, electrically conductive CFRCs.

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