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The effect of measuring procedure on the apparent rheological properties of self-compacting concrete

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Abstract

Torque versus time during testing of the rheological properties of fresh concrete has been investigated. The testing was performed in a BML viscometer and on a self-compacting concrete (w/c = 0.45, 70% rapid hardening Portland cement, 3% silica fume, 27% fly ash, third generation superplasticizer). The relaxation period needed to obtain steady-state flow may affect the rheological properties estimated and should be taken into account in the selection of measuring procedures. Nonsteady state is likely to cause an overestimation of the plastic viscosity and an underestimation of the yield value. Furthermore, lack of steady state may explain the apparent shear-thickening behaviour of self-compacting concrete reported elsewhere.

Keywords: Self-compacting concrete; Rheological properties; Measuring procedure

1. Introduction

The flow of ordinary fresh concrete can be characterized by the Bingham equation, $\sigma = \sigma_B + \eta_{pl}(d\gamma/dt)$, where σ is the shear stress, $d\gamma/dt$ is the shear rate, σ_B is the Bingham yield stress and η_{pl} is the plastic viscosity. Self-compacting concrete, however, has been observed to exhibit an apparent shear-thickening behaviour, which can be described by the Herschel–Bulkey model, $\sigma = \sigma_y + k(d\gamma/dt)^n$, where σ_y is the yield stress, and k and n are constants, where $n > 1$ [1]. The nomenclature used is in accordance with Ref. [2].

The apparent shear-thickening behaviour of self-compacting concrete has recently been suggested to be an artefact from the experimental set-up, caused by a lack of steady state during the rheological measurements [3,4]. The present paper documents that the relaxation period needed to obtain steady-state flow of a self-compacting concrete may affect the rheological properties estimated and should be taken into account in the selection of measuring procedures.

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2. Materials and testing

Concrete of the composition given in Table 1 was mixed in a 60-l laboratory paddle-pan mixer (Zyklus). In Denmark, fly ash is normally used as filler in self-compacting concrete. The batch size was 45 l, the mixing was undertaken at high speed and the following mixing schedule was used: aggregate + 1/2 water; 2–4 min: resting; 4–5 min: cement + fly ash + silica fume, almost all the remaining water; 6–6.5 min: air entrainer plus approximately 0.1 l water; 6.5–

Table 1
Concrete mix composition (5% air)

Constituent material	Density (kg/m^3)	Composition (kg/m^3)
Cement, CEM I 52.5	3160	245
Fly ash	2300	94.5
Silica fume	2290	10.5
Water	1000	140
SikaAer 15b conc.	1001	1.05
Viscocrete34	1010	3.67
Sand 0/4 mm	2618	754
Coarse aggregate 4/8 mm	2642	453
Coarse aggregate 8/16 mm	2637	597

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Table 2
Measuring procedures, input parameters

	Transient time (s) (no data logging)	Sampling time (s) (data logging)	Number of measuring points (rotational speeds)	Number of sampling points at each speed	Range of rotational speeds (rev/s)
	Total measuring time at each speed				
Typical values [5]	2	3	5	50	0.1–0–6
Values applied	0	5, 8, 10, 15 and 25	7 or 8	50	0.01–0.5 and 0.01–0.57

7 min: plastizicer plus approximately 0.1l water; 9 min: end of mixing.

The fresh concrete was tested at the age of 16 min in a coaxial cylinder BML viscometer (ConTec, BML viscometer 3) according to the procedures given in Table 2 and illustrated in Fig. 1. After placing concrete in the viscometer, the measuring procedure was initiated with a 30s pause followed by measuring at constant rotational speed for a selected time period (transient time + sampling time), starting with the highest speed and subsequently lower rotational speeds. The measuring procedure included a final test for segregation, by repeated measurement at 0.3 rev/s.

3. Results and discussion

Fig. 2 illustrates the relation between the shear rate and the torque during testing when measuring for 5, 10 and 25 s at each rotational speed, respectively. During the first measurement, at high rotational speed, the torque is observed to decrease and not reach steady state within the first say 20 s. For the last measurements, at low rotational speed, the torque is observed to increase, indicating a rebuilding of the microstructure.

Particle suspensions of colloidal particles exhibit structural breakdown or rebuilding of flocks of particles when subjected to changing shear rate. The larger the increase in shear rate, the larger the numbers of flocks broken down into smaller flocks or primary particles (single cement particles) and the longer the so-called relaxation time (i.e., longer time to reach equilibrium shear stress). At decreasing shear rate, the cement particles start to coagulate again, the suspension returning to its original structure. Both structural breakdown and rebuilding can be observed in Fig. 2.

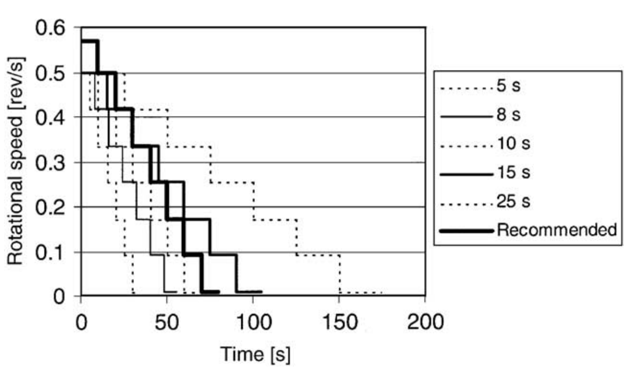

Fig. 1. The measuring procedures (rotational speed as a funtion of time) investigated.

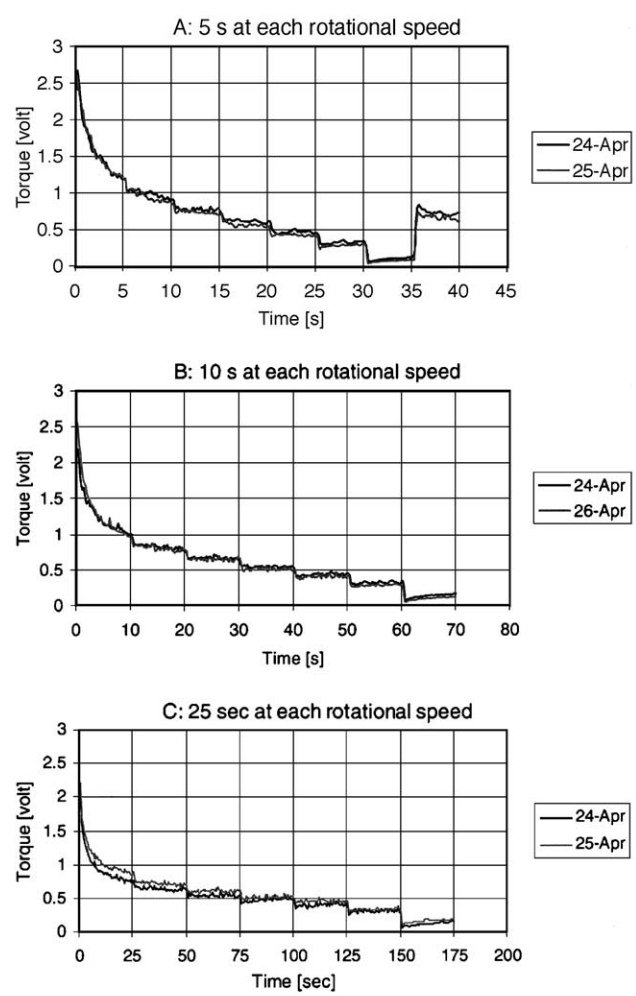

Fig. 2. Torque versus time for measuring for 5, 10 and 25 s at each rotational speed, respectively. The vertical gridlines illustrate the change of rotational speed. Vertical segregation was visually observed at the fourth measurement, when measuring for 25 s at each rotational speed.

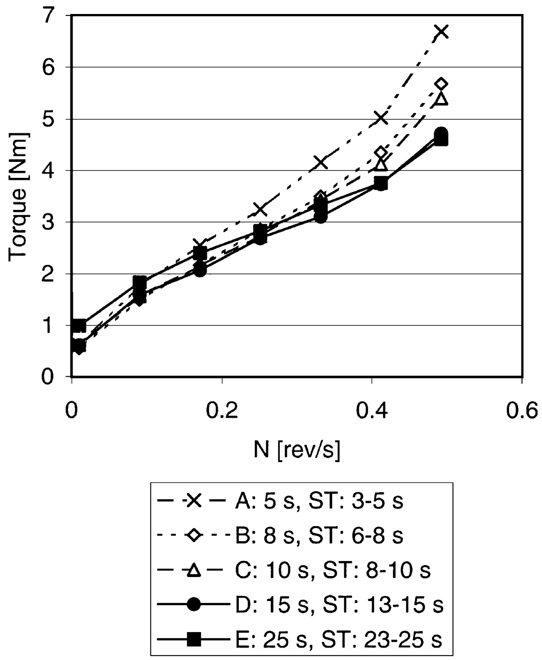

Fig. 3. Torque versus rotational speed for measurement for 5, 10 and 25 s at each rotational speed and estimating torque from the 50% lowest values in selected sampling intervals 'ST'.

The effect of the measuring procedure and the sampling time applied on the estimated torque is illustrated in Fig. 3. The torque determined at high rotational speeds is dependent on both the total measuring time and the sampling time. In general, the highest torque is obtained at the shortest measuring time (5 s) due to lack of steady state (curve A in Fig. 3). However, at the lowest rotational speed (0.01 rev/s), the highest torque is obtained at the latest sampling time (measuring time at 25 s and sampling interval 23–25 s) due to an assumed rebuilding of the microstructure (see Figs. 2C and 3, curve E).

The effect of the measuring procedure and the sampling time applied on the rheological properties obtained is illustrated in Fig. 4. For increasing measuring time and late sampling intervals, the estimated plastic viscosity decreases and the estimated yield value increases (Points A through E). Thus, the total time at each shear rate should be long enough to obtain steady state, and the transient and sampling times should be adequate. However, long measuring times can lead

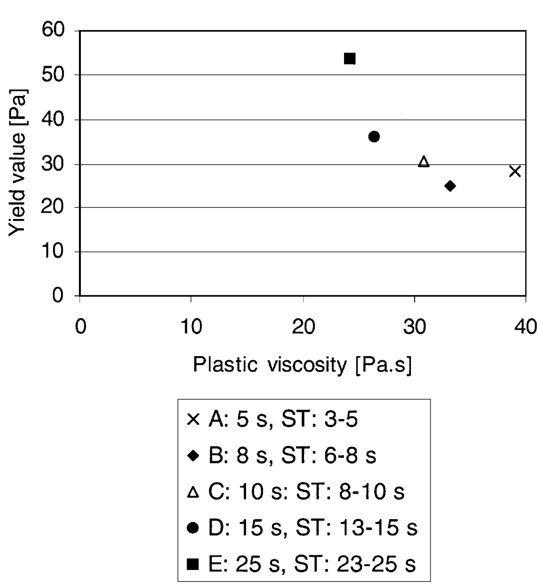

Fig. 4. Rheological parameters estimated form the data given in Fig. 2. (Reiner–Rivlin equation, $r_i = 0.1$ m, $r_o = 0.145$ m, $h = 0.2$ m. Bingham model. Data points for plug flow and segregation are omitted.)

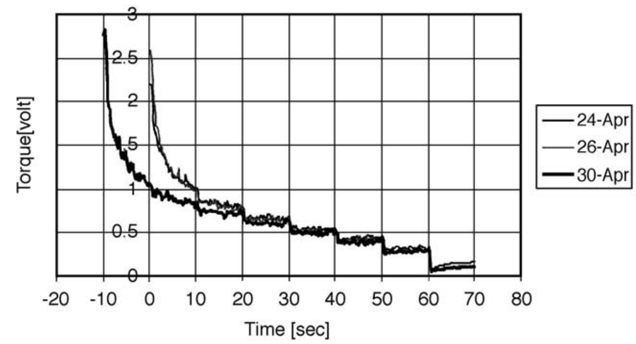

Fig. 5. Torque versus time for measuring at 10 s at each rotational speed and rotational speed interval at 0.01–0.5 rev/s (24 and 26 April) and 0.01–0.57 rev/s (30 April). No segregation was visually observed during the tests. Data for 30 April have been horizontally shifted.

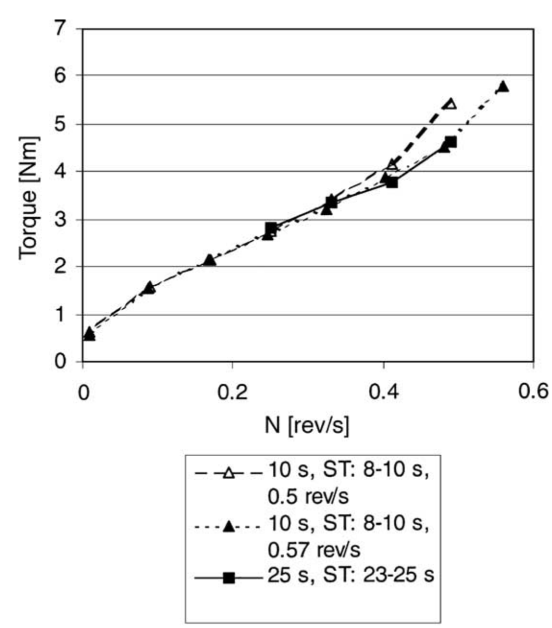

Fig. 6. Torque versus rotational speed for measuring at 10 s at each rotational speed and rotational speed interval at 0.01–0.5 and 0.01–0.57 rev/s. The torque is the mean of five lowest values in the interval 8–10 s. For comparison, data for measuring for 25 s at each rotational speed and no segregation are included.

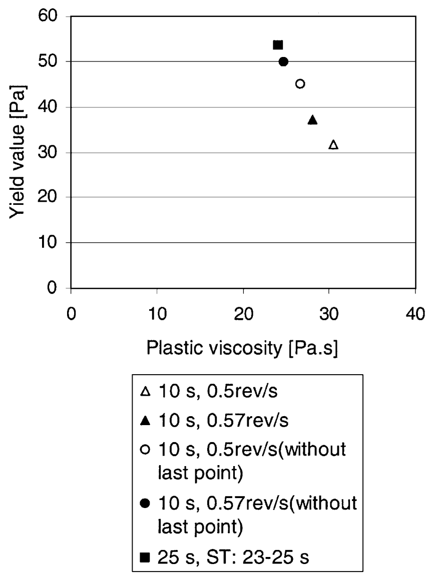

Fig. 7. Estimated yield value versus plastic viscosity for the data given in Fig. 6 (data below plug flow speed have been omitted).

to segregation of the mix. Vertical segregation—in the form of disappearance of aggregates from the top surface—has been visually observed when measuring for 15 and 25 s at each rotational speed. Thus, the time at each rotational speed should be limited, e.g., to 10 s. Horizontal segregation may also occur and was observed to a minor extent for all mixes in the form of coarse aggregates being fixated at the lamellae of the outer cylinder.

As concrete typically obeys Bingham equation (have a yield stress) and as the shear stress varies across the gap, part of the material will move as a solid plug at low shear rates. This phenomenon is referred to as plug flow [6].

Adding an extra measuring point at higher speed (0.57 rev/s) to the measuring procedure leads to obtaining more rapidly the steady state at the succeeding rotational speeds (see Fig. 5). The effect on the torque is illustrated in Fig. 6. Due to the lack of steady state at the first measuring point (at the highest rotation speed), this should not be used when estimating the rheological properties, else the yield stress will be underestimated and the viscosity overestimated (see Fig. 7, triangles versus circles).

Based on the above, the measuring procedure given in Table 3 was selected as the optimal for the actual concrete. To increase the reliability of the data, the period of sampling should cover the entire period where steady state is observed. Furthermore, it may be considered to increase the number of sampling points from 20 to minimum 40.

Compared to self-compacting concretes produced in other countries, the concrete investigated has low water content. The observed prolonged time to obtain steady-state flow is assumed to be partly due to the low water content, partly caused by the third generation superplasticizing admixture used [3,4].

When testing unknown concrete mixes, it is recommended to select the measuring procedure and estimate the rheological properties based on measured torque (Nm) versus shear rate (rev/s), showing the time necessary to obtain steady-state flow (see Figs. 2 and 5), combined with visual observations for possible vertical segregation.

4. Conclusions

The relaxation period needed to obtain steady-state flow has been found to affect the estimated rheological properties of self-compacting concrete when measuring according to the normal procedure for the BML viscometer. To minimize the possible effects of nonsteady state and segregation, the following procedure for testing the rheological properties of the investigated concrete is proposed: measure for 10 s at each rotational speed in the interval 0.05–0.57 rev/s; and estimate the torque from the lowest points obtained in the sampling interval 8–10 s, omitting the data point at the highest rotational speed and any data points at speeds below speed, where plug flow occurs.

As prolonged time to obtain steady-state flow also has been observed for other self-compacting concretes, it is recommended to select the measuring procedure and estimate the rheological properties based on the data for the torque (Nm) versus the shear rate (rev/s), showing the time necessary to obtain steady-state flow, combined with visual observations for possible vertical segregation.

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Table 3
Proposed measuring and data processing procedure for the actual mix, input parameters

	Transient time (s) (no data logging)	Sampling time (s) (data logging)	Number of measuring points (rotational speeds)	Number of sampling points at each speed	Range of rotational speed (rev/s)
	Total measuring time at each speed				
Data logging	0	10	8	100	0.05–0.57
Estimation of parameters	8	2	7	20	0.05–0.5

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