ABSTRACT: Flow value and slump are applied for the evaluation of consistency of polymer-modified sprayed mortar. These values are very easy to use, but can’t explain the consistency in detail. Moreover the prediction of pumpability, rebound and sagging are almost impossible, because flow value and slump are not physical quantity. Therefore new evaluation indexes are required to improve the construction quality. A viscometer with four vanes was used for evaluate the fresh properties of polymer-modified sprayed mortar in this study. And the applicability of this technique was examined. As a result, the recommendation of experimental conditions for the evaluation of polymer-modified mortar is presented. Moreover, new evaluating indexes derived from the $\tau-\theta$ curve, the curve of shear stress in dependence of the rotational angle of vane, were proposed.

1 INTRODUCTION

Sprayed mortar is widely used for the repair and strengthening of concrete structures such as bridge slabs. And polymer-modified mortar, PCM, is often used for spraying material. However, at present, there is no device which can take an accurate measurement of PCM’s quality and the standardized mix design of each spraying method. The quality of PCM is an important factor that influences the quality of workability: when the quality of PCM is low, the deterioration in working environment and material loss due to rebound and sagging are caused. In such a background, indexes which can evaluate not only the quality of fresh mortar but also predict the spraying quality are needed. Then, the new indexes which are measured by vane-type viscometer are proposed as a method for evaluating the quality of sprayed mortar.

2 MATERIALS AND METHODS

2.1 Used materials, mixture proportion and production method of mortar

Three kinds of PCM on the market, shown in Table 1, were used. The water to PCM weight ratio, W/C, of each mixture was fixed as shown in Table 2. In the table, the standard W/C was fixed by the slump of 170 ± 15mm with reference to some guides for construction[JSCE(2005)]. A revolving-paddle mixer for mortar of 100 liter was used, mortar was mixed in the order of dry-mixing for ten seconds and wet-mixing for five minutes.

2.2 Outline and evaluating value of vane-type viscometer

Fig.1 shows the image of the vane-type viscometer, which has a speed adjustable motor from 6°/min to 240°/min, and measures the torque while the vane rotates in mortar. The measurements are displayed on the logger. Three sizes of the vane as shown in fig.2 were used. The consistency of PCM was evaluated by the shear stress, which was calculated by equation
Table 1. The composition of each PCM

<table>
<thead>
<tr>
<th>Symbol of PCM</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM-1</td>
<td>special cement, fine aggregate, organic admixture, organic fiber</td>
</tr>
<tr>
<td>PCM-2</td>
<td>cement, fine aggregate, admixture, fiber, acrylic powder resin</td>
</tr>
<tr>
<td>PCM-3</td>
<td>PVA-fiber premixed mortar, SBR-type polymer emulsion</td>
</tr>
</tbody>
</table>

Table 2. The level of W/C

<table>
<thead>
<tr>
<th>Symbol of PCM</th>
<th>W/C(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Series 1</td>
</tr>
<tr>
<td>PCM-1</td>
<td>18*, 20, 22</td>
</tr>
<tr>
<td>PCM-2</td>
<td>13, 14*, 16</td>
</tr>
<tr>
<td>PCM-3</td>
<td>16, 17, 18*</td>
</tr>
</tbody>
</table>

The sign * is a symbol of standard W/C

Figure 1. Vane-type viscometer.

Figure 2. Three types vane.

(1) and (2). Equation (1) was used when the same stress acts on the upper and lower edge of vane, and equation (2) was used when the upper edge of vane doesn't shear the mortar.

\[
\tau = \frac{M}{\pi D^2 (H/2 + D/6)} \quad (1)
\]

\[
\tau = \frac{M}{\pi D^2 (H/2 + D/12)} \quad (2)
\]

where

- \( \tau \): shear stress (Pa)
- \( M \): torque (Nm)
- \( D \): total width of vane (m)
- \( H \): height of vane (m)

Due to PCM has two phases, the Bingham fluid and the plastic body, different measurement tools are used for each phase when evaluating its consistency. But the proper use of the tools is not so easy at construction site. In case of plastic body, the adaptability of a vane-type viscometer used in this research was confirmed. On the other hand, spindle-type viscometer which is widely used for measurement of consistency of the Bingham fluid has a limit of adaptability for mortar, because mortar with low adhesion to rotor slides on the surface of rotor. Therefore a vane-type viscometer, which has the same rotational mechanism as a spindle-type viscometer and has no care of the slide on rotor, was used in this research.

2.3 Evaluating condition of vane-type viscometer
Table 3. Experimental factors and each level

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>size Vane</td>
<td>Vane-L: D=3cm, H=6cm</td>
</tr>
<tr>
<td></td>
<td>Vane-M: D=2cm, H=4cm</td>
</tr>
<tr>
<td></td>
<td>Vane-S: D=1cm, H=2cm</td>
</tr>
<tr>
<td>rotation speed: $v_{\text{rot}}$</td>
<td>6, 30, 60, 150 and 240°/min</td>
</tr>
<tr>
<td>(Vane-M, $h_v=4cm$, $\phi=10cm$, $t=20min$)</td>
<td></td>
</tr>
<tr>
<td>insertion depth: $h_v$</td>
<td>0, 4 and 8 cm</td>
</tr>
<tr>
<td>(Vane-M, $\phi=10cm$, $v_{\text{rot}}=30°/min$, $t=20min$)</td>
<td></td>
</tr>
<tr>
<td>diameter of vessel: $\phi$</td>
<td>10, 15 and 20 cm in diameter and 20 cm in height</td>
</tr>
<tr>
<td>(Vane-M, $\phi=10cm$, $v_{\text{rot}}=30°/min$, $t=20min$)</td>
<td></td>
</tr>
<tr>
<td>measurement time: $t$</td>
<td>0, 20 and 40 min</td>
</tr>
<tr>
<td>(Vane-M, $\phi=10cm$, $v_{\text{rot}}=30°/min$)</td>
<td></td>
</tr>
</tbody>
</table>

The maximum shear stress, $\tau_{\text{max}}$ of W/C=18% of PCM-1 was compared. The diameter of vessel $\phi$, the rotation speed of the vane $v_{\text{rot}}$, the insertion depth of the vane $h_v$, and the measurement time $t$, were selected as experimental factors. Table 3 shows the experimental factors and each level.

The above presented experimental factors and the levels were chosen due to the following reasons. Using a plastic mould for concrete of 10cm in diameter and 20cm in height was assumed, since it has a light weight and it is easy to handle. Both reasons are very important for the measurement in construction site. Vane-M which is not influenced by the friction between mortar and vessel, was used and the propriety was discussed. The rotation speed was adjusted between $6^\circ$/min to $240^\circ$/min: the minimum speed of $6^\circ$/min is the recommended speed for soil [JSG(2004)] and the maximum speed of $240^\circ$/min is the maximum speed of this device.

2.4 Evaluating method focussed on the shape of the shear-stress curve

Three kinds of PCM which are shown in Table 1 were used. The experimental conditions were as follows: Vane-M, $v_{\text{rot}}=60^\circ$/min, $h_v=4cm$, $\phi=10cm$, $\tau$ was measured every five seconds until three minutes correspond to $180^\circ$ of the rotation angle $\theta$.

3 RESULTS AND DISCUSSION

3.1 The relation between measurement conditions and the maximum shear-stress($\tau_{\text{max}}$)

3.1.1 Vane size and the diameter of vessel

The relation between the vane size and the maximum shear stress $\tau_{\text{max}}$ is shown in fig.3. Vane-M and Vane-L have the same measurement results regardless of the diameter of vessel. However, $\tau_{\text{max}}$ of Vane-S is two times larger than of Vane-M and Vane-L. It would be actualized that the influence of shear stress on the surface of the shaft which connects the vane with the motor. The relation between $\phi$ and $\tau_{\text{max}}$ is shown in fig.4. The smaller the diameter of the vessel is, the larger $\tau_{\text{max}}$ is, for W/C=18%, but the gap is very small. The larger sized vane is better for high accuracy measurement, because this device picks up the torque caused by the mechanism of the device. From these results, it was judged that Vane-M is matched well with vessel of 10cm in diameter.
3.1.2 Insertion depth of vane

Fig.5 shows the relation between $\tau_{\text{max}}$ and $h_v$. Equation (1) for $h_v=4\text{cm}$ and $8\text{cm}$ and equation (2) for $h_v=0\text{cm}$ were used for calculation of $\tau_{\text{max}}$. It is shown clearly, that the insertion depth does not influence the measurement result. On the other hand, the positioning of the top edge of the vane blade is difficult in case of $h_v=0\text{cm}$, because the top of mortar sinks due to the insertion of the vane as shown in fig.6. $\tau_{\text{max}}$ was measured at position (a) in case of $h_v=0\text{cm}$, however it is not suited for the use in construction site due to the difficulty of positioning. For the above reason, it is recommended that the insertion depth of vane is set to 4cm which is the same length as the vane has in height.

3.1.3 Rotation speed of vane

Fig.7 shows the relation between $\tau_{\text{max}}$ and the rotation speed of the vane $v_{\text{rot}}$. As shown in this figure, $\tau_{\text{max}}$ of each W/C has the same value as that of $v_{\text{rot}}=6^\circ/\text{min}$: the recommended rotation speed for soil, and there is no influence of rotation speed of the vane. For speeding up of the measurement, $v_{\text{rot}}=240^\circ/\text{min}$ is better. However, $v_{\text{rot}}=60^\circ/\text{min}$ was selected for the recommended rotation speed, due to respect for the standard for soil and for the speeding up of the measurement. The time of the appearance of the peak is one minute or less and the time for the rotation through $180^\circ$ is three minutes.

3.1.4 Measurement time

Fig.8 shows the relation between $\tau_{\text{max}}$ and the measurement time $t$. The measurement time of 20 minutes was proposed as a recommended value with consideration of the time occupied by the preparation before measuring and stabilization of fluidity.
3.2 The comparison of shear-stress curve (τ–θ curve)

3.2.1 The comparison of W/C

Fig.9, fig.10 and fig.11 show the results of PCM-1, PCM-2 and PCM-3 respectively. τ of PCM-1 peaks between θ = 30° and θ = 60°. The lower W/C is, the clearer and larger the peak is. Further τ at θ = 130° or higher is constant in W/C = 17% and W/C = 18%. In case of PCM-2 and PCM-3, both curves have the same shape. The comparison of the τ-θ curves at standard W/C is shown in fig.12, in which PCM-1 has a distinctive shape. The peak of τ-θ curve may evaluate the thixotropy of PCM. Thixotropy is one of the characteristics of the fluid: the fluid resistance is low when shear stress acts on it, however it is high after remove of the shear stress. As for paints, this characteristic is a good parameter for the easy painting and sagging control. Thixotropy of PCM also plays a useful role: while viscosity is low in the pipe, it is high after
spraying. The adaptability of evaluation method by the $\tau$-$\theta$ curve must be checked by another exclusive measurement method [Fujiwara, Ebina and Nito (2006)] or a model experiment in construction site. The peak of $\tau$-$\theta$ curve is expected to apply for the quality control of PCM, the choice of spraying condition and the development of a new type of PCM.

3.2.2 The comparison of the measurement time

Fig.13, fig.14 and fig.15 shows the results of PCM-1, PCM-2 and PCM-3 respectively. $\tau$ of PCM-1 peaks between $\theta=30^\circ$ and $\theta=90^\circ$, and the longer the measurement time is, the clearer and larger the peak is. Further $\tau$ at $\theta=130^\circ$ or more converges at about 600Pa in any case.

On the other hand, PCM-2 and PCM-3 shows different shapes of the $\tau$-$\theta$ curve from that of PCM-1: $\tau$ of PCM-2 increases until about $\theta=20^\circ$, and after that, $\tau$ keeps a constant value. In case of PCM-3, the shapes of the $\tau$-$\theta$ curve are the same regardless of the measurement time.
3.2.3 The comparison of the rotation speed of the vane

The results of PCM-1, PCM-2 and PCM-3 are shown in fig.16, fig.17 and fig.18 respectively. \( \tau \) of PCM-1 peaks between \( \theta = 30^\circ \) and \( \theta = 90^\circ \). The longer the measurement time is, the clearer and larger the peak is. In case of PCM-1, which is shown in fig.16, the shape of the \( \tau-\theta \) curve has peaks in any rotation speed. Larger \( v_{rot} \) means larger peak value of \( \theta \). However values for \( \tau_{\max} \) show almost the same level. On the other hand, the shape of the \( \tau-\theta \) curve of PCM-2 is the same independent of \( v_{rot} \). Further the \( \tau-\theta \) curve of PCM-3 has its peak at \( v_{rot} = 6^\circ /\text{min} \), while the curves with \( v_{rot} = 60^\circ /\text{min} \) and \( v_{rot} = 240^\circ /\text{min} \) have no peak.

As stated above, it is clear that the shape of \( \tau-\theta \) curve is influenced by the rotation speed of the vane. This phenomenon should be caused by the difference of PCM’s flow behind the vane blade.

3.3 Proposition of evaluation indexes from \( \tau-\theta \) curve

Fig.19 shows the \( \tau-\theta \) curve and the evaluation indexes: the maximum shear stress \( \tau_{\max} \), the stable shear stress \( \tau_{\text{sta}} \) and the difference of both values \( \tau_{\max} - \tau_{\text{sta}} \). \( \tau_{\max} \) can be used for the generation forecast of sagging and the presumption of spraying thickness. Sagging can be prevented when \( \tau_{\max} \) is larger than the shear stress that acts on PCM. Similarly, the maximum spraying thickness can be presumed when PCM adheres to the concrete surface.

The relation between \( \tau_{\text{sta}} \) and the flow value of three PCMs are illustrated in fig.20, and the correlation between \( \tau_{\text{sta}} \) and the flow value is linear. \( \tau_{\text{sta}} \) would be able to the index for quality of PCM takes the place of flow value. Moreover, they may be able to explain in detail the PCM’s consistency, because it is a physical quantity.

\( \tau_{\max} - \tau_{\text{sta}} \) may evaluate the thixotropy of PCM. If so, it would be used to develop new type PCM. Although it is necessary to confirm the applicability of these indexes by the model experiment in construction site, the improvement of construction quality can be expected by clarifying the relation between these indexes and the construction characteristics pumpability, rebound, sagging and spraying thickness.

4 CONCLUSIONS

The result of this research and the finding are shown below.

1. Concerning vessel, vane and the measurement time, the experimental conditions of the vane-type viscometer for the evaluation of the consistency of polymer-modified mortar were recommended.

   Vessel: A cylinder which is 10cm in diameter and 20cm in height.
   Vane: Four plates which have 1cm in width and 4cm in height, combined with an insertion depth of 4cm and a rotation speed of 60°/min.

   Measurement time was 20 minutes after mixing.
(2) The flow value correlates with \( \tau_{\text{sta}} \), the shear stress during the stable period in the \( \tau-\theta \) curve, which expresses the relation between shear stress \( \tau \) and the rotational angle of the vane \( \theta \).

(3) Singular points of the \( \tau-\theta \) curve, such as the maximum value \( \tau_{\text{max}} \), the stable value \( \tau_{\text{sta}} \) and the difference between \( \tau_{\text{max}} \) and \( \tau_{\text{sta}} \) can be applied for the choice of spraying condition and the development of new type PCM.

ACKNOWLEDGMENT

The authors thank Dipl.-Ing. Alexander Assmann for good advice.

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