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REVIEW PAPER

Rheological Properties of a Honge Oil-based Magnetorheological Fluid used as Carrier Liquid

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ABSTRACT

Developing a sudden damping and its control which is demanded in many engineering applications with the existing conventional methods are difficult and critical too. A magnetorheological (MR) fluid with good rheological properties can exhibit very fast damping characteristics and can be controlled just by varying the applied magnetic field to that fluid. Thus in this paper, a MR fluid is proposed with a non-edible vegetable oil such as Honge oil as a carrier liquid. Three samples of such MR fluid containing different percentages by volume of carbonyl iron powder as suspensions are prepared for comparing their rheological properties. An experimental setup consisting of a capillary viscometer with a pair of solenoid type of electromagnetic coils is developed. The rheological properties of the proposed MR fluid are investigated under the application of different magnetic fields and the results are presented. It was observed that the one of the samples containing 40 per cent by volume as suspensions exhibits a maximum viscosity of 334 Pa-s and yield stress of 13.23 kPa at a magnetic field of 0.3816 T. The results have been compared with those obtained by other researchers.

Keywords: Biodegradable carrier liquid, Honge oil, magnetorheological fluid, yield stress

NOMENCLATURE

M	Magnetic moment
H	Applied field
B	Theoretical value of magnetic field density without any core
μ_o	Permeability of the free space= $4\pi \times 10^{-7}$
I	Current
Δp	Pressure difference
R	Radius of capillary tube
L	Length of the capillary tube where magnetic field applied
Q	Volumetric flow rate of MR fluid in the capillary
S_w	Shear stress of the fluid at the wall of the capillary
γ	Shear rate

1. INTRODUCTION

Magnetorheological fluid (MR), a class of smart materials ,has been in use as dampener for landing gears of military aircraft. The MR technology is well developed in USA, Canada and some European countries. It is widely incorporated in MR brakes, MR clutches, and MR suspension systems of automobiles. It is widely used in military vehicles due to their sudden response and remotely-controllable behaviour. MR fluid consists of three constituents namely; carrier liquid, suspension and additive. Carbonyl iron particles are widely used suspensions because of their high magnetic permeability, low remanant magnetisation, and also these are magnetically multi-domain. When the magnetic field is applied, the suspended particles present in the MR fluid become magnetised and align themselves like a chain in the directions of the magnetic field[1]. This transforms the MR fluid from fluid state to solid like state within milliseconds. It increases the viscosity and yield stress with the formation of columnar structures, parallel to the applied magnetic field, and which must be broken for the fluid to flow. The increase in yield stress, however, is not linear, since the particles are ferromagnetic or ferrimagnetic and the magnetisation in different parts of the particles occurs non-uniformly[2]. The additive, the other constituent, helps to decrease sedimentation, prevents both agglomeration and oxidation, modifies viscosity, and inhibits wear.

Carrier liquid is the major constituent of MR fluids (50-80 per cent by volume) which greatly influences the rheological properties of MR fluids. Its primary function is to provide a medium for magnetically active particulates to remain suspended during the absence of a magnetic field and to facilitate realignment once magnetic field is applied. But the type of carrier liquid used in a MR fluid may differ. In literature, different carrier liquids have been considered in the preparation of MR fluids and some are detailed here. These are polyvinyl-*n*-butyl and naphthol-thickened kerosene[3], silicon oil[4, 5], white and light grade mineral oils[6], a combination of synthetic oil, water and organic liquids[7], etc. MR fluids are also available commercially which contain hydrocarbon-based fluid, silicon-based fluid, etc. but these options are very costly.

The literature review reveales that mineral oil, silicon oil and synthetic oil are commonly-used carrier liquids. The mineral oils, which are derived from petroleum, are neither biodegradable nor environmentally friendly, and likely to be depleted within few years. Silicone oil has low surface

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tension, wets the clean surfaces quickly, and makes it dirty. Synthetic oils are made artificially but cost more. According to an estimate the quantity of MR fluid needed just for use as damper of an automotive platform model alone is of the order of 1-2 ton per day[8]. Considering various other applications and their growing demands, the quantity needed multiplies. These limitations of commonly used liquids have motivated to identify an alternative carrier liquid. In the present work, a non-edible vegetable oil like Honge oil, which is bio-degradable, is environmentally friendly, and abundantly available in many parts of the world, is used as carrier liquid. Also there is no evidence in the literature regarding the use of this oil as carrier liquid. This oil is selected after evaluating different properties desirable for a carrier liquid (Table 1). Further it is non-volatile, thermally stable, and does not form sedimentation up to 80 °C and 50 hr of heating duration.

Table 1. Basic properties of Honge oil

Property	Value
Viscosity @ 40 °C (Pa-s)	0.048
Flash point	230 (°C)
Fire point	282 (°C)
Specific gravity	0.927
Density	932 kg/m^3
Pour point	–3 °C
Cloud point	1 °C
Market cost	0.83

Quality (state) of a MR fluid can be known by measuring different rheological properties like viscosity, shear stress, yield stress, etc. at a given shear rate. For reliable functioning of a MR fluid in military devices as discussed, it is important to know these properties to fit in various applications. The rheological properties are measured using various combinations of viscometers/rheometer with electromagnetic circuits. Parallel plate rheometer[9] is used to measure viscosity and normal stresses of a MR fluid at high shear rates. In this, magnetic flux generated is measured by placing a gaussmeter probe between the rheometer plate and the electromagnet. At the same time, strain rate-controlled double Couette rheometer comprising a cup and bob fixtures is also used[4]. But this instrument is not suitable to measure very low shear stresses encountered in low field on-state (with magnetic field) measurements. Later rotational rheometer with a provision to control coil current, and thereby to control magnetic field strength through software, is used[5]. A capillary viscometer with a provision to apply the magnetic field at the capillary is adapted to measure viscosity and yield stress of MR fluid[10]. The fluid is forced through a fine-bore tube (capillary) which has fixed radius and length. Viscosity is determined by measuring the flow rate of MR fluid and applied pressure and tube dimensions. In addition to these, various other viscometers are also proposed; a rotational magnetic plate–plate viscometer[3], an online measuring system for true flux density using plate–plate rheometer[11], etc. In most of the MR fluid devices used for military applications, like landing gear of a military aircraft and other automobile components of military vehicles, the fluid is in flow condition during the operation. Hence in this paper, an experimental setup with capillary viscometer and a pair of solenoid type of electromagnetic coils was developed to investigate the various magnetorheological properties of the proposed MR fluid prepared from Honge oil as carrier liquid.

2. EXPERIMENTAL SYSTEM

2.1 Material Preparation

Three samples of MR fluid were prepared with carbonyl iron particles (6 μm to 9 μm and density 7860 kg/ml) as suspension, grease as additive and Honge oil as carrier liquid (Table 2). The samples were prepared by taking the desired quantity of carbonyl iron particles and adding the right quantity of Honge oil to it. The constituents were mixed thoroughly using a glass stick with subsequent addition of additive to obtain a homogeneous mixture. The off state viscosity of MR fluid at 27 °C is 0.08 Pa-s.

Table 2. Constituents of MR fluid samples

Sample no.	per cent by volume of		
	Suspension	Additive	Carrier liquid
1	20	5	75
2	30	5	65
3	40	5	55

2.2 Magnetic Properties of Carbonyl Iron Powder

Magnetic properties of carbonyl iron particles are found in terms of M-H curve using vibrating sample magnetometer (VSM). A cylindrical sample of the particles was prepared and placed it in a cylindrical glass tube and then placed between strong magnetic coils of magnetometer. When the mechanical vibrations were applied to the sample of magnetic material in a constant magnetic field, the induced voltage proportional to the magnetic moment of the material was generated in the pick-up coils. Thus hysteresis (M-H) curve as shown in Fig.1 was drawn to determine saturation magnetisation of carbonyl iron powder and was obtained as 216 emu/g (2.16 T).

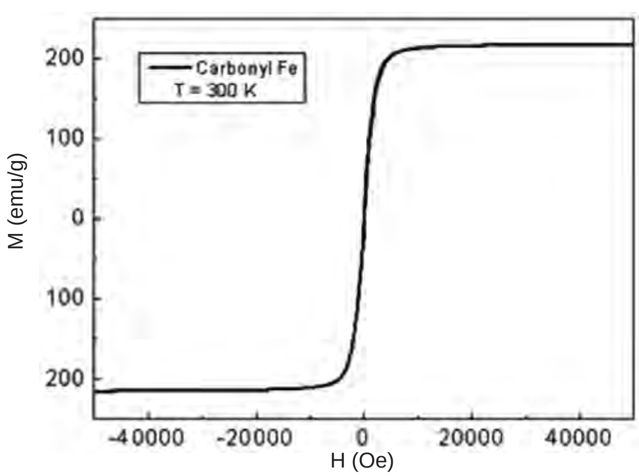

Figure 1. Hysteresis curve for carbonyl iron powder.

2.3 Electromagnetic Circuit

The electromagnetic coils were made and were characterised by comparing the magnetic fields estimated theoretically with that generated during the experiment. It was to know the actual magnetic field that could be obtained during the experiments at different input currents. The electromagnetic circuit is shown schematically in Fig. 2. It consists of a pair of magnetic coils A and B and dc power supply (0-5 A and 0-60 V) connected in series. The magnetic fields were measured by inserting the probe of Hall probe Gaussmeter (2 T). The pole plates themselves were placed at a gap from 0.01 m to 0.1 m (P). The magnetic fields are measured at various gaps from 0.01 m to 0.1 m (by changing gap in steps of 0.01 m) for different input currents from 0 A to 4.5 A in steps of 0.5 A. The measured magnetic field values were compared with theoretically estimated values. Specification of the electromagnetic coils and chemical compositions of core material are given in Table 3 and 4, respectively.

The theoretical magnetic fields generated by these coils are estimated using Eqns. (1) to (5)[10].

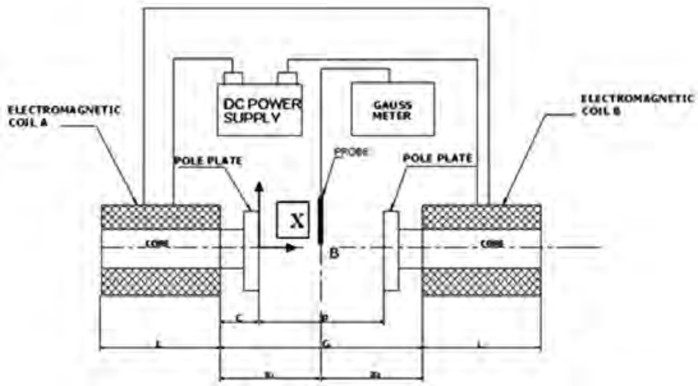

Figure 2. Electromagnetic circuit.

Table 3. Specification of electromagnetic coils

Item	Details
Core material	Cold-rolled low-carbon annealed steel
Core diameter	$40^{\pm(0.00,\ 0.02)}$ mm
Material and gauge number of copper coils	Copper, 17 gauge
No of solenoid coils	2
Resistance of each solenoid coil	5.3 ohm
Inner radius of solenoid coils	0.02 m
Outer radius of solenoid coils	0.065 m
Length of each solenoid coil	0.097 m
Number of turns per meter length	17900 n
Relative permeability (μ_r)	6.92

Table 4. Chemical compositions of cold-rolled low-carbon annealed steel (Wt. per cent)

C	Si	Mn	Fe
0.15-0.20	0.15-0.35	0.30-0.60	Balance

$$B_{T(withoutcore)} = \frac{\mu_o in}{2(r_2 - r_1)}\left[X_2 \ln \frac{\sqrt{r_2^2 + X_2^2} + r_2}{\sqrt{r_1^2 + X_2^2} + r_1} - X_1 \ln \frac{\sqrt{r_2^2 + X_1^2} + r_2}{\sqrt{r_1^2 + X_1^2} + r_1} \right] \quad (1)$$

$$\mu_r = \frac{B_{withironcore}}{B_{withoutironcore}} \quad (2)$$

$$B_{\vec{TA}} \text{ or } B_{TA(withironcore)} = B_{TA(withoutironcore)*\mu_r} \quad (3)$$

$$B_{\vec{TB}} \text{ Or } B_{TB(withironcore)} = B_{TB(withoutironcore)*\mu_r} \quad (4)$$

$$B_{\vec{T}} = B_{\vec{TA}} + B_{\vec{TB}} \quad (5)$$

where X_1 and X_2= distances (m) along the X-axis, from both ends of the solenoid to the magnetic field measurement point, $B_{with\ iron\ core}$ and $B_{T\ (without\ core)}$ =Experimental magnetic field generated by the coils in the presence and absence of iron core respectively and were determined experimentally using Gaussmeter.

$B_{TA\ (with\ iron\ core)}$ and $B_{TA\ (without\ iron\ core)}$ are total theoretical magnetic field generated by coil A with and without iron core at a distance X_1, $B_{\vec{T}}$ = total theoretical magnetic field generated by two solenoid coils A and B.

The magnetic field values obtained for various gaps (0.01 m to 0.1 m) by theoretical and experimental methods for an input current of 4.5 A using a magnetic circuit (Fig. 2) are plotted in Fig. 3 for comparison. It was observed that the magnetic field values increased with decrease in distance between the pole plates. A maximum field of 0.3816 T was measured experimentally at a gap of 0.01 m. Hence, a gap of 0.01 m between the pole plates was used during the actual experiments.

The magnetic field values obtained theoretically and experimentally at different input currents from 0 A to 4.5 A, when the distance between the pole plates was 0.01 m have been plotted in Fig. 4. It was observed that the magnetic field values increase linearly with increase in input current as determined by both the methods. It is controlled by controlling the input current.

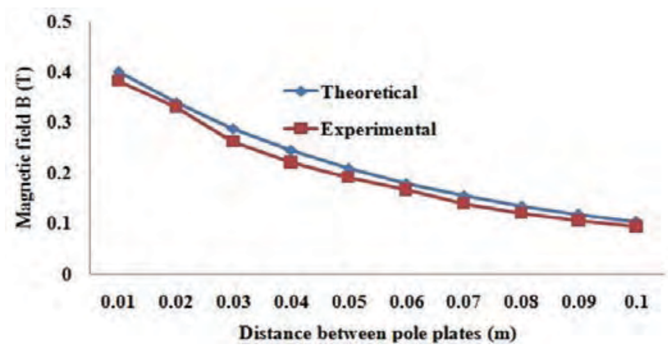

Figure 3. Comparison of theoretical and experimental magnetic fields at gap of 0.01 m.

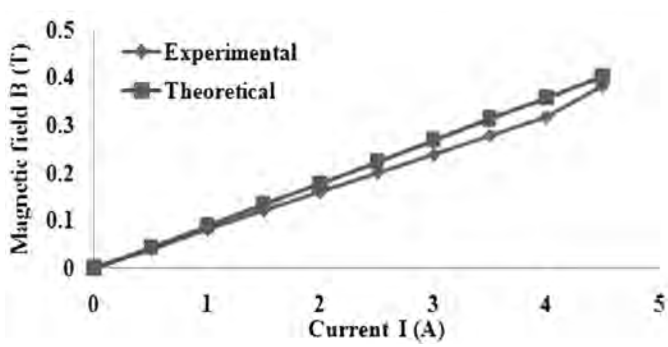

Figure 4. Comparison of theoretical and experimental magnetic fields at different currents for OA to 4.5 A..

2.4 Working of Capillary Viscometer

The capillary tube, piston, and MR fluid cylinder are important components of a capillary viscometer as shown in Fig. 5. A mild steel capillary tube is made such that the ratio of length of the capillary tube (L_c) where magnetic field is applied[12] to its radius (R_c), is maintained 60. Typically, fluid gaps from 0.00025 m to 0.002 m are recommended for ease of manufacture and assembly[13]. The magnetic field is applied perpendicular or across the flow direction of MR fluid. Magnetic chains are formed parallel to applied field and load is applied perpendicular to this. The viscometer setup provides higher magnetic flux density which is concentrated on the small portion of the capillary containing small amount of MR fluid.

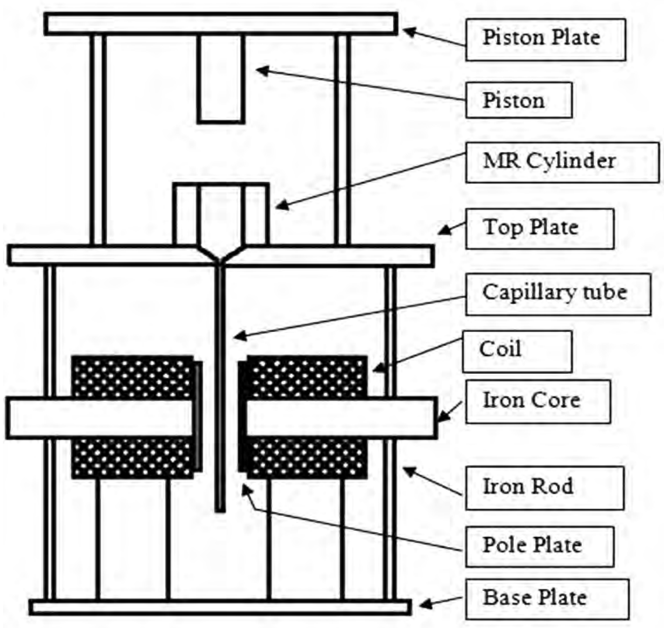

Figure 5. Capillary viscometer.

3. METHODOLOGY

The experimental set up (Fig. 6) to determine various magnetorheological properties of the proposed MR fluid consists of a hydraulic loading device, capillary viscometer, a pair of solenoid coils, dc regulated power supply and Hall probe digital Gaussmeter. Hydraulic loading device was used to apply the load on the piston to force the MR fluid in the capillary tube under magnetic field. Solenoid coils were placed on either side of the capillary tube to energise the MR fluid and a Gaussmeter probe was placed in between them.

Experiments are conducted with initial current of 0.5 A and then in steps of 0.5 A up to 4.5 A to study the effect of magnetic field on the viscosity of the MR fluid. During the test, the magnetic fields between the pole plates were varied from 0.0398 T to 0.3816 T. The pressure was varied from 11.2 bar to 33.85 bar to measure the viscosity of MR fluid at these fields. At each pressure, flow rate of the fluid (Q) was measured. Shear stress and shear rate of the fluid were calculated as $S_w = \Delta pR/2L$ and $4Q/\pi R^3$, respectively[14].

The variation of shear rate with shear stress for 40 per

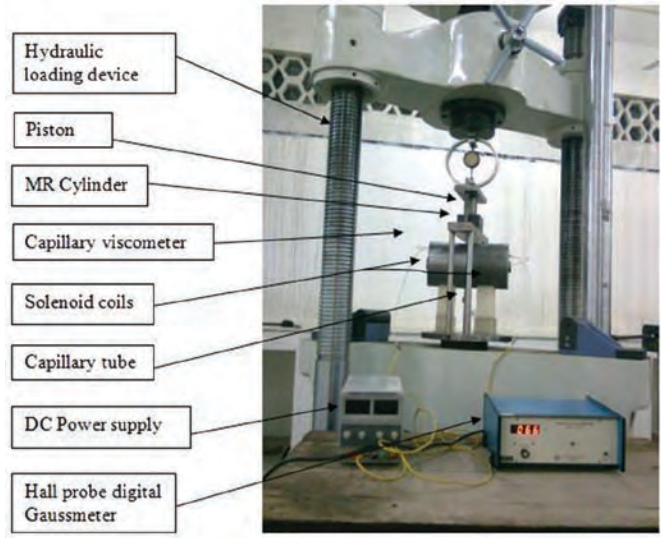

Figure 6. Photograph of test set-up to determine rheological properties of MR fluid.

cent by volume of suspensions (Φ) and 2.5 A current (0.1995 T) is plotted in Fig. 7. The plastic viscosity of the fluid was calculated as the inverse of the slope of the straightline of this figure with equation $4Q/\pi R^3 = 0.004Sw - 48.18$[14]. The yield stress was determined by the extrapolation of the straight line drawn between the shear stress and shear rate on to the shear stress axis and dividing the value by a coefficient factor of 4/3[14] to take true intercept with certainty. Viscosity and yield stress of the fluid at 0.1995 T magnetic field were calculated to be 281 Pa-s and 9.03 kPa, respectively.

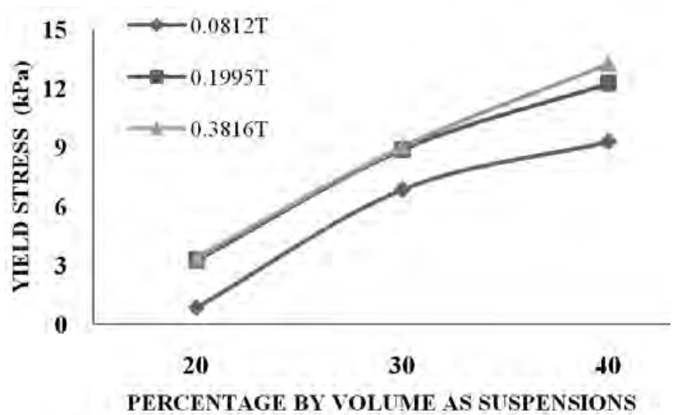

Figure 7. Variation of shear stress with shear rate for 2.5 A current and 0.1995 T.

4. RESULTS AND DISCUSSIONS

In the absence of an applied magnetic field, the MR fluid exhibits Newtonian like behaviour and its properties are the same as those of carrier liquid and it flows freely in the capillary. But as magnetic field is applied, its viscosity starts increasing. At low magnetic field (up to say 0.0350 T), the MR fluid flows by itself through the capillary and is not able to resist any applied pressure. As the magnetic field is increased, MR fluid becomes visco-plastic, and thus not able to flow itself. Thus, fluid needs pressure to flow through the capillary.

4.1 Curve of Viscosity With Magnetic Field

The variation of viscosity of the proposed MR fluid at different magnetic fields for three samples of MR fluid having different percentages of suspensions is shown in Fig. 8. It was observed that there is an increase in viscosity with increase in volume of magnetic suspensions from 20 per cent to 30 per cent, and from 30 per cent to 40 per cent. The increase in viscosity was more when volume of suspension was increased from 20 per cent to 30 per cent as compared to when it was increased from 30 per cent to 40 per cent. The viscosities of MR fluid also increase with increase in magnetic field for all the samples. At a magnetic field of 0.0398 T, the viscosity increase from 208 Pa-s to 245 Pa-s when suspension volumes increase from 20 per cent to 40 per cent. A maximum viscosity of 334 Pa-s was obtained with 40 per cent volume of suspensions (sample 3) and 0.3816 T as magnetic field.

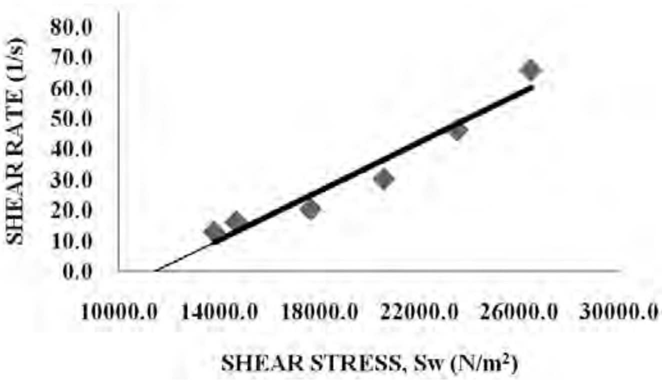

Figure 8. Variation of viscosity with magnetic field.

4.2 Curve of Yield Stress with Magnetic Field

Yield stress developed by the MR fluid due to applied magnetic field speaks for nature. The variation of yield stress of the proposed MR fluid at different magnetic fields for three samples of MR fluid having different percentages of suspensions is shown in Fig. 9. It was observed that there is an increase in yield stress with increase in magnetic suspensions at all the magnetic fields. The increase in yield stress was more when volumes of suspension was increased from 20 per cent to 30 per cent as compared to that when increased from 30 per cent to 40 per cent. The yield stress increased as magnetic field increased for all the three samples. The magnetic field

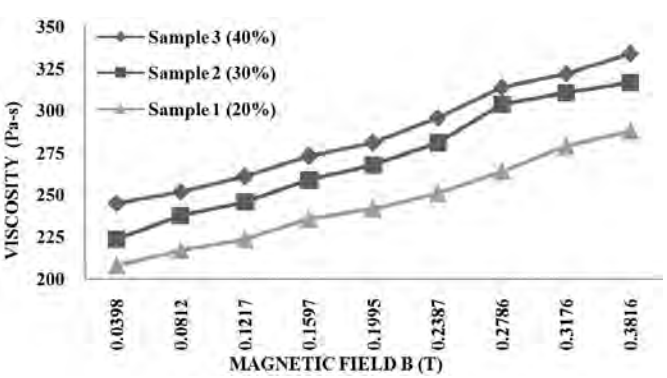

Figure 9. Variation of yield stress with magnetic field.

caused the particles to get polarised and align themselves like a chain in the magnetic field direction[1]. The ideal structure of MR fluids is a body-centered tetragonal (BCT) lattice at higher magnetic fields[15, 16]. The yield stress of MR fluids depends on the microstructure, i.e., the way magnetic particles are arranged in a magnetic field. A BCT lattice structure has a much higher yield stress than a singlechain structure[17]. Hence, as the carbonyl iron particle concentration increases, these chains grow in length and eventually aggregate to form thick columnar structures. Hence, the force required to break this structure of particles may be larger than that required to break the structure of a single chain, leading to a larger yield stress. A maximum yield stress of 13.23 kPa was obtained with 40 per cent by volume of suspension (sample 3) and 0.3816 T magnetic field. In the absence of a magnetic field, carbonyl iron particles show no permanent dipole moment and application of a magnetic field induces a magnetic dipole moment in each particle, which increases as the magnitude of the magnetic field increases.

4.3 Effect of Per cent Volume of Magnetic Suspensions on Yield Stress

The yield stresses at different magnetic fields of 0.0812 T, 0.1995 T, and 0.3816 T are plotted as a function of the per cent by volume of suspensions (Fig. 10). The values of yield stress increase with increase in per cent by volume as suspensions. The yield stress increase rapidly when volume per cent of suspensions increased from 20 per cent to 30 per cent as compared to that of 30 per cent to 40 per cent for all the three magnetic fields. This may be because of the formation of magnetic clusters at higher magnetic field. The yield stress has an approximately linear relation with the per cent by volume of suspensions.

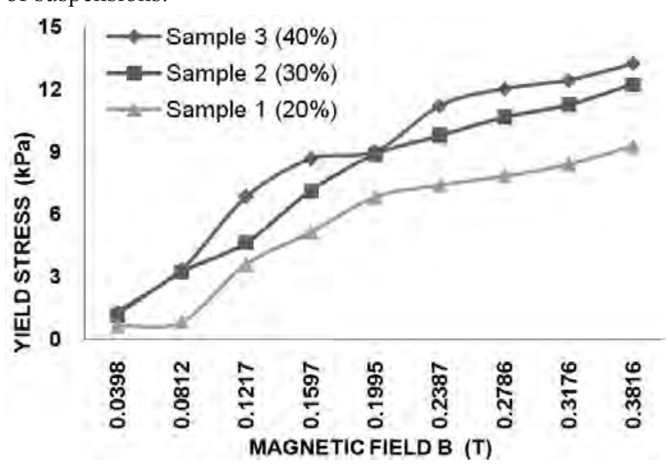

Figure 10. Yield stress function of per cent by volume as suspensions and magnetic field.

Further, the data presented in Figs 9 and 10 are compared with data published by other researchers. With iron-based MR fluid, a yield stress of approximately 15 kPa is obtained with 53 per cent as suspension and 0.3 T as flux density[18]. Then with 20 per cent iron particles as suspension and rest silicone oil as carrier liquid, a yield stress of 8 kPa is reported at 0.3 T as flux density[19]. Later with 20 per cent by volume of carbonyl iron particles as suspensions, 20 per cent by volume of *SiC* abrasive and 60 per cent by volume as visco-plastic base medium, obtained a yield stress of 7.11 kPa at 0.252 T magnetic field[10]. But in the present study, with Honge oil-based MR fluid, a yield stress of 8.22 kPa is obtained with 20 per cent by volume as suspensions (sample 1) and 0.3 T as magnetic field and 13.23 kPa with 40 per cent by volume as suspension (sample 3) and 0.3816 T as magnetic field. The values of yield stresses are comparable with those obtained by the other authors.

5. CONCLUSIONS

Three different samples of the proposed Honge oil-based MR fluids containg different volume per cent of carbonyl iron particles were prepared. An experiment consisting of a capillary viscometer, electromagnetic coils and the loading device was set up to investigate the rheological properties of the fluid. The variation of viscosity and yield stress with magnetic field for these samples were determined. It was observed that the magnetic field values increase linearly with increase in input current as determined by experimental and theoretical methods. A maximum field of 0.3816 T was measured experimentally for a gap of 0.01 m and input current of 4.5 A. It was observed that there is an increase in viscosity with increase in magnetic suspensions at all magnetic fields. The increase in viscosity and yield stress was more when volume of suspension was increased from 20 per cent to 30 per cent as compared to when increased from 30 per cent to 40 per cent. Viscosity was increased from about 8 per cent to 15 per cent (at different magnetic fields) when volume of suspension was increased from 20 per cent to 30 per cent, whereas this increase was 4 per cent to 9 per cent (at different magnetic fields) when volume of suspension was increased from 30 per cent to 40 per cent. A maximum viscosity of 334 Pa-s and yield stress of 13.23 kPa was obtained with 0.3816 T and 40 per cent by volume as suspension. Hence, Honge oil-based MR fluid may be used in possible applications which requires sudden controlled damping (yield stress), in high temperature subjected for prolonged duration of heating and even at low temperatures which come across in military applications.

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