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

Theodore Roshavelov*

HSCE "L. Karavelov" School of Civil Engineering, 32 Suhodolska Str., 1373 Sofia, Bulgaria

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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.

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-

* Tel.: +359 888 967 819; fax: +359 2 920 5391.
E-mail address: roshavelov@vsu.bg.

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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