STUDY OF PROPERTIES OF SAND ASPHALT USING A TORSIONAL RHEOMETER

A Thesis

by

LAVAN KUMAR REDDY KASULA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2003

Major Subject: Mechanical Engineering

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ABSTRACT

Study of Properties of Sand Asphalt Using a
Torsional Rheometer. (August 2003)
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The modeling of Sand Asphalt and experiments to measure their rheological properties are of vital concern to many industrial processes especially highway and roadway pavement construction industry. A variety of hot mix asphalt mixtures are used in highway and runway pavement construction, with each mixture catering to a specific need. These mixtures vary in type and percentage of aggregates and asphalt used and consequently exhibit marked differences in their response. The main thrust of this research is to provide experimental data which would be helpful in determining the efficacy of the constitutive models that have been developed for these hot mix asphalt mixtures. Here we attempt to provide experimental data in the raw form for Sand Asphalt mixtures that would be helpful in the theoretical modeling efforts involving asphalt materials using a continuum point of view. For example the data obtained can be of immense help to evaluate the constitutive model developed by Murali Krishnan and Rajagopal. The Sand Asphalt mixture in their model is modeled as 'homogenized' single constituent due to the peculiarity of its makeup. The constitutive model of Murali Krishnan and Rajagopal is based on a thermodynamical framework for materials possessing multiple natural configurations (multiple stress free states) to derive the constitutive equations. Recently an Orthogonal Rheometer was built to characterize the granular solids by Gupta and

Rajagopal which was later used by Baek in the torsional mode. In this work we have used the same Torsional Rheometer with some minor modifications in the design to measure some general properties of Sand Asphalt mixtures. Sand Asphalt mixtures, due to their non-linear viscoelastic character, exhibit ‘normal stress effects’ and ‘stress relaxation’. The Rheometer that we used was able to capture these responses with high precision. We have laid out proper procedures for the further testing of asphalt related mixtures. A typical sand asphalt mixture sample in cylindrical shape was used as the test specimen. From this work some interesting data was obtained. A remarkable observation was that as the shear rate is increased, the normal force and torque generated initially decrease, but beyond a certain shear rate they attain a constant value.

To My Parents

ACKNOWLEDGMENTS

I would like to thank Prof. Rajagopal for his guidance, encouragement and inspiration throughout this work and for being the embodiment of immense patience. I would like to express my appreciation to Dr. Dallas Little and Dr. Murali Krishnan for extending their help in the successful running of the experiments as well as their support, invaluable classes and help in this project. I would also like to express my sincere gratitude to Krishna Kannan, Parag Ravindran, Anand Mohan, Pradeep Hariharakumar, Sharat Chandra, Raghuram Kannan and Seungik Baek for their constant feedback throughout the period of the project work.

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CHAPTER I

INTRODUCTION

“All moves,” said the Ephesian Heraclitus; the alternate connotation, “everything flows,” applies to earth’s materials and is the basis of the science of flow, or Rheology (see Barth [2]). Rheology is the branch of science concerned with the flow properties and deformations of matter, and asphalts are among the most unique materials for the rheologist. Understanding the rheological response of asphalt is necessary for determining how and where these materials can be used. A rheometer is an experimental setup or instrument used for this specific purpose of characterizing the material response (in other words, the rheological properties of the materials).

A. Characterization of the Behavior of Asphalt Mixtures

Asphalt is one of man’s oldest engineering material. Its adhesive and waterproofing properties were known at the dawn of civilization. The derivation of the word asphalt is from the Homeric Greek, asfalton, or asfaltos, meaning sticky, and later as an adjective meaning firm. Asphalt is defined as ‘a brown to black cementitious material, solid or semisolid in consistency, in which the predominating constituents are bitumens which occur in nature as such, or are obtained as a residue by refining petroleum’ as defined in Barth [2]. The behavior and properties of asphalt are dependent on their constitution or physical make-up. Hot Mix Asphalt is one of the commercially available asphalt types used mainly in the paving industry due to its high strength and durability. There are many different varieties of hot mix asphalt mixtures available in the market today.

The journal model is *IEEE Transactions on Automatic Control.*

Asphalt Rheology basically concerns studying: 1. The kind of colloidal system (to be measured in rheological units), 2. The physical or mechanical stability of this colloidal system under varying conditions of temperature, time, pressure, load application, percentage of asphalt content and other such factors imposed on asphalt. According to the review done by Barth [2], the foundation of Asphalt rheology was mainly laid by the research work of Hencky, Weissenberg and Reiner followed by that of Lee, Rigden, Blair and Bikerman. According to Barth [2], Walther compares various asphalts in a large series of rheological diagrams for propane asphalts, asphalt-wax mixtures, lignite tars and pitches, etc while Schlosser and Hempel discuss the mathematical aspects of asphalt rheology. Ferry discusses the viscoelastic properties of polymers and their dependence on chemical composition while Asbeck discusses the basic calculations for several viscosimeters.

B. Torsional Rheometer

The torsional rheometer is essentially two parallel disks rotating about an axis, while in the orthogonal rheometer the axis are non-coincident (see Maxwell and Chartoff [10]). A characteristic response of non-linear fluids and solids is that significant normal forces develop while trying to enforce a torsional shear flow (see Truesdell and Noll [26]). The torsional rheometer is capable of measuring the required normal force and the shear forces generated by the application of torsion and also the forces in the x and y directions. It is also capable of measuring and controlling the rotation rate between the top and the bottom axes. Torsion flow is locally a shear flow and it is defined through

$$V_x = \lambda z y \ , \ V_y = \lambda z x, \ V_z = 0, \tag{1.1}$$

where λ is a constant, and V_x, V_y, V_z are the x, y and z components of the velocity field V. Torsional flow defined through (1.1) is a viscometric flow. Rajagopal [18] considered a generalization of above class of flows wherein

$$V_x = \omega(z)y,\ V_y = \omega(z)x,\ V_z = 0, \tag{1.2}$$

where $\omega(z)$ is an arbitrary function of z that needs to be determined by solving the equations of motion. The next step in the data reduction procedure is to assume a specific constitutive model, enter the above expressions into the balance of linear momentum to obtain the governing equations, which have certain material moduli that appear as coefficients. Solution of the boundary value problem and comparison of the expressions for the torque and the axial force in the z-direction will provide a means for obtaining some information concerning the material moduli. Since there are many constitutive models available in the literature, it is necessary that with the available experimental data, we choose the right model before actually working on any data reduction scheme.

CHAPTER II

SAND ASPHALT

Asphalt is one of the oldest materials available and its use by mankind for diverse purposes has been continuing from times immemorial. Hence there is an ever growing need to understand the behavior and material response of Asphalt related materials. Maxwell [11] was one of the earliest researchers to recognise the viscoelastic nature of Asphalt and in fact describes a viscoelastic material using Asphalt by 'Thus a block of pitch may be so hard that you cannot make a dent in it by striking it with your knuckles, and yet it will in course of time flatten itself by its own weight, and glide downhill like a stream of water.'

The mechanical and flow properties of Asphalts cannot be adequately described by the classical Newtonian fluid model. For these kind of materials, an imposed shear usually results in a change in the internal structure of the material. These materials also require an additional normal force on the surface of the shearing motion to maintain the surface in its original position. This phenomenon was first demonstrated by Weissenberg in 1949 for the case of fluids at the first international congress of rheology, where he showed that if some fluids are subjected to torsional shearing between parallel co-axial or non-co axial discs, the liquid can force the plates apart unless a normal force is applied. This is also applicable to materials such as Asphalt. Saal and Koens [22] recognised that viscosity of asphaltic material depended both on shear components and normal components. Moreover these materials exhibit 'memory effects' or viscoelastic behavior i.e., they have a tendency to both store and dissipate mechanical energy. These materials respond to a suddenly applied and maintained state of stress by an instantaneous deformation followed by a flow process i.e., they are said to have 'relaxation' and 'creep' characteristics, which means that the stress in these types of materials depends upon the history of deformation. Traxler and Coombs [25] in 1937 found that the development of internal structure inhibits the flow of the Asphalt material.

From the above discussion, it becomes obvious that any effort to characterize the response of Sand Asphalt or Asphaltic materials in general, requires a comprehensive system of tests, which include examinations of parameters such as 1. Viscosity 2. Elasticity 3. dilatancy or 'normal stress effects' 4. strain hardening. Unfortunately the present testing procedures do not account for all of these above mentioned factors. Nevertheless these studies are important due to the fact that they provide some insight into the behavior of Asphalt.

Presently there are many different testing procedures available which are used to characterize the mechanical response of Asphalt, based on its performance. These tests take into account different criteria like the test geometry, type of load applications and the type of load pulse. Some of these tests in wide use today are Direct Shear Test, Simple Shear Test, Direct Tensile Testing, Torsional or Rotational testing, Uniaxial or Triaxial Compression Testing, Indirect tensile testing, Flexural beam testing, Triaxial Creep Testing. The objective of these test methods is to accurately and reliably measure the mixture response characteristics or parameters that are highly correlated to the occurance of pavement distress over a diverse range of traffic and climactic conditions. Mainly three distress types are considered by the above mentioned test procedures, namely permanent deformation or rutting, fatigue cracking or cracking, thermal cracking. The Triaxial Dynamic Modulus Test is used to study rutting and is one of the oldest and best documented of the triaxial compression tests. It essentially consists of applying a uniaxial sinusoidal compressive stress to an unconfined or confined HMA cylindrical test specimen and studying the stress-strain relationship for linear viscoelastic material, defined by a number called the 'complex number' (E^*).

The Superpave Shear Tester and the Field Shear Tester are aimed at measuring mixture properties in terms of Shear Modulus (G^*) which is analogous to the Complex Modulus, while the Triaxial Compressive Strength Tests are used to measure a mixture's unconfined compressive strength. Confining pressures are also used to let the failure envelopes develop, which in a way reflects the interlocking capability of the aggregate matrix and also the cohesion, c, which shows the bonding mechanisms of the binder. In the Static Triaxial Creep Tests on asphaltic materials, the Compliance *D(t)* (which is the reciprocal of resilient modulus) is used to study the pavement distress, which allows for the separation of the time-independent and the time- dependent components of the strain response. The static creep tests, using either one load -unload cycle or incremental loading- unloading cycles, provides information to determine instantaneous elastic (recoverable) and plastic (unrecoverable) components (which are time independent), as well as the viscoelastic and viscoplastic (which are time dependent) of the material response. Indirect tensile tests are used for evaluating the HMA mixture's susceptibility to moisture damage. These testing procedures are described in NCHRP [14].

Most of these testing procedures are based on the assumption of an implicit model e.g., most of the models falling in the purview of SUPERPAVE etc.(see Murali Krishnan and Rajagopal [13] for more details) are for linearly viscoelastic materials. Given the non-linear viscoelastic response of asphalts, such testing procedures do not yield results that truly characterize the behavior of asphalt. Moreover the testing procedures do not exactly replicate the working conditions of asphaltic materials or asphalt concrete (e.g for the triaxial test, the maximum load applied is around 275 kpa (100 psi) whereas the tyre pressure on the pavements vary from 80 psi- 640 psi(

in case of aircrafts)). Since the internal structure of asphaltic materials or asphalt concrete keeps changing with time and conditions, it is necessary to have a testing procedure that is capable of replicating the field conditions of asphalt. Any testing procedure adopted should be able to characterize the very important characteristics of asphalts like the normal stress effects, stress relaxation and their dependence on the shear rate. Previous experiments on granular materials using Torsional Rheometer by Gupta [7] and Baek [1], show that the Torsional Rheometer is ideal to study the effects due to normal stresses or dilatancy and also the shear rate dependence of these. Moreover the experimental data obtained for this was in the raw form, without any implicit assumptions on the constitutive model to be used. Hence it was felt ideal to study the behavior of asphalts using Torsional Rheometer setup. More information on Torsional Rheometer and its background is provided in Chapter-III.

The following sections deal with the preparation of Sand Asphalt test specimens for the experiments using Torsional Rheometer.

A. Gradation of Sand Asphalt Mixtures

The Sand Asphalt mixture consisted of River Sand of 92 % of total weight and Asphalt PG 64-22 binder of 8% of the total weight of the mixture. The composition of sand mixture is shown in the table below. The gradation of the sand particles in the mixture was according to the specifications of the ASTM D 1073/ grading 3 specifications. The different sieve size and the weight proportion of them are shown in detail for a single specimen of $6''$ height and $6''$ diameter. The sand particles size varied from 2.36 mm to 75 micron. Before the preparation of the specimens, the rice specific gravity (R.S.G) of the sand asphalt mixture was to be determined in order to determine the theoretical maximum specific gravity of the material and thus the amount of material required for the preparation of the samples. The Air void percentage was taken to be 4.4 % in the calculations to determine the amount of material required for fabrication of samples. The procedure of determining the R.S.G is given in the next sub-section. Composition of Sand-Asphalt mixtures for a single specimen of 6 in. height and 6 in. dia. is shown below:

Asphalt (by wt.)-8 % , Sand -92 %

Asphalt weight = 621.9 gm.

Volume of sample = $\pi D^2 H/4 = \pi$ *152*16.5/4=2916 cm^3

Air Void percentage =4.4 %

Weight of sample = (Volume of Sample) *(R.S.G)* [(100-Air Void percentage)/100]

= 7.152 kg

R.S.G =2.349 g/cc

Table I. Gradation of Sand Aggregates as per ASTM D 1073 / Grading 3.

Sieve size	% Passing (Permissible)	% Passing	% Retained	Wt. of aggregate (ea. $6'' * 6''$ Sample)
No-8	95-100	100	0	0
No-16	85-100	92.5	7.5	0.5364 kg
No-30	65-90	77.5	15.0	1.0728 kg
No-40	30-60	45.0	32.5	2.3244 kg
No-100	5-25	15.0	30.0	2.1456 kg
No-200	0-5	2.0	13.0	0.9298 kg
Pan	-	-	2.0	0.1431 kg

B. Determination of R.S.G of Sand Asphalt Mixture

Before the preparation of the specimens, it was necessary to determine the R.S.G of the material to estimate the theoretical maximum specific gravity of the specimens and hence the amount of material required for preparation. The Test procedure involved taking 1500 gm of Sand Asphalt material with Sand aggregate percentage being 92% and Asphalt being 8% and heating them separately in a conventional oven up to a temperature of 155^{o}C. The gradation of the sand mixture is the same as specified by the ASTM D 1073 / grading 3 manual. The sand material is heated for duration of 2 hours while the asphalt binder is heated for 1 hour duration. The sand aggregate and the asphalt binder is then mixed thoroughly and allowed to cool to room temperature. Then the weight of the mixture in air is determined (A) and the weight of the pycnometer and solution (water) is determined (B). The mixture is then suspended in the pycnometer apparatus and vibrated till the loose sediments are washed away and the weight of the sample and the pycnometer is determined (C). From this the volume of the sample is determined (D= A+B-C). Thus the R.S.G of the sand asphalt mixture is then determined (A/D).

R.S.G of Sand Asphalt = A/D where A, B, C, D are as defined earlier.

C. Fabrication of Sand Asphalt Samples

The samples were first prepared in the size of $6''$ height and $6''$ diameter (shown in Fig [1]). The preparation of these samples of $6''$ diameter involved taking sufficient amount of sand mixture and asphalt binder as per the specifications of the ASTM D 1073 / grading 3 specifications. The Air Void percentage was fixed to be 4.4 % in the calculations.

Fig. 1. Sample Before Coring Test Specimens

1. Preparation of Samples

The Sand aggregate was taken in amounts required to prepare the sample and kept for heating in a conventional oven for duration of 1 day at temperature of 155^oC. The asphalt binder was heated to the same temperature for duration of 2 hours. Then the aggregate and asphalt were mixed thoroughly in a mixer and kept for heating in an oven for duration of 1 hour.

2. Compaction of Samples

The sample after duration of 1 hour, was then removed from the oven and transferred into a Gyratory Compactor for compaction, using a mold of height $6''$ and $6''$ diameter. The Gyratory Compactor enables in achieving uniform compaction in the material (and hence uniform density distribution more or less) since the compaction takes place in a gyratory motion. It also enables to fix the number of gyrations required to attain the Air Void Percentage required in the samples. Likewise the sample is kept in Gyratory Compactor for compaction and the number of gyrations fixed so as to attain the air void percentage as fixed in the calculations.

Fig. 2. Test Specimen After Coring

3. Coring of Samples

The compacted sample was then kept for cooling for duration of 1 day period. Then the 6$''$ diameter sample is cored to get the required cylindrical test specimens of 0.75$''$ diameter and 1.75$''$ height. The core bits (shown in Appendix C)were custom made which enabled to attain the required lowest diameter of 0.75$''$ for the test specimens. The test specimen is shown in Fig[2].

CHAPTER III

ORTHOGONAL RHEOMETER

The instrument used for characterizing the material response is the Orthogonal Rheometer. The instrument which we are presently using to test the sand asphalt samples was originally developed by Gupta [7] and we later modified it to operate under torsional mode. The Orthogonal Rheometer was originally developed for measuring the properties of viscoelastic solids. Maxwell and Chartoff [10] later modified this instrument to measure the properties of polymer melts and viscoelastic solids. The operating principle of the Orthogonal Rheometer is that non-linear materials exhibit phenomena called ‘dilatancy’ and ‘normal-stress effect’. Dilatancy is most predominant in granular materials and is defined as the phenomenon of expansion of voidage that occurs in a tightly packed granular arrangement when it is subjected to deformation. This in a way results in the exertion of forces in the normal direction i.e., leading to normal stress effects similar to the ones in Non-Newtonian fluids.

The Orthogonal rheometer that we have used for our work is the same one Baek [1] used for testing granular materials, except for minor modifications in the design. We modified the Torsional Rheometer used by Baek by replacing the disk and cup to hold the granular material, with two grippers for holding the sand asphalt sample and also adding a speed reducer so as to be able to run the experiments at a very low RPM speeds. The sand asphalt sample was held tightly by the grippers by the application of glue Epoxy DP 460, which had a high Bond Strength sufficient to hold the samples to the grippers. The Rheometer was also re-designed to accommodate a speed reducer attached to the DC motor which would enable the Rheometer to run at very low RPM rate (upto the order of 1 rev / 50 min). Consequently the alignment of the DC Motor was changed to a horizontal alignment due to space constraints.

The kinematics of the orthogonal rheometer is very well understood, hence is ideal to study the flow properties involving granular and asphalt materials.

The Torsional rheometer (shown in Fig [3] and Appendix C.) for this testing consisted of a main frame, upper shaft unit, lower shaft unit, 2 grippers and a Data Acquisition system along with sensors to measure the load signals generated. The material we used for the fabrication of grippers (diagram shown in Fig [4]) is aluminum as we found out that aluminum was able to withstand the stresses that develop in the sample while testing. The main frame dimensions are $5\frac{1}{2} * 2 * 1$ ft size and made by 1 inch steel plate for base and half inch steel plate for the sides. The upper shaft unit is fixed to the top of main frame and connected to a DC motor. The two biaxial x-y load cells, the uniaxial z load sensor are fixed to this upper shaft unit. The lower shaft unit is connected to the bottom of the main frame and is placed on a positioning table so as to control its movement in the z direction (top-bottom) and in the y direction (back -forth). The torque sensor, the DC motor (torque motor) and the speed reducer are fixed to this lower shaft unit. The two grippers are attached to the top and bottom shaft units for holding the samples while being tested.

A. Operating Principle of Orthogonal Rheometer in Torsional Mode

The Orthogonal Rheometer when the axes are set to be coincident is the Torsional Rheometer. It essentially consists of two grippers attached to the two shaft units capable of rotating at distinct angular speeds about a common axis. The sand asphalt samples to be tested is placed between the 2 grippers and held to the grippers by the application of glue Epoxy DP 460. The depth of the sample glued to the grippers is 1.75 inch, thus having a clearance length of 1.25 inch. When the DC motor is turned on, due to the rotation of the grippers, normal forces develop in addition to the shear forces due to the non-linear nature of the samples. Measuring these forces helps us in characterizing the material response of the samples. The sensors attached to the main frame measure these forces.

A uniaxial load cell attached to the upper shaft unit measures the normal force (in z-direction). This is a split thrust bearing type sensor. The 2 biaxial load cells attached to the upper shaft unit measure the forces in the x, y directions. The torque sensor, which is an in line rotary transformer type sensor, attached to the lower shaft unit measures the shear forces developed. The forces along 2 mutually perpendicular directions of the grippers is measured by using a bearing one end of which is in contact with the load cell. The analog data generated from the sensors is converted to digital form by the A/D converter and fed into the Data Acquisition system of the computer for data processing after Signal Conditioning. Signal Conditioning involves amplifying the signals from the sensors so as to isolate them from other noise signals and then filtering them to eliminate the noise signals.

B. Design of Torsional Rheometer

The design aspects of the Torsional Rheometer is the same as in Gupta's design (Gupta [7]) except for minor modifications like rebuilding the DAQ systems and data processing tools, replacing the disk-cup arrangement with 2 grippers (see Fig [4], Appendix C) and replacing the DC motor with the one which is capable of running at very low rpm values (upto 1 rev/6 min) and attaching a speed reducer (external gear) to the motor which had which would enable the DC Motor to run at low RPM (upto the order of 1 rev/ 50 min.). Due to space constraint while accommodating the Speed Reducer in the Experimental Setup, the DC Motor's alignment was changed to be horizontal. The re-designed Torsional Rheometer is shown in Fig [3] and Appendix C.

1. Grippers

The grippers (shown in Fig [4], Appendix C.)are used to hold the test specimen while testing and they were made of aluminum material, each attached to the upper shaft unit and the lower shaft unit and each gripper capable of rotating at distinct angular speeds with the help of the DC motors attached to these shaft units. The design of the grippers is of utmost importance as it is very important that while testing the sample, it is gripped properly to the grippers. After much deliberation over the design of the gripper, we decided to use aluminum material for the fabrication of the gripper, after we made sure with the help of SolidWorks design software that aluminum grippers will be able to withstand the stresses that will be developed while testing. The method of gripping the sample to the grippers was by the application of glue Epoxy DP 460. We compared the high Bond Strength of the glue (around 3000 psi) to the shear strength of the samples to be tested and after making sure that the glue will be able to grip the sample to the gripper, we opted for this glue type.

2. Data Acquisition System (DAQ system)

a. Transducers

Transducers play an important role in the DAQ system in providing reliable and perfect data from the sensors. The DAQ system is shown in Fig [5]. The role of the transducers is to convert the physical response of the material under testing into electrical signals, which can be read and analyzed by the DAQ system. Gupta [7] in the design used an in line rotary transformer type sensor for measuring the torque.

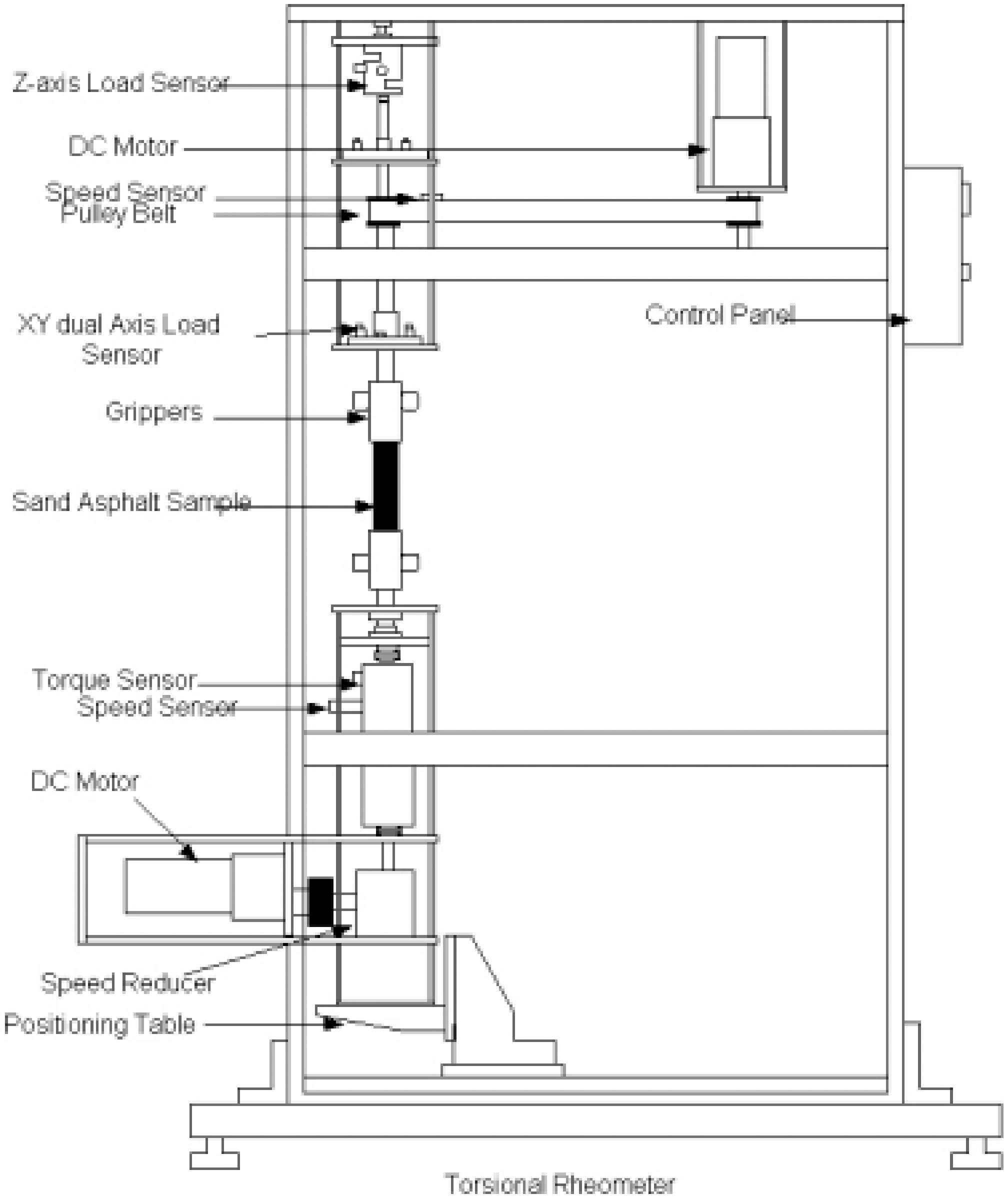

Fig. 3. Torsional Rheometer

Fig. 4. Grippers for Holding Sand Asphalt Test Specimens

All the transducers in this experimental setup were voltage output type transducers which converted the physical response into voltages. Excitation and amplification was needed for all the sensors except the torque sensor as it had its own source of excitation and strain gage indicator attached to the instrument.

b. Signal Conditioning

The signals generated from the transducers must be converted into a form, which the DAQ system can analyze. Signal Conditioning basically consists of 3 main parts- excitation, amplification and filtering. The strain gages require a continuous source of excitation voltage for stable functioning. Hence we provided a 10 V excitation voltage source for 5 units, which were - 1 unit of uniaxial load cell and 4 units of biaxial load cells. The generated signals being in the millivolts range (0-20mV), requiring amplification as to isolate them from the other noise sources and also being able to be read by DAQ system. For this we used a National Instruments SCXI-1120 amplifier module along with the terminal block SCXI-1320 which ensured smooth and proper connection between the signals and the SCXI-1120. These signals after amplification were passed to the filtering module SCXI-1141 that filtered the unwanted noise signals

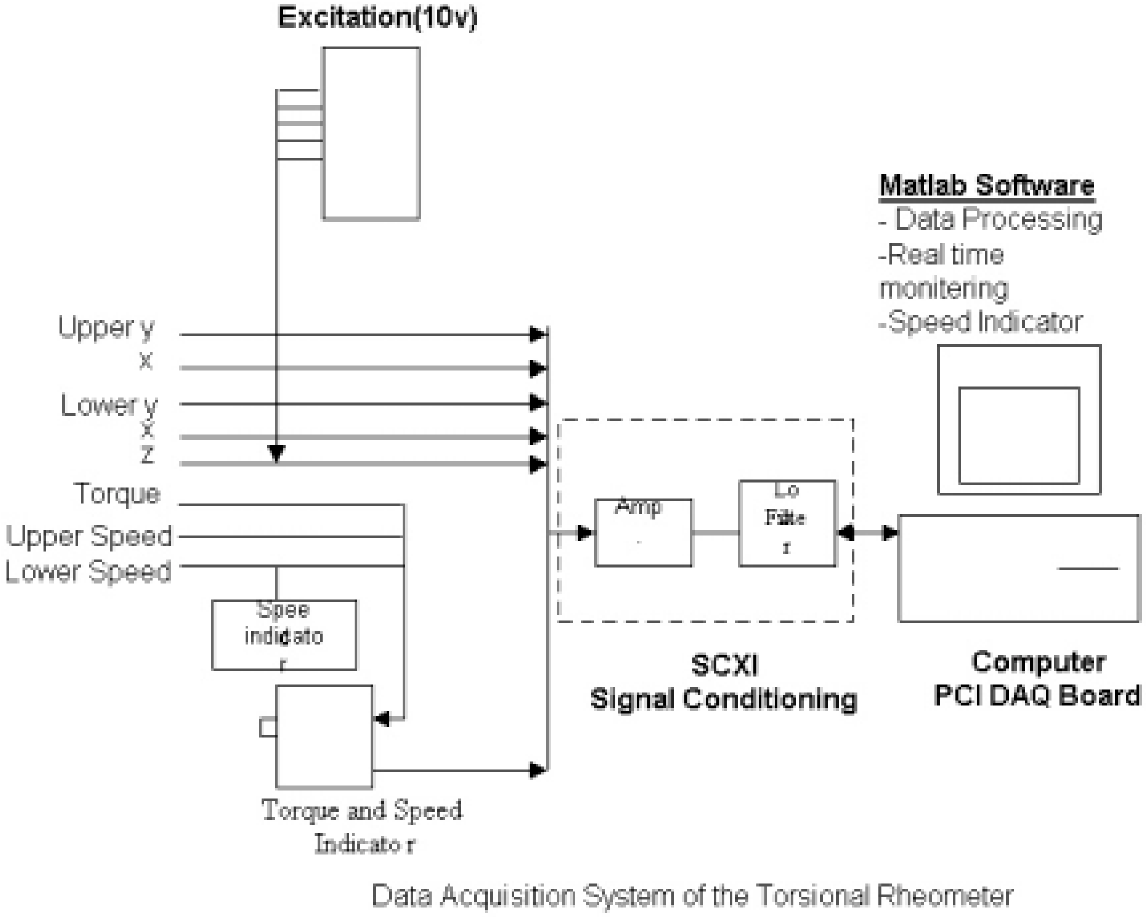

Fig. 5. Data Acquisition System of the Torsional Rheometer

and sends only the signals from the loads to the DAQ system. The gain set for the z-axis strain gage is 500 and x, y axes strain gage is 1000.

c. DAQ Hardware

The DAQ hardware is the interface between the computer and the analog, digital signals from the transducers. This hardware helps in data acquisition and data processing. We used PCI-6023 E DAQ board for this purpose. It has a 12-bit resolution with 16 analog input channels. We used all the channels with 8 double analog inputs. The maximum sampling rate of the DAQ board is 200 k Samples/sec with each channel having a sampling rate of 25 k Signals/sec. It is advisable to use the sampling rate to the maximum allowed by the DAQ board as we get a better representation of the material response by taking large number of data. For this, we set a sampling rate of 50 signals/sec for each channel. The sampling number was set to be 3000 signals/min. The DAQ Hardware components used is shown in Table III in Appendix [A].

d. DAQ Software

The DAQ software is a powerful graphical programming interface featuring interactive graphics, state-of-the art user interfaces to do data processing. We modified the system used by Baek [1] by replacing the DAQ software LABVIEW program with MATLAB program. The idea behind doing so was that MATLAB program provided for Data Acquisition and also had a toolbox providing simple steps in writing the program code for data acquisition in MATLAB. This served our purpose and moreover it was cheap, hence the decision to install it. The only drawback of MATLAB was that the experimental data will not be available unless the sampling is done, very unlike LABVIEW which provided the graphical view of the behavior of the material as the sampling was in progress. We configured the settings for the transducers with the help of the NI DAQ driver software provided and the Measurement and Automation Explorer (MAX software) provided along with it. This configuration involved setting the channels and the gains for each channel, setting the type of input (Differential input). The program code was written in MATLAB which is listed in Appendix [B].

3. Errors and their Sources

There is always a possibility of errors in experimental data. Error sources are classified into two main types -1. Fixed Bias Errors 2. Random Precision Errors

Fixed Bias Errors mean that there is a fixed amount of variation (bias) between the final measured value and the true value. Fixed Bias Error sources are present in the instrument itself, during the design stage or improper calibration of instruments. These errors cannot be corrected by repeated measurements of experimental data as they do not depend on it. One way to correct them is by calibrating the transducers and instruments from time to time so that they are within the range as specified by the company manuals.

CHAPTER IV

EXPERIMENTS AND CONCLUSIONS

The experiments were conducted in sets by varying two criteria - 1. Loading time of the test specimen and 2. Rotation rate of the motor. The test specimen is the specimen obtained by coring the $6''$ diameter sample. The different loading times and rotation rates used in the experiments are shown in the Table II. A total of three specimens were tested at a particular rotation rate and for a particular loading time in order to achieve some consistency in the results. In total 36 test specimens were tested for different loading times and rotation rates.

Table II. Criteria Varied During the Experiments

Loading Time	15 sec	30 sec	45 sec	
Rotation Rate	1 rev/25 min.	1 rev/30 min.	1 rev/35 min.	1 rev/40 min.

The test specimens for any particular set of experiments were cored from the circumference of the $6'' * 6''$ Sample so as to maintain same density variation in all the specimens, as the density distribution was varying in the Sample radially outward. After the test specimen is obtained from coring, it is glued to the gripper with the help of Epoxy DP460 glue. Then the grippers with the test specimen are attached to the lower and upper shafts of the rheometer and are kept for a period of 6 hours, so that the glue settles completely and attains its maximum strength. The test specimen is then pre-stressed for a period of 5 sec, i.e., the motor is turned on for a period of 5 sec with the specimen attached to it (before the actual running of the experiments), and then it is allowed to relax completely for a period of 20 min. This was done so as to maintain some uniformity in the test specimens, as there was a possibility of the presence of stresses in them induced during coring. After the specimen is relaxed to its initial state, the DC motor is turned on for a duration which is the loading time for that experimental set and at the same time the DAQ system is also switched on to acquire data from the experiment. The duration of the DAQ system to acquire data is set to 20 min. during which time it will acquire data both for the loading time and the stress relaxation mechanism of the specimen. The DC motor is switched off after the loading time but the DAQ system is still kept to collect data. The data collected is stored in the form of a data file. Once the data collection is over the sample is allowed to relax for a period of 20 min. during which time it regains its initial stress free configuration. The test specimen is then loaded again for that particular loading time and data is collected from it. Likewise there were 4 sets of repetitions for the same set of experiment. This was done to study the mechanism involving the regaining of the initial stress free state of the test specimen. The data presented in the following sections is that pertaining to the first set of each experiment.

A. Failure Test

In order to set the loading time for the experiments to be conducted, it was necessary to make sure that the Sand Asphalt specimen did not fail within the time of loading for all the RPM values to be varied during the experiments. Hence it was necessary to study the failure time of the samples at different RPM values. Hence the test specimens were prepared and tested to fail at different RPM values and the time for their failure was recorded. This is plotted in Fig [6], along with the logarithmic trendline. From the plot it can be clearly seen that the lowest time required by the specimens to fail is around 55 sec at rotation rate of 1 rev/ 40 min. Hence choosing loading times of 15 sec, 30 sec and 45 sec respectively does not lead to the failure of

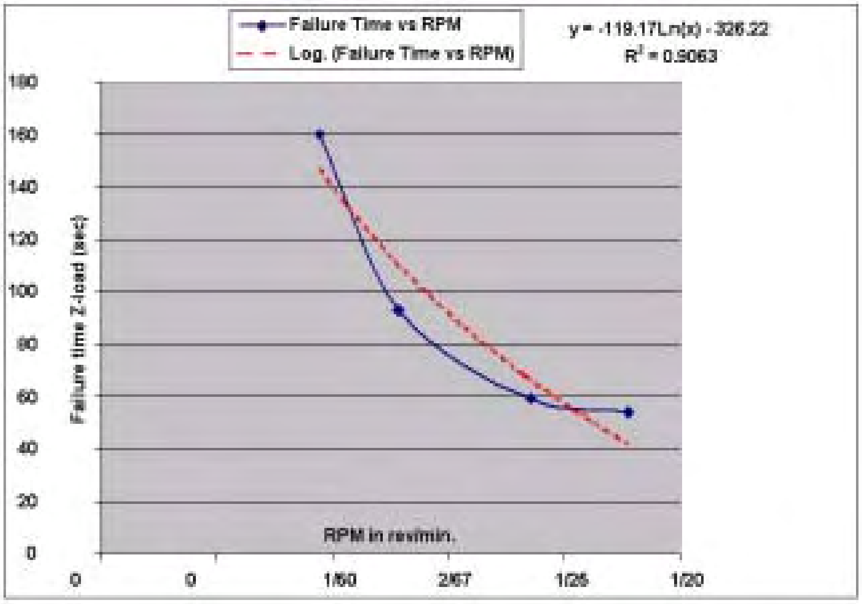

Fig. 6. Failure Test for Test Specimens [Z-load time(sec) vs RPM (rev/min)]

the test specimen while being tested.

B. Results

1. Normal Stress Effects and Stress Relaxation

The figures Fig [7] to Fig [18] show the stress relaxation mechanism in asphalt as well as the normal stress effects coming into play. These are for different loading times and RPM values. The figures 7 to figures 9 are for 1 rev/25 min with varying loading. Similarly figures 10 to 12 are for Rotation Rate of 1 rev/30 min, figures 13 to 15 are for 1 rev/35 min and figures 16 to 18 are for Rotation Rate of 1 rev/40 min. It can be clearly seen from the plots that the Normal Forces depend on the time of loading, and so does the time taken for stress relaxation of the asphalt specimens. The Torque required increases from 15 sec loading time to 30 sec loading time much faster but it

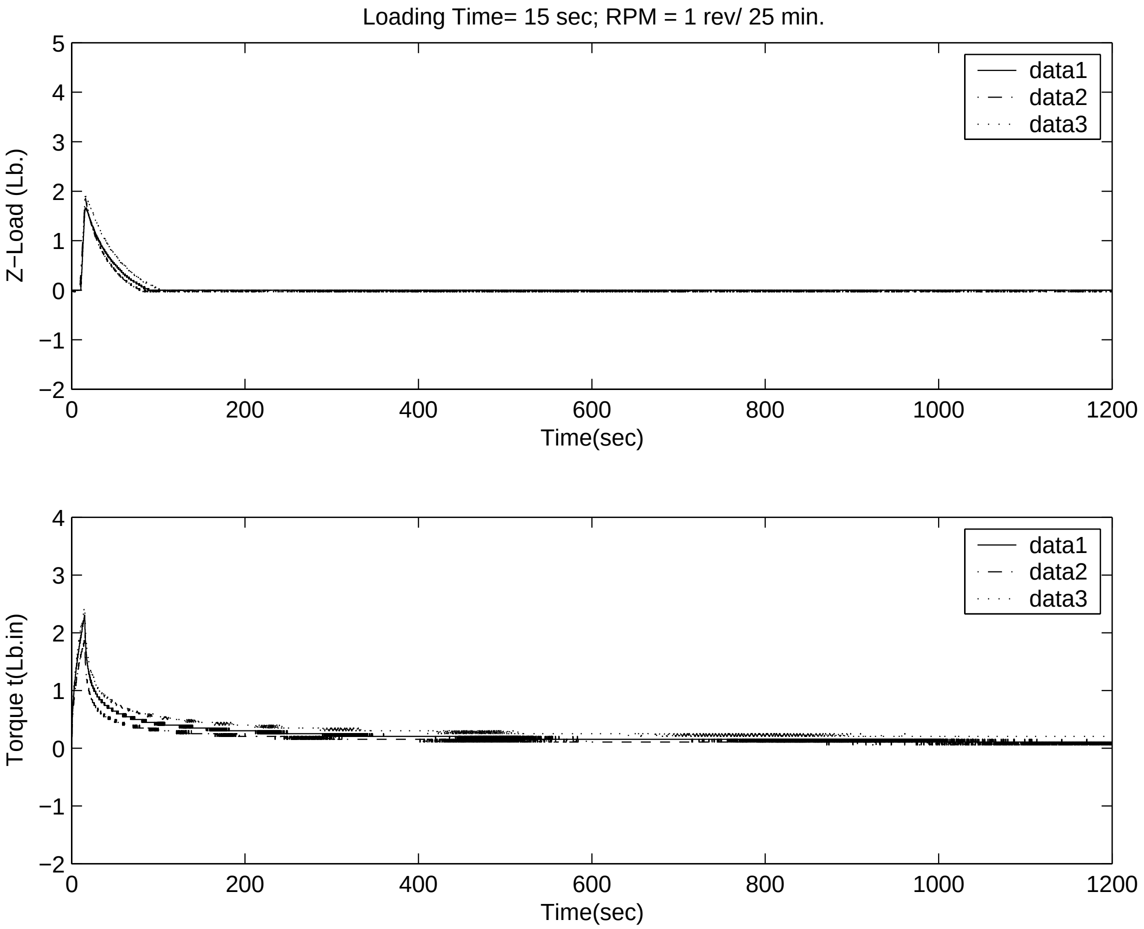

Fig. 7. Torque and Normal Load for Loading Time=15 sec, RPM =1 rev/25 min.

increases marginally from 30 sec to 45 sec loading time. Also the normal forces tend to decrease with the increase in rotation rate for any given loading time.

2. Shear Rate Dependence

The non-linear viscoelastic behavior is amply proved in figures 19 to 21 which clearly show that the normal stress effects are dependent on the rotation rate i.e., the rate at which the shearing of the test specimen is taking place. Each of these figures show

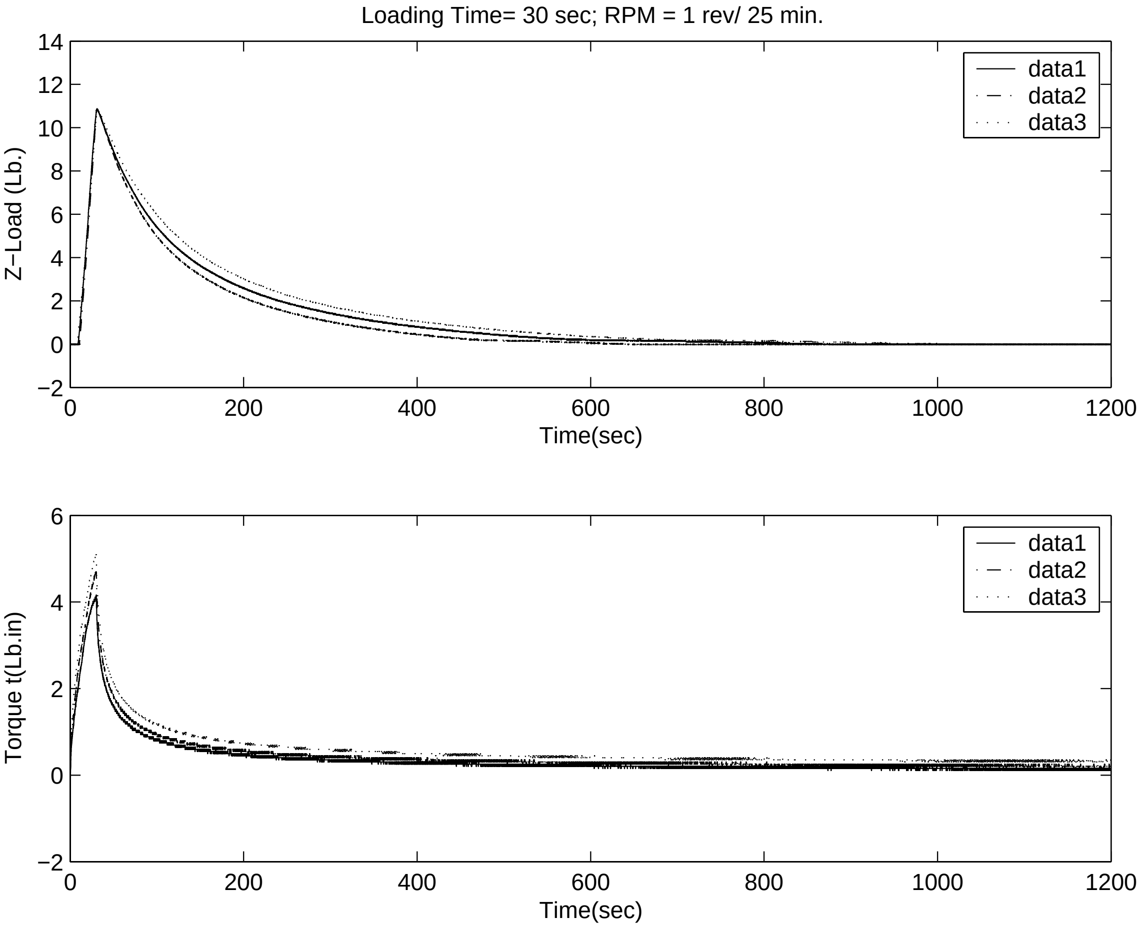

Fig. 8. Torque and Normal Load for Loading Time=30 sec, RPM =1 rev/25 min.

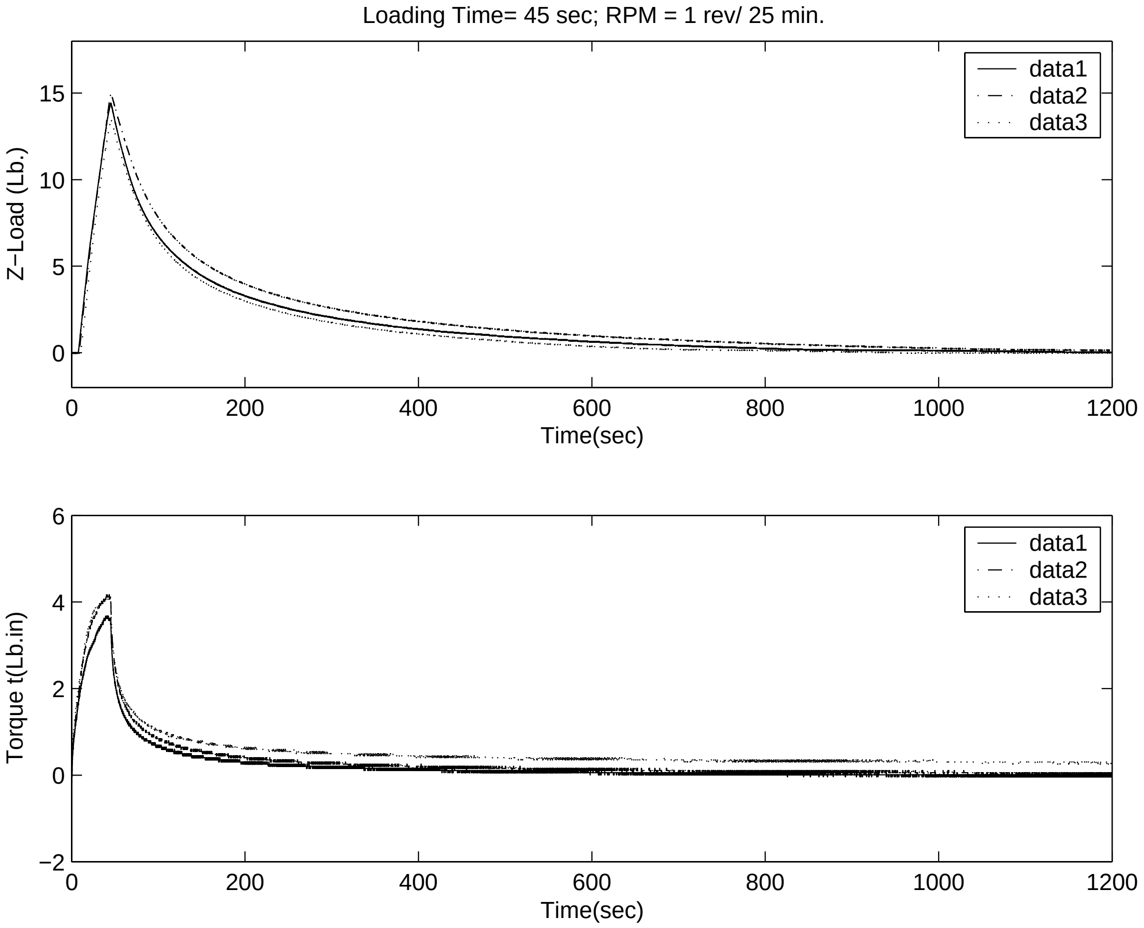

Fig. 9. Torque and Normal Load for Loading Time=45 sec, RPM =1 rev/25 min.

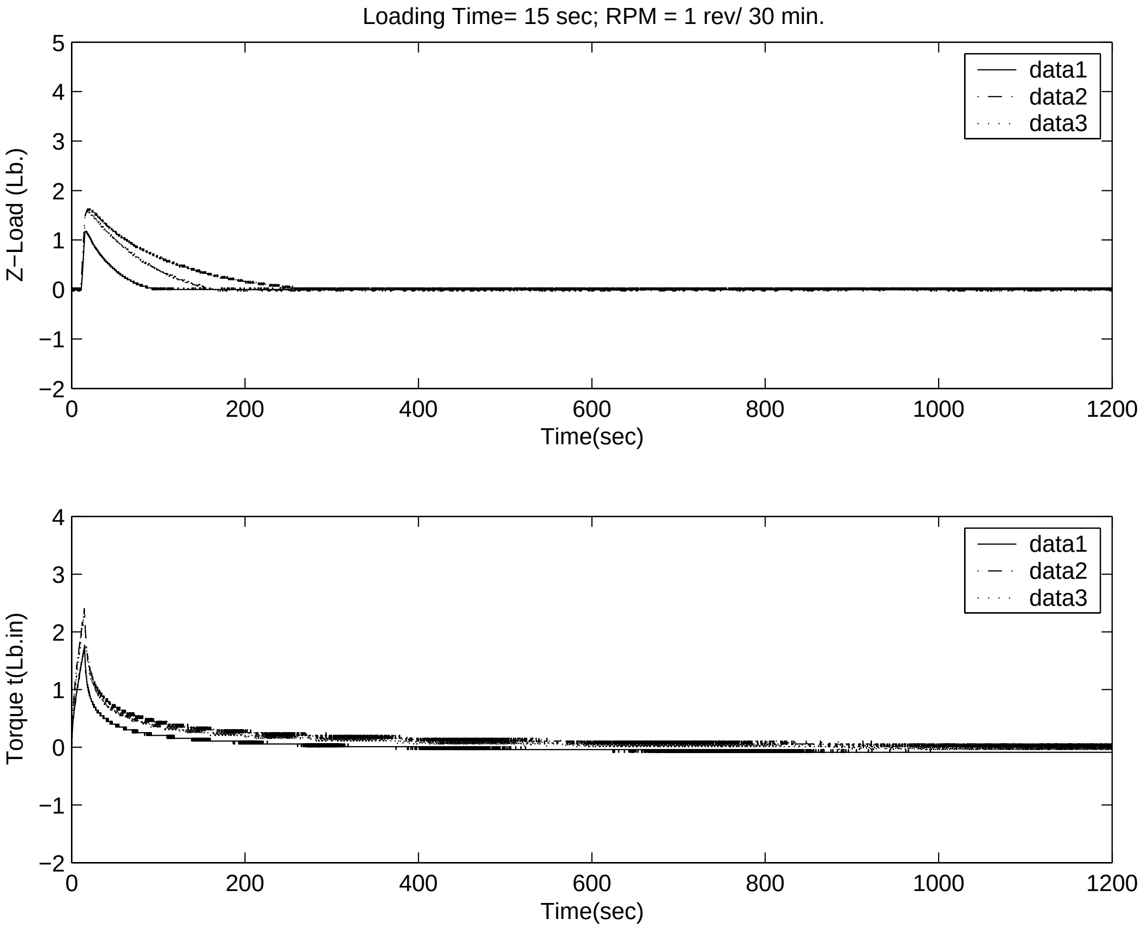

Fig. 10. Torque and Normal Load for Loading Time=15 sec, RPM =1 rev/30 min.

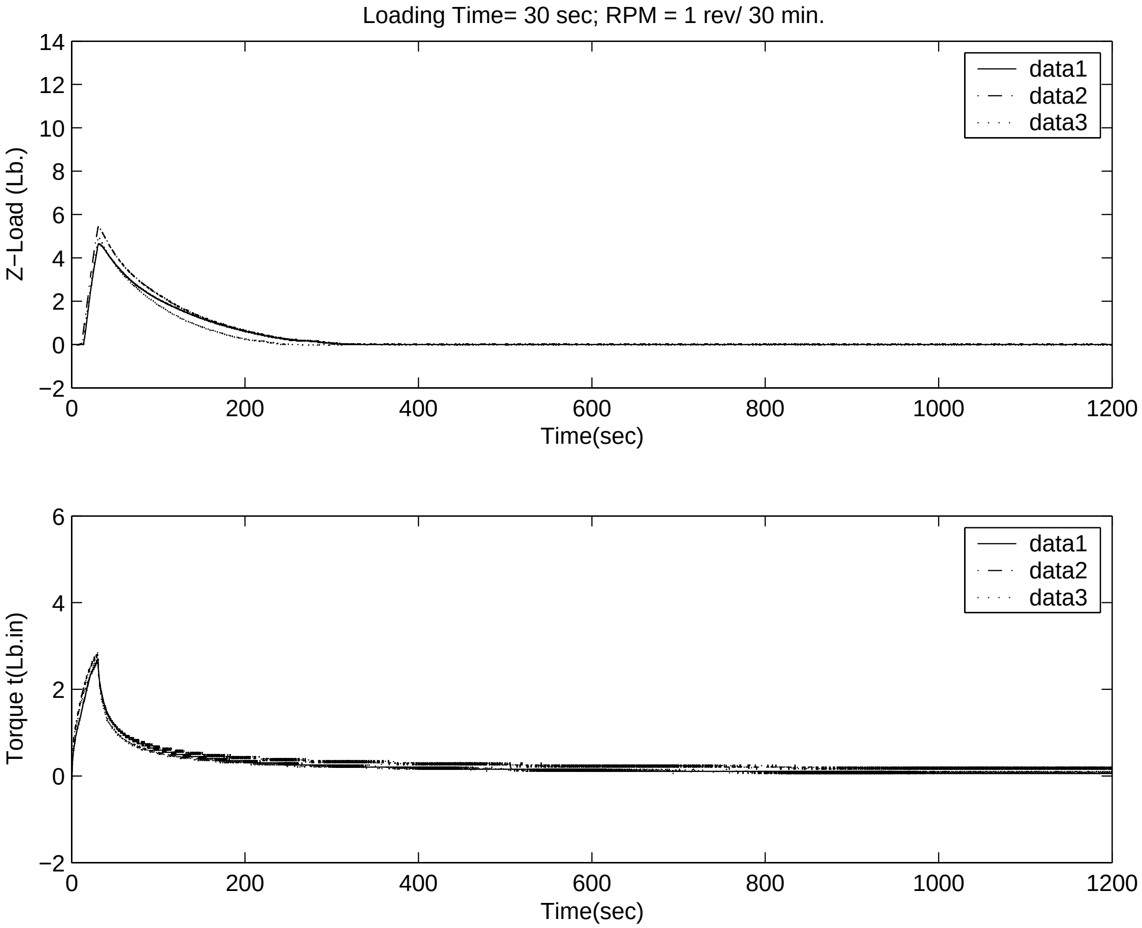

Fig. 11. Torque and Normal Load for Loading Time=30 sec, RPM =1 rev/30 min.

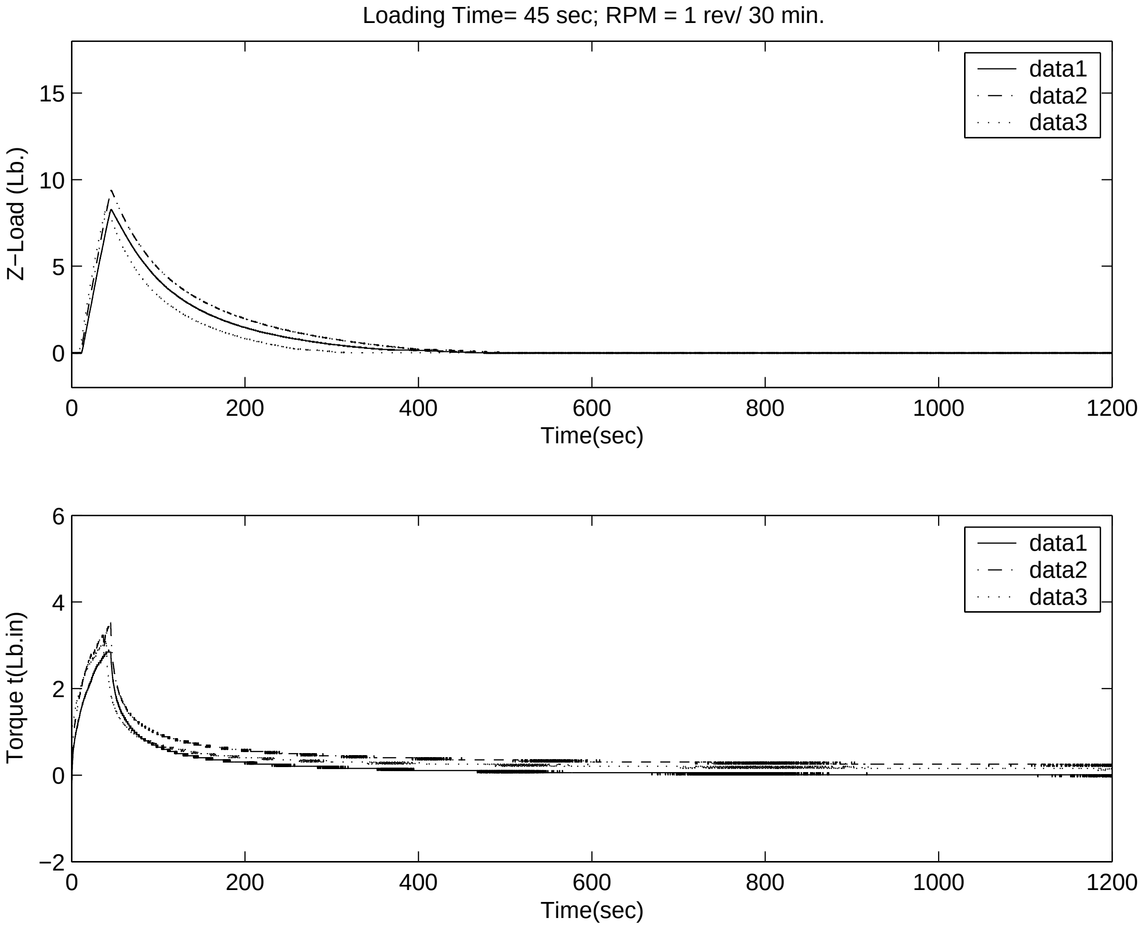

Fig. 12. Torque and Normal Load for Loading Time=45 sec, RPM =1 rev/30 min.

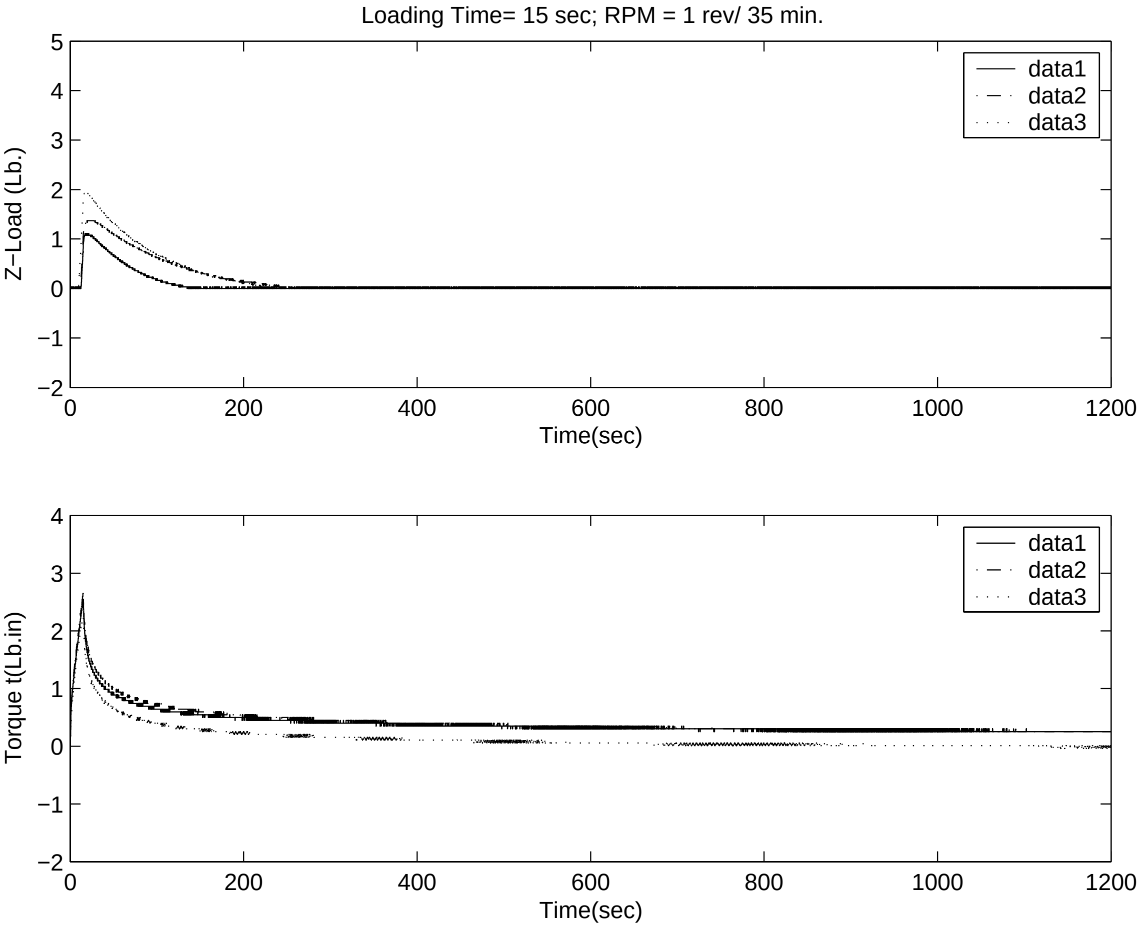

Fig. 13. Torque and Normal Load for Loading Time=15 sec, RPM =1 rev/35 min.

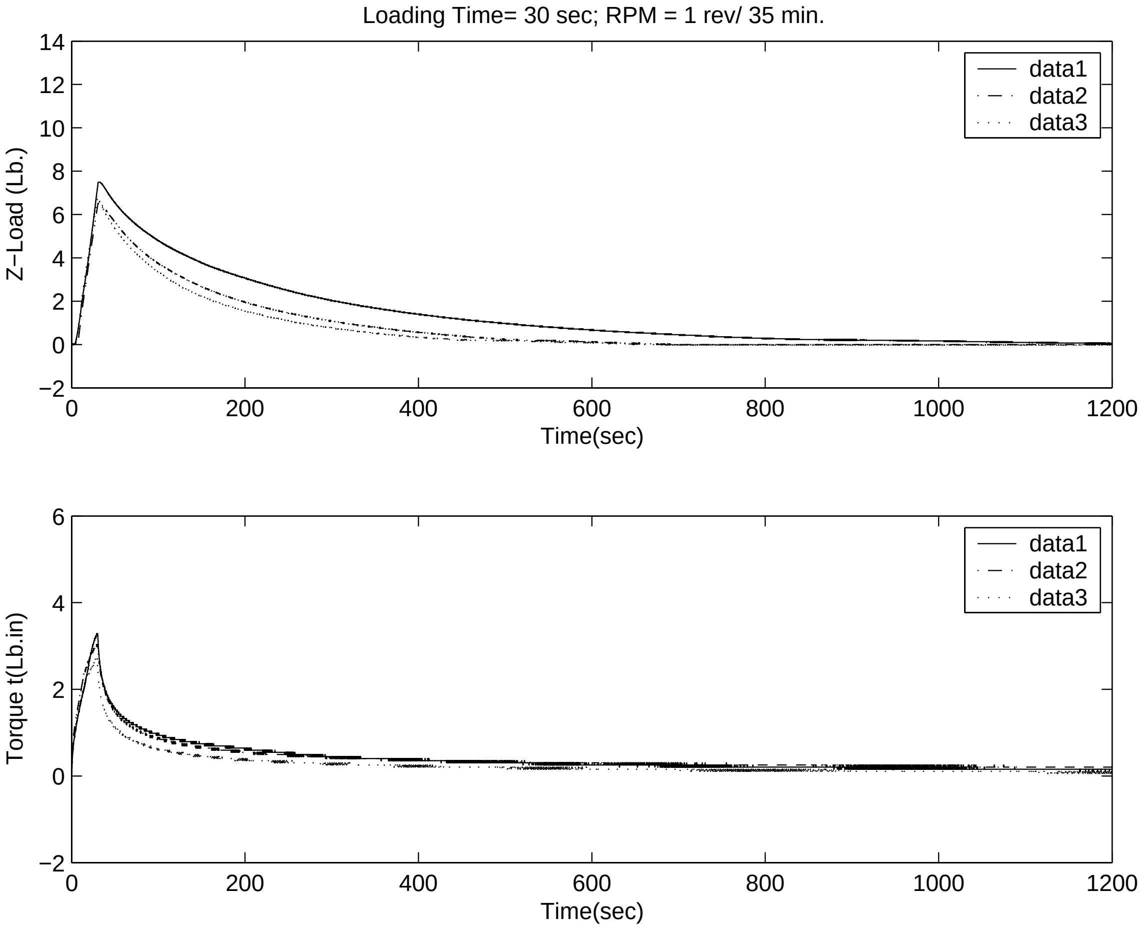

Fig. 14. Torque and Normal Load for Loading Time=30 sec, RPM =1 rev/35 min.

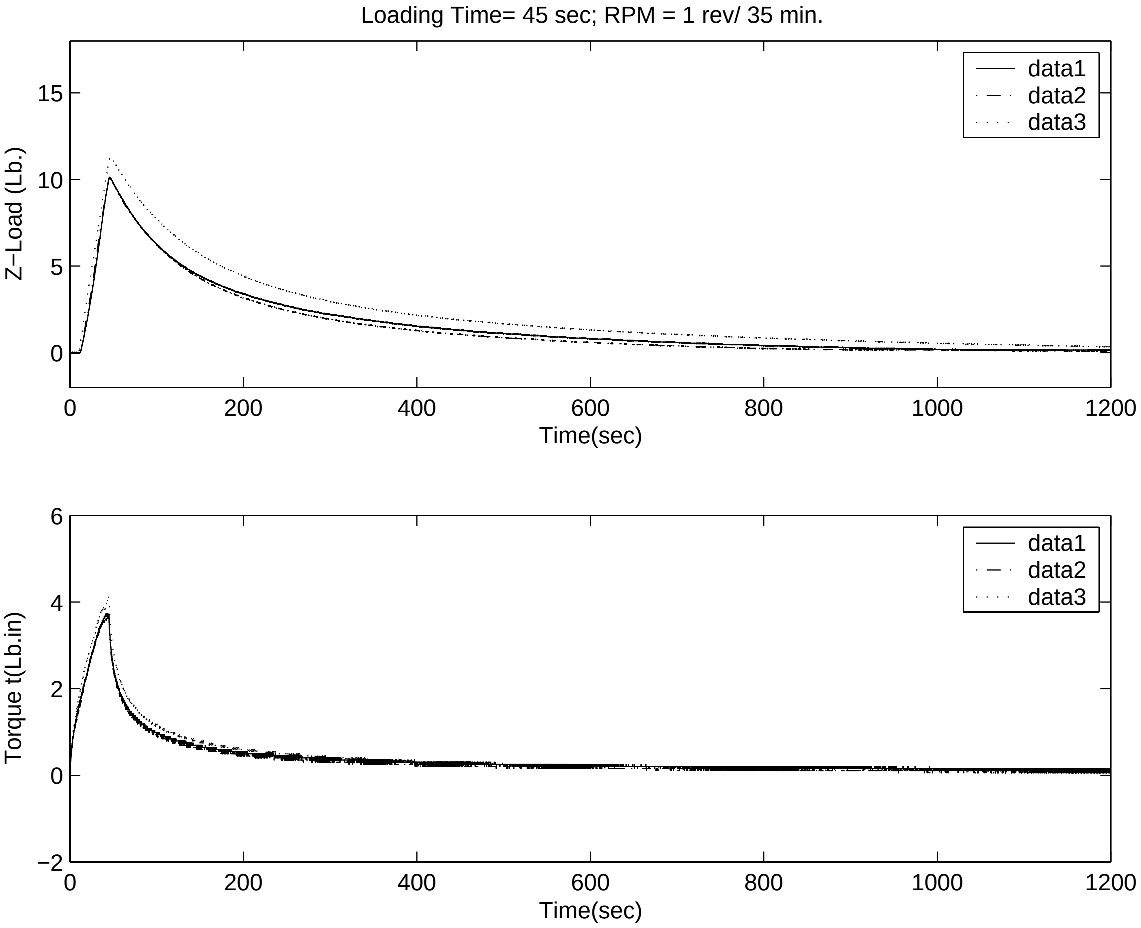

Fig. 15. Torque and Normal Load for Loading Time=45 sec, RPM =1 rev/35 min.

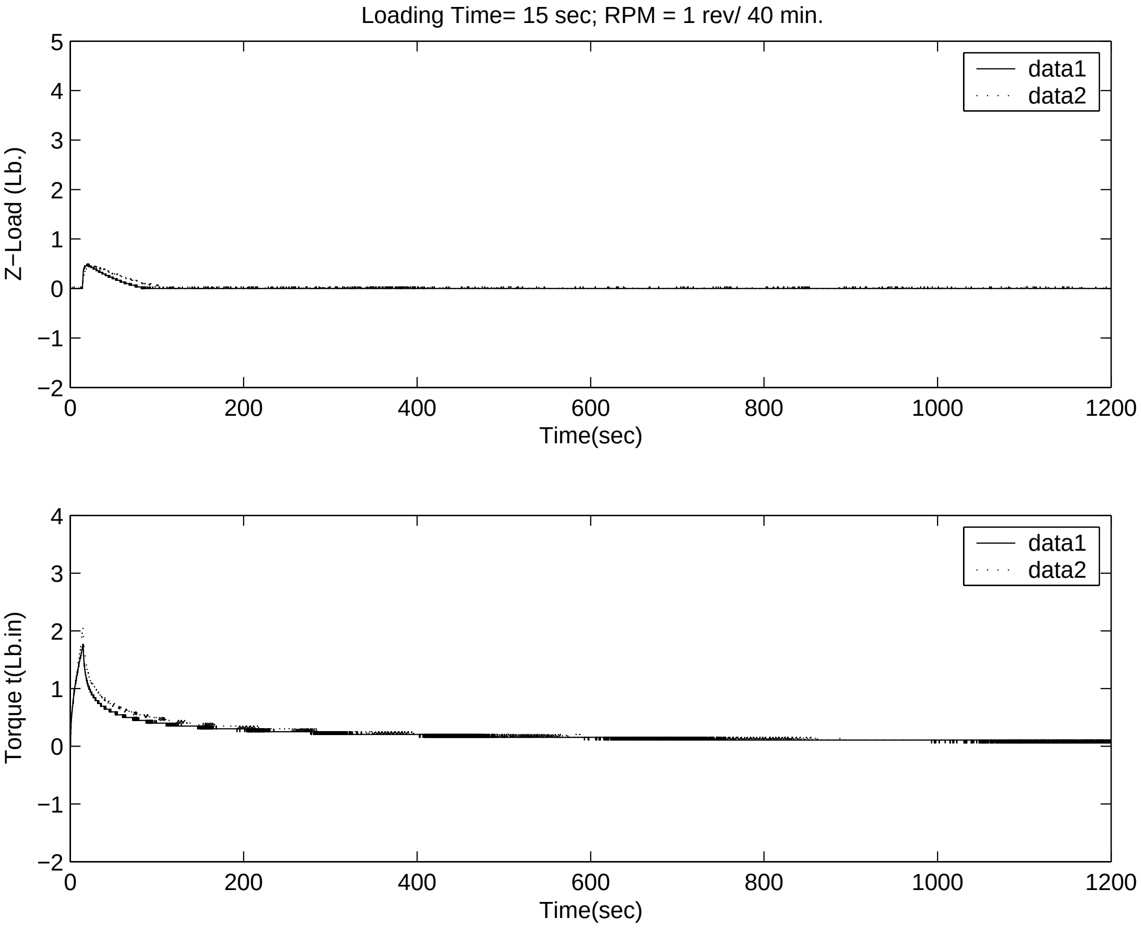

Fig. 16. Torque and Normal Load for Loading Time=15 sec, RPM =1 rev/40 min.

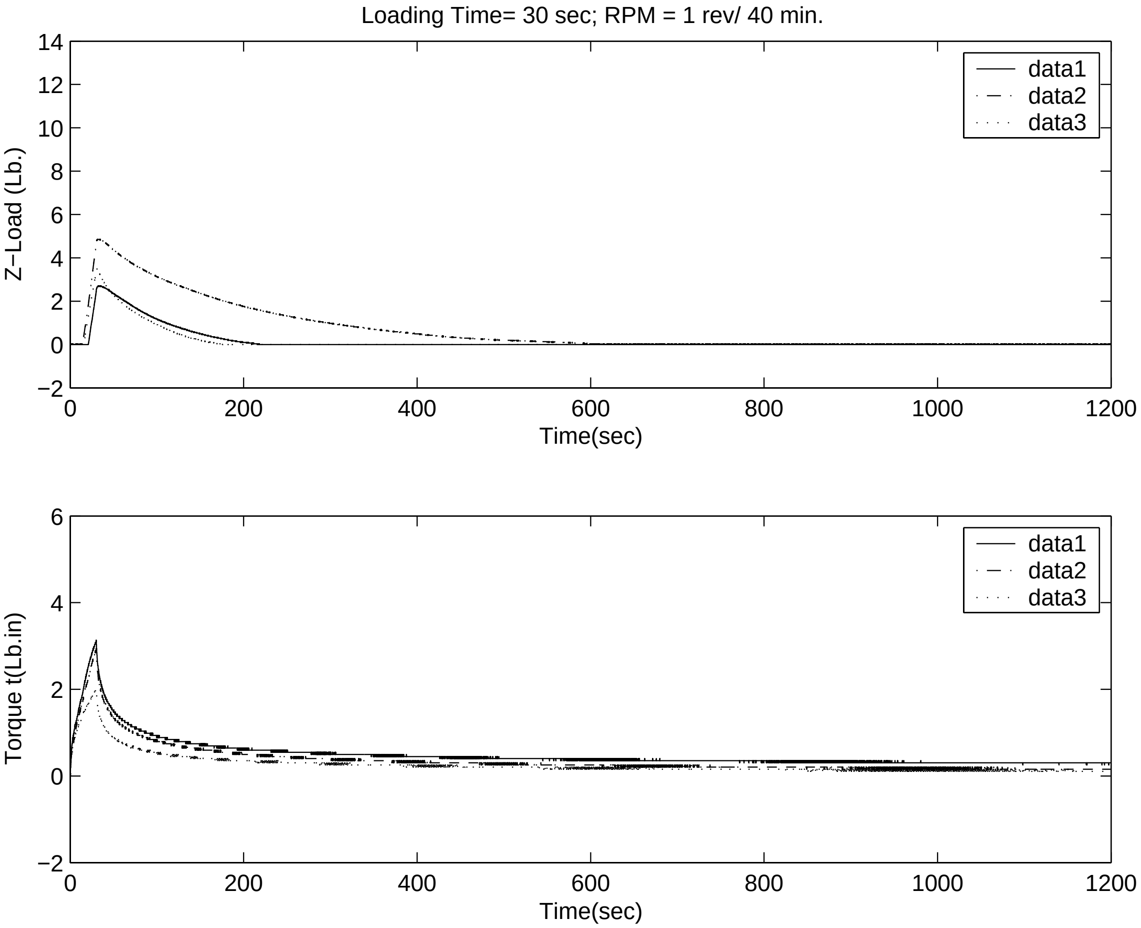

Fig. 17. Torque and Normal Load for Loading Time=30 sec, RPM =1 rev/40 min.

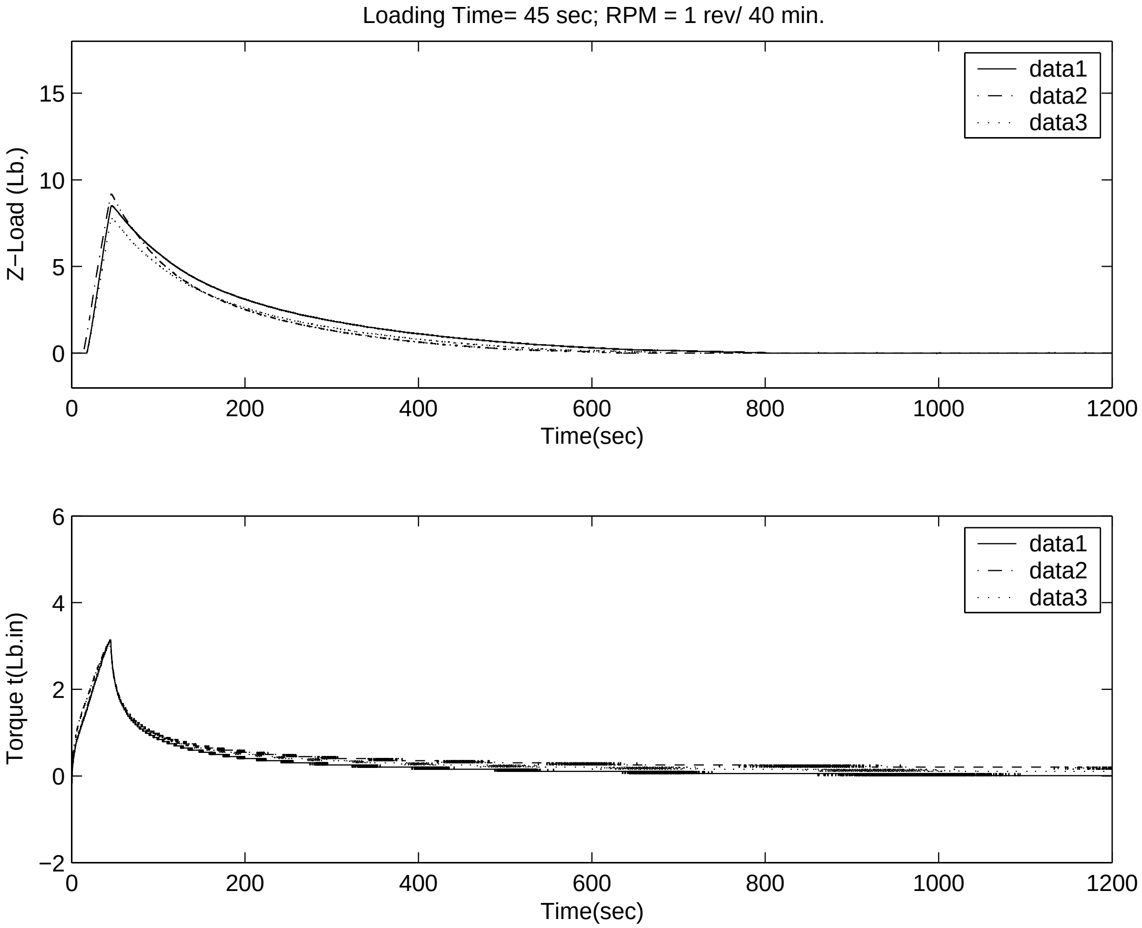

Fig. 18. Torque and Normal Load for Loading Time=45 sec, RPM =1 rev/40 min.

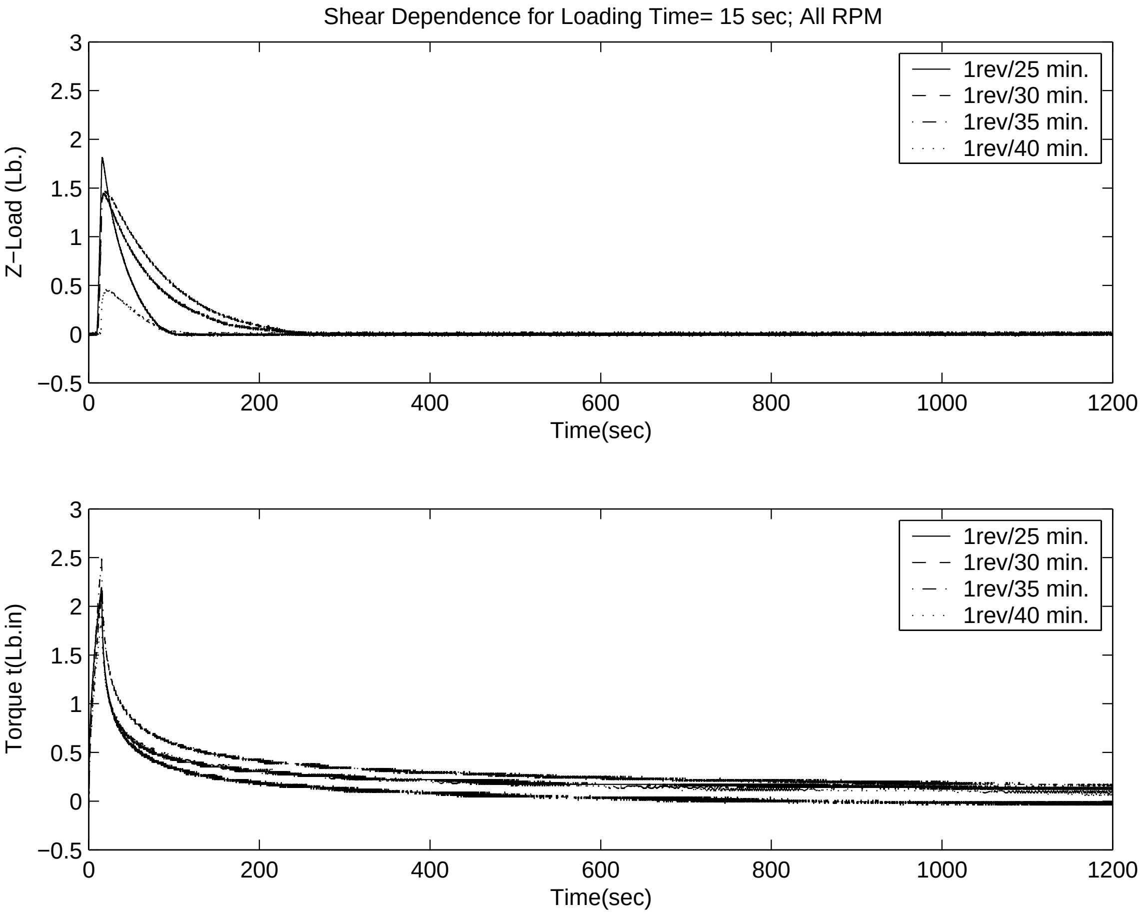

Fig. 19. Comparison of Normal Loads and Torque for All RPMS, Loading Time=15 sec

the comparison between the developed Normal Forces and Torque at different RPM values for any particular loading time. From the plots it can be observed that as the rotation rate becomes slower, the normal forces developed also become smaller but upto a point after which the change in the forces is marginal. Some discrepancy is also observed in the plots for a particular case of rotation rate being 1 rev/30 min. The possible reason might be because of presence of eccentricites in the test specimen used while testing for this particular rotation rate.

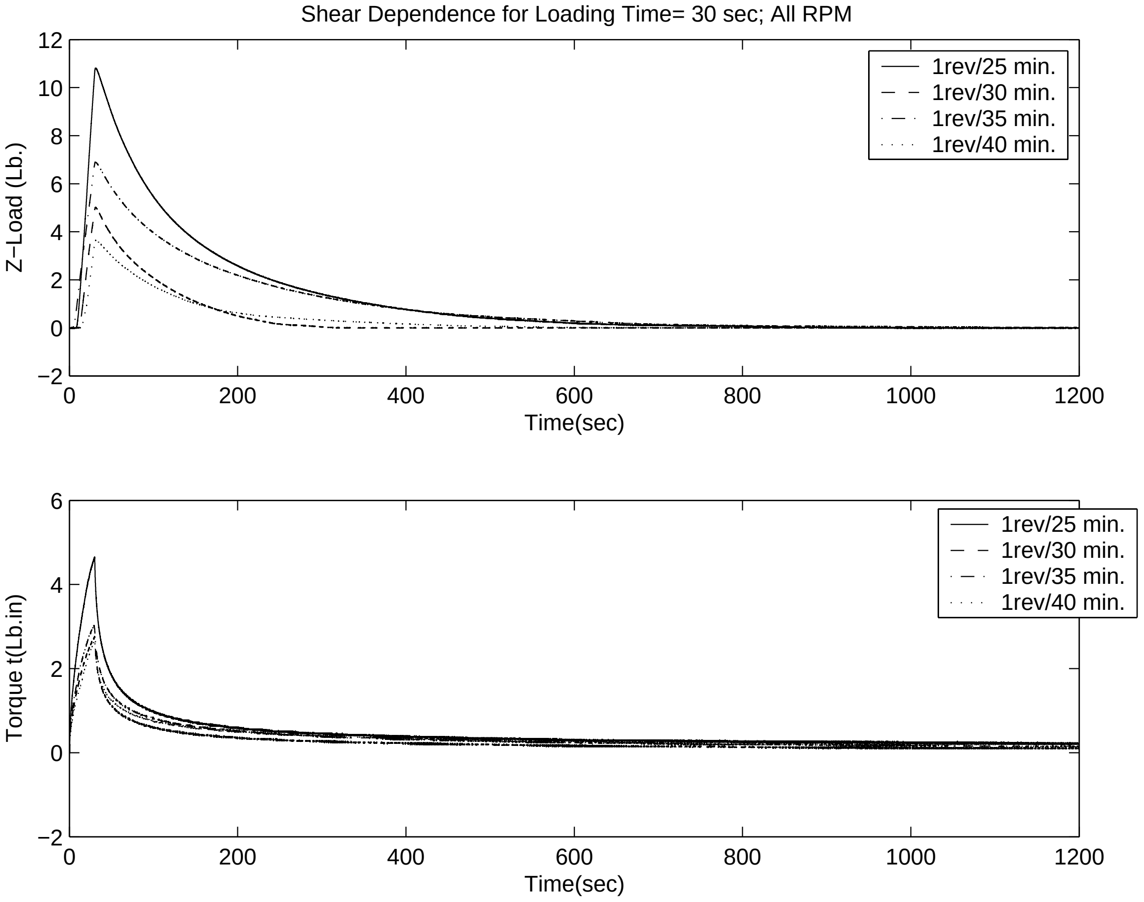

Fig. 20. Comparison of Normal Loads and Torque for All RPMS, Loading Time=30 sec

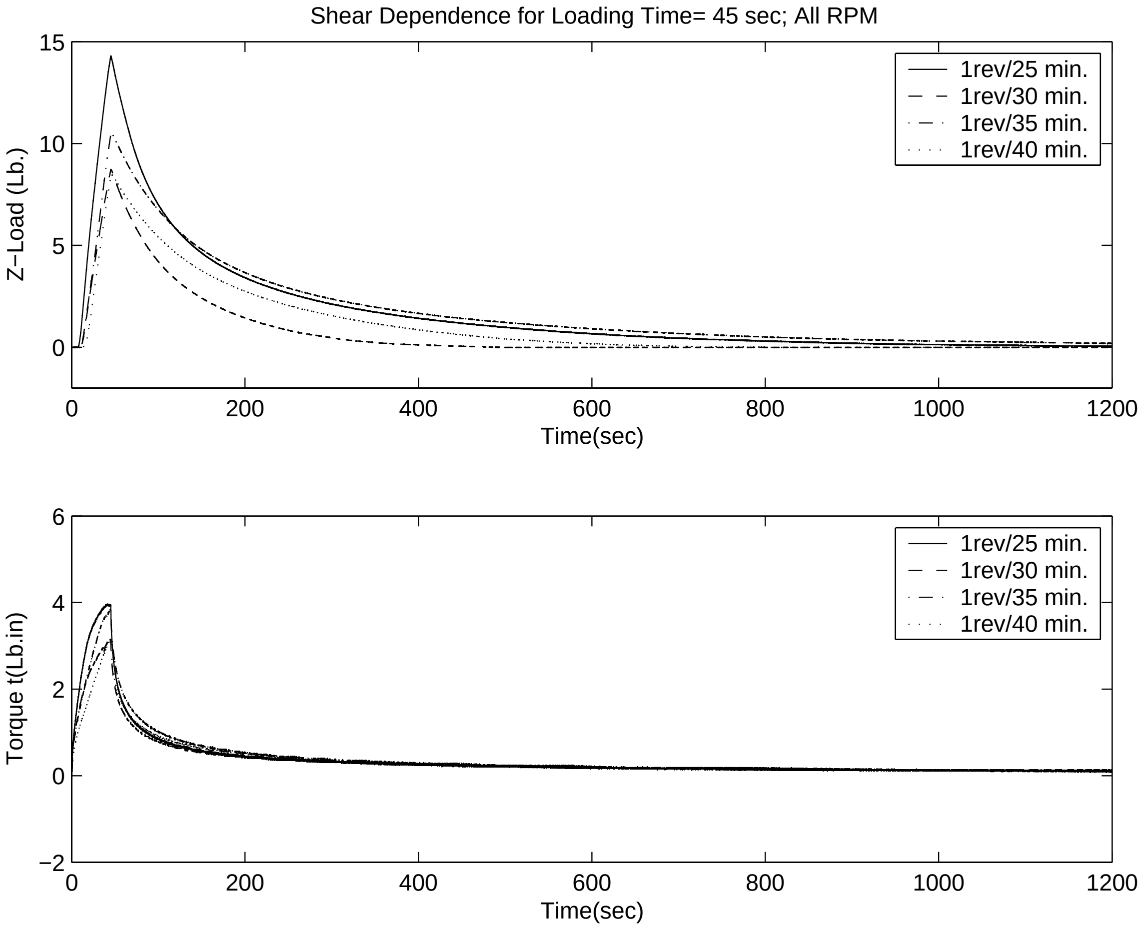

Fig. 21. Comparison of Normal Loads and Torque for All RPMS, Loading Time=45 sec

C. Conclusions and Further Experiments

In this work, we have developed the method to measure the properties of sand asphalt material using a torsional rheometer and we have also verified that the procedure we adopted is repeatable in this experimental setup. In this series of experiments, we have also made significant observations into the viscoelastic response behavior of sand asphalt material by observing the stress relaxation mechanism of the material and also the normal stress effects coming into play in the experiments on application of shear force and their variation and dependence on the shear rate. The experiments provide raw data without assuming the kind of the model to be used beforehand. Hence this raw experimental data can be of immense use to the modeling efforts of asphaltic materials and is applicable to any chosen model (whether linear viscoelastic or non-linear viscoelastic). For the proper and thorough characterization of the mechanical response of asphalts, it is necessary that we obtain experimental data pertaining to different kinds of aggregate asphalt mixes. Hence conducting the same kind of experiments for different kinds of aggregate asphalt mixes like asphalt concrete, stone matrix asphalt etc. can be the work for the future. Moreover for the immediate future, the data obtained from the present work can be used for the data reduction scheme for the model developed by Murali Krishnan and Rajagopal [12] to determine the efficacy of the model. The Torsional rheometer with some minor modifications can be further used to study the properties of a wide variety of materials in the future.

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APPENDIX A

DATA ACQUISITION HARDWARE

Table III. Data Acquisition Hardware

Description	Model)	Manufacturer
Load Cell(z-axis)	13SP	Revere Transducer
Strain Gage(x,y-axis)	6443-146	Lebow
Torque Sensor	1804	Lebow
Magnetic Speed		AIRPAX
Low Cost Multi-function I/O Board	PCI-6023E	National Instruments
8-Channel Amp. and Isolate	SCXI-1120	National Instruments
Terminal for SCXI-1120	SCXI-1320	National Instruments
8-Channel Low Filter	SCXI-1141	National Instruments
Terminal for SCXI-1141	SCXI-1304	National Instruments
4 Slot Chassis	SCXI-1000	National Instruments
Cable	SCXI-1349	National Instruments

APPENDIX B

DAQ PROGRAM CODE IN MATLAB

For a Sample Test of Sample79

```
ai=analoginput(‘nidaq’,1);
chan3=addchannel(ai,7);
chan2=addchannel(ai,4);
set(chan3,‘InputRange’,[-10 10]);
set(chan3,‘UnitsRange’,[0 100]);
set(chan3,‘SensorRange’,[0.1382 10.1382]);
set(chan3,‘Units’,’Lb.in’);
set(chan2,‘InputRange’,[-10 10]);
set(chan2,‘UnitsRange’,[0 100]);
set(chan2,‘SensorRange’,[2.625 17.625]);
set(chan2,‘Units’,’Lb’);
set(ai,‘SampleRate’,50);
ActualRate0=get(ai,‘SampleRate’);
duration=1200;
set(ai,‘SamplesPerTrigger’,duration*ActualRate0);
set(ai,‘TriggerType’,‘Manual’);
ActualRate=get(ai,‘SamplesPerTrigger’);
start(ai);
trigger(ai);
[data, time]= getdata(ai);
```

```
save sample79-1.mat;
load sample79-1.mat;
data
zraw=data(:,2);
traw=data(:,1);
figure;
subplot(2,1,1),plot(time,zraw);
hold on;
axis([0 duration -2 30]);
title(‘Sample79-1(30 sec Loading)’);
xlabel(‘Time(sec)’),ylabel(‘Z-Load (Lb.)’);
subplot(2,1,2),plot(time,traw);
hold on;
title(‘Torque Sensor Data’);
xlabel(‘Time(sec)’),ylabel(‘Torque t(Lb.in)’);
axis([0 duration -2 20]);
stop(ai);
delete(ai);
clear ai;
clear;
```

Fig. 22. Core Bits Design

APPENDIX C

Fig. 23. Torsional Rheometer Setup

Fig. 24. Grippers and Specimen in the Setup

VITA

Lavan Kumar Reddy Kasula graduated with a B.Tech. degree in civil engineering from Indian Institute of Technology-Madras (IIT-Madras), India in May 2001. He was ranked first in a graduating class of 80 students. In August 2001, he joined the Department of Mechanical Engineering at Texas A&M University as a graduate student. He graduated with a Master of Science degree in mechanical engineering, in August 2003.

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