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Simultaneous determination of Bingham material parameters using a ball probe concrete rheometer

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A new evaluation method allowing direct determination of the Bingham parameters from ball probe rheometers. A non-linear relationship between the direct measured variables and the material parameters is revealed through numerical parameter studies. The method was validated on two devices of the ball probe type with different dimensions. Comparison with other methods showed good agreement. It is pointed out how the evaluation method can be transferred to devices having other dimensions by performing a limited number of straightforward calibration experiments. This work closes the gap between established ball probe rheometer evaluations and objective material parameters. Objective material parameters can be extracted from every ball probe rheometer. Even existing data can be converted.

1 Introduction

Modern construction methods impose high demands on the properties of fresh concrete: it should be built as climate friendly as possible at the lowest possible cost. Ultra-high-performance concretes (UHPCs) contribute to these requirements because they have a long service life and their high strength allows slim designs. Due to the high concentration of granular components and furthermore due to chemical interactions during cement hydration, fresh concrete exhibits a complex flow behavior, which is usually associated with a yield stress. For the processing of fresh concrete, it is necessary to adjust the flow properties while mixing. Well-established rheometer types such as Couette cell are unsuited due to the grain structure. Building material rheometers are usually reduced to relative measuring systems, with no direct deduction of the objective material parameters due to the complex flow within such devices.

2 Evaluation approach

Although the ball measuring systems of different manufacturers differ in dimensions, the devices share essential geometrical and physical characteristics described in fig. 1: a ball probe rheometer consists of a cylindrical container into which the fresh concrete sample is placed. Relative to the container, a sphere rotates on an orbit with the radius l around the cylinder axis at the rotational velocity Ω. Fresh concrete is usually described as Bingham plastic with plastic viscosity μ and yield stress τ_y. The sample causes a torque M on the ball probe. From the physical description of the system, the torque is given in the expression $M = f(\tau_y, \mu, \rho, \Omega, D, D_a, l, H, k)$ or in its dimensionless equivalent $\Pi_1 = f(\Pi_2, ...\Pi_7)$ (dimensionless Π_i listed in table 1). The quantitative description of this relation is required to determine the material parameters from measurement curves. In the next step, this relationship will be examined by the help of a numerical parameter study.

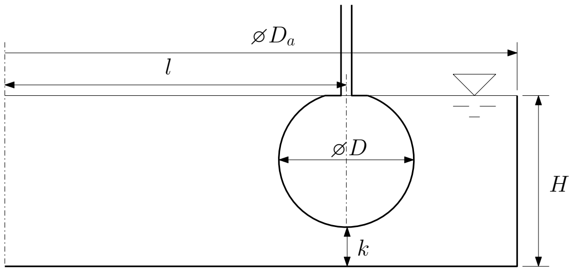

Fig. 1: Generic ball probe rheometer geometry.

Table 1: Dimensionless numbers describing ball probe rheometers.

i	formula	description
Π_1	$M/l^2\eta\Omega D$	diml. torque
Π_2	$\rho\Omega l D/\eta$	Re
Π_3	$\tau_y l/\mu\Omega D$	Bm
Π_4	H/D	[-]
Π_5	k/D	[-]
Π_6	D_a/D	[-]
Π_7	l/D	[-]

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3 Numerical investigations

Due to the low rotational velocity and the consistency of the concrete, we are dealing with creeping flows (quasi-stationary). Moreover, the concrete is modeled to be incompressible, so that mass and momentum balance hold:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1}$$

$$\rho \nabla \boldsymbol{v} \cdot \boldsymbol{v} = -\nabla p + \nabla \cdot \mathbf{T} \tag{2}$$

with the stress tensor $\mathbf{T} = 2\eta(\dot{\gamma})\mathbf{D}$ based on the Bingham plastic model and related to the velocity gradient tensor $\mathbf{D}$. The Bingham viscosity function $\eta_{\mathrm{Bm}}(\dot{\gamma}) = \frac{\tau_y}{\dot{\gamma}} + \mu$ shows singularity for vanishing shear rate and must therefore be regularized with regard to the numerical application. Therefore, the Papanastasiou regularization has been applied [1]. No-slip conditions apply to the container walls and the measuring ball, while taking into account the relative velocity. The phase interface at the top of the sample is modeled stress-free and flat with constant pressure, which is supported by experiments we carried out. In order to resolve the velocity gradients, the mesh needed refinement near the walls. The numerical solution with the finite volume method was obtained using OpenFOAM v1712 with a second order spatial discretization. Further details can be found in [2]. The results of the numerical study (parameters: rotational speed, yield stress, plastic viscosity) allow to approximate the dimensionless relationship (eq. (3)) sought and the retransformation in the dimensional form (eq. (4))

$$\Pi_1 = a_0 + a_1 \left(\mathrm{Bm}\right)^{a_2} \tag{3}$$

$$M = l^2 \mu \Omega D \left(a_0 + a_1 \left[\frac{\tau_y l}{\mu \Omega D} \right]^{a_2} \right). \tag{4}$$

The coefficients a_0, a_1 and a_2 are functions of the geometrical dimensionless numbers and thus depend on the rheometer's dimensions. However, the functions are not explicitly formulated, but instead treated as device coefficients. Due to the creeping flow condition, there is no correlation between the dimensionless torque and the Reynolds number. For the geometries investigated, the exponent a_2 is always smaller than 1.0, and thus the torque-speed relation is non-linear. This is an essential difference to the expected linear-affine curve progression in Couette rheometers with small gap. It is plausible, however, because with increasing shear rate the shear stress in the sample exceeds the yield stress at more and more locations. This effect can also be expected in the Couette arrangement of cylinders as soon as the assumption of the small gap is no longer valid [3]. By fitting eq. (4) using the material parameters on measurement curves, it is now possible to characterize the Bingham flow behavior. The method has already been successfully applied to fiber reinforced concrete of different consistencies [4, 5]. In particular, Schleiting [4] was able to validate the prediction of the yield stress using reference methods.

4 Conclusion: Calibration of arbitrary device

As a result of the numerical parameter study we identified the shape of the torque-rotational speed relation in the form of eq. (4) for two ball probe rheometers (one with one and one with two specimens each having different orbits) of different dimensions. With this knowledge, other instruments of the same type with different dimensions can now be calibrated. For this purpose the device coefficients a_1, a_2, a_3 must be determined. For the identification of the three parameters, theoretically three measuring points at different Bingham numbers are sufficient. In practice, a_0 should be determined for Newtonian reference material, since with the disappearing Bingham number the two remaining device coefficients have no influence. The coefficient a_1 has a greater effect on the range of low Bingham numbers, whereas a_2 describes behavior at higher Bingham numbers. Accordingly, a_1 should be evaluated at medium Bingham numbers and a_2 at high Bingham numbers. Both Bm ranges can theoretically be reached with the same Bingham fluid by varying the rotational velocity. In practice, however, the accuracy of torque measurement is limiting at low rotational speeds and at the same time the rotational speed is limiting at high loads. It is therefore advisable to select reference fluids with different yield points to determine the device coefficients. If calibration experiments are run at varying speed, the range of measurement data increases significantly. By fitting the eq. (3) with known flow properties of the calibration fluids, the device parameters a_0 to a_2 can be determined without the need for any numerical simulations.

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