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Prediction of the plastic viscosity of self-compacting steel fibre reinforced concrete

Akbar Ghanbari, Bhushan L. Karihaloo*

School of Engineering, Cardiff University, Cardiff CF24 3AA, UK

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ABSTRACT

Micromechanical constitutive models are used to predict the plastic viscosity of self-compacting steel fibre reinforced concrete (SCFRC) from the measured plastic viscosity of the paste. The concrete is regarded as a two-phase composite in which the solid phase is suspended in a viscous liquid phase. The liquid matrix phase consists of cement, water and any viscosity modifying agent (VMA) to which the solids (fine and coarse aggregates and fibres) are added in succession. The predictions are shown to correlate very well with available experimental data. Comments are made on the practical usefulness of the predicted plastic viscosity in simulating the flow of SCFRC.

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1. Introduction

The rheological study of concrete is of prime importance for the construction industry because concrete is placed in its plastic state. This is even more relevant when dealing with a self-compacting concrete (SCC) [1,2]. However there is as yet no systematic coverage of this topic in the literature. Part of the reason for this may be the various ranges of particle size used in the concrete industry and different devices used to measure the plastic viscosity [3-5] of the heterogeneous concrete mix. The aim of this paper is to develop a micromechanical basis for determining the plastic viscosity of selfcompacting concretes with or without short steel fibres from the knowledge of the plastic viscosity of the paste alone. The latter can be measured with a reasonable degree of confidence, whereas the measurement of the plastic viscosity of the concrete mix is fraught with many difficulties and inaccuracies, especially when steel fibres are present. To overcome these, concrete is regarded as a two-phase composite - solid and liquid phases in the present paper. The liquid matrix phase consists of cement, water and any viscosity modifying agent (VMA). The plastic viscosity of this liquid matrix phase is assumed to be known. The increase in plastic viscosity due to the addition of a solid phase (i.e. any cement-replacement materials, fine and coarse aggregates) to this matrix is predicted from the two-phase composite model. The model is applied in stages; in the first stage, the solid phase is the finest solid material which could be the cementreplacement material in the viscous fluid (paste). In the next stage, when the second finest solid (it could be fine aggregate) is added, the composite from the first stage is regarded as the continuous fluid

* Corresponding author. *E-mail address:* karihaloob@cardiff.ac.uk (B.L. Karihaloo). matrix phase. This procedure is continued until all the solid phase constituents have been added to make the SCC.

The plastic viscosity of the viscous concrete consisting of the liquid and solid phases is further increased if steel fibres are added to it. The volume fraction of steel fibres is usually small, so that the dilute approximation is sufficient. In order to estimate the effect of the addition of steel fibres, these are treated by the rigid slender body approximation in a viscous medium [6,7]. The main assumption in this approximation is that the fibres undergo only a rigid body motion in the viscous flow, i.e. translation and rotation, but no elastic deformation. The predictions of this micromechanical approach are shown to correlate very well with available experimental data. Finally, comments are made on the practical usefulness of the predicted plastic viscosity in simulating the flow of SCFRC. It can be used both at the mix design stage to simulate the flow in a cone or an L-box test and at the industrial use stage to simulate the flow in the formwork.

2. Plastic viscosity of self-compacting concrete without steel fibres

2.1. SCC as a concentrated suspension of solid particles in a viscous liquid

The SCC consists of solid aggregate particles (solid phase) suspended in the viscous paste (liquid phase). The particles are modelled as spheres. The viscous behaviour of the resulting suspension depends on the volume fraction of the solid phase. At low concentrations of the solid phase, the plastic viscosity of the suspension does not change much with the shear rate, so that it is reasonable to assume that the suspension behaves like a Newtonian fluid. The behaviour becomes non-Newtonian once the volume fraction of solids reaches a critical value, roughly equal to ϕ_m – the maximum attainable volume concentration which will be defined later. The other parameters influencing the viscosity of the suspension

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are the shape, size, and distribution of the solid phase particles, especially at high concentrations.

2.1.1. Low concentration ($\phi < 0.1$)

A low concentration of solid phase is also called dilute, in the sense that the particles are sufficiently far apart from one another, so that the relative motion of the fluid near one particle is unaffected by the presence of the others and the hydrodynamic interaction of the particles can be neglected [8]. Einstein (see, e.g. [9]) was the first to derive the viscosity of a dilute suspension of rigid spheres. He showed that the addition of second phase to a suspension leads to an increase in the bulk viscosity proportional to volume fraction of particles

$$\eta_{\rm r} = 1 + [\eta]\phi. \tag{1}$$

Here, η_r is the relative viscosity i.e. ratio of viscosity of the suspension (mortar or concrete) to that of the liquid phase (cement paste), ϕ is the volume concentration of particles, and $[\eta]$ is the intrinsic viscosity which is a measure of the effect of individual particles on the viscosity [9]

$$[\eta] = \lim_{\phi \to 0} \frac{\eta_r - 1}{\phi}.$$
 (2)

A value of $[\eta] = 2.5$ is adopted when the particles are rigid and packed randomly in a hexagonal arrangement, and the distance between them compared to the mean particle diameter is large. It is also important that the movement of the particles is sufficiently slow so that their kinetic energy can be neglected.

Einstein's equation has been widely used by other researchers in this field even at higher volume concentrations of particles. Ford [10] modified Einstein's equation using a binomial expression

$$\eta_{\rm r} = (1 - [\eta]\phi)^{-1}.\tag{3}$$

As reported by Utracki [11], Simha modified Einstein's relation to read $\eta_r = 1 + 2.5f(a_1)\phi$, where $f(a_1)$ is the so-called shielding factor, by using a cage model and a reduced volume fraction, ϕ/ϕ_m , where ϕ_m is the maximum packing fraction. In this model each solid spherical particle of radius *a* is placed inside a spherical enclosure (cage) of radius *b*. A simplified version of the resulting equation for a low volume concentration can be written as

$$\eta_{\rm r} = 1 + 2.5 \varphi \bigg[1 + \frac{25}{32} \bigg(\frac{\varphi}{\varphi_{\rm m}} \bigg) - \frac{21}{64} \bigg(\frac{\varphi}{\varphi_{\rm m}} \bigg)^{\frac{5}{3}} + \frac{625}{128} \bigg(\frac{\varphi}{\varphi_{\rm m}} \bigg)^2 + \dots \bigg].$$
(4)

Based on the Simha calculation for concentrated suspensions, Thomas arrived at the following relation for dilute suspensions [10]:

$$\eta_{\rm r} = 1 + 2.5 \phi \left(1 + \frac{25\phi}{4a_1^3} \right). \tag{5}$$

For low volume fractions, $a_1 = 1.111$.

2.1.2. High concentration $(0.1 < \phi < \phi_m)$

At higher volume concentrations of particles, the volume fraction is not the only parameter that influences the viscosity. It is now necessary to consider the size and type of particles used and their hydrodynamic interaction. The general expression of the viscosity can be written as [10–15]

$$\eta_{\rm r} = 1 + [\eta]\phi + B\phi^2 + C\phi^3 + \dots \tag{6}$$

where *B* (in some references this is called *Huggins coefficient*) and *C* are very sensitive to the structure of suspension. Tables 1 and 2 give the

offerent values f	or parameter B	available in the	literature.

Reference	[10]	[10]	[15]	[16]	[17]	[18]	[19]	[20]
B value	10.05	6.25	4.84	6.2	14.1	7.35	12.6	6

values of constants *B* and *C* that have been reported in the literature [10,15–19].

The variation in the cited values of parameters *B* and *C* is the result of taking into account one or several effects appearing due to the increase in solid concentration.

Thomas (chapter in [13]) suggested that the *C* term in Eq. (6) could be replaced by an exponential term

$$\eta_{\rm r} = 1 + 2.5\phi + 10.05\phi^2 + 0.00273\exp(16.6\phi) \tag{7}$$

because the resulting expression fits the experimental data very well in the range of $\phi = 0.15$ –0.60.

In view of the uncertainties in the parameters *B* and *C*, Krieger and Dougherty [21], and others, have used the concept of maximum packing fraction, ϕ_m for a better description of the suspensions. ϕ_m corresponds to the situation in which the particles have the minimum possible separation i.e. the void fraction (porosity) is the least and the viscosity is infinite. The value is 0.74 for hexagonal closed packing, 0.637 for random hexagonal packing and 0.524 for cubic packing [10].

Krieger and Dougherty [21] proposed a generalized version of Einstein's equation; they used the maximum packing volume fraction and intrinsic viscosity parameter to a non-Newtonian suspension of rigid spheres. Ball and Richmond [12] used the results of Krieger and Dougherty but simplified their complex mathematics conceptually based on Einstein's equation. In their formulation, the viscosity of the suspension increases in two ways; firstly, if the volume fraction of spherical solid particles increases by $d\phi$, the spheres already present in the suspension raise the total viscosity by $(1/\phi_m)\phi d\phi$, where $1/\phi_m$ is the so-called crowding factor. Therefore, the increment in the viscosity according to Einstein's equation becomes

$$d\eta = [\eta]\eta d\phi + \phi / \phi_{\rm m} d\eta. \tag{8}$$

Secondly, in the presence of other particles, the volume available for an additional particle is decreased by $(1-\phi/\phi_m)$ so that the increment in the total viscosity is

$$d\eta = [\eta] \frac{\eta d\phi}{1 - \frac{\phi}{d\phi}}.$$
(9)

Combining the two effects (Eqs. (8) and (9)) they reached the well-known Krieger and Dougherty [21] equation

$$\eta_{\rm r} = \left(1 - \frac{\varphi}{\varphi_{\rm m}}\right)^{-[\eta]\varphi_{\rm m}} \tag{10}$$

 $\phi_{\rm m}$ is strongly dependent on the particle size distribution. Also, the intrinsic viscosity [η] and $\phi_{\rm m}$ depend upon the shear rate; the former tends to decrease with increasing shear rate whereas the latter shows the opposite trend. However [η] and $\phi_{\rm m}$ change in such a way that an increase in the one leads to a decrease in the other, but the product of

Table 2Different values for parameter *C* available in the literature.

Reference	[10]	[18]	[20]
C value	15.7	16.2	35

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