Rheological behavior of fresh mortar

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Abstract: Rheological parameters are considered to be more suitable to characterize the workability of fresh cement-based materials than slump value or flowability. The rheology of fresh mortar can be affected by different factors. The effects of water-binder ratio (vary from w/b=0.35 to w/b=0.45), sand-binder ratio (vary from s/b=0 to s/b=2.0) and mineral admixtures addition on rheology of fresh mortar were investigated in this paper. Fly ash and slag with different proportions were individually added as a partial replacement for cement in w/b=0.3, s/b=1.0 mortar mixtures. Both yield stress and plastic viscosity which are described in Bingham model were employed to characterize rheological behavior of fresh mortar and tested by rheometer. The investigation herein is not only to acquire how rheology was influenced by the various factors, but also to establish models to predict values of rheological parameters. A new model is proposed to predict the plastic viscosity of fresh mortar, and the verification results show that the model is reliable.

1. INTRODUCTION

The properties of fresh concrete or mortar, especially workability, significantly affect the transporting, placing and compacting of the fresh mixture and exert great influences on the properties of hardened concrete, such as uniformity, strength and durability. So it is extremely important to study the rheological behavior of fresh concrete or mortar. According to the American Concrete Institute, workability is defined as “the property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to homogeneous condition”. Concrete must have proper flowability, or rheology, so as to obtain desirable workability. Rheology has been considered to be a more suitable parameter to characterize the workability of fresh cement-based materials than slump value or flowability[1]. Some authors[1-4] have claimed that the fresh concrete or mortar is a Bingham fluid. In Bingham model, flow is defined by two parameters: yield stress and plastic viscosity. Yield stress gives the quantitative measure of initial resistance of concrete to flow and plastic viscosity governs the flow after it is initiated. The Bingham model can be represented with the following equation:

\[ \tau = \tau_0 + \mu \dot{\gamma} \]  

(1)

The term \( \tau \) is the shear stress [Pa], \( \tau_0 \) is the yield stress [Pa], \( \mu \) is the plastic viscosity [Pa·s] and \( \dot{\gamma} \) is the shear rate [s\(^{-1}\)].

The most common approach adopted for quantifying the rheological properties of fresh concrete or mortar is to experimentally measure shear stress versus shear strain rate using rheometer. By
assuming that the flow of fresh concrete or mortar obeys Bingham model, an estimate of the yield stress and plastic viscosity is obtained. Some researchers have attempted to give some models. Struble and Sun (1995) [5] considered that the Krieger-Dougherty equation can be used to describe the relationship between viscosity and concentration of dispersed cement paste. An experiential plastic viscosity model based on large numbers of experiments was proposed by Ferraris and deLarrard [1]. Zholkovskiy et al. [6] proposed a revised formulation based on the cell method. Mahmoodzadeh and Chidiac [7] revised Zholkovskiy et al. formulation for quantifying the plastic viscosity of fresh concrete and considered that their model was more suitable to predict the plastic viscosity of fresh concrete. However, the above models cannot be used in the fresh mortar.

The rheology of fresh concrete or mortar can be affected by different factors. In this paper, the effects of water-binder ratio (vary from w/b=0.35 to w/b=0.45), sand-binder ratio (vary from s/b=0 to s/b=2.0) and mineral admixtures addition on rheology of fresh paste/ mortar have been investigated. Since the existing models are not suitable to predict the plastic viscosity of fresh mortar, a new model is proposed in this paper.

2. EXPERIMENTAL

2.1 Materials

Portland Cement P·II 52.5, fly ash and slag are used as cementitious materials in this study. The specific gravity of cement, fly ash and slag is 3.12g/cm³, 2.24g/cm³ and 2.75g/cm³, respectively. And their chemical compositions are listed in Table 1. ISO sand with 2.66g/cm³ specific gravity and polycarboxylate-based superplasticizer (PCA II) produced by Jiangsu Bote New Materials Co., Ltd are also used in the research.

<table>
<thead>
<tr>
<th></th>
<th>CaO</th>
<th>SiO₂</th>
<th>MgO</th>
<th>Fe₂O₃</th>
<th>Al₂O₃</th>
<th>SO₃</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>LOI</th>
</tr>
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<td>20.00</td>
<td>5.31</td>
<td>3.46</td>
<td>4.64</td>
<td>3.15</td>
<td>0.49</td>
<td>0.15</td>
<td>2.44</td>
</tr>
<tr>
<td>slag</td>
<td>32.2</td>
<td>33.20</td>
<td>7.24</td>
<td>1.40</td>
<td>18.60</td>
<td>4.86</td>
<td>0.47</td>
<td>0.15</td>
<td>2.78</td>
</tr>
<tr>
<td>fly ash</td>
<td>4.64</td>
<td>46.60</td>
<td>1.41</td>
<td>4.27</td>
<td>37.70</td>
<td>1.52</td>
<td>0.52</td>
<td>0.23</td>
<td>2.45</td>
</tr>
</tbody>
</table>

LOI=loss of ignition

2.2 Test methods

Since the new plastic viscosity model proposed in this paper is based on plastic viscosity of cement paste, cement paste is necessary. Cement paste and mortar were prepared by standard mixing methods based on the criterion GB/T1346 -2001 and GB/T17671-1999, respectively. A Brookfield R/S SST2000 rheometer was used to measure the rheology parameters of cement paste and mortar. Mode CC-15 was used for cement paste, and V40-20 for mortar. The rheology measuring procedure [8] was shown in figure 1. After placing the paste/mortar into the rheometer, the specimens were left to equilibrate for 30 s and were then sheared at a constant rate 180s⁻¹ for 1min (referred to as "preshear"). Following the preshear, the vane would be stopped for 1min, during which the sample was gently stirred to mitigate the formation of preferential shear planes.
due to particle orientation. The sample was then subjected to a controlled rate hysteresis loop where the shear rate was increased from 0 to 180 s\(^{-1}\) over 1 min and then immediately decelerated back to 0 s\(^{-1}\) over an additional 1 min. The slope of the linear region of the down curve of the hysteresis loop is the value in the Bingham equation.

Figure 1. Test program.

3. EFFECTS OF SOME FACTORS ON FRESH MORTAR

With a constant sand-binder ratio 1.0, the effects of water-binder ratio (vary from w/b=0.35 to w/b=0.45) on mortar rheology and relevant cement paste rheology are shown in figure 2. As expected, the increasing of water-binder ratio results in a reduction of the plastic viscosity and yield stress of fresh mortar and relevant cement paste. Water content is well known to have the most significant influence on the rheological behavior of cementitious materials including cement paste, mortar and concrete. The plasticity of cement paste/mortar can be attributed to a combination force between cement/sand particles and the lubricating action of the water between them. The increase of water content causes the paste to become softer because it leads to a greater dispersion of particles. The freedom of individual particles thus increases. Liberation becomes greater, and the mobility of the paste increases, which further causes the decrease of yield stress and plastic viscosity.

Figure 2. The effect of water-binder ratio.

While a constant water-binder ratio 0.4 is held, the effects of sand-binder ratio (vary from s/b=0 to s/b= 2.0) on mortar rheology are shown in figure 3. It can be clearly seen that the plastic
viscosity and yield stress of fresh mortar increase with the increasing of sand-binder ratio. The increase of sand content causes the increase of friction between sand particles and the water demand for the lubricating action which results in a decrease of free water. The freedom of individual particles thus reduces. Liberation becomes lower, and the mobility of the paste reduces, which further causes the increase of yield stress and plastic viscosity. Moreover the effects of mineral admixtures addition on rheology of fresh mortar and relevant cement paste were investigated. Fly ash and slag with different proportions were individually added as a partial replacement for cement in w/b=0.3, s/b=1.0 mortar mixtures with 0.8% superplasticizer addition and relevant cement paste. Fly ash was used as mass replacement for cement at percentages of 10%, 20%, 30% and 40%. The test results are shown in figure 4. Addition of increasing levels of fly ash results in a reduction of yield stress of mortar and relevant cement paste. The effect on the plastic viscosity is to some extent interesting. Plastic viscosity of mortar increases from 10% up to 30% level and then decreases, which is different from its relevant cement paste. Slag was also used as mass replacement for cement at percentages of 10%, 20%, 30% and 40%. The test results are shown in figure 5. Addition of increasing levels of slag generally leads to a reduction of plastic viscosity and yield stress of mortar and relevant cement paste.

Mineral admixtures addition act complexly on the rheology of fresh mortar and cement paste. The improved gradation of the binder and the lubricating effect imparted by the mineral admixtures could possibly reduce the aggregate interlocking, and hence reduce the yield stress. The interposition of mineral admixtures grains between cement particles may lower their electrostatic attraction and thus disperse their flocculated structure. Furthermore, partially substituting cement by another reactive powder with a different specific surface area would change the total wettable surface area and the amount of water adsorbed. Consequently, the rheology of fresh mortar and cement paste with mineral admixtures addition will depend on the coupling action of the above effects, and would be more complicated[9-11].

4. MODELING OF PLASTIC VISCOSITY FOR FRESH MORTAR
The spherical cell approach is an approximate method to address macroscopically uniform and isotropic media in terms of the parameters describing their microscopic structure. During the past several decades, the spherical cell approach has been extensively employed for describing
thermodynamic equilibriums, dielectric dispersion, and electrokinetic phenomena in colloid and disperse systems. The spherical cell approach can also be a good method for studying the role of interfacial forces in rheological behavior of colloid systems. The spherical cell approach has been used to study the plastic viscosity of suspensions by some researchers and many theories have been proposed\cite{6}.

There is an assumption in spherical cell approach that a representative part of the suspension is a spherical cell which contains a particle surrounded by the continuous phase.

$$\lambda = \frac{b}{a}$$  \hspace{1cm} (2)

Where $a$ is the particle radius, $b$ is the spherical cell radius and is $\lambda = \lambda (\phi)$ function of the volume fraction of dispersed spherical particle $\phi$.

As a result of different definitions of the boundary conditions, Simha and Happel give two spherical cell theories for the viscosity of suspensions which are most widely used now.

Simha’s theory:

$$\lambda (\phi) = \left(\frac{\phi}{\phi^*}\right)^{1/3}$$  \hspace{1cm} (3)

$$\eta_r (\phi, \lambda) = 1 + \phi \left( \frac{10(1 - \lambda)}{4(1 + 10^3) - 25\lambda(1 + \lambda^2) + \lambda^3} \right)$$  \hspace{1cm} (4)

Happel’s theory:

$$\lambda (\phi) = \phi^{1/3}$$  \hspace{1cm} (5)

$$\eta_r (\phi) = 1 + \phi \left( \frac{22\phi^{7/3} + 55 - 42\phi^{7/3}}{10(1 - \phi^{10/3}) - 25\phi(1 - \phi^{4/3})} \right)$$  \hspace{1cm} (6)

Different models based on Simha and Happel’s theories have been established by many researchers. Mahmoodzadeh and Chidiac revised the spherical cell models for quantifying the plastic viscosity of fresh concrete and considered that their model was more suitable to predict the plastic viscosity of fresh concrete. Mahmoodzadeh and Chidiac models take the following form\cite{7}.

$$\eta_r (\phi) = 1 + \eta_i \lambda^3 \left( \frac{4(1 - \lambda^7)}{4(1 + 10^3) - 25\lambda(1 + \lambda^2) + 42\lambda^3} \right)$$  \hspace{1cm} (7)

$$\lambda (\phi) = \left(\frac{\phi}{\phi^*}\right)^{1/3} \left( \frac{1}{2(1 + k) - \left(\frac{\phi}{\phi^*}\right)^{1/3}} \right)$$  \hspace{1cm} (8)

or

$$\lambda (\phi) = \left(\frac{\phi}{\phi^*}\right)^{1/3} \left( 1 - k \right)$$  \hspace{1cm} (9)

Where $\eta_i$ is the intrinsic viscosity and is a function of the particle shape (For spherical particles,
= 5/2), \( \Phi^* \) is the maximum packing density, \( k \) is a function of the concrete mixture and is defined as follows:

Without high range water reducer admixture

\[
k = 0.006 \times \frac{\text{binder}}{\text{water}}
\]

(10)

With high range water reducer admixture

\[
k = 3.8 \times \frac{\text{wra water}}{\text{binder binder + sand}}
\]

(11)

Previous study shows that Mahmoodzadeh and Chidiac models can be used to predict the plastic viscosity of fresh mortar, but they leads to a great error. In this paper, Mahmoodzadeh and Chidiac models have been revised to be more suitable to predict the plastic viscosity of fresh mortar.

Calculating the plastic viscosity of mortar by postulating that sand particles are suspended in cement paste, the new models take the following form:

\[
\eta_r = \frac{\eta_m}{\eta_c} = 1 + m \eta_i \Phi^{1/3}
\]

(12)

Where \( \eta_r \) is the relative plastic viscosity; \( \eta_m \) is plastic viscosity of mortar; \( \eta_c \) is plastic viscosity of cement paste; \( \Phi \) is volume fraction of sand; \( m \) is a new parameter:

\[
\Phi \geq 0.34, \quad m = \frac{1}{2} \left( \frac{\text{sand}}{\text{binder}} \right)^{\frac{5}{3}}
\]

\[
\Phi < 0.34, \quad m = \frac{1}{2}
\]

\( y \) is a parameter from Simha’s theory:

\[
y = \frac{4 \left( 1 - \lambda^7 \right)}{4 \left( 1 + \lambda^{10} \right) - 25 \lambda^3 \left( 1 + \lambda^4 \right) + \lambda^5}
\]

(13)

\( \lambda \) is the same as Mahmoodzadeh and Chidiac’s model

\[
\lambda(\phi) = \frac{\left( \phi / \phi^* \right)^{1/3}}{2 \left( 1 + k \right) - \left( \phi / \phi^* \right)^{1/3}}
\]

(14)

\( \phi^* \) is the maximum packing density of sand, which can be calculated from Hu and deLarrard’s maximum packing density formula:

\[
\phi^* = 1 - 0.45 \left( \frac{d_{10}}{d_{90}} \right)^{0.19}
\]

(15)

\( d_{10} \) and \( d_{90} \) are the sieve sizes corresponding to 10% and 90%, respectively, of sand passing the sieve.

The plastic viscosity of mortar can be calculated from the above formulae when the plastic viscosity of cement paste is obtained. The model predictions and the experimental data are shown in Figure 6. All the points are in or around the line \( Y=X \), so it can be concluded that the
new model is consistent and reliable in predicting the plastic viscosity of fresh mortar.

![Graph showing the relationship between predicted and measured plastic viscosity.](image)

Figure 6. Plastic viscosity according to the new model.

5. CONCLUSIONS

The rheology of fresh mortar can be affected by various factors. The increasing of water-binder ratio results in a reduction of the plastic viscosity and yield stress of fresh mortar and relevant cement paste. The increasing of sand-binder ratio increases the plastic viscosity and the yield stress of the fresh mortar. The effects of mineral admixtures addition on rheology of fresh mortar are also significant. Addition of increasing levels of fly ash results in a reduction of yield stress of mortar and relevant cement paste, however the influence on plastic viscosity is complex. Addition of increasing levels of slag generally leads to a reduction of plastic viscosity and yield stress of mortar and relevant cement paste. Based on the experiment results of corresponding fresh cement paste, the plastic viscosity of fresh mortar can be predicted by a new model that is put forward in this paper. The verification results show that predicted plastic viscosity is in good agreement with the measured plastic viscosity, which proves the validity and reliability of the model.

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REFERENCES


