DEVELOPMENT AND TESTING OF DIRECT SHEAR RHEOMETER AS AN ALTERNATIVE LOW COST INSTRUMENTATION FOR MEASURING VISCOSITY AND COMPLEX MODULUS OF BITUMEN BINDERS

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ABSTRACT

Viscosity and Complex Modulus are very important rheological parameters in the characterization of bitumen used as binder material in construction of flexible pavements. In India, the bitumen is characterized by Viscosity grading system and four grades have been specified primarily based on the viscosity of the sample and other parameters. Viscometer and rheometer are the instruments used to determine the viscosity and complex modulus of bitumen respectively. Out of these two equipments, many highway agencies procure viscometer while leaving the rheometer as this equipment is unaffordable on many occasions. It would be beneficial for these agencies if an indigenous as well as cost effective instrument be developed and made available at reasonably low price with acceptable accuracy levels.

With this background in mind, an attempt has been made in this work to devise an instrument used to measure the viscosity and complex modulus based on loads applied in direct shear mode indigenously. A microcontroller based temperature control unit has been set up with a relay control to maintain the temperature of the water medium in which the sample will be sheared at the desired level. A standardized bitumen sample specimen will be encapsulated in a mould which has a fixed top portion and movable bottom portion. The bottom portion of the mould is moved forward horizontally at a predefined rate of shear loading in water medium. The shearing process of the sample is recorded in a video and is retrieved subsequently for further analysis.

From the time Vs shear displacement graph, the velocity profile of the trolley or the shearing phenomenon of the bitumen sample can be understood and shear stress, strain and strain rates are mathematically computed. From these parameters, the viscosity and complex modulus of the sample can be determined

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using standard mathematical models. A few experimental investigations, carried out on bitumen with known properties, have revealed that the results are validated within acceptable tolerance limits.

Key Words: Bitumen rheology, Viscosity, Complex Modulus.

1. Introduction

Viscosity and complex modulus are two important parameters considered in the in bitumen rheology and are used in the super-pave specification of bitumen used as a binder material in the construction of flexible pavement. It is a Viscous Visco-elastic liquid at room temperature [2]. In India bitumen is characterized as per Viscosity grading system and four grades have been specified in IS 73 – 2006 [3]. Measurement of viscosity of bitumen at 60^0C is necessary to identify the grade of bitumen. It is not very not clear until now with regard to the mode of measurement of viscosity [4] whether it is static effective or dynamic effective, i.e., the maximum resistance offered by the material (static effective) to flow and sustained resistance (dynamic effective) after yielding. In other words, the force required to start the deformation process and force required to sustain the same. Brookfield Viscometers [6] are very popular in measuring the viscosities but they measure at any given temperature with out bringing in the static and dynamic effects. Further, there is no provision to get a graphical relation between the viscosities and period of measurement as one would be interested to know the yielding behavior of bitumen in terms of maximum torque demanded by the sample and sustained torque after the shearing process. Here the word the torque analogous to force is used as the Brookfield’s viscometer is essentially a rotational viscometer.

The other parameter of interest is *complex modulus*, G*, defined as the ratio between the shear stress and shear strain. The term *complex* is used as there will be elastic as well as viscous response when loads are applied. The equipment used for the viscosity measurement. Rheometers [1] are very popular in measuring the Complex modulus and phase angle, a parameter which can speak of the degree of departure either from a truly elastic behavior or a truly viscous behavior.

The above instruments are very costly and hence there is a great need to devise the instruments indigenously. The authors are now developing a Rotational Viscometer which can address not only measuring just the viscosity value but also its variation over the span of measurement period as discussed in the earlier paragraph.

The present article focuses on yet another devise, a low cost alternative for measuring the viscosity and complex modulus of bitumen binders especially for medium and low temperatures. The present set up is not suitable for high temperatures, i.e., greater than softening point.

2. Direct Shear Rheometer Test Setup

The direct shear rheometer developed in the present study is intended to measure complex modulus and viscosity of the bitumen sample. The apparatus consists of a table on which the set up is placed. A glass beaker in which the sample will be sheared at the desired temperature is kept on the table. A trolley is made to lie inside the water pored in the beaker to maintain the desired temperature. The sample is held between two moulds as shown in the Fig 1.

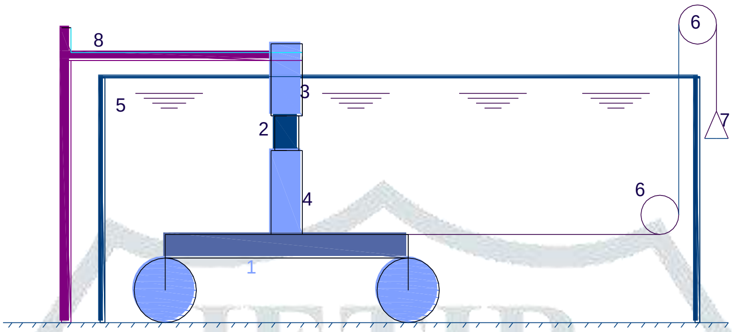

Fig. 1 Schematic Diagram of Direct Shear Rheometer

The instrument has the following components and are listed as per the number given in Fig 1.

1. Trolley
2. Lower Mould
3. Upper Mould
4. Bitumen Sample
5. Water Medium
6. Pulleys
7. Loading Pan
8. Fastenings
9. RTD Sensor
10. Heater

A Resistance Temperature Detector Sensor (RTD) integrated with the Microprocessor based Temperature control unit and Relay Unit is placed near the sample to detent the temperature of the sample.

3. Methodology

The component parts of the instrument proposed in the present study has been discussed in the previous section. The process of testing and the methodology adopted to arrive at viscosity and complex modulus will be discussed in the present section.

The bitumen sample to be tested in the present study will have the shape of square prism. The bitumen is heated and poured in the moulds and then cured under water at room temperature. The sample is then removed and is inserted into the moulds. The height of sample for strain measurement and the cross section dimensions are measured using a calipers with a precision of 0.01mm before the commencement of the test.

The lower mould will be fixed to the trolley and the upper one will be attached to the rigid support. Once the sample is inserted, the temperature is set up to the desired value and the medium is heated. When the temperature reaches the desired value, the relay mechanism of the microprocessor based temperature controller unit will switch off the heater automatically using magnetic switches. After few cycles of fluctuations, the temperature gets stablised and the loads are now added to the pan at a predefined rate and the shearing process is captured in a video. The data is retrieved from the video file for further analysis. From the recorded video, the shear displacement undergone by the sample is determined at every 2 or 5 seconds interval. The deformation verses time graphs are prepared for further analysis. The variables measured in the present study include: the load applied, deformation produced at a specified time during the shearing process, time of observation. From the geometry of the sample, and from the measured variables the shear stress, shear strain, shear strain rate are calculated.

The shear stress is given by the expression

$$\tau = \frac{F}{A} \quad \text{............Eqn. (1)}$$

The shear strain is expressed as

$$\gamma = \frac{x}{h} \quad \text{............Eqn. (2)}$$

and the strain rate is written as

$$\dot{\gamma} = \left(\frac{1}{h}\right)\frac{dx}{dt} \quad \text{............Eqn. (3)}$$

And finally

$$\eta = \frac{\tau}{\dot{\gamma}} \quad \text{............Eqn. (4)}$$

The complex modulus is given by

$$G = \frac{\tau}{\gamma} \quad \text{............Eqn. (5)}$$

Where

τ - *Shear stress*

γ - *Shear strain*

γ - *Shear strain rate*

η - *Viscosity*

F - Shear force

x - deformation produced at any instant 't'

h - sample thickness

A - area of cross section

In order to calculate the strain rate, time verses deformation scatter plots are prepared and equation is fit and expressed in the form

$$x = a_0 + a_1 t + a_2 t^2 \quad \text{.......................................Eqn. (6)}$$

Since bitumen behaves as non-Newtonian fluid. For fluids which obey Hooke's Law, the deformation function would be obviously be linear. Once the function is obtained in the above form, the first derivative at any given time 't' divided by the sample height 'h' would give the corresponding strain rate as mentioned in the Eqn. (3).

4 Test results

The testing of the instrument developed is in process and the authors are presenting here the measurements corresponding to a temperate of 30 degrees. Measurements and analysis for other temperatures is under progress. A set of graphs developed for the samples tested at 30^0C is presented in this section.

Test Data:

Rate of loading = 100gm /20sec

= (0.1x9.81/20)*60

= 2.94 N/min

Height for strain measurement = 22 mm

Length of embedment into the moulds =25mm

Test Temperature = 30^0C

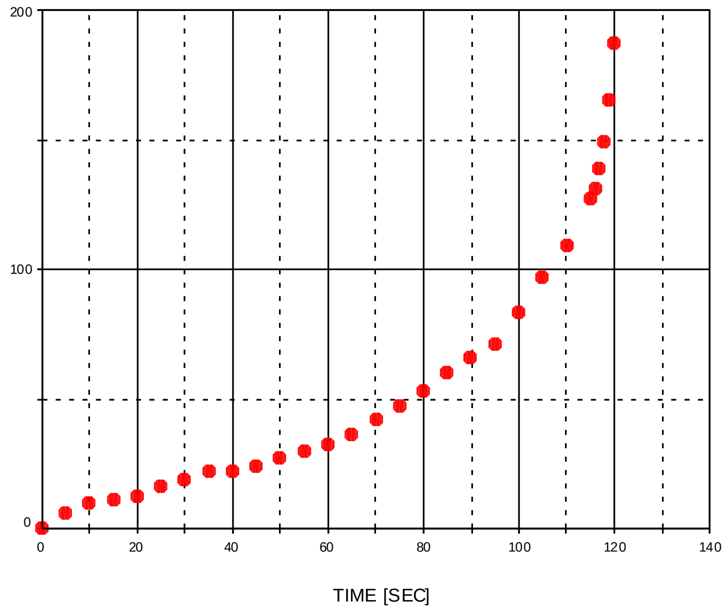

Fig. 2(a) Shear deformation Vs Time Plot

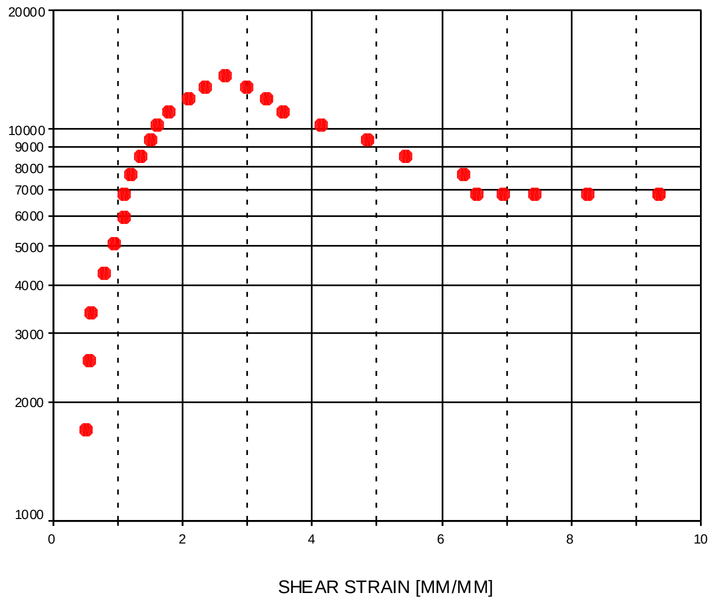

Fig. 2(b) Shear stress Vs Shear Strain Plot

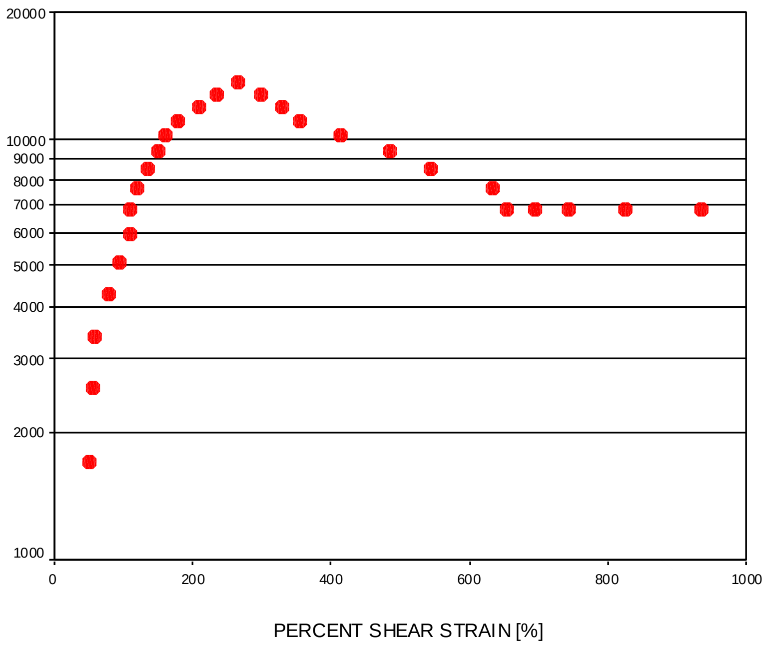

Fig. 2(c) Shear stress Vs Percent Shear Strain Plot

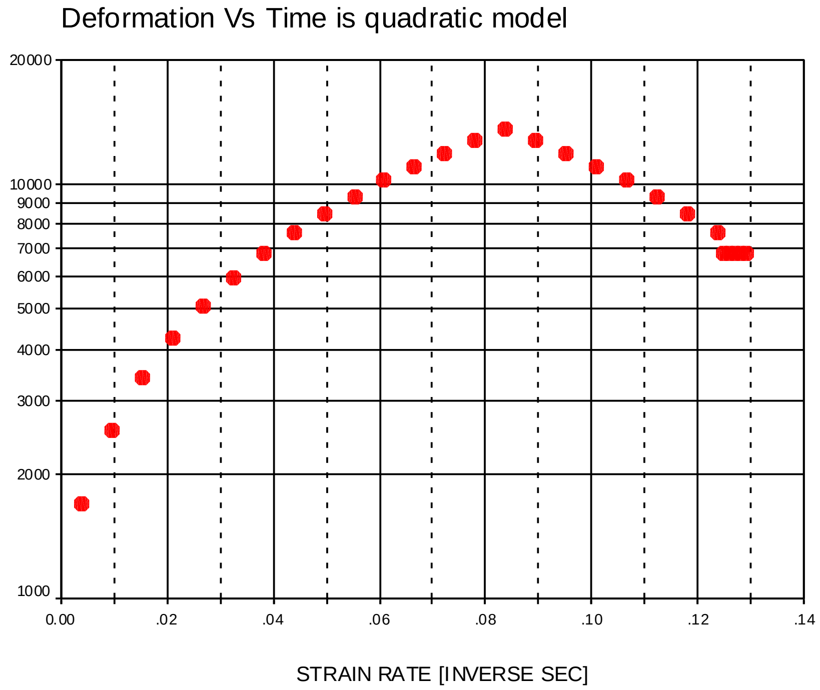

Fig. 2(d) Shear Stress Vs Shear Strain Rate Plot

Time Verses shear deformation is plotted and presented in the Fig 2(a). From the figure it is evident that the bitumen behaves as non-Newtonian fluid. The shear stress and shear strain variation is presented in the Fig 2(b) from which the complex modulus can be assessed at any given strain by taking the first derivative of the stress function expressed in terms of strain. Since at time zero, the deformation is zero the equation will not have a constant and so for other cases. From the equations developed, at predefined time intervals, derivatives have been computed and shear strain rates have been found and a graph between the shear stress and shear strain rate is plotted and shown in Fig 2(d). The regression analysis done different variables is presented in Table 1.

Table 1 Summary of statistical Models

Sl. No	Regression	Model	R^2	F
1	Deformation on time	$x = -0.1476t + 0.0114t^2$	0.976	290.57
2	Shear Stress on Shear strain	$\tau = 7084.11\gamma - 985.80\gamma^2$	0.979	512.76
3	Shear stress on shear strain rate	$\tau = 280410\dot{\gamma}$ -2.E+06 $\dot{\gamma}^2$	0.988	1067.13

Table 2 Complex Modulus Values

Parameter	Complex Modulus Value (Pa)
Initial Tangent Modulus	7084
Secant Modulus at 15% of Ultimate stress	6864
Secant Modulus at 25% of Ultimate stress	6721
Secant Modulus at 50% of Ultimate stress	6280

Table 3 Viscosity Values

Parameter	Viscosity Value (Pas)
Slope of the tangent drawn at origin on stress verses strain rate curve named as initial tangent viscosity	280410
Secant Viscosity at 15% of Ultimate stress	269039
Secant Viscosity at 25% of Ultimate stress	260749
Secant Viscosity at 50% of Ultimate stress	237576

It is customary to report a number of modulii for the materials where the stress verses strain relation is non linear. The value of the initial tangent modulus, representing the slope of the tangent at origin and secant modulus representing the slope of a line joining a point on stress strain curve for a specified proportion of ultimate stress. In Table 2 the complex modulus values have been presented and Table 3 shows the values of viscosity at the temperature of 30^0C. The analysis for other temperatures is in progress and hence could not be presented here in this study.

5 Summary

This article has presented a possibility of measuring Viscosity and Complex modulus of bitumen binders using a low cost alternative instrument named Direct shear Rheometer. The samples are sheared using direct shear mode and will confirm to square prism shape. The sample is sheared in a water medium by inserting between two moulds where the upper mould will be fixed and the lower mould will be attached to a trolley which will move in horizontal direction. The temperature control was achieved using a Microcontroller based temperature controller integrated with a relay unit and an Resistance Temperature detector Sensor. The shearing process is captured in a video and the deformation data is retrieved for further analysis. The method of computation of Complex Modulus and Viscosity has been discussed and the results were presented for a temperature of 30^0C. As the experimental work is in still progress the data pertaining to other temperatures was not presented.

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