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Avoiding inaccurate interpretations of rheological measurements for cement-based materials

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ABSTRACT

Rheology is a high quality tool to evaluate the effect of variations in constituent materials and mixture proportions on fresh properties of cement-based materials. However, interpreting rheological measurements is relatively complicated, and some pitfalls can lead to wrong conclusions. This paper offers a review of measuring devices and transformation equations used to express rheological parameters in fundamental units. The paper also discusses some of the major issues that can lead to errors during the interpretation of rheological measurements. Although the Bingham model is mostly used for cement-based materials, some non-linearity has been observed, necessitating the selection of an alternative rheological model, which could influence the rheological parameters. Other measurement errors related to thixotropic and structural breakdown, plug flow and particle migration are also demonstrated. The paper also discusses the challenges of using numerical simulations to derive rheological parameters for complicated rheometers or industrial devices, such as a concrete truck.

Contents

1. Introduction

Research on cement-based materials has expanded rapidly over the last decades, focusing on multiple aspects and materials that influence the behavior in fresh, hardening and hardened state. In the last decade, many initiatives have been made to render concrete a more sustainable material and increase the service life of concrete structures. Advances in concrete science have led to new greater use of alternative materials, including supplementary cementitious materials (SCMs) [1–4] and SCMs from alternative sources [5,6]. Several efforts dealing with the development of novel construction materials have necessitated better understanding of aggregate packing [7–10] and the implementation of a variety of chemical and mineral admixtures to enhance concrete performance [11–13]. In addition, large efforts have been made by the cement industry to create more sustainable products and reduce energy

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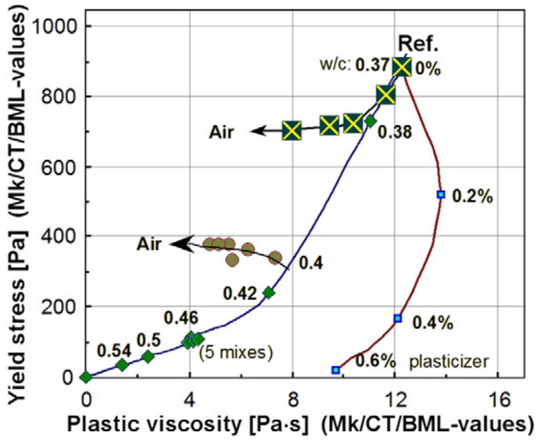

Fig. 1. Effect of mix design parameters (*w*/*cm*, AEA and plasticizer) on the rheological properties of mortar [20].

needed in cement production. In parallel, many advances have been made in the last few years regarding the use of rheology to optimize the behavior of novel construction materials, such as self-consolidating concrete (SCC) and evaluate material science aspects of the suspension, including binder–admixture interaction and hydration kinetics. Understanding the rheological properties is key in automation and special material processing, such as 3-D printing with cement-based materials.

The consequences of the developments in research and implementation of new cement-based construction materials are being studied in the fresh, the hardening and the hardened state of the material. New advances are also made in the characterizing equipment, adding specifications on concrete properties, beyond the 28-day required compressive strength. Similarly, to characterize fresh properties, rheology is introduced as an alternative to the nearly 100-year old slump test [14–16]. The advantage of rheology is the scientific description of the flow properties of cement-based materials and the more complete information gathered. In general, the resulting rheological properties are highly dependent on how the measurements are executed and on data interpretation [15,17]. Rheological measurements enable the determination of yield stress, plastic viscosity as well as thixotropic build-up at rest, thixotropic- and structural breakdown, and their variations with time. Slump testing offers an indication of yield stress of cement-based materials [18,19]. Further workability-oriented tests are necessary to evaluate other important rheological parameters, such as plastic viscosity and structural build-up at rest.

The more complete characterization of fresh cement-based materials by means of rheology is a helpful tool in the development of

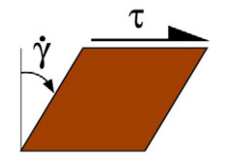

Fig. 3. Deformation of a fluid element.

specific chemical admixtures that alter the fresh properties [11,20,21] (see Fig. 1). Furthermore, even the cement properties, which show some variation slightly alter due to the complexity of the production process, can in some cases significantly affect the fresh properties of cement-based materials [22–27]. Examples are known of variations in yield stress and plastic viscosity, and their evolution in time, with cement date are illustrated in Fig. 2 [26]. Rheology allows a more precise characterization of cement-based materials, based on principles also applied in other scientific domains. Rheology extends our capacity in finding analytical or numerical solutions for specific flow problems.

Rheology is a complex tool, especially for a complex composite material as concrete. Many errors or inaccuracies in measurements and data interpretation can occur leading to erroneous conclusions. The paper presented here offers a general review of rheological principles and measurements and reviews some of the major pitfalls of rheology measurements to enhance the reliability of rheological measurements. The paper presents transformation equations that can be used with different rheological models. It also discusses data interpretation problems that can result from high thixotropy, plug flow and particle migration during rheological testing.

2. Definitions

In the science of rheology, the relationship between shear stress (τ, in Pa) and shear rate ($\dot{\gamma}$, in s^{-1}) describes the behavior of a liquid. Shear stress and shear rate are fundamental quantities, which are independent of the measuring system. These two quantities are calculated by $\tau = \sqrt{\sigma : \sigma/2}$ and $\dot{\gamma} = \sqrt{2\,\dot{\varepsilon}{:}\dot{\varepsilon}}$, in which σ is the extra stress tensor, and $\dot{\varepsilon}$ is the rate-of-deformation tensor [28,29]. As demonstrated in [30], the definition of shear rate $\dot{\gamma}$ actually coexists with the definition of shear stress τ, as it should be, since when a shear stress τ is applied on a fluid element, a certain rate of shear will result as shown in Fig. 3.

The simplest relationship between shear stress and shear rate can be expressed with a linear model that goes through the origin of the shear stress–shear rate graph. This corresponds to Newtonian liquids, such as water and oil in which the only parameter describing the rheological properties of the liquid is the viscosity (η, Pa s) [17]. The power-law

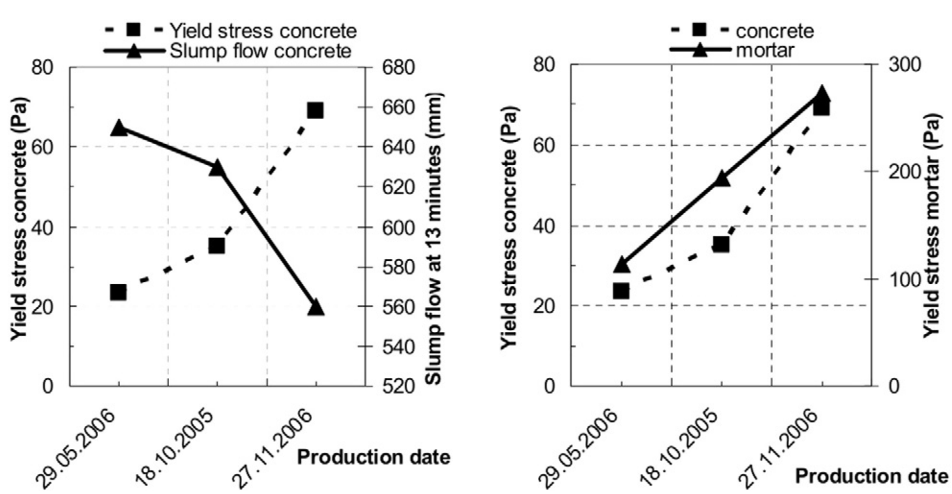

Fig. 2. Example of variation in slump flow and yield stress of concrete and mortar with changes in cement production date [26].