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Cement and Concrete Research 33 (2003) 1901–1903

CEMENT AND CONCRETE RESEARCH

Discussion

A discussion of the paper "The effect of measuring procedure on the apparent rheological properties of self-compacting concrete" by Mette R. Geiker, Mari Brandl, Lars N. Thrane, Dirch H. Bager and Olafur Wallevik☆

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Received 18 March 2003

1. Shear-thickening behavior of self-compacting concrete (SCC): artifact or reality?

The authors report an interesting study on the correct determination of the apparent rheological parameters of SCC, i.e., yield stress and viscosity [1]. By the use of the BML rheometer (coaxial cylindrical geometry) tested in Ref. [2], the authors measured torque versus rotational speed (high to low) to get free of the time-dependent behavior and to begin measurements at the best structural breakdown [3]. They draw attention to the fact that steady-state flow (constancy of torque) must be achieved for the concrete at each angular velocity if the rheological properties are to be correctly estimated. Like any other reader, we endorse this fact and thank the authors for recalling it to researchers who intend to characterize the flow behavior of concrete rigorously.

Nevertheless, according to the authors, the apparent shear-thickening behavior of SCC is an experimental artifact due to the absence of a steady state during measurement, especially for high rotational speeds. We would like to show, from our experiments performed at different scales and under a controlled measuring procedure, that the torque–rotational speed relationships for pastes and SCC are not necessarily linear; thus, materials can exhibit a true shear-thickening behavior.

2. From cement pastes to SCC

2.1. Experimental conditions

The results presented here are part of an overall project on the study of the rheology of SCC. The cement pastes (PC1 and PC2) which had the same static yield stress (15 Pa) contained constituents usually included in SCC (Table 1). At 15 min of age, each paste was subjected to shear by means of coaxial cylinders. The width of the gap between the inner and outer cylinders (Fig. 2) was different for PC1 and PC2 to appreciate whether the possible curvilinear portion of torque-versus-rotational speed plots at low velocities was due to geometry or to an inherent property of suspension. Two SCCs were studied. SCC1 came from an industrial design used in prefabrication and mentioned here only for comparison with SCC2, which was a ready-mixed concrete designed using fine constituents included in PC2. For each concrete, two identical batches were tested to verify the validity of the rheological measure-

Table 1
Characteristics of cement pastes

	PC1	PC2
Cement	CEM I 52,5R	CEM I 52,5
Mineral additive	Limestone filler (25% by mass of cement)	Limestone filler (28% by mass of cement)
Superplasticizer	Naphthalene sulfonate	Polycarboxylic ether
Viscosity-enhancing admixtures	Not used	Amorphous precipitated silica
Volume concentration of solids	0.58	0.61

☆ Cem. Concr. Res. 32 (11) (2002) 1791–1795.

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0008-8846/$ – see front matter
doi:10.1016/S0008-8846(03)00197-2

Table 2
Workability characteristics of SCC and power-law parameter

	SCC1	SCC2
Average spreading diameter	740 mm	700 mm
Laitance width at the slumped material periphery	≤ 5 mm	≤ 10 mm
L-box-average filling ratio H2/H1	0.81	0.75
Laitance π (%) at 5 mm sieve	11%[a]	11%[a]
Exponent c (with/without the highest speed data)		
Batch1	1.49/1.27	1.38/1.14
Batch2	1.89/1.63	1.36/1.32

[a] According to GTM criteria, if $\pi \leq 15\%$, a good segregation resistance is expected at rest.

ments. Average workability features of SCC1 and SCC2 are shown in Table 2. Five-liter samples of SCC1 and SCC2 were tested at 20 min of age in a RheoCAD rheometer designed by CAD Instrumentation. The fully automated apparatus, already utilized by researchers [4], was manually operated here to wait for the steady state to be reached at each rotational speed. The measuring tool was a four-bladed anchor. This kind of impeller is of interest because it generates a whirled axial secondary flow on the vicinity of the anchor blades [5]. In this way, segregation was limited, but drawbacks existed at low rotational speeds for which the flow principally became plane and tangential close to the anchor. Indeed, below 0.166 rev/s, segregation occurred and the displayed volume of shearing decreased.

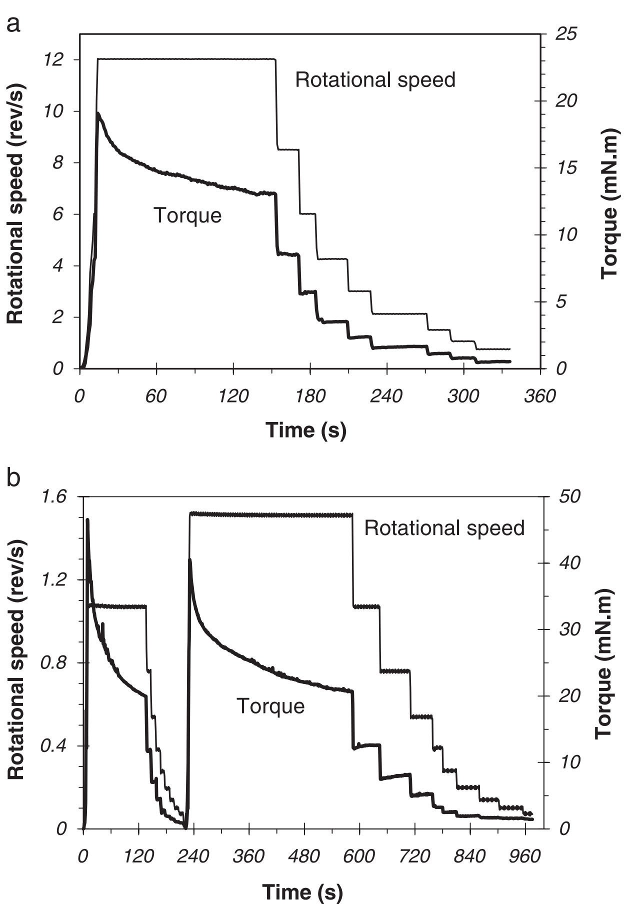

Fig. 1. Rotational speed versus time and torque versus time for PC1 (a) and PC2 (b).

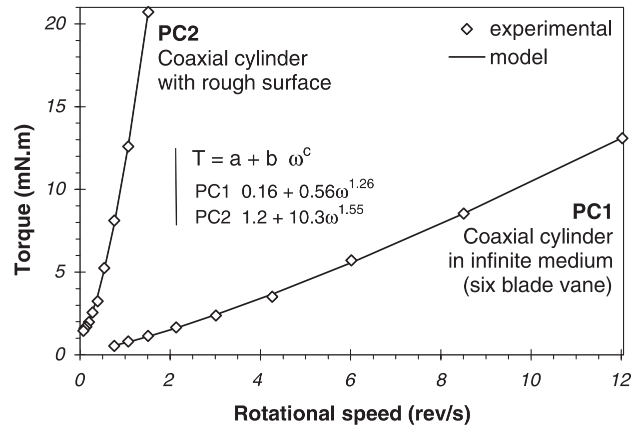

Fig. 2. Torque versus angular velocity experimental data and model.

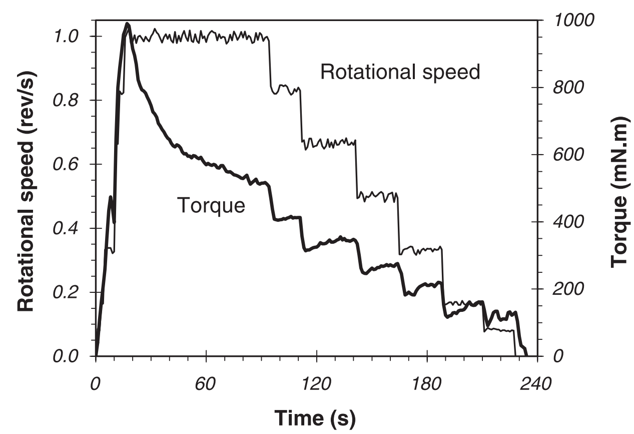

Fig. 3. Velocity–time and torque–time variations for SCC1.

2.2. Results

Fig. 1 illustrates the rotational speed and the torque variations for PC1 and PC2. Different shearing histories were intentionally applied (preshearing on PC2 and not on PC1). At each angular velocity, steady state was clearly achieved. Fig. 2 shows the relationship between the mean[1] value of the torque T and the mean value of the rotational speed ω. Experimental and model ($T = a + b\omega^c$) data are plotted in Fig. 2. In both cases, exponent c is greater than 1. Even if the higher speed, which can be considered as an extra measuring point according to Geiker et al. [1], is not taken into account, it remains greater than 1 (1.28 for PC1

[1] The mean value of torque is derived from the last 10 values at a given speed (1 value/s).

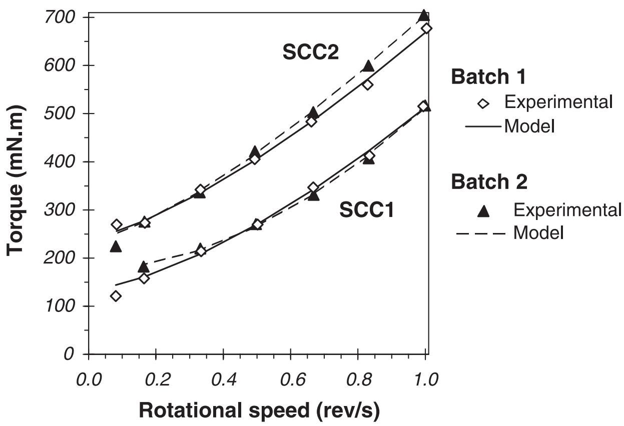

Fig. 4. Torque–rotational speed relationships for SCC1 and SCC2.

and 1.57 for PC2). Although the curvilinear section of the curves has been reported to correspond to the condition in which flow occurs in only the inner portion of the gap due to stress falling below the yield value at low shear velocities [6], our results show that the pastes exhibit shear-thickening behavior, whatever the gap width investigated. This behavior has been noticed already on superplasticized and concentrated cement pastes with or without mineral additives [7] and on an attempt made to explain the occurrence of shear thickening, based on the order–disorder and clustering theories, briefly described in [7].

Rheological tests performed on SCC by other researchers have shown that flow could be influenced by shear-thickening behavior of the paste [8]. Fig. 3, which gives the shear history of sample SCC1, shows that the measuring time at each angular velocity was sufficient to achieve the steady-state flow. The same results were obtained for SCC2. The experimental data plotted in Fig. 4 clearly depict a nonlinear relationship between average torque values, T, and average rotational speed, ω. A least mean square regression using a power-law model $T = a + b\omega^c$ gives an exponent c greater than 1. This regression does not take into account the values below 0.167 rev/s because of visible segregation. When the highest speed is removed, exponents c remain greater than 1 in all cases (Table 2).

From our data, it seems that the shear-thickening behavior of SCC exists and is not an artifact. We simply ask the following question: Is the Bingham equation a simplified view of the rheological behavior of SCC?

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