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Cement and Concrete Research 35 (2005) 831–835

Cement and Concrete Research

Prediction of fresh concrete flow behavior based on analytical model for mixture proportioning

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Received 3 March 2004; accepted 20 September 2004

Abstract

Large number of experimental techniques and models has been developed recently in an attempt to link the parameters of Bingham equation to concrete composition. On the other hand, concrete mixture proportioning methods based on rheological approach usually do not provide direct input of a measurable rheological parameter(s) into the proportioning expression. In this study, series of concrete mixtures have been proportioned by the use of a theoretical model. The experimental results were compared with the predicted rheological quantity by the model. The evaluation of concrete flow parameters has been performed using a newly developed tube viscometer for concrete. The discussion presents a comparison between the model calculated apparent viscosity and the measured plastic viscosity of fresh mixes as function of volume fraction of solids, normalized with respect to their maximum packing values.
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Keywords: Fresh concrete; Mixture proportioning; Rheology; Modeling

1. Introduction

The appearance and extensive use of new types of concretes in variety of applications gave an impetus to development and implementation of the rheological approach to depiction of fresh mixes. These new classes of concrete usually contain high powder content and third generation HRWRA, which makes the characterization of their fresh properties by traditional way rather awkward or even an impossible task. Several rheological devices have been introduced during the last decades [1], in an attempt to properly measure flow behavior of fresh mix. All of these apparatus, however, operate on the principles of rotational rheometry, which predetermines their complicated mechanical construction and relatively high price. Also, over the years some models have been developed to design concrete mixture by use of rheological approach [2,3]. These models usually do not provide a direct input of a measurable rheological parameter into the proportioning expression. The theories underlying the design methodologies are usually based on rheological dependencies of relative viscosity on concentration of a suspension. But parameters, such as the compaction index, or the reference viscosity are adjustable constants based on author's observations and research. Consequently, in a broad sense, a method for concrete mixture proportioning based entirely on rheological categories was not yet developed.

This paper presents the results from evaluation of concrete rheology on series of concrete mixtures by a newly developed tube viscometer, RCVC. The comparison of the rheological quantity involved in the analytical model for mix proportioning suggested by the author with a measurable experimental parameter is introduced, as well as a discussion of some relationships obtained by other authors.

2. Theoretical approach

The theory of the model was presented elsewhere [3,4]. Here, only the basic concepts will be summarized.

Mooney's equation for a poly-disperse suspension enables the relative viscosity to be estimated by determi-

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doi:10.1016/j.cemconres.2004.09.019

nation of packing densities of dry, suspended spheres using the following equation:

$$\eta_r exp \sum_{i=1}^{n} \frac{2.5\Phi_i}{1-\sum_{j=1}^{n}\lambda_{ij}\Phi_j} = exp \sum_{i=1}^{n} \frac{2.5r_i}{\left(\frac{1}{P}-\frac{1}{P_i}\right)} \quad (1)$$

where η_r is the relative viscosity; Φ_i is the volume concentration of fraction i; λ_{ij} is crowding function, representing the crowding action of fraction j, on the arrangement of fully packed fraction i; r_i is the fractional solid volume of phase i; P is the packing density of the whole system. The packing density of a system with i-class spheres fully packed (P_i) is:

$$P_i = \frac{\varphi_i}{\left(1-\sum_{j=1}^{n}(1-\lambda_{ij}\varphi_i)r_j\right)} \quad (2)$$

where φ_i is the volume concentration of fraction i, separately packed, i.e. the packing density of ith component estimated by tests of dry monofractions [2]. The smallest P_i is the maximum random packing density of the mixture, i.e. P^*=min (P_i). The crowding function, λ_{ij}, introduced by Mooney can be calculated precisely using following equations:

$$\lambda_{ij} = \left\{\frac{\left(\cos^3\frac{\theta_i}{2}\left(1+\frac{d_j}{d_i}\right)^3-1\right)}{\left(\cos^3\frac{\theta_i}{2}\left(1+\frac{d_j}{d_i}\right)^3-\varphi_i-\frac{\varphi_i}{\varphi_j}(1-\varphi_j)\left(\frac{d_j}{d_i}\right)^3\right)}\right\}\frac{1}{\varphi_j},$$

$$\lambda_{ji} = \left\{\left[1-\left(1-\sqrt[3]{\frac{\pi}{6\varphi_j}}\frac{d_j}{d_i}\right)^3\right](1-\varphi_j)+\frac{\pi}{6}\right\}\frac{1}{\varphi_i}, \text{ and } \lambda_{ii}=\frac{1}{\varphi_i} \quad (3)$$

A software has been developed [5] that enables the porosity of a concentrated suspension to be evaluated (together with mixture proportioning), and also, the relative viscosity of a suspension to be predicted based on existing components proportions (or predicting apparent viscosity of a mix).

3. Experiment

3.1. Materials

Fourteen mixes were proportioned with local materials from Sofia area—see Table 1. The characteristics of materials used and the compositions of mixes are given in Ref. [6]. The ranges of mix compositions parameters are: binders-to-total solids content, $P/(P+A)$, from 0.22 to 0.3, coarse-to-fine aggregate ratio, G/S, from 1 to 1.4 and free water-to-cement ratio W_f/C from 0.30 to 0.48. The mixtures from 1 to 7 were proportioned as ordinary concrete containing river gravel 5/20 mm and the other (from 8 to 14) contained gravel 5/10 mm and HRWRA. Mix 13 contained crushed aggregate 5/15 mm and mix 14 contained gravel 5/20 and limestone filler as partial (30%) replacement of the cement.

3.2. Apparatus for rheological characterization of fresh concrete

The rheological experiments with the fresh mixes were performed in the recently developed tube viscometer for concrete, RCVC [6]. The outline of the viscometer is shown in Fig. 1. Its principle of operation is based on the classical capillary method, where the test fluid is driven through a tube as a result of hydrostatic pressure and auxiliary loadings, thus employing several test regimes with a few pressure fields. The device consists of a steel container (fixed on a supporting frame) and a pipe. Between the orifice of the container and the pipe a sliding gate is positioned. Fresh concrete of known weight is

Table 1
Characteristics of concrete mixes and test results with RCVC viscometer

Mix no.	$P/(P+A)$	G/S	W_f/C	Slump (mm)	Spread (mm)	Plastic viscosity (Pa s)	Yield stress (Pa)	Max shear rate (s^{-1})	η_{app} at max. shear rate (Pa s)	Φ/Φ^*	$\eta_{app, calc.}$ (Pa s)
1	0.30	1.00	0.38	235	490	2.7	283	65.30	7.23	0.948	3.46
2	0.30	1.40	0.38	225	460	4.2	288	33.42	13.01	0.961	5
3	0.28	1.20	0.40	235	470	6.2	243	46.17	11.13	0.973	5
4	0.28	1.00	0.39	240	490	6.3	169	53.53	9.35	0.972	7.87
5	0.28	1.40	0.40	245	560	8.7	134	48.28	11.33	0.973	5
6	0.25	1.00	0.46	265	640	7.5	74	47.66	8.94	0.971	5.04
7	0.25	1.20	0.39	255	630	3.2	90	102.63	4.22	0.959	2.80
8	0.28	1.25	0.31	240	540	20.5	211	13.77	36.74	0.986	36.40
9	0.28	1.00	0.30	250	590	19.4	207	14.07	35.3	0.987	36.82
10	0.24	1.25	0.36	205	370	11.8	508	4.38	126.42	0.998	106.82
11	0.28	1.00	0.30	230	480	21.1	331	6.47	73.6	0.994	72.24
12	0.22	1.25	0.36	255	640	9.1	127	42.41	12.323	0.975	13.00
13	0.22	1.10	0.48	230	460	1.9	329	33.38	11.81	0.974	12.00
14	0.25	1.35	0.45	210	420	4.6	463	17.88	30.84	0.980	29.85

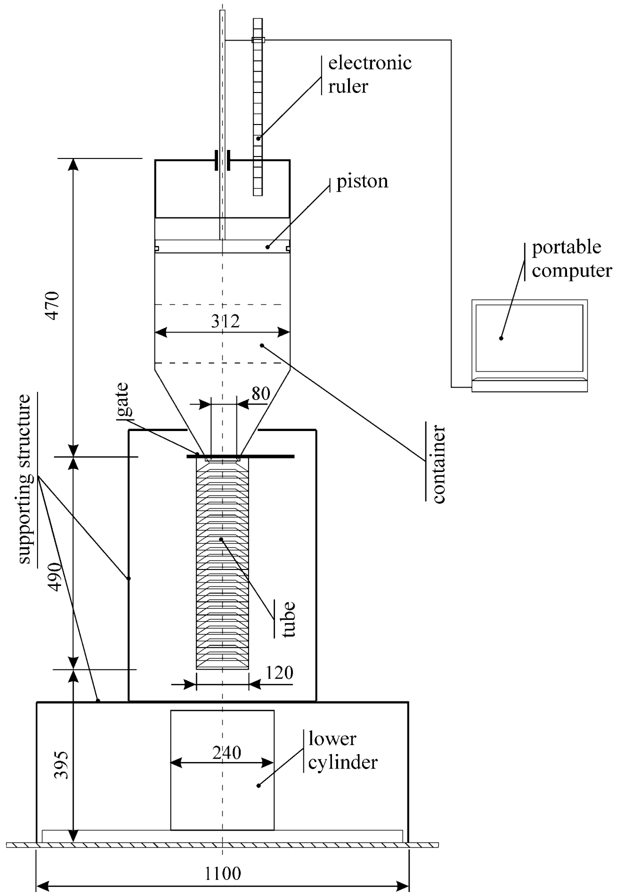

Fig. 1. Schematic of the RCVC viscometer; all dimensions are in (mm).

placed inside the container when the gate at its bottom end is closed. A piston with a steel guide-bar is situated on top of the sample. At the bottom face of the piston a flexible spring segment is attached for prevention of jams and paste seepage in the space above the piston. At the upper end of the guide-bar an electronic ruler is attached by which the vertical motion of the piston is registered by computer software approximately every 0.4 s with a precision of 1/100 mm. Below the sliding gate a polypropylene cylindrical pipe 490 mm of length is rigidly fastened to the container. Its bottom end is opened to the atmosphere. Inside the pipe equally spaced stainless steel truncated cones are fixed firmly to three vertical combs. The distance between the cones is 20 mm, which corresponds to the maximal size of aggregates in the mix. The function of the truncated cones is to prevent or minimize the wall slippage of the material located at the pipe/concrete interface. The upper diameter of the cones is 80 mm, which forms an inner diameter of the vertical viscometer tube where the actual shear flow takes place (see Fig. 1). Beneath the tube of the viscometer, a hollow cylinder with levers is fastened on a horizontal platform. The objective of this cylinder is to estimate the static yield stress of the tested specimen and to compare it with the value obtained in the dynamic experiment—the flow test. The pressure drops and flow rates are measured and registered by computer. From the pressure vs. flow rate plot the best-fit linear regression line is calculated from the data taken at a selected interval. For calculation of η_{pl} and the yield value $\hat{o}_0$, the slope and the intercept of the regression line are used.

3.3. Calculations procedures

The goal was to verify the model (Eq. (1)) by comparing the measured and calculated viscosities, and also, to check the previously established models [2,7].

Using a computer software [5], the concrete compositions were determined for slump value of 230 mm, corresponding to η_r=5000. On consecutive steps, water was added in order to obtain an adequate consistency of the mix that is proper for measurements with the viscometer. Finally, the ratio (P/P^*) and the apparent viscosities, η_{app}, as a ratio of η_r and the viscosity of water (0.001 Pa s at 20 °C) were calculated by Eq. (1) for the compositions tested with RCVC viscometer.

4. Results and discussion

The results from measured slump, spread and Bingham constants, $\hat{o}_0$ and η_{pl}, together with the maximal shear rate value reached in each tests with RCVC viscometer and its corresponding η_{app} are given in Table 1. The yield stress, $\hat{o}_0$, is in a favorable correlation with the determined slumps and spreads, as reported by many authors [1, 2]. As can be seen from the plots in Fig. 2 and Table 1, the measured η_{app} in the tests for all the compositions are in excellent correlation with calculated values $\eta_{app,\ calc.}$ by the model (Eq. (1)). More significant deviations have been observed for ordinary concretes. This discrepancy could be linked to the flocculation of granular mixture due to absence of HRWRA. Thus, during the shear the agglomerates undergo destruction and lower shear rates (corresponding to higher η_{app}) than predicted by the model are observed. On the contrary, the correlation between the measured η_{pl} and the value of $\eta_{app,\ calc.}$ is low, mainly for mixes with HRWRA and those with high powders contents. This result is probably due to the stronger influence of the dispersion effect of the HRWRA on yield stress rather than on η_{pl}. The reason to compare the measured η_{pl} and $\eta_{app,\ calc.}$ is to check the previously established correlation [2] between η_{pl} and the relative viscosity, η_r (proportional to η_{app}). Almost all published concentration dependencies (Mooney, Farris, Krieger-Dougherty, etc.) are deduced with the assumption of an existing correlation between η_r of a suspension and its concentration. For example, based on Farris's equation, Hu [7] suggested a model for predicting η_{pl} from mixture proportions, assuming a correlation between η_{pl} and η_r. A similar model has also been proposed in Ref. [2]. It must be

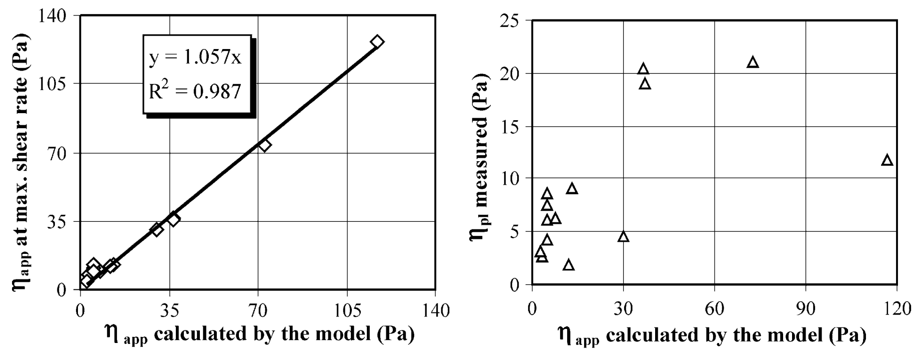

Fig. 2. Relationships between the measured apparent viscosity at the maximal shear rate reached in the experiment (left), and measured plastic viscosity (right) and calculated apparent viscosity by Eq. (1).

recalled however, that for a certain volume fraction of solids, a shear induced ordering of particles takes place with increasing shear stresses [8]. Thus, in the regime of low shear (stress) flow a yield stress develops due to the predominant effect of structure forces. At high shear state, where the hydrodynamic forces are predominant, a plateau value of the shear dependent viscosity is observed due to the maximum degree of ordering of the disperse phase, described by a maximum packing fraction of solids Φ^*. The term Φ^* is independent of the flow conditions and therefore, it could be correlated to a maximum packing fraction of dry solids P^*. It is definitely known [2,8] that the rheological behavior in the high shear state (stress) region is controlled strictly by the ratio (Φ/Φ^*). As one would assume, the data from Table 1 show that the inconsistency between the values of the measured η_{pl} and $\eta_{app,\ calc.}$ are smaller at higher shear rates, comparing to values obtained at lower shear rates regimes. If it is agreed that fresh concrete can be adequately described by the Bingham model [2,3], and that no correlation exists between ô$_0$ and η_{pl} [1,2] the observed effect is anticipated. Furthermore, Chang and Powell [9] observed in experiments with concentrated suspensions a shear thinning effect in low shear rates region (γ=0.001–0.3 s^{-1}). Ferraris and de Larrard [2] reported an opposite behavior, i.e. shear thickening in tests with concrete. Therefore, without further experiments it is hard to conclude on the exact flow behavior of concrete in low shear rate region.

To check that η_{app} correlates with η_r for a suspension rather than with η_{pl}, the experimentally measured plastic and calculated apparent viscosities were fitted with the ratio (Φ/Φ^*)—see Fig. 3. The ratio (Φ/Φ^*) between the volume fraction of solid materials, Φ, and its maximal value for close packing, Φ^*, has been interpreted as equivalent to the ratio (P/P^*) in this paper. As can be seen from the graph in Fig. 3 the correlation coefficient of 0.923 has been obtained between $\eta_{app,\ calc.}$ (predicted by Eq. (1)) and ratio (Φ/Φ^*). On the other hand, the correlation between η_{pl} and (Φ/Φ^*) is rather low. It appears that the correlation could be increased if higher shear stresses were applied, where the maximum packing fraction of solids Φ^* in flow state will approach closer the same parameter obtained for dry materials. From this result, the following conclusion can be made: concentration dependencies, underlying the basics of most theories for mix design of concrete mix in respect to its rheological behavior are in fact models of η_{app} in the high shear (stress) state, rather than a model of η_{pl}. This finding could be valuable, as long as it shows that the model is capable of predicting the measurable apparent viscosity of fresh concrete. Alternatively, concrete proportioning can be performed by defining the requirements for flow behavior of the fresh mix in terms of apparent viscosities. So now, the only unsolved problem remains the establishment of a model for the yield stress or the plastic viscosity that could precisely depict the Bingham flow behavior. This assumption will be examined in future work.

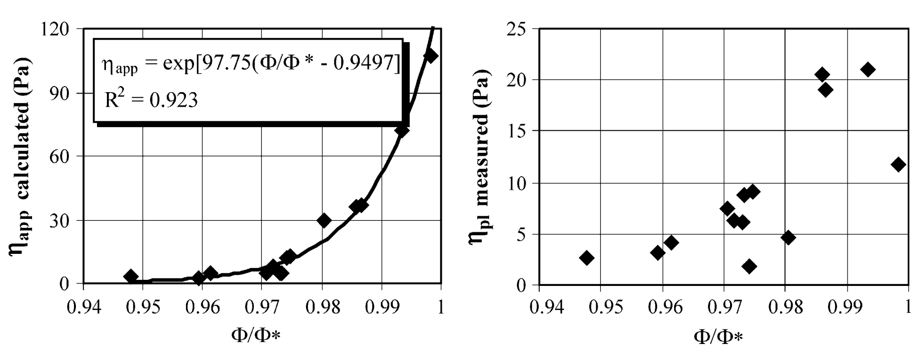

Fig. 3. Relationships between calculated apparent viscosity by Eq. (1) (left) and measured plastic viscosity (right) with the model given in Ref. [2].

5. Conclusions

Most of the concentration dependencies relate the concentration of a suspension to the viscosity or the shear stress to shear rate, thus assuming that there is only one value for the viscosity of the whole system. This approach would be realistic in high shear stress regimes of flow, where the plastic and the shear dependent apparent viscosities are of a comparable magnitude. Proposed method for mixture proportioning [6] and the experimental verification of the model presented in this report will be of use to promote the rheological approach in the concrete industry. The author feels that although the results are encouraging, still more work needs to be done in order to ensure a well-deserved place of the rheology in contemporary concrete industry. An effort should be done to develop a precise model for the yield stress or the plastic viscosity in order to accurately design the flow behavior of fresh mix. A verification of the model with data taken from the literature and extended series of concrete compositions must be examined in future work.

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