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Measurement of yield stress of cement pastes using the direct shear test

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ABSTRACT

The direct shear test is widely used in soil mechanics to determine the cohesion (C) and angle of internal friction (ϕ). This paper aims to assess the suitability of this test to evaluate yield stress (τ_0) of cement pastes having different flowability levels. Special emphasis was taken to eliminate friction between shear boxes, thus allowing the measurement of C ranging from several kPa to just a few Pa. Tests have shown that the maximum shearing stress prior to failure is not a material constant, but rather varies with the normal stress as per the Mohr–Coulomb law. Good correlations between C and τ_0 determined using the vane method were established. Nevertheless, the vane method was found to over-estimate τ_0 when the blades are positioned inside the specimen, particularly for cohesive materials.

1. Overview on yield stress measurements

The yield stress (τ_0) is of interest for various industries; it is regarded as the transition stress between elastic solid-like behavior and viscous liquid-like behavior [1]. The measurement of τ_0 is generally performed using direct rheometric techniques that consist of slowly shearing the material and recording the peak shear stress required to initiate flow. However, such measurements are not easy to implement, given the need to accurately monitor variations of shear stresses at low shear rates [2–4]. Most importantly, the wall-sample interactions can result in slip effects associated with displacement of the dispersed phase(s) away from the boundaries, resulting in a low-viscosity particle-depleted layer near the wall and under-estimation of τ_0 [5,6]. The probability of wall slip increases when dealing with smooth walls, relatively small gaps, low flow rates, and concentrated suspensions of large and flocculated particles. A common way to reduce the extent of slip is to roughen the wall's surface in order to increase friction with the suspension [7,8]. It is to be noted that τ_0 can also be determined using indirect techniques that consist of extrapolating to zero shear rate a series of shear stress vs. shear rate rheological data. Nevertheless, such measurements are very sensitive to the assumed constitutive model as well as the accuracy and range of experimental flow data especially at low shear rates [2,4].

Over the last decades, various techniques have been more or less successfully developed to overcome the complications related to wall slip and enable reliable measurement of τ_0 [9–13]. The most popular techniques were those realized under quasi-static conditions and whose basic principle requires that shearing takes place within the material itself, i.e. not between the material and an object. Hence, ideally, this requires that a virtual plane of material should move inside the suspension, and the material–material shearing stresses recorded at low shear rates [9,10,14]. The peak shear stress needed to initiate flow can thus be considered as the "true" τ_0 of tested material.

The vane method is probably the most popular for measuring τ_0, since slip is physically impossible and shearing completely occurs within the material [6,9,15]. Its concept originated from soil mechanics, where vanes are used to determine shear strength of soils as described in ASTM D2573 [16]. Hence, a four, six, or eight-bladed vane of diameter D and height H, connected to a stress-controlled rheometer is fully immersed in the material and rotated at sufficiently low shear rate to determine the maximum torque required to initiate flow. Nguyen and Boger [9] suggested a series of criteria for satisfactory τ_0 measurements of various concentrated suspensions including $H/D < 3.5$, $D_T/D > 2$, $Z_1/D > 1$, and $Z_2/D > 0.5$ (see Fig. 1 for notations). Elsewhere, Nguyen and Boger [3] reported that $Z_1 + H + Z_2 > 2H$. Alderman et al. [17] utilized a set-up where $Z_2 = H$, $Z_1 = ½\, H$, and $D_T = 3D$.

To calculate τ_0, the maximum torque (T_m) is taken as the algebraic sum of shear stress exercised by the lateral area (T_s) and the vane's upper and lower areas (T_e), such that:

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$T_m = T_s + 2T_e$.

In terms of shear stress, the torque can be written in Eq. (1) as:

$$T_m = \left(\frac{\pi}{2} D^2 \tau_s\right) H + 4\pi \int_0^{D/2} \tau_e r^2 dr \tag{1}$$

where r is a radial coordinate, τ_e is the shear stress on the upper and lower circular ends of the cylinder, and τ_s is the stress on the curved cylindrical surface. Assuming that yielding occurs at the cylindrical surface defined by the tips of the blade, and that τ_e and τ_s are uniform and equal to τ_0 at maximum torque, T_m becomes equal to:

$$T_m = \left(\frac{\pi D^3}{2}\right)\left(\frac{H}{D} + \frac{1}{3}\right)\tau_0 \tag{2}$$

During τ_0 evaluation of various emulsions, Yoshimura et al. [18] considered positioning the top edges of the blades vane aligned with the upper material's surface, so as to eliminate the stress contribution from emulsion located above the blades on torque measurements. Consequently, T_m becomes equal to $T_s + T_e$ and the factor (1/3) in Eq. (2) is replaced by (1/6), as follows:

$$T_m = \left(\frac{\pi D^3}{2}\right)\left(\frac{H}{D} + \frac{1}{6}\right)\tau_0 \tag{3}$$

To measure τ_0 at very low shear rates, Zhu et al. [10] and Zhang et al. [14] developed the plate technique in which a slotted plate submerged in a test material is pulled out slowly while measuring the required load that comes from the material's resistance to this motion. The plate was hung to a balance through very thin stainless steel wires and its velocity precisely controlled from 0.003 to 60 mm/min [10,14]. The height of slots was at least 100 times larger than the maximum particle size in the suspension. This strengthens the assumptions that the suspension remains static in the slots with no secondary flow, and that shearing occurs only at the slot edges (i.e., material in slot shearing against material in bulk). Zhang et al. [14] considered that, unlike the vane method, the plate technique does not rely on an assumed yield surface area. The τ_0 was calculated as $F_{net} = (F - F_i)$ divided by the slotted plate area; where F refers to the force recorded by the balance, and F_i is the initial force reading calculated as the gravitational force due to plate and wire mass minus the buoyant force in suspension.

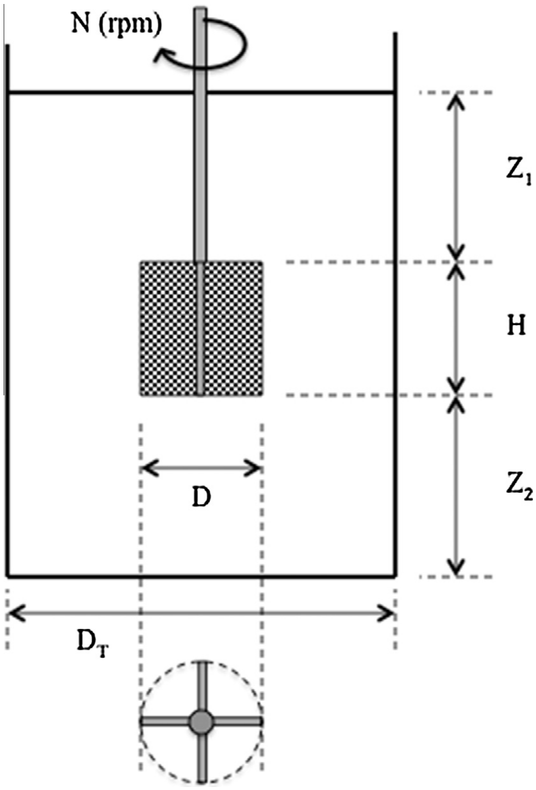

Fig. 1. Notations used for vane configuration.

The plate technique was found adequate to determine τ_0 of various non-Newtonian fluids such as bentonite and TiO_2 suspensions; however, several difficulties were encountered when testing cement pastes [14]. For example, τ_0 could be over-estimated if the plate is not in a fully vertical position during testing, given that the force measured would be higher than that for a vertical plate. Another difficulty in determining τ_0 occurs in cases when it is important to use a correction factor for edge effects [14]. The determination of this factor is time-consuming, as it requires the use of various plate sizes and batching of cement pastes with different water-to-cement ratios (w/c).

Assaad and Harb [19] proposed using the triaxial and unconfined compression tests to overcome the complications related to slip effects, secondary flow, or confinement conditions encountered in rheometric techniques. These tests are widely used in geotechnical applications to analyze the soil's shear strength properties, including cohesion (C) and angle of internal friction (ϕ), and are standardized by ASTM D2166, D2850, and D4767 [20–22]. Two main drawbacks were however attributed to these tests, including a considerable time needed for specimen preparation (i.e., around 15–20 min) and inadequacy of testing flowable mixtures having a flow exceeding around 140 mm, as per ASTM C1437 [23]. A cohesion threshold of around 4 kPa was determined on tested mortars, below which the specimens are no longer capable to self-stand in a vertical position for testing [19]. Tests realized under drained conditions displayed higher C values than those performed under undrained ones, given the resulting increase in friction generated between solid particles within the matrix.

2. Use of direct shear to measure τ_0

The direct shear test is the oldest and simplest method used in soil mechanics to determine the C and ϕ parameters, and analyze failure mechanisms occurring along interfaces [24–26]. The procedure for specimen preparation is quite simple, and drawback related to verticality encountered in triaxial and unconfined compression tests is not present [19]. In this test, two portions of a specimen are made to slide along each other by the action of steadily increasing horizontal shearing force while a constant load is applied normal to the plane of relative movement. The direct shear test is realized under quasi-static conditions, and shearing takes place within the material itself along a pre-defined interface represented by the horizontal surface area of the shearing box. This physically enables the determination of "true" τ_0, since all problems related to wall slip and secondary flow are eliminated. The direct shear is standardized equipment documented in ASTM D3080 [27] and available in most research centers.

Besides its use in geotechnical applications, the direct shear test has been popular when studying rheology of extrudable materials like plastics, fiber composites, rubbers, clays, and asbestos [28,29]. In fact, conventional shear-driven rheometers such as parallel plates, rotors, and concentric cylinders are not adapted to measure rheology of highly cohesive pastes due to the difficulty of sample preparation, wall slip, and plug flow. Alfani and Guerrini [29] reported that the direct shear is among the most promising and suitable methods for rheological characterization of cement-based extrudable materials including the interfacial flow behavior between the bulk materials and equipment forming wall systems. For adequate extrusion, Toutou et al. [30] found that τ_0 has to be high enough to allow the material to