Indigenous development and testing of rotational viscometer for bituminous binders

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ABSTRACT

The measurement of consistency of construction materials has been the keen interest of many researchers in the recent past. It can be observed that the empirical methods are being used for measuring consistencies of Bitumen, Cement Paste, Soil Mass and Fresh Concrete in many countries. The need of the hour is to develop instrumentation for measuring the consistencies based on Mechanistic Approaches which essentially depend on the assessment of deformation behavior in response to application of loads. This paper presents a method by which a Rotational Type Viscometer can be devised. The instrument is validated with glycerin at a specified temperature and further used to measure the viscosity of bitumen for temperatures ranging upwards from the softening point. Two terms; Static effective & Dynamic Effective Viscosity have been introduced for bitumen and a methodology has been suggested to assess these parameters.

Key words: Viscosity Measurement; Shear Viscosity; Static Effective Viscosity; Dynamic Effective Viscosity; Rotational Viscometer.

1. Introduction

Viscosity is an important property of consistency and presently the Bitumen, a material used as a binder in the construction of flexible pavements, is characterized by Viscosity Grading System. The Viscometers in general and rotating concentric cylindrical type viscometers in particular, available in the market, are very costly and this article presents the methodology adopted in devising a Rotating Concentric Cylinder Type Viscometer indigenously which measures the viscosity of fluid subjected to shear force by application of torque.

Viscosity is defined as the resistance offered by the fluid when it is subjected to a force. The force can either be a direct shear or shear produced by torsion. As per the Newton’s Law of Viscosity, the shear stress is proportional to the rate of shear deformation and the constant of proportionality is defined as the coefficient of Viscosity. Fluids which obey Newton’s Law are called Newtonian Fluids and which does not obey are Non-Newtonian Fluids. A wide variety of instruments are available to measure viscosity of fluids. They include: Rotating Concentric Cylinder Type, Rotating cone and Plate type, Rotating parallel discs, Sliding parallel plates, Falling body etc. In this paper, Rotating concentric cylinder type viscometer, also known as Rotational viscometer or Searle type viscometer is being discussed.

1.1 Scope and objective
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The paper attempts at presenting the methodology adopted to measure the shear viscosities of bitumen in rotational mode where the flow of bitumen is confined between two concentric cylinders with the prime objective of developing a low cost instrument indigenously.

1.2 Methodology adopted for viscosity measurement in the present study

As mentioned in the previous section, ‘Concentric Cylinder’ configuration is devised in the present study. In this type of viscometer, the fluid is made to flow in the gap between the two concentric cylinders, the outer being stationary and the inner one is movable with a spindle attached to a motor. The angular speed of the motor and the torque applied are measured and viscosity is determined at any given temperature. The main advantage of this type of viscometer is that the sample can be sheared continuously at a particular strain rate so that other steady state measurements can be performed. The expression for shear stress, as presented in [1] is given by

$$\tau(r) = \frac{T}{2\pi r^2 L_e}$$  \hspace{1cm} (1)

Where \( r \) represents the radius at which the torque is being measured, \( T \) is the measured torque and \( L_e \) is the effective length of the spindle used for torque measurement.

For a narrow gap between the cylinders (\( \beta = R_c / R_s \approx 1.2 \)), where \( R_c \) represents the inner radius of the outer cylinder while \( R_s \) represents the radius of the shaft, the velocity profile can be assumed, irrespective of the fluid type, as linear and the shear strain rate (\( \gamma \)) within the gap will be uniform and is represented by

$$\gamma = \frac{\omega_R - R}{R_c - R_s}$$  \hspace{1cm} (2)

In the above equation \( \omega_R \) represents the relative angular speed of two cylinders and \( \bar{R} \) represents the average radius of \( R_c \) and \( R_s \). The shear strain rate profile across the gap between the cylinders depend on the relative rotational speed, radii of cylinder and spindle and an unknown fluid property which still appears to be an open ended mystery. This is a complex problem and possible solutions are provided by different researchers in the form of infinite series.

In the present case, \( \omega_R \) can be represented as \( \omega_s \) or \( \omega_r \), the angular speed of the shaft, as the outer cylinder is always stationary. However, there is a simpler procedure that has been laid down in and also established by Germent Standards that for any fluid including Non-Newtonian, there is a radius at which the shear rate is virtually independent of fluid type for a given \( \omega_R \). This radius being a function of geometry alone is called representative radius, \( R_R \) and is determined as the location corresponding to the so called representative shear stress \( \tau_{ave} \), the average of shear stress at the interfaces of shaft and outer cylinders. The expression for \( R_R \) as presented in is given in equation (3) for ready reference.
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\[
R_R = R_0 \left( \frac{2\beta^2}{1+\beta^2} \right)^{\frac{1}{2}} = R_e \left( \frac{2}{1+\beta^2} \right)^{\frac{1}{2}}
\]  

(3)

Since the shear rate at the representative radius is virtually independent of the fluid type (Newtonian or Non-Newtonian), the representative shear rate is calculated for Newtonian fluid according to \[6\] is:

\[
\dot{\gamma}_R = \dot{\gamma}_{r=R_e} = \omega \left( \frac{\beta^2 + 1}{\beta^2 - 1} \right)
\]

(4)

It was observed in the same work that for a wide range of fluid types and cylinder geometries (\(\beta = 1\) to \(1.2\)), the expected errors were less than 1%. Therefore, the error associated with representative parameter concept is virtually negligible for all practical measurements.

Now, the apparent fluid viscosity is determined as the ratio between the shear stress and strain rate by dividing Equation (2) with (5), as given below.

\[
\eta = \eta_k = \frac{T}{R^2} \left( \frac{\beta^2 - 1}{4\pi \beta R^4 \dot{\gamma}_{r=R_e}} \right) = \frac{T}{\omega} \left( \frac{\beta^2 - 1}{4\pi \beta R^4 L_t} \right) = \frac{T}{\omega} \left( R^2 - R_e^2 \right)
\]

(5)

\[
\eta = \eta_k = \frac{T}{\omega} C
\]

(6)

It can be observed from the above equation that C is a constant, which depends on geometry of the outer cylinder, radius and the effective length of the spindle used for measurement. For measuring the torque and rotational speed of the spindle for determining the viscosity of the fluid, Permanent Magnet Direct Current Motor is used as the shearing devise in the present work. The Rotational Speed and Current drawn during the shearing process is taken for measuring the torque indirectly, as discussed in art. 5.

2. Description of the instrument and its operation

The instrument developed in the present study consists of a Worm Gear Screw Jack, used as a Mounting Device, which can be lowered or lifted; a shearing devise mounted on Screw Jack, Permanent Magnet Direct Current (PMDC) Motor, a regulated power supply unit for converting AC to DC, with a display of current and voltage, a cup consisting of two concentric chambers in cylindrical shape, a ball bearing for ensuring the verticality and a number of spindles used to shear the sample. A photo showing various components of the working model developed has been presented in Figure 1 for reference. The spindle is attached to the motor before the test. The temperature conditioning is achieved through a micro controller based temperature controller unit integrated with a relay based mechanism. The heater, RTD sensor and the relay unit are connected to temperature controller and the temperature to be conditioned can be set and ON/OFF modes of heater is achieved through magnetic switches of the controller. The sample whose viscosity is to be determined is poured in the inner Chamber and the outer chamber does the process of conditioning the fluid available in the inner chamber at the desired temperature. Once the sample attains the desired temperature, displayed by the display board, the motor is powered through regulated power.
supply. The display panel starts displaying the voltage and the current drawn by the motor for shearing the sample.

![Figure 1: Rotational viscometer](image)

The static effective and dynamic effective states can be deciphered clearly from the fact that the current drawn becomes stable after the initial shearing process. The tachometer attached with the instrument provides the angular speed corresponding to the stable state. The recorded measurements, both during unstable and stable states, are used to compute shear stress and the shear strain rate from the observed shearing speed. Then the static effective viscosity in unstable regime and dynamic effective viscosity in stable regime is computed using the expression presented in eq. (6). It is observed that the approximate time required to measure both static and dynamic effective viscosities at a chosen temperature and a chosen constant voltage is approximately 90 minutes. The unique feature of this instrument is that it can measure viscosities in a wide range of working temperatures ranging upwards from the softening point of bitumen. In addition, the developed instrument is capable of measuring the viscosities in a wide range of 1 Pas to 400 Pas in a reasonably accurate manner.

### 2.1 Motor selection

The crucial task of the development of the instrument is the selection of a suitable motor for shearing the bitumen, which has a wide range of viscosities expected at different temperatures. Based on the back calculation of torque requirements as shown in Table 1, the motor selection has been done. The geometric details of the cup and spindle used for bitumen are given in Table 2 for ready reference.

#### Table 1: Predictable viscosity values for the DC motor with varying Voltage

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Volts</th>
<th>24</th>
<th>18</th>
<th>12</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Speed</td>
<td>Rev/sec</td>
<td>15.33</td>
<td>10.07</td>
<td>4.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Torque to Speed Ratio</td>
<td>Kg.cm/rev per sec</td>
<td>0.53</td>
<td>0.81</td>
<td>1.7</td>
<td>3.4</td>
</tr>
<tr>
<td>Maximum Viscosity</td>
<td>Pa.s</td>
<td>63</td>
<td>95</td>
<td>200</td>
<td>400</td>
</tr>
</tbody>
</table>

#### Table 2: Detail of cup and spindle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of the Cylindrical Inner Chamber R_c</td>
<td>14.40</td>
</tr>
<tr>
<td>Radius of the Spindle R_s</td>
<td>12.24</td>
</tr>
<tr>
<td>Ratio $\beta$</td>
<td>1.17</td>
</tr>
<tr>
<td>Effective Length of Spindle L_e</td>
<td>12.54</td>
</tr>
</tbody>
</table>
Based on the spindle constant C, as given in the eq. (6), the torque to speed ratios have been worked out for various viscosity values and presented in the Table 3 for reference.

<table>
<thead>
<tr>
<th>Viscosity (Pas)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T/ω) (Kg.cm/rev per sec)</td>
<td>0.54</td>
<td>1.09</td>
<td>1.63</td>
<td>2.18</td>
<td>2.72</td>
<td>3.27</td>
<td>3.81</td>
<td>4.36</td>
<td>4.90</td>
<td>5.45</td>
</tr>
</tbody>
</table>

Keeping in mind the maximum viscosity to be measured and the geometric configuration of the cup, the motor has been selected and the torque to speed ratios, as mentioned in Table 2 are being ensured.

A DC motor with code EC 2409, used by the manufacturer, has been selected and the torque-speed and torque current characteristics plotted from the data supplied by the manufacturer and verified by a load test were presented in the Figure 2 & 3 for ready reference.
2.2 Static effective and dynamic effective viscosity

In any shearing process to determine the resistance offered by a material in response to applied torque, there will be a state where the material is about to be sheared, the material offers maximum resistance, torque will be maximum at this stage and hence the current drawn by the motor and the rotational speed will be a minimum. The viscosity corresponding to this stage is termed as Static Effective Viscosity and once the material gets sheared, the torque required to sustain the shearing process will be lesser and the rotational speed will increase accordingly. The viscosity corresponding to this state is called Dynamic Effective Viscosity. The terminology was earlier used in [9] where the viscosities have been computed for bituminous mixes rather than for binder alone. A hypothetical curve demonstrating the two types of viscosities is presented in the Figure 4 for clear understanding of this phenomenon.

![Figure 4: Static & dynamic effective viscosities (Hypothetical)](image)

In the present work, the instantaneous torque from the maximum current measured has been used to calculate the Static Effective Viscosity. However, it is to be noted here that if the angular velocity verses time profile for complete shearing period is captured using a micro controller based interfacing module, it is possible to calculate the static effective viscosity in a more accurate manner. The constant torque after stabilization period is used to calculate dynamic effective viscosity.

3. Validation of the instrument

The validation of the Instrument developed has been done with Glycerin, with a known viscosity at a specified temperature of 33°C. The sample is poured in the inner chamber, the temperature of which is controlled by the outer chamber. The spindle is attached to the motor shaft and the motor is operated at a specified voltage. Regression models have been developed to estimate the torque using the data provided by the motor supplier. These regression equations are summarized along with $R^2$ values for varying voltages in Table 4.

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Voltage (V)</th>
<th>Model</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>T=297.60-0.236*rpm</td>
<td>0.99</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>T=223.32-0.237*rpm</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>T=148.35-0.237*rpm</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>T=-2.2+18.598*i</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>T=-2.02+18.607*i</td>
<td>0.99</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>T=-1.688+18.566*i</td>
<td>0.99</td>
</tr>
</tbody>
</table>
It can be observed that the regression coefficient for the variable ‘rpm’ which is the angular speed in revolutions per minute is nearly same for all voltages indicating that the torque speed curves are parallel to one another for different voltages. The test results for Glycerin when subjected to shear were presented in the Table 5 for different voltages supplied.

**Table 5: Test results on Glycerin**

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Voltage (V)</th>
<th>Mean Current (amp)</th>
<th>Stable Speed (rpm)</th>
<th>Torque from Current (amp)</th>
<th>Viscosity (Pas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>18</td>
<td>0.210</td>
<td>929</td>
<td>1.89</td>
<td>1.91</td>
</tr>
<tr>
<td>12</td>
<td>0.190</td>
<td>569</td>
<td>1.84</td>
<td>3.03</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.175</td>
<td>300</td>
<td>1.46</td>
<td>2.14</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>2.36</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It can be observed that the average viscosity obtained using the fabricated instrument is very close to that of glycerin at the stated temperature. To verify the reproducibility of the results, same experiment is being carried out number of times and the values have not deviated beyond Plus or minus 0.5%. Hence, studies have been carried out on VG – 30 grade bitumen samples, the details of which are presented in the following article.

**3.1 Details of experiments carried out on Bitumen**

As per the existing grading system, out of the 4 grades specified in the code of practice, VG-30 grade has been recommended for use in India based on the prevailing environmental conditions [11]. For the purpose of grading the bitumen, many agencies adopt capillary viscometer, where viscosity is measured based on the flow under gravity, though this viscometer is not so versatile to capture dynamic and static states of flow, due to its availability at cheaper price.

In the present work, an attempt is being made to measure the shear viscosity of VG 30 grade bitumen in rotational mode covering the range of temperatures from the softening point up to 135°C so that the property of consistency can be understood at varying temperatures. The results observed have been summarized and presented in Table 6. In this Table, first five columns indicate the observed / set variables which include: The temperature of the test, voltage, maximum current, stable current and stable angular speed. Variables in the remaining four columns indicate the estimated variables. As discussed in the art. 7, the torque is estimated from the equations presented in Table 4, from the measured current, the viscosity is computed using eqn. (6) by computing the constant C. The time versus current plots and shear viscosities for various temperatures are presented in Fig. 5 & 6. It is clear that the viscosity profiles follow that of current drawn during the shearing process.

**Table 6: Test Results on Bitumen**

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Voltage (V)</th>
<th>Max. Current (Amp)</th>
<th>Stable current (Amp)</th>
<th>Stable Speed (RPM)</th>
<th>Torque from current (Ncm)</th>
<th>Torque corr. to max. current (Ncm)</th>
<th>µ&lt;sub&gt;static&lt;/sub&gt; (PaS)</th>
<th>µ&lt;sub&gt;dyn&lt;/sub&gt; (PaS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>18</td>
<td>4.42</td>
<td>2.09</td>
<td>787</td>
<td>36.88</td>
<td>80.23</td>
<td>150</td>
<td>53</td>
</tr>
<tr>
<td>65</td>
<td>18</td>
<td>3.83</td>
<td>1.28</td>
<td>828</td>
<td>21.80</td>
<td>68.70</td>
<td>121</td>
<td>30</td>
</tr>
<tr>
<td>75</td>
<td>12</td>
<td>1.05</td>
<td>0.48</td>
<td>557</td>
<td>10.60</td>
<td>11.72</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>95</td>
<td>12</td>
<td>0.33</td>
<td>0.29</td>
<td>603</td>
<td>7.07</td>
<td>7.82</td>
<td>8</td>
<td>7</td>
</tr>
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</thead>
<tbody>
<tr>
<td>120</td>
<td>12</td>
<td>0.31</td>
<td>0.27</td>
<td>590</td>
<td>6.70</td>
<td>7.44</td>
</tr>
<tr>
<td>135</td>
<td>12</td>
<td>0.22</td>
<td>0.20</td>
<td>610</td>
<td>2.02</td>
<td>2.39</td>
</tr>
</tbody>
</table>

120° 12° 0.31 0.27 590 6.70 7.44
135° 12° 0.22 0.20 610 2.02 2.39

Figure 5: Time Vs current plot for different temperatures

![Time Vs current plot for different temperatures](image)

Figure 6: Shear viscosities of Bitumen in rotational mode

![Shear viscosities of Bitumen](image)

4. Conclusion

In this paper, an attempt has been made to give a brief overview of viscosity measurement and the details of design and fabrication of an indigenous Rotational Viscometer for measuring viscosity of bitumen. The direct measurement of torque is done with due to high cost involvement for the necessary data acquisition systems and hence, an alternative technique of measurement of the torque has been presented using angular speed and current observations. There is no visible history of measuring static effective and dynamic effective viscosities for bitumen and an attempt is being made in this research activity to estimate the viscosity values both at static and dynamic effective stages. The validation of the equipment
is done with Glycerin at a stated temperature of 33\(^\circ\)C and it is observed that the viscosity calculated is almost matching the rated viscosity of glycerin even during numerous reproducibility checks. Further, the process of establishing both static and dynamic effective viscosities at various temperatures above the softening point of bitumen is also been demonstrated using the instrument developed with fair level of accuracy. Further fine-tuning of the instrument is still in progress with a view to make the process more automatic and accurate.

5. References


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9. Laszlo A.Gomze et al, (2008), The effect of temperature and composition to the rheological properties of asphalt pavements; Material Science Forum; 589, pp 85-91
