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Fresh concrete: A Herschel-Bulkley material

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ABSTRACT

Some preliminary results of an experimental program on the rheological behavior of fresh concrete are presented. In the rheological tests, performed with a plane-to-plane rheometer, it appears that the relationship between torque and rotation speed is not exactly linear. The fresh concrete behavior is better described by the Herschel-Bulkley model: $\tau = \tau'_0 + a\,\dot{\gamma}^b$; τ and $\dot{\gamma}$ are the shear stress and the strain gradient applied to the specimen, respectively. τ'_0, a and b are three material parameters describing the concrete behavior. Among other advantages, this new description avoids the problem of negative yield stress encountered with the Bingham model.

RÉSUMÉ

Quelques résultats préliminaires d'un programme expérimental de grande envergure, traitant de la rhéologie du béton frais, sont présentés. Les caractéristiques rhéologiques des mélanges sont mesurées avec le rhéomètre BTRHEOM. Il apparaît que la relation entre couple et vitesse de rotation n'est pas strictement linéaire; une description plus fine est fournie par le modèle de Herschel-Bulkley, de la forme $\tau = \tau'_0 + a\,\dot{\gamma}^b$; τ est la contrainte de cisaillement, et $\dot{\gamma}$ le gradient de vitesse imposé à l'échantillon. Les paramètres τ'_0, a and b décrivent le comportement du béton. Entre autres avantages, cette nouvelle approche permet d'éviter le problème des seuils négatifs, rencontré avec le modèle de Bingham.

1. INTRODUCTION

The rheology of fresh concrete is a relatively young science. There have been many attempts to characterize the consistency of fresh concrete by a variety of technological tests [1, 2], but few researchers have applied continuous media mechanics to the rheological behavior of fresh concrete.

Tatersall was probably the first to carry out systematic investigations in this field, which have been summarized in a book [3]. Pointing out that testing fresh concrete in a classical coaxial viscometer would require a gigantic apparatus, he suggested the use of a more modest device (the 'Two-point test') where the concrete is mixed in a sort of instrumented mixer. Finding a linear relationship between the increase of the torque and the rotation speed of the impeller, Tatersall stated that fresh concrete had a *Bingham* behavior, which can be expressed by the relationship:

$$\tau = \tau_0 + \mu\,\dot{\gamma} \quad (1)$$

where τ is the shear stress, $\dot{\gamma}$ the strain gradient (or shear rate), τ_0 the yield stress, and μ the plastic viscosity. The two last parameters are assumed to be material constants.

However, this relationship was only suggested by an analogy between fundamental parameters (stress, strain gradient) and macroscopic measurements (torque, speed of rotation). More recently, de Larrard *et al.* developed a parallel-plate rheometer called BTRHEOM [1] [4], where the strain field is imposed by the geometry (see Fig. 1). From the relation between the torque and the rotation speed, one can deduce the material law of behavior. Therefore, for the first time, characteristics in funda-

1) The names of manufacturers are identified in this report to adequately describe the experimental procedure. Such an identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material identified is necessarily the best available for this purpose.

Editorial Note
F. de Larrard and T. Sedran work at Laboratoire Central des Ponts et Chaussées (LCPC), France, a RILEM Titular Member. Dr. de Larrard is a RILEM Senior Member and a member of the Technical Advisory Committee (TAC). He participates in the work of TCs 145-WSM (Workability of Special Concrete Mixes), 158-AHC (The Role of Admixtures in High Performance Concrete) and 174-SCC (Self Compacting Concrete). He was awarded the Robert L'Hermite Medal for excellence in research in 1989. C. F. Ferraris works at the National Institute of Standards and Technology (NIST), USA, a RILEM Titular Member. Dr. Ferraris is a RILEM Senior Member and a corresponding member of TC 158-AHC.

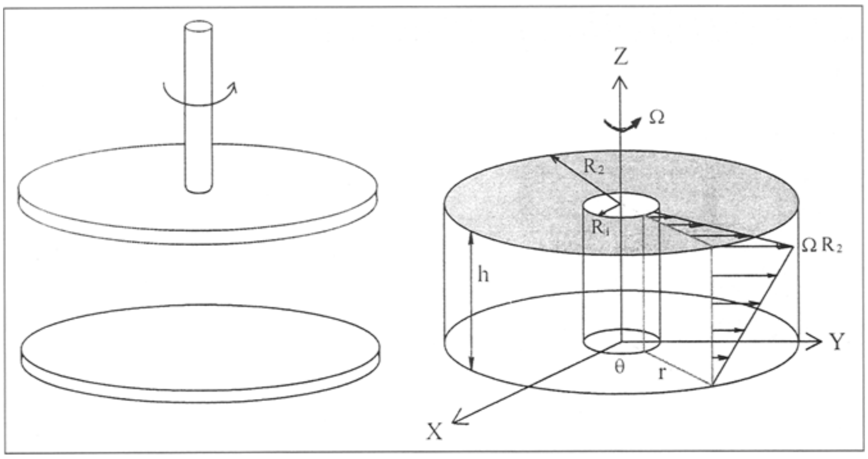

Fig. 1 – Velocity field in BTRHEOM [3, 4].

mental units can be measured on fresh concrete. This rheometer was developed taking into account a comprehensive series of specifications, encompassing both engineering and scientific requirements. The measurements were validated by finite-element calculations, and comparisons with most existing types of concrete rheometers [5, 6]. The use of this rheometer for characterizing a series of concretes, mostly high-performance concretes, led to the conclusion that the Bingham behavior was an acceptable description of the flow behavior of most fresh concretes [5, 7]. However, some of our recent measurements suggest that this is not always a good approximation and that a more general description of the flow curves seems necessary. A possible model is similar to the one used by Coussot and Piau, who studied the rheology of coarse aggregate-mud suspensions with a large coaxial rheometer [8].

2. EXPERIMENTAL PLAN

In an on-going experimental plan carried out at the National Institute of Standards and Technology (NIST), an attempt is made to assess the rheological behavior of all feasible concretes within a fixed set of components. In a first series of tests, 33 concretes or mortars without admixtures were generated by systematic variations of cement content, coarse/fine aggregate ratio and water content. In a similarly designed series, the mixtures were highly "superplasticized", with a high-range water reducer agent (HRWRA). Finally, two more series completed the program, one with intermediate amounts of HRWRA, and one with various additions of silica fume. A total of 78 mixes was studied. The concretes were produced with a gravel having a maximum size of 12 mm, a coarse sand, a single-size fine sand from Ottawa (Illinois), and an ordinary Portland cement (ASTM Type I/II). The HRWRA used is of the naphthalene type (having a solid content of 40%). Some of the mixtures are detailed in Table 1.

Within the three series considered herein, the mutual proportions of dry materials remain constant. Only the water concentration was changed from one mixture to another. The mixtures had water-cement ratios in the range 0.55-0.60 by mass ('Normal-Strength Concretes'), 0.36-0.38 ('High-Performance Concretes'), and 0.26-0.27 ('Self-Compacting Concretes'), respectively.

A slump test (ASTM C143 [9]) and a BTRHEOM rheometer test were performed on every mix. All slump values were higher than 80-100 mm, which ensured that the concretes were sufficiently fluid for testing in the rheometer. For the rheometer tests, a 15 s previbration was applied to the specimens (with a frequency of 40 Hz)[2], then the shear tests were carried out without vibration. Five measurements were taken for rotation speeds ranging between 0.2 and 0.8 rev/s. This corresponds to a strain gradient between 0.25 and 6 s-1. Lower rotation speeds would be desirable, but lead to difficulties in regulating the rotation speed of the rheometer. At each rotation speed level, torque measurements are taken after twenty seconds, in order to decrease the contribution of thixotropy. However, it has been shown that, for a constant rotation speed, no real stabilization of the torque appears within a

Table 1 – Mixture-proportions of some concretes. *: free water/cement ratio

Series	Mixtures	Coarse aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Ottawa Sand (kg/m^3)	Cement (kg/m^3)	HRWRA (kg/m^3)	Water (kg/m^3)	w/c*
Normal-Strength Concretes	B01C	953	614	191	360	0	209	0.55
	B01B'	952	614	190	360	0	214	0.57
	B01A	940	606	188	355	0	217	0.58
	B01A'	943	608	189	356	0	222	0.60
High-Performance Concretes	BHP1A'	992	617	176	419	10.5	159	0.36
	BHP1B	990	616	176	418	10.4	161	0.37
	BHP1C	984	612	175	415	10.4	166	0.38
Self-Compacting Concretes	BHP8C	882	549	157	619	15.5	162	0.26
	BHP8B	878	546	156	616	15.4	167	0.27
	BHP8A	868	540	154	609	15.2	171	0.27

2) The previbration ensures that the placement of the concrete sample is not influenced by the operator [5].

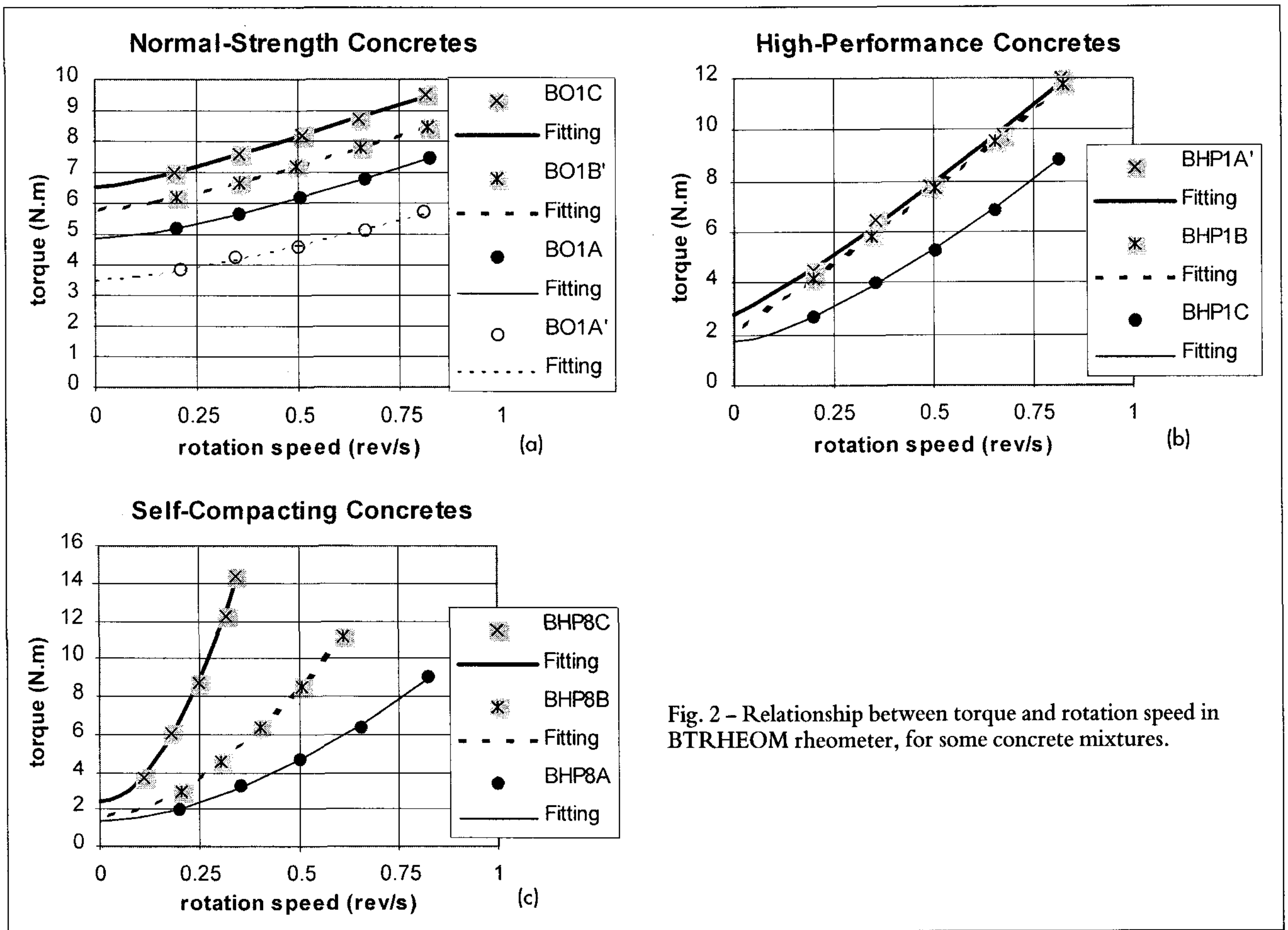

Fig. 2 – Relationship between torque and rotation speed in BTRHEOM rheometer, for some concrete mixtures.

Table 2 – Properties of the concretes at the fresh state. *mean diameter of the spread after the slump test

Mixtures	Slump (mm)	Slump flow* (mm)	Bingham model: Yield stress (Pa)	Bingham model: Plastic viscosity (Pa.s)	Herschel-Bulkley model: Yield stress (Pa)	a ($Pa.s^b$)	b	Equivalent plastic viscosity (Pa.s)
BO1C	80		1717	174	1804	111	1.23	156
BO1B′	100		1489	163	1599	86	1.33	140
BO1A	130		1219	160	1341	74	1.40	134
BO1A′	165		881	133	983	62	1.40	111
BHP1A′	180		593	517	774	385	1.15	479
BHP1B	205		473	530	608	430	1.10	501
BHP1C	235		141	439	471	205	1.40	370
BHP8C	265	560	*-452*	1960	675	792	1.88	2956
BHP8B	285	700	*-373*	879	457	269	1.73	795
BHP8A	290	750	*-147*	488	385	132	1.70	376

reasonable time [5]. There is first a decrease of the torque due to a structural breakdown phenomenon. Then, an increase appears, caused by the early cement hydration. Therefore, the obtained measurements slightly depend on the test duration, which is unavoidable in the case of cementitious materials. For two very thick mixtures (BHP8C and BHP8B), the maximum rotation speed had to be reduced, because the power of the motor was not high enough to reach the intended maximum speed. The results of the tests are given in Table 2 and Fig. 2.

As a preliminary result, it appears that experimental relationships between torque and rotation speeds generally deviate from a straight line (see Fig. 2), even if the linear correlation is rather high (between 0.970 and 0.999). Moreover, if a linear regression is applied to the experimental points (following the usual procedure to deduce the Bingham parameters), a *negative* yield stress is sometimes found (in the case of the Self-Compacting mixtures).

3. FITTING THE EXPERIMENTAL CURVES WITH THE HERSCHEL-BULKLEY MODEL

It seems that a better model for representing the experimental points is the following

$$\Gamma = \Gamma_0 + A\,N^b \qquad (2)$$

where Γ is the measured torque (bulk value minus the contribution of the empty rheometer [10]), N the speed of rotation (in rev/s), Γ_0, A and b numerical parameters determined by the least square difference method. This type of model has been referred to as the Herschel-Bulkley (HB) model. HB behavior is the same as the Bingham behavior when the exponent is equal to 1 [11]:

$$\tau = \tau'_0 + a\,\dot{\gamma}^b \qquad (3)$$

Following this model, the description of the rheological behavior requires three parameters: τ'_0 (the HB yield stress), a and b.

Integrating the contribution of each surface element to the torque, the following equations are obtained:

$$\Gamma_0 = \frac{2\pi}{3}\left(R_2^3 - R_1^3\right)\tau'_0$$
$$A = \frac{(2\pi)^{b+1}}{(b+3)h^b}\left(R_2^{b+3} - R_1^{b+3}\right)a \qquad (4)$$

where R_1 and R_2 are the inner and outer radii, and h the height of the sheared concrete specimen. In BTRHEOM, R_1 = 20 mm, R_2 = 120 mm and h = 100 mm.

These equations can be inverted to deduce the material parameters from the fitting of the bulk curve. A 10% correction is applied to the a parameter to account for the skirt friction effect, as is normally done in determining the plastic viscosity [6]. Therefore, we have for the HB parameters:

$$\tau'_0 = \frac{3}{2\pi\left(R_2^3 - R_1^3\right)}\Gamma_0$$
$$a = 0.9\frac{(b+3)}{(2\pi)^{b+1}}\frac{h^b}{\left(R_2^{b+3} - R_1^{b+3}\right)}A \qquad (5)$$

The fitting of the experimental points appears in Fig. 2, and the parameters found are given in Table 2. The experimental relative errors are about 0.7% and 1% for the torque and for the rotation speed, respectively [5]. Here, the coefficients of variation provided by the regressions have been found close to 1%. Thus, it appears that the HB model provides an excellent approximation to the measurements. The HB yield stress is always positive, and, within each series, it decreases when the water content increases. Also, the exponent b differs significantly from 1, which shows the limits of the Bingham model.

In favor of the Bingham model, it could be argued that the Bingham yield stress values provide a better ranking of the mixtures than the HB yield stress, with respect to the slump values (see Table 2). However, it is thought that the ability of the Self-Compacting Concretes to produce high spread in the slump test is due not only to the low yield stress, but also to the high amount of cement paste (here, about 40%), which lubricates the aggregates up to the end of the test. The paste volume of the high-performance concretes is less (32%), then a part of the paste is squeezed from the skeleton during the slumping of the sample, until friction between aggregates stops the flow.

4. CONCLUDING REMARKS

The Herschel-Bulkley model appears to offer some benefit in describing the flow behavior of concretes. However, its ability needs further confirmation. Nevertheless, after a systematic fitting of 62 tests dealing with HPCs made in the past at the Laboratoire Central des Ponts et Chaussées (LCPC), the b parameter was only rarely equal to 1. Further, a link seems to exist between a and b (Fig. 3). However, this link could depend on some mixture-design parameters, *e.g.* the presence of HRWRA.

From a practical viewpoint, a 3-parameter model may be difficult to handle (especially if the aim is to specify the rheological characteristics, and to control them by optimizing the mixture-design). If a systematic link exists between a and b in equation (3), then the model only contains two independent parameters. If the relationship between a and b is not general, another solu-

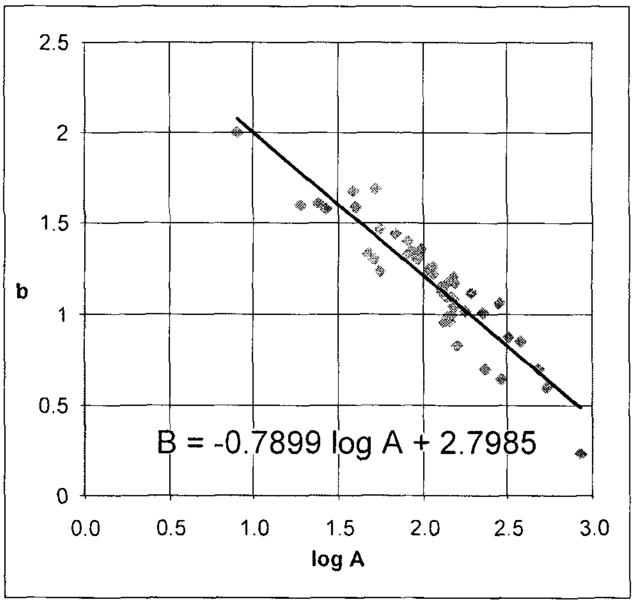

Fig. 3 – Relationship between a and b parameters, in a set of High-Performance Concretes tested at LCPC.

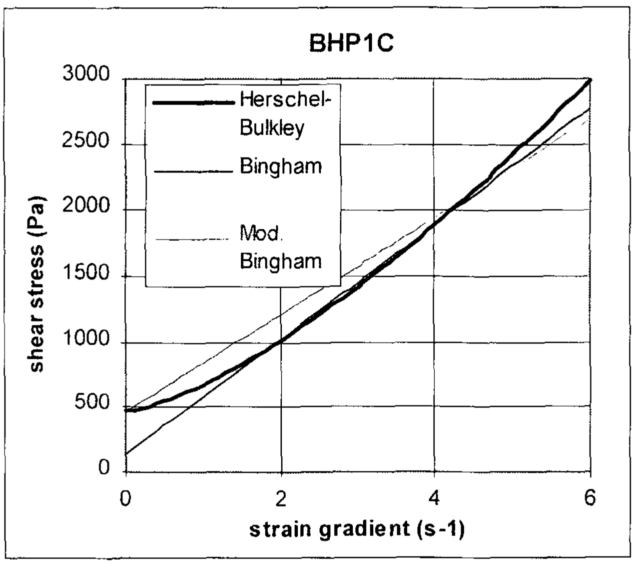

Fig. 4 – Approximation of the HB rheogram by a modified Bingham straight line.

tion would be to keep the Bingham model, with parameters deduced from the HB model. Then the yield stress would be τ_0, and the equivalent plastic viscosity μ' would be calculated enabling the Bingham straight line to give the best possible approximation of the HB curve, in a certain strain gradient range $[0, \dot{\gamma}_{max}]$ (Fig. 4). By using the least square method, it is found that:

$$\mu' = \frac{3a}{b+2}\dot{\gamma}_{max}^{b-1} \qquad (6)$$

In this case, μ' would become a good parameter for characterizing the secondary aspects of concrete workability. For the mixtures tested, $\dot{\gamma}_{max} = 6\ s^{-1}$ (see Table 2).

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