EMPIRICAL RELATIONSHIPS BETWEEN VISCOSITY AND FLOW-TIME MEASUREMENTS FROM MINISLUMP TESTS FOR CEMENT PASTES FORMULATED FROM SCC

Nathan Tregger (1), Liberato Ferrara (2) and Surendra Shah (1)

(1) ACBM, Northwestern University, USA

(2) Department of Structural Engineering, Politecnico di Milano, Italy

Abstract

The paper deals with the behavior of fluid cement pastes, formulated from Self Consolidating Concretes (SCCs), and the experimental correlation of fundamental rheological properties, such as the yield stress and the viscosity, with measurements from field tests, such as the mini-cone slump flow test. As a matter of fact, several studies have shown that a correlation can be established between the yield stress and the cone flow diameter but hardly any parameter which could be correlated to the viscosity was found. In this study time flow measurements from mini-cone slump tests are considered and their suitability as indicators of the fluid cement paste viscosity investigated. An extension of the methodology to self consolidating concrete is also foreseen.

1. INTRODUCTION

Research on the rheology of both cement paste and concrete is proving to be very important in improving mix designs that take advantage of different processing techniques during construction. As further understanding of the rheological properties increases, the information can be applied to modify mix designs in order to attain desired rheological characteristics. SCC (self-consolidating concrete) is a perfect example. However, new technology, such as SCC, can be confidently applied to field applications only if proper quality control methods are known.

Currently, simple tests such as the flow test are used to determine the quality control of SCC. Yet, as SCC mixes are refined and tailored for specific applications such as slipform paving and low-formwork pressure castings, the flow test by itself will not yield enough information to determine whether or not a mix is acceptable. Advanced mixes depend on certain rheological properties such as yield strength and viscosity, which can be easily measured in the laboratory, but not practically in the field. It is therefore desirable to be able to ensure that these properties are checked in the field in order to guarantee quality control.

Corresponding author’s e-mail: n-tregger@northwestern.edu

Corresponding author’s fax: 847-491-4011

This requires a link between parameters from simple field tests to parameters found in the laboratory.

This paper presents an on-going study where relationships between slump flow and yield stress and time it takes to reach final slump and viscosity are explored. Currently, there are several studies that have shown a strong correlation between the yield strength and final spread from a flow test [1-5]. These references include work concerning both experimental correlation and simulation correlation. Nevertheless, there is scarce amount of work concerning the correlation between viscosity and any results that can be garnered from the flow test. In the present work, an experimental approach is employed in order to determine these relationships.

2. EXPERIMENTAL PROCEDURE

Cement pastes employed for rheology tests consisted of Type I Ordinary Portland Cement, Class C fly ash, water, and a polycarboxylate based superplasticizer (SP). Table 1 contains the paste composition for the experimental program. Variables have been combined as shown in the test matrix in Figure 1: three water-binder (w/b) ratios have been employed (0.32, 0.36 and 0.40), and three different dosages of the SP (0.35, 0.45 and 0.55 % by weight of solids). The fly ash volume replacement ratio was kept constant at 30% for all the mixes. The SP dosages were chosen within the range suggested by the manufacturing company. The following mixing protocol was adopted: cement and fly ash were placed together with water and SP in a planetary mix and mixed for 1 min at low speed. After 1 min rest for scraping the sides of the bowl, the paste was further mixed for 1 min at high speed.

Table 1 –paste composition

volume % of cement (of solids)		70	
volume % of fly ashes (of solids)		30	
w/b ratio (by weight)	0.32	0.36	0.4
weight % superplasticizer (of solids)	0.35	0.45	0.55

The rheological properties of the paste were measured through mini-slump and rheometer tests. A mini-slump cone was used with the following dimensions: an upper and lower diameters of 100 mm and 70 mm respectively and a height of 50 mm. After filling the cone, the cone was lifted and once the cement paste stopped flowing, the slump flow diameter was taken as the average of two perpendicular diameters. Each flow test was video recorded using a digital camera in order to obtain relationships between flow and time, specifically, the time when the flow stopped. This information was collected in order for comparison to the numerical modeling as well as in order to further seek correlation, if any, with common rheological properties measured through rheometer tests.

The rheometer tests were performed on a BTT-Haake rheometer with a concentric cylinder configuration (0.8 mm gap between the cylinders). Employing this configuration gives both the yield strength and viscosity [6-8]. For the rheometer tests the following protocol was adopted: after the mini-cone flow test a suitable amount of cement paste was transferred into the cup of the rheometer and, after one minute rest, the shear rate was ramped up to 300 s^{-1} over a 10 seconds interval. This maximum value of the shear rate was then held constant over

Corresponding author’s e-mail: n-tregger@northwestern.edu

Corresponding author’s fax: 847-491-4011

a 45 sec interval and then decreased down to 5 s^{-1} in six equally spaced steps, in each one of them the shear rate having been held constant. The duration of each step was set equal to 10 seconds, except for the first and second one, which lasted 30 and 20 seconds respectively, to allow for the proper attainment of equilibrium state. Six measuring points per second were sampled along the ascending branch, while only one measure per second was taken along the constant shear rate steps. A typical evolution of the measured shear stress vs. time is shown in Figure 2, together with the adopted test protocol as above described.

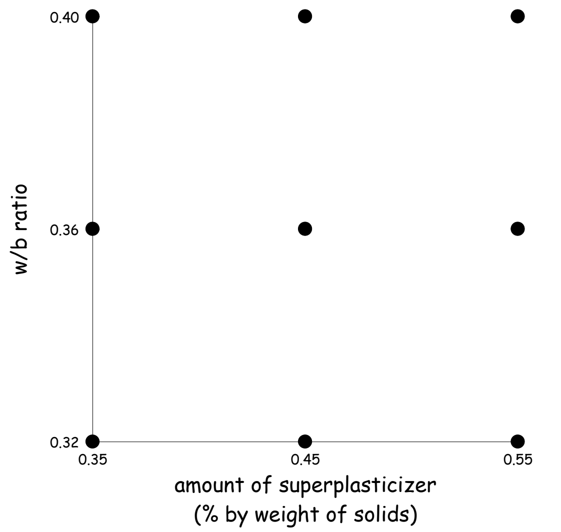

Figure 1 – test design matrix for cement paste

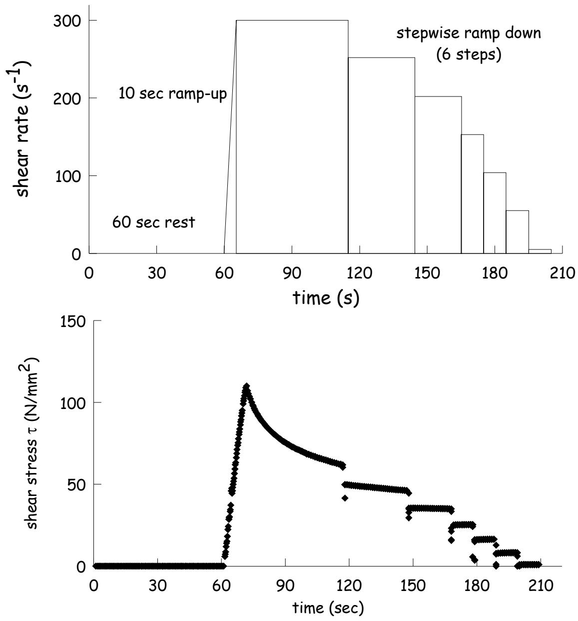

Figure 2 – rheometer test protocol and example of measured shear stress vs. time

A steady equilibrium state was rapidly attained except for the step at the highest shear rate. As such, when identifying the yield strength and viscosity via regression analysis, only data referring to the six steps in which a steady equilibrium state was reached were used. In fitting the data to the Bingham model, it was found that the model gave inconsistent results, such as negative values of the yield stress. A power law fitting was then attempted, according to the Herschel-Buckley model:

$$\tau = \tau_0 + a\dot{\gamma}^b \qquad (1)$$

where τ_0 is the yield strength and the viscosity can be calculated as [9]:

$$\eta = \frac{3a}{b+2}\dot{\gamma}_{\max}^{b-1}. \qquad (2)$$

3. RESULTS AND DISCUSSION

The relationship between the final flow test radius and the yield strength for both the experiments and a theoretical model are given in Figure 3. It can be seen that there does exist a clear relationship between the final flow radius and yield strength, even with varying viscosities. The data fitting of the model proposed by Roussel et al. [3] clearly highlight the

Corresponding author's e-mail: n-tregger@northwestern.edu
Corresponding author's fax: 847-491-4011

importance of the surface tension correction term in the case of very fluid cement pastes, with low values of the yield stress, such as the ones formulated from SCCs and herein dealt with. In Figure 3, λ represents a surface tension coefficient, which is a function of the surface tension and contact angle. Here, it is taken as 0.005.

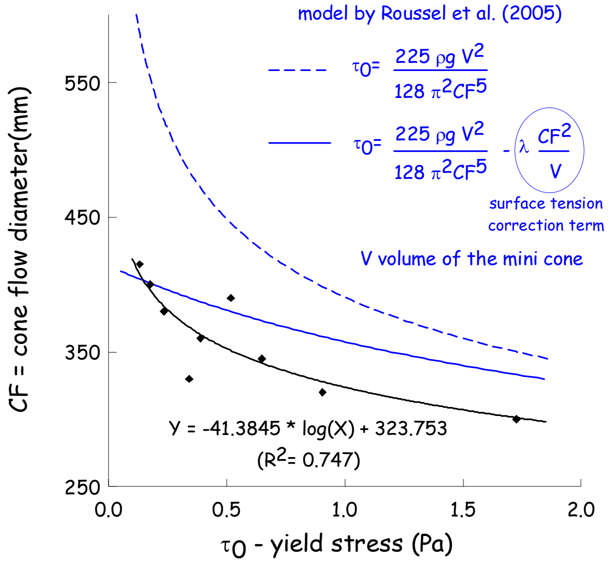

Figure 3: experimental and model relationships between cone-flow diameter and yield stress

Concerning relationships involving viscosity, first it has been compared to the time it takes to reach a prescribed spread, chosen equal to 300 mm (Figure 3a). It can be observed that the higher the viscosity, the higher the time it takes to reach the prescribed spread, but hardly any reliable correlation could be found, since for very close values of the viscosity, quite different values of the spread time were measured. Further information is given in Figure 3b, where the interdependence between the time to 300 mm spread and both the yield stress and the viscosity are shown. The increasing trend of the flow time with the viscosity can be seen to depend on the value of the yield stress of the cement paste.

In Figure 4a the viscosity is compared directly to the time it takes to reach the final radius, while in Figure 4b, the viscosity was divided by the final radius and compared to the time it takes to reach the final slump. Both these relationship yield power law fits, with very high R^2 correlation coefficients, and it seems that the first relationship hints that higher the viscosity, the shorter time it takes for a spread to reach its final destination, which differs from the previous results.

A possible explanation for this behavior can be the following. It was noticed that most of the time that it takes for the cement suspension to spread occurred after the height slump loss was completed. During this time, the driving force of the flow is a balance between gravity and surface tension and the material resistance. Higher viscosities would cause the flow to stop quicker, while the lower viscosities would allow the material to spread for a longer time. It is important to note that the distance traveled during the end of the test was not very large, and this is why the yield stress–final radius relationship is not affected.

Corresponding author's e-mail: n-tregger@northwestern.edu

Corresponding author's fax: 847-491-4011

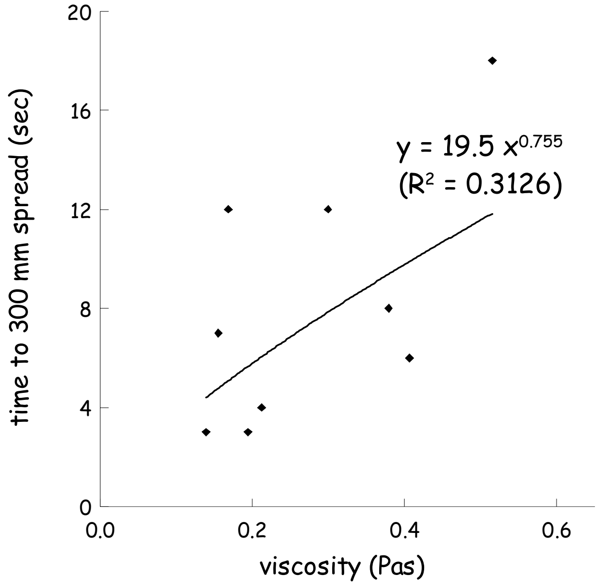

Figure 3a: time to 300 mm vs. viscosity

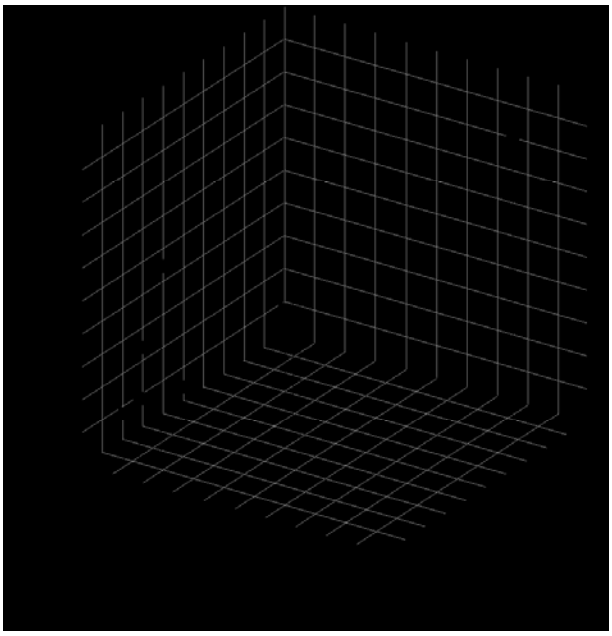

Figure 3b: time to 300 mm vs yield stress and viscosity

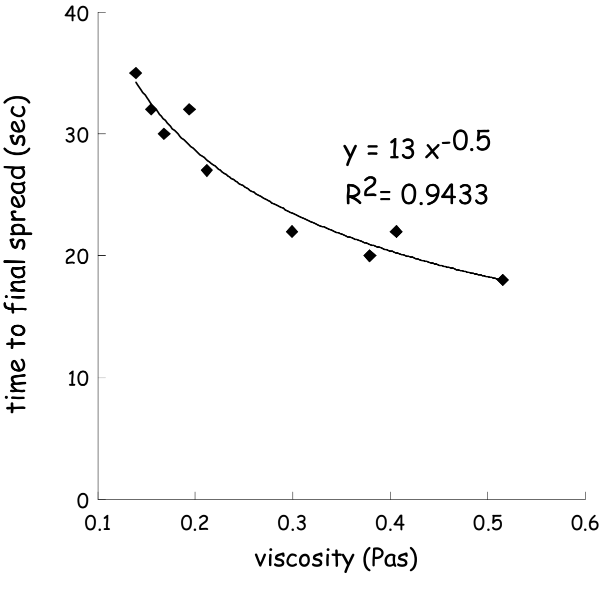

Figure 4a: time to final spread vs. viscosity

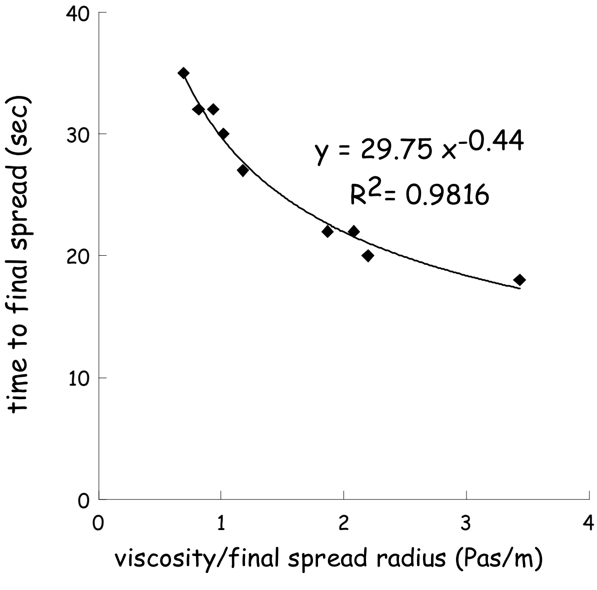

Figure 4b: time to final spread vs. ratio between viscosity and final spread radius

4. FUTURE WORK AND CONCLUSIONS

The empirical models can obviously be refined with more and more tests. However, now that there seems to be a link between the viscosity and time to final spread, it is more interesting to understand why through theory and computational modeling [10]. Currently research is being carried out in order to develop a theory based on transient behavior of thinlayer liquids. Of particular importance to these models is the incorporation of a yield material and surface tension. Computational modeling is also being developed. In particular, this will be useful when considering the effects of aggregates to take the model from cement to concrete. At Northwestern, there is a research group that works extensively with particulate flow. Including particulates in fluid flow is very computationally expensive; however, there are methods that attempt to incorporate the effects of one aggregate and extend it to the entire fluid. Using computational methods such as these will prove to be very exciting in the future.

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REFERENCES

[1] Saak, A.W., Jennings, H.M. and Shah, S.P., ‘A generalized approach for the determination of yield stress by slump and slump flow’, Cement and Concrete Research. 34 (3) (2004) 363-371.

[2] Roussel, N. and Coussot, P., ‘”Fifty-cent rheometer” for yield stress measurements: From slump to spreading flow’, Journal of Rheology. 49 (3) (2005) 705-718.

[3] Roussel, N., Stefani, C. and Leroy, R., ‘From mini-cone test to Abrams cone test: Measurement of cement-based materials yield stress using slump tests’, Cement and Concrete Research. 35 (5) (2005) 817-822.

[4] Flatt, R.J., Larosa, D. and Roussel, N., ‘Linking yield stress measurements: Spread test versus Viskomat’, Cement and Concrete Research. 36 (1) (2006) 99-109.

[5] Roussel, N., ‘Correlation between yield stress and slump: Comparison between numerical simulations and concrete rheometers results’, Materials and Structures. 39 (288) (2006) 501-509.

[6] D'Aloia Schwartzentruber, L., Le Roy, R. and Cordin, J., 'Rheological behaviour of fresh cement pastes formulated from a Self Compacting Concrete', Cement and Concrete Research, 36 (7) (2006) 1203-1213

[7] V.K. Bui, J. Akkaya, S.P. Shah, Rheological model for self-consolidating concrete, ACI Materials Journal, 99 (6) (2002) 549-559.

[8] Ferrara, L., Park, Y.D., Shah, S.P.: “A method for mix-design of fiber reinforced self compacting concrete”, Cement and Concrete Research, *under review*.

[9] Durour, F. and Pijaudier-Cabot, G., ‘Numerical modeling of concrete flow: Homogeneous approach’, International Journal for Numerical and Analytical Methods in Geomechanics. 29 (4) (2005) 395-416.

[10] Mori, H. and Tanigawa, Y., ‘Simulation methods for fluidity of fresh concrete’, Memoirs of the School of Engineering, Nagoya University. 44 (1) (192) 71-134.

Corresponding author’s e-mail: n-tregger@northwestern.edu

Corresponding author’s fax: 847-491-4011