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On the identification of rheological properties of cement suspensions: Rheometry, Computational Fluid Dynamics modeling and field test measurements

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ABSTRACT

Cementitious composites with customized rheologies are becoming increasingly popular throughout a wide variety of civil engineering applications. Assessing their fundamental rheological properties is crucial for the success of a particular application. Their measurement is not a trivial task and typically requires dedicated and expensive equipment. These equipment may not be compatible with field applications and not even available in every laboratory. Correlations between fundamental rheological properties and field test measurements have been assessed, as for the yield stress versus the slump flow diameter. As for the plastic viscosity, different attempts have been made, with flow time parameters measured from different tests. This work provides further evidence to the aforementioned correlations, with reference to a broad range of cement pastes and mortars formulated from SCCs, as well as employing a tool for Computational Fluid Dynamics (CFD) modeling developed by the authors.

1. Introduction

The construction industry is paying increasing attention to the rheology of fresh cementitious suspensions, both in concept and applications. As a matter of fact, measuring rheological properties of fresh cementitious composites has become as important as the identification of more traditional hardened state properties. This importance is highlighted not only by their significance in quality control, but also for solving challenges in production, placement and manufacturing processes. In the framework of a "holistic" approach to the engineering (and structural) design with advanced cement based materials, rheology has been recognized as an effective tool which enables the entire process, from material concept and production to structure casting, to be tailored to the achievement of the multifold set of engineering properties required for successful accomplishment and performance of the intended application.

The appearance of SCC technology in the construction market and its continuously growing acceptance have doubtlessly played a major role in promoting the aforementioned increasing interest in rheology of fresh cementitious materials. Suitable manipulation of the rheological properties of cement pastes and/or mortars (meant as the suspending fluid phase of the aggregate solid skeleton) allows the designer not only to achieve the required set of fresh state properties [1–4] and to ensure the robustness of the day-by-day production [5], but also, for example, to control the pressure exerted on the formwork by fresh concrete and its rate of decay with time [6,7]. This results in a more rational design of formwork, as a function of the construction process (e.g. rate of casting), which can fully realize SCC-related advantages, such as increased speed of construction.

It has been furthermore shown that through manipulation of fundamental rheological properties, innovative material concepts tailored to the intended application can be effectively implemented into engineering practice [8]. A challenging and, in the authors' opinion, cutting edge application of this idea is represented by High Performance Fiber Reinforced Cementitious Composites (HPFRCC). Thanks to a suitably adapted rheology of the cement based matrix, homogeneous dispersion of fibers within castings can be achieved, even when challenged by vibration, compaction, manual placement, etc. [9]. Furthermore, if devised, a casting-flow driven orientation of the fibers can be achieved and tailored to the intended application, from which the mechanical performance at both the material and structural levels can highly benefit [10]. This opens opportunities to design structures with a high engineering and architectural value, which merge a desirable closer correspondence between the shape and the structural function. The constructability of the former in fact benefits from superior fresh state performance of the material, which allows an orientation of the fibers tailored to the optimum structural function to be obtained, for example by making the casting flow direction match as close as possible with the direction of principal tensile stresses within structural elements when in service [11].

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As long as the use of such advanced cement based materials is pushed towards more and more daring applications, such as in high-rise buildings, underwater pumping, etc., the design of distribution and placement equipment begins to play a crucial role. Rheology, among several other factors, governs the flow and placement of concrete through plug/slip and shear flow mechanisms. Suitable relationships correlate the flow through a pipe with pressure loss and rheological properties for a laminar flow in a Bingham fluid, which is the so-called Buckingham–Reiner equation [12–15].

In view of the aforementioned fields, it appears that the rheology of cement suspensions needs to be controlled at a multi-scale level (cement paste, mortar, concrete, fiber reinforced composite) and all along the material production, placement and element manufacturing stages, in order to guarantee success. This not only implies that the influence of different mix-constituents and mix-design variables on the fresh state performance of the material has to be assessed, but it also requires sound and effective theoretical/numerical models and testing equipment and techniques to be developed and calibrated for the identification of relevant material properties and model parameters which enter into governing equations.

The Bingham model, commonly employed to describe the rheological behavior of cement suspensions, requires two fundamental rheological properties to be quantified, namely the yield stress τ_0 and the plastic viscosity μ.

Custom-built and/or commercially available rheometers have become widely employed for the identification of the aforementioned parameters. This allows a thorough characterization of the material rheology, including thixotropy, temperature dependence, pressure sensitivity, rheo-optical or rheo-magnetical measurements, etc. Yet, cost may represent a serious hindrance to their widespread use in current construction practice, either at a construction site and/or in a precast factory. Moreover, the reliability and robustness of measures garnered from rheometers are highly debated, since values of fundamental properties obtained from two different equipment may be substantially different [16,17]. This can seriously undermine any ambition not only to govern the rheology of the material, but also, more simply, to develop reliable and robust quality control procedures.

Field tests, which are much more suitable for routine measurements, are widely employed for qualitative assessment of fresh state performance of concrete (see, e.g. the mini-cone slump and the EN445 cone tests for pastes, mortars and grouts, the slump-flow and the V-funnel tests for SCC). Establishing and thoroughly validating correlations between field test measurements and fundamental rheological properties will be instrumental to a more widespread use of rheology in the quality control of production of advanced cement based materials for high-end structure and infrastructure applications. The slump or mini-slump flow diameters, for example, have been shown to be strongly correlated to the yield stress [18]. Recent studies have also demonstrated that a correlation exists between the time for the flow to stop in a slump/mini-slump test and the plastic viscosity [19,20]. As for the EN445 cone, it has been shown that the time employed by a prescribed amount of material (paste or mortar) to flow out of the cone nozzle is correlated to the plastic viscosity [21], but a robust correlation still needs to be assessed. The same is true for the V-funnel flow time in the case of self consolidating concrete [22].

This study originates in the framework described above and has been cued by wider research projects focused on promoting structural applications of both Steel Fiber Reinforced Self Consolidating Concretes (SFR-SCCs) and HPFRCCs. The fresh state performance of cement pastes formulated from SFR-SCCs [3] has been thoroughly investigated by means of both rheometer and field tests (both the mini-cone slump and the EN445 cone tests). The correlation between the Bingham parameters acquired from rheometer measurements and the parameters measured from field tests has also been assessed by means of Computational Fluid Dynamics (CFD) modeling, employing a customized code implementing an approach developed by the authors [23]. This gives the ability to obtain local information on flow phenomena, as occurring in the modeled tests, and thus to more confidently validate the choice of a field test (in this case, time) parameter which could be effectively employed for a quantitative estimate of the plastic viscosity. As a whole, this work is intended to be an example towards a wider use of experimental rheology and CFD modeling in the optimization of mix-composition and quality control of advanced cement based materials.

Table 1
Physical compositions of cement and fly ash.

OPC type I (ASTM C150-04)		Fly ash class C (ASTM C 618)	
Chemical data	%	Chemical data	%
Silicon dioxide (SiO_2)	20.1	Silicon dioxide (SiO_2)	31.35
Aluminum oxide (Al_2O_3)	4.9	Aluminum oxide (Al_2O_3)	16.77
Ferric oxide (Fe_2O_3)	2.8	Ferric oxide (Fe_2O_3)	5.57
Calcium oxide (CaO)	64.3	Calcium oxide (CaO)	23.26
Magnesium oxide (MgO)	2.5	Magnesium oxide (MgO)	5.45
Sulfur trioxide (SO_3)	2.4	Sulfur trioxide (SO_3)	2.02
Loss on ignition	1.55	Loss on ignition	0.13
Insoluble residue	0.25	Moisture content	0.12
Free lime	1.52	Sodium oxide (Na_2O)	2.07
Tricalcium silicate (C_3S)	66	Potassium oxide (K_2O)	0.31
Tricalcium aluminate (C_3A)	8		
Available alkali (equivalent Na_2O)	0.51	Available alkali (equivalent Na_2O)	1
Blaine specific surface, m^2/kg	352		
% passing at #325 mesh	98.7	% passing at #325 mesh	87.2
Density, kg/m^3	3150	Density, kg/m^3	2740

Table 2
Cement paste mix designs (per 1 l).

Mix code	Cement [g]	Fly ash [g]	Water [g]	HRWRA [g]	Density [kg/m^3]
wb32hr35	1120.1	417.6	492.0	5.4	2008.4
wb32hr45	1120.1	417.6	492.0	6.9	2007.2
wb32hr55	1120.1	417.6	492.0	8.4	2005.8
wb36hr35	1055.2	393.4	521.5	5.1	1950.9
wb36hr45	1055.2	393.4	521.5	6.5	1949.4
wb36hr55	1055.2	393.4	521.5	8.0	1948.4
wb40hr35	997.4	371.8	547.7	4.8	1899.4
wb40hr45	997.4	371.8	547.7	6.2	1898.4
wb40hr55	997.4	371.8	547.7	7.5	1897.4

2. Experimental program

2.1. Materials: cement pastes formulated from SCSFRC

A series of cement pastes was prepared consisting of an ASTM Type I Ordinary Portland Cement (OPC), Class C fly ash, water and a polycarboxylate based High Range Water Reducing Admixture (HRWRA). The properties of cement and fly ash are listed in Table 1, while Table 2 gives the details of the different paste compositions, formulated from typical SFR-SCC mixes investigated in a previous study [3]. Mix codes employed in Table 2 and elsewhere have the

Table 3
Mixing protocol.

Time	Task
0:00	Mix dry materials at low speed
1:00	Add water and HRWRA
3:00	Scrape sides
4:00	Mix on high speed
6:30	Scrape sides
7:30	Mix on high speed
10:00	Test mix