Cement and Concrete Research 63 (2014) 29–34

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Obtaining rheological parameters from flow test — Analytical, computational and lab test approach

Annika Gram *, Johan Silfwerbrand, Björn Lagerblad

Swedish Cement and Concrete Research Institute (CBI), Drottning Kristinas väg 26, SE-100 44 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 4 October 2013
Accepted 28 March 2014
Available online xxxx

Keywords:
Simulation
Cement paste
Workability Bingham material model (A)
Rheology (A)
Modeling (E)
Mortar (E)

ABSTRACT

In the mix design process of cementitious suspensions, an adequate rheology of the cement paste is crucial. A novel rheological field test device for cementitious fluids is presented here and investigated theoretically, by computer simulation and by lab tests. A simple flow stoppage test with a timed spread passage point provides accurate rheological parameters according to the Bingham material model. Values for yield stress and plastic viscosity are obtained for a test specimen of no more than $19.75 \cdot 10^{-6}$ m^3 of fluid. This volume is equivalent to 19.75 g of water at room temperature. Such a small volume allows reliable tests even for small amounts of fillers. Promising results show that both yield stress and plastic viscosity can be determined by this simple test. This novel rheological test method also enables the correlation of different rheological equipment used by different laboratories.

1. Introduction

With the current trend towards the use of crushed aggregate material, crushed fillers of different minerals and crushing techniques, a simple filler quality assessment is now in demand by the construction industry. Traditional grading curves used for mix design are not simply applicable on powders and on irregularly shaped particles. An increased demand in quality field tests for crushed fillers, together with the wish for mix design and customize rheology calls for an easy-to-use simple test method. A small, L-box shaped apparatus is developed and presented as a flow test to obtain rheological Bingham parameters of suspensions. This allows a quick and reliable test for fillers and for the cement paste that is important for the mix design of especially Self-Compacting Concrete, SCC. The rheology of the paste samples has been tested in the laboratory using a rheometer and the here described novel test method. The obtained results are compared to computer simulations and theoretical solutions. Previous lab tests and numerical simulations of the ASTM mini cone show a model for the determination of yield stress, τ_0, [1] and plastic viscosity, μ_{pl}, [2,3] for mortars. Previously, the relationship between slump or slump flow and yield stress has been thoroughly investigated in for example [4–8]. It is stated in [8], that the correlation between slump and plastic viscosity is low. As early as 1993, slumping tests and slump flow tests for concrete were linked to rheological constants in Japan [9]. There, an estimation method of plastic viscosity was proposed by evaluation of flow time and different flow shapes or slump shape parameters. Numerical, analytical and experimental studies on Bingham parameters for the Abrams cone are also to be found in Japan [10]. There, it is stated that flow time and plastic viscosity correlate well, however only for similar slump flow values. Flow studies on flow behavior and apparent viscosity for open channel flow are found for large lava flows considering channel depth, speed of flow as well as angle of slope [11]. However, a verification of lava viscosity assessment is unfortunately not possible. This paper will focus on an easy-to-use model for obtaining both yield stress and plastic viscosity of cement pastes with a small open channel flow measuring device. This rheological measuring apparatus is intended to be employed in the laboratory, in the concrete factory or out in the field in a quarry using just small sample volumes. In the past, a similar large scale elongated L-box was introduced to obtain rheological Bingham parameters of concrete [12].

Bingham parameters acquired from rheometer measurements and the parameters obtained from the measuring apparatus are correlated to analytical solutions for open channel flow and to computer simulations, using Computational Fluid Dynamics, CFD. The results obtained lead to correlations between Bingham parameters and flow parameters.

2. Flow test

2.1. Box geometry and experimental setup

Fig. 1 shows the rheological measuring apparatus, developed to determine rheological characteristics. It consists of an open channel manufactured from frosted glass to ensure a low slip condition of the material. The channel is a 350 mm long horizontal open channel of

* Corresponding author.
E-mail address: annika.gram@cbi.se (A. Gram).

http://dx.doi.org/10.1016/j.cemconres.2014.03.012
0008-8846/

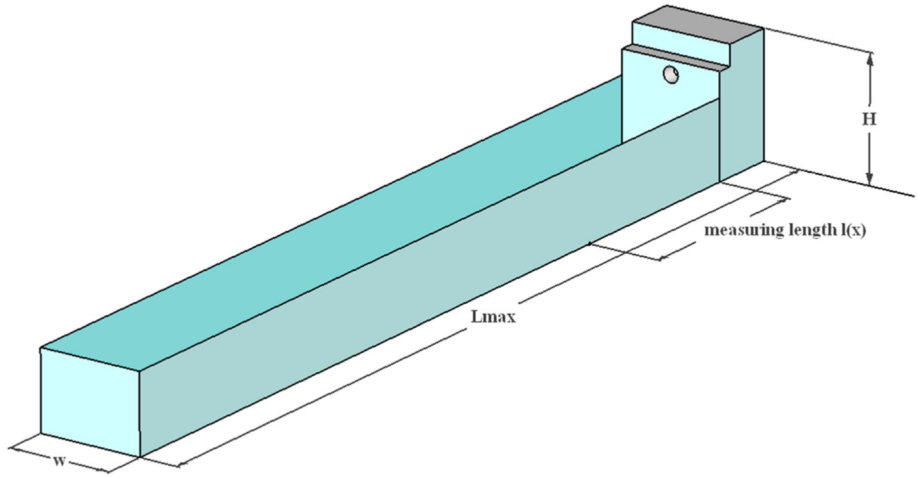

Fig. 1. Geometry of the measuring box.

25 mm width. At one end of the channel, a $H = 50$ mm high, gated column, or chimney, is attached to hold the fluid sample to be released. A volume of $19.75 \cdot 10^{-6}$ m^3 of fluid is filled into the container and then released into the channel once the gate is quickly opened. Opening the container gate is performed by hand in one swift movement, the operator is the same for all laboratory experiments. The time frame taken to open the gate has been filmed for every laboratory test and is estimated to average the blink of an eye, ≈0.2 s.

A camera mounted straight above the measuring box captures the flow propagation of the released fluid. The gate opening time has been excluded from the duration of flow propagation by starting the clock at the first sign of fluid flow exiting the gate. In addition to filming the spread in the transparent channel on graph paper and charting its propagation, time t_x for the spread to reach a certain distance from the gate ($X = 70$ mm) was recorded as well. Final spread length L was measured from the back end of the container to the center of the front line after flow stoppage.

2.2. Fluid rheology

The consistency of the granular mixtures is determined with the Haegermann cone according to [13]. The dimensions of this cone are: height = 60 mm with upper and lower values for the diameter being 70 and 100 mm, respectively. A w/p range of 0.24 up to 0.50 for the cement paste with and without addition of fillers ensures different values for the plastic viscosity. A lower w/p value allows a more distinct evaluation of powder quality. The yield stress was adjusted by the amount of added superplasticizer aiming for Haegermann slump flows between 300 and 400 mm. Workability of the mixes was evaluated with a rheometer to determine Bingham parameters. This way, a large area of the rheograph [14] shown in Fig. 2 was covered and tested.

Bingham parameters for the numerical simulations were chosen randomly within this area of the rheograph to be representative with the same values of flow and similar densities as the cementitious mixtures. Both experimental mixes and numerical simulations are evaluated according to flow parameters in the measuring box and compared to their Bingham parameters. Details of the experimental set-ups are found in Sections 4 and 5.

3. Analytical approach

3.1. Rheology of suspensional flow

Concrete and other concentrated particle suspensions are often modeled as a Bingham material. For stress levels above the so called yield stress, τ_0, the material flows. This relation is written as:

$$\begin{aligned} &\tau = G\gamma \quad \text{for } \tau < \tau_0 \\ &\text{and} \\ &\tau = \tau_0 + \mu_{pl}\dot{\gamma} \quad \text{for } \tau \geq \tau_0 \end{aligned} \tag{1}$$

with τ and γ being the stress and shear of the material, respectively, and G a spring constant [15]. For Pascalian liquids, meaning incompressible fluids (such as concrete and cement pastes), we have for the fluid velocity vector $\mathbf{u}$

$$\nabla \cdot \mathbf{u} = 0. \tag{2}$$

The governing equation for non-Newtonian fluid flow, called Cauchy's equation of motion [16], is given by:

$$\rho \frac{D\mathbf{u}}{Dt} = \nabla \cdot \boldsymbol{\sigma} + \rho\, \mathbf{g} \tag{3}$$

where $\mathbf{g}$ is the gravitational acceleration vector acting on the system, ρ is the material density and the stress tensor $\boldsymbol{\sigma} = -p\,\mathbf{I} + \mathbf{T}$. Here, p denotes pressure, $\mathbf{I}$ is the unit dyadic and $\mathbf{T}$ is the extra stress tensor, associated with the apparent viscosity η of the fluid. For concrete being a viscoplastic material, the relation used for $\mathbf{T}$ is [17]:

$$\mathbf{T} = 2D\mathbf{u} \tag{4}$$

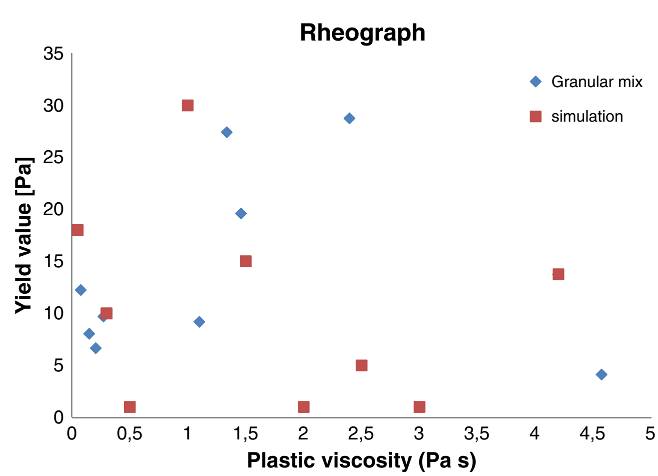

Fig. 2. Scatter chart showing measuring field of Bingham parameters for granular mixes and simulated flow.