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Experimental study and rheology of magneto-rheological fluid for a suspension system

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The formulation and synthesis of magneto-rheological (MR) fluids formed by submerging iron particles in carrier fluids are the key points of this work. To reduce the corrosion, agglomeration, and sedimentation constraints of the MR fluid (MRF), iron particles are coated with natural gums like guar and xanthan. Various MR fluid samples were prepared using combinations of carrier fluids (paraffin oil and synthetic oil), magnetic particles (carbonyl iron and atomized iron dust), and additives. The magnetic particles were characterized using scanning electron microscopy (SEM). Carbonyl iron has a fiber-like structure, whereas atomized iron dust has a granular structure. The MR fluid containing xanthan gum-coated iron particles showed improved sedimentation properties. Furthermore, the magnetic field of the magnetic piston was tested by supplying power, and it was observed that the magnetic flux density increased with an increase in the current in amperes. By conducting a visual inspection, the sedimentation analysis of the prepared MR fluids demonstrated that MRF 2 and MRF 1 improved the sedimentation rate more significantly than the others. The rheological properties of the MR fluids were determined by measuring their yield stress with respect to the applied magnetic flux density. Paraffin oil-based MR fluid mixed with xanthan gum-coated carbonyl iron (MRF 2) showed higher yield stress than other fluids. The higher value of yield strength will boost the damping force of the MR damper to effectively suppress vibrations in the system.

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1. Introduction

MR fluid is a kind of smart fluid, enhances its apparent viscosity up to the visco-elastic solid when exposed to a magnetic field. Fine-tuning the magnetic field intensity, the yield stress of the fluid in its magnetic state is regulated extremely precisely. The magnetic particles in micrometer or nanometer scale, are suspended in the carrier oil and dispersed randomly [1,2].

The three essential elements of MR fluids are additives, carrier fluid, and carbonyl iron particles. Carbonyl iron flecks with a purity of 99 percent are commonly utilized as magnetic particles because they have high magnetic permeability and dispersion magnetization. Synthetic oil, silicone oil, or any other mineral oil with a low viscosity is employed as the carrier fluid. Surfactants are commonly used as additives to avoid magnetic particle agglomeration or to slow down the pace of magnetic particle settling [3]. The usage of additives is a crucial criterion since the particles have a propensity to silt or settle down due to their high density, which if not addressed might render the device useless. The particles align in a line when a magnetic field is applied, simulating fiber structures. The fluid behaves like standard hydraulic oil in the absence of a magnetic field. The magnetic particles link together under a magnetic field and the MR fluid behaves like a solid. This fluid offers various benefits, including high strength, impurity resistance, and a wide operating temperature range. Engineering systems like dampers, brakes, and clutches employ such fluids for active and semi-active control.

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MR fluid dampers have great potential to achieve semi-actively controlled variable damping system. Fig. 1 shows MR fluid damper in opened and assembled state. The mixture development, as well as the maintenance of MR fluids, involves several challenges. MR fluids have a major problem with sedimentation. Sedimentation is a key challenge in operating fluid for moderate periods of time [3]. In the next section, the literature review is performed for articles related to MR fluids. In Section 3, the methodology of present experimental study is discussed. Results and discussion is given in Section 4 and 6. Concluding remarks are specified in the last section.

2. Literature review

Several researchers studied the performance of MR fluids. Jacob Rabinow is the first to develop a magnetic clutch at the National Bureau of standards using MR fluid. The principle behind the Magnetic clutch mechanism is that when the magnetic field is established with the help of current between two rotating plates, magnetic iron particles bind the plates together against rotating movement [1]. With the application of a magnetic field, the magnetic particles rearrange themselves in a chain-like structure in the on state and return to their initial form in the off state. Applications for this material, that changes fluid by the magnetic field from liquid to semi-solid, includes dampers, brakes, clutches, and valves [2]. The ability of magneto-rheological fluid to extend the application is considered to be constrained by a few reasons. Sukhwani et al. concluded that analysis of particle distribution and its size is very essential for the synthesis of fluid [3]. Guar and xanthan gum are employed to coat iron components in order to prevent sedimentation and agglomeration of the MR fluid. Also, grease and supplementary thixotropic additives are added to the carrier fluid. To increase performance of MR fluid additives are added in small proportion. Due to the significant density difference among iron particles and carrier fluid, iron particles have a tendency to settle down when MR fluid is not in use. Grease and thixotropic additives can be added with natural gum to prevent the microbiological deterioration over a longer time period [4]. Since MR fluid's rheological characteristics change when it comes into contact with a magnetic field, changing its damping force within milliseconds, MR dampers are cutting-edge, potentially semi-active devices that include MR fluid [5]. They provide a more comfortable and stable ride compared to active suspension systems. Sedimentation and cake formation in the majority of applications are the MRF's most crucial issues [6]. Stanway et al. described a feasibility study to develop a controllable vibration isolator using MR squeeze-flow damper. They also extended the existing damper model to consider isolator dynamics and forecast its transmissibility versus frequency characteristics. They concluded that it is possible to control the transmissibility of the vibration isolator by changing supplied current to the MR damper. Further, they developed a mathematical model which accurately predicted transmissibility versus frequency characteristics but overestimated the amplitude of reasonable peaks [7].

Park and Jung proposed a novel electronically controlled power steering which utilizes MR fluid. They performed an experimental study to verify the performance of the developed MR system [8]. UmitDogruer studied a semi-active fail-safe MR fluid damper for off-highway, high mobility automobiles. He constructed a 2 degree of freedom quarter car model and utilized various control algorithms to control MR fluid damper. MR Fluid performance is simulated using the Bingham Plastic model, and the magnetic field circulation is obtained by a three-dimensional electromagnetic finite element analysis. [9]. Lin et al. experienced the performance of a retro designed MR damper under dynamic loading conditions. They utilized an online detection algorithm and modified Bouc-model to develop a mathematical model of the performance of the MR model. Further, they applied MR damper with experimental structure [10].

Wray et al. tested MR fluid semi-active damper suspension system on a Stryker vehicle. The entire model was tested, encompassing eight dampers and controllers using an algorithm [11]. Nabaglo studied the version of the control system modeling of MR fluid dampers in vehicle suspension systems with law energy requirements (maximum 20 W per damper) experimentally and numerically. Objective was to reduce significant amount of vertical acceleration against moments and forces acting on the vehicle in different riding conditions [12]. Aydar et al. studied the theoretical analysis, design and characterization of slender MR fluid damper.

(a) (b)

Fig. 1. MR fluid damper (a) Disassembled and (b) Assembled state.

They found that the controllability of MR damper allows adjusting of damping requirement for different frequencies and reduces noise at resonance occurring at high vibrations [13]. Susan-Resiga presented a rheological damper for MR fluid by combining a quasi Newtonian behavior at very low shear stress with the Herschel-Bulky model for considerable shear stress. They showed that their model perfectly fits experimental results over a wide shear rate range. Further, they showed that an essential advantage of their model is that it can be used in computational fluid dynamics codes to calculate MR fluid flow in practical applications [14]. Dong et al. compared the performance of various controllers that can be used with MR dampers, namely, skyhook, fuzzy logic, LQG, hybrid, and sliding mode controllers. They reported that sliding mode-controlled MR dampers provide the best suspension performance [15]. Mansour et al. developed engine mount using MR damper for variable displacement engines. As the requirement of damping varies during activation and deactivation operating modes of engines, MR fluid dampers provide the best control over vibration minimization in automotive[16].Lozoya-Santos et al. proved that MR dampers provide excellent damping characteristics by controlling the magnetic field [17]. Tudon-Martınez et al. tested artificial neural networks (ANNs) model for MR dampers. They concluded that MR dampers could be modeled better using the proposed ANN than other parametric models [18]. Shojaei et al. determined the damping properties of fuzzy logic and skyroot controlled MR dampers using the customized Bouc-Wen model. They proved the suitability of the damper in the car suspension system using analytical modeling [19]. The magnetic and rheological properties of several commercial MR fluids are presented by Jolly et al. They compared these fluids and discussed their present-day applications. Also, they showed that material properties are easily tuned to obtain optimal performance [20].

Particle sizes varying from 0.05 μm to 10 μm have been tested by authors with different carrier fluid combinations. Consequently, Brownian random forces will be imposed to particles smaller than 0.1 μm, destroying the chain-like structure and reducing yield stress. Besides particles with more than 10 μm size produce the sedimentation trouble. Guar gum-coated particles will help establish a strong chain-like structure to lessen the effects of sedimentation [21]. In the quarter vehicle concept, the active seat suspension system is approximated using the equivalent damping model and the Bingham model. They are first exposed to a bump input before being driven on a random road with varying levels of road roughness. The Equivalent Damping Model is found to perform better than the damper behaviour than the Bingham model in both scenarios, i.e., bump input and random road input [22]. The ability of the designed hybrid MR damper to absorb shocks in difficult driving circumstances is demonstrated by authors [23]. In the present paper, an experimental analysis is performed for the selection criteria of MR fluid in the MR damper of the suspension system. Firstly, magnetic micro-particles, coating powder, non-magnetic base oil, and additives are selected. Magnetic iron particles coated with guar gum and xanthan gum powder are characterized using a scanning electron microscope (SEM). Then, samples of MR fluid are prepared according to the experimental design. Afterward, samples are observed for sedimentation, magnetic flux density, and damping force.

3. Experimental

3.1. Materials

While developing MR fluid, one of the most challenging tasks is avoiding sedimentation. In the present experimental study, various combinations of carrier fluid, additives, and magnetic particles are tested to develop an MR fluid with minimum sedimentation.

In the current study, four combinations of micro scale magnetic particles are employed to develop an MR fluid, as listed in Table 1. The iron particles, namely, carbonyl iron and atomized iron dust, are coated with guar gum and xanthan gum powder in these combinations. Further, three different non-magnetic oils were selected as given in Table 2. Carbonyl iron with a particle size of 2 μm to 5 μm is procured from Industrial Metal Powders India Pvt. ltd., India. Atomized Iron Dust having a particle size of 10 μm to 20 μm is procured from Höganäs AB, Sweden. From the Table 1, it is observed that density of atomized iron dust with xanthan gum is more than other samples and if density is more, chances of sedimentation increases. Hence only first three samples are used further for mixing with oil.

Paraffin oil, Silicone oil and Synthetic oil samples are used as carrier fluid to test the MR fluid. Paraffin oil has the highest value of kinematic viscosity of 173 cSt. These carrier fluids are mixed with different additives to improve the rheological and sedimentation properties of MR fluid as shown in Table 3. Prepared fluids are tested on Brookfield DVE Viscometer for checking shear stress change with varying shear rate. Fig. 2 shows that fluid 1 and fluid 2 has higher amount of shear stress.

As to increase damping force higher value of shear stress is desirable, hence fluid 1 and fluid 2 are selected for further combinations of MR Fluid. Method of MR fluid preparation and percentage of ingredients selected is specified in flow chart as shown in Fig. 3.

Initially, MR fluids are prepared using a high-speed stirrer, as shown in Fig. 4(a). Then, kinematic viscosity of these fluids are measured after stirring using Brookfield DV-E viscometer, as shown in Fig. 4(b). As described in flow chart final fluid is prepared by stirring all the ingredients for 12 h.

Table 1
Coated magnetic particles.

Sample No.	Magnetic particles and coating	Density in gm/cm^3
Sample A	Carbonyl Iron + Guar Gum Powder	1.42
Sample B	Carbonyl Iron + Xanthan Gum powder	1.51
Sample C	Atomized Iron Dust + Guar Gum powder	2.81
Sample D	Atomized Iron Dust + Xanthan Gum powder	2.94

Table 2
Carrier fluid properties.

Carrier fluid	Density in gm/cm^3	Kinematic Viscosity in centistokes
Paraffin oil	0.812	173
Synthetic oil	0.783	35.3
Silicone oil	0.760	10.4

Table 3
Combination of carrier fluid and additives.

Carrier fluid with additive	Base fluid	Additives	Density in gm/cm3
Fluid 1	Paraffin oil	Grease + Oleic acid	0.873
Fluid 2	Synthetic oil	Grease + Stearic acid	0.824
Fluid 3	Silicone oil	Glycerine + Ethanol	0.918

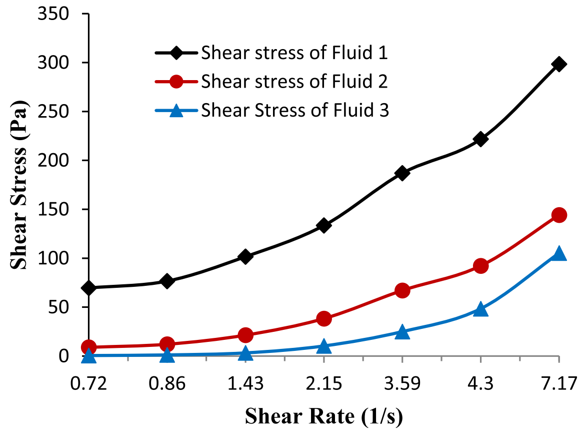


Fig. 2. Shear stress change with varying shear rate.

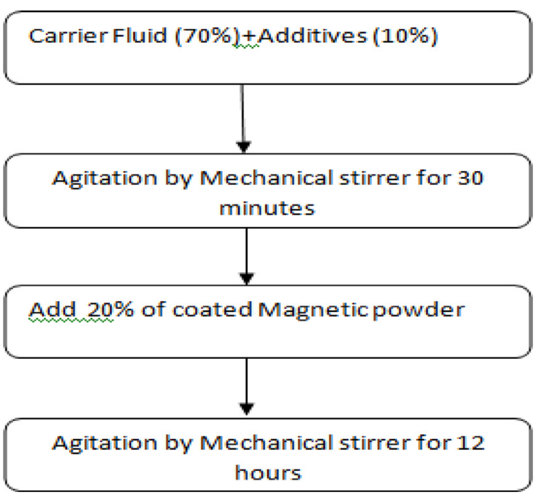


Fig. 3. Flow chart for preparation of MR Fluid.

3.2. Morphology of magnetic particles

The particle shapes and sizes are observed by Field Emission Scanning Electron Microscopy (FESEM) at central Instrument Facility (CIF) at the SavitribaiPhule Pune University. Samples A, B and C as shown in Table 1 are tested for observing size and shape. The SEM figures of the samples A, B, and C (magnetic powders) coated with guar gum and xanthan gum are shown in Fig. 5.Coating of gum became smooth membrane on iron particles like coating surfaces. Carbonyl iron powder coated with guar gum and xanthan gum has size of particle from 1 to 5 µm, whereas atomized iron dust coated with guar gum size ranges from 5 µm to 20 µm. Magnetic strength of larger iron particles is higher than the smaller iron particles, but they tend to settle down at the bottom of fluid and have problem of sedimentation.

Atomized iron dust-coated with guar gum powder possesses a smooth surface with spherical in shape, but are having a large size up to 20 µm. Carbonyl iron powder coated with guar and xanthan gum also own a smooth surface and has a fiber-like structure which is helpful in forming a chain-like structure in the magnetic field area, as a result increasing the damping force of the MR damper.

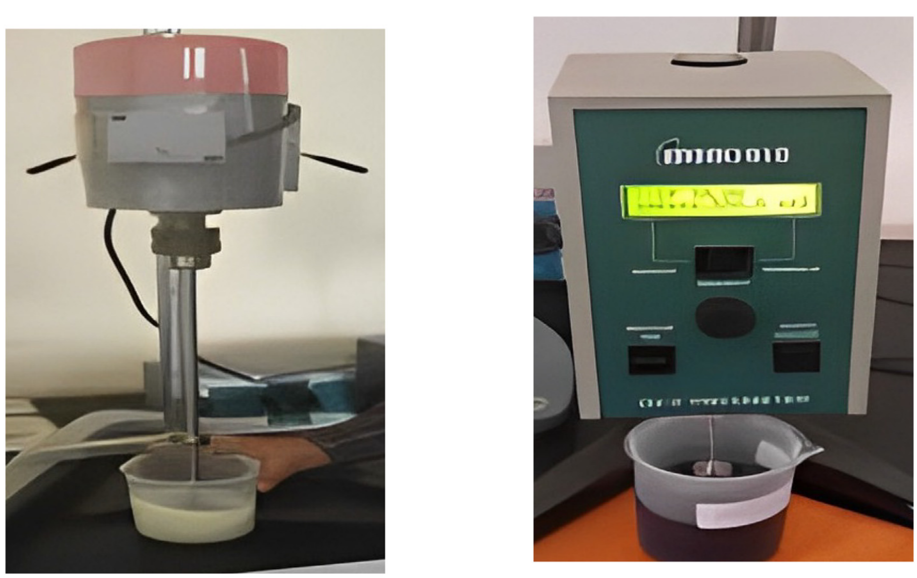
3.3. Synthesis of magneto-rheological fluid

In the present work, two carrier fluids (fluid 1 and fluid 2) with different additives suitable for MR damper application and three types of iron particles (guar gum coated carbonyl iron, xanthan gum coated carbonyl iron, and guar gum coated atomized iron dust) are used to prepare MR Fluid. Five types of MR fluids are prepared as shown in Table 4. As atomized iron dust-coated with guar gum size ranges from 5 µm to 20 µm, only one combination is prepared, as higher size particles will settle down soon.

Different MR fluid mixtures as shown in Table 4 are prepared by agitation of fluid with the mechanical stirrer at running at 900 rpm for 12 h to make it homogeneous.

4. Sedimentation analysis

Visual inspection is performed to compare the height of dispersed phase (Hd) and height of settled phase (Hs) along different



(a) (b)

Fig. 4. (a) Stirrer, (b) Viscometer.

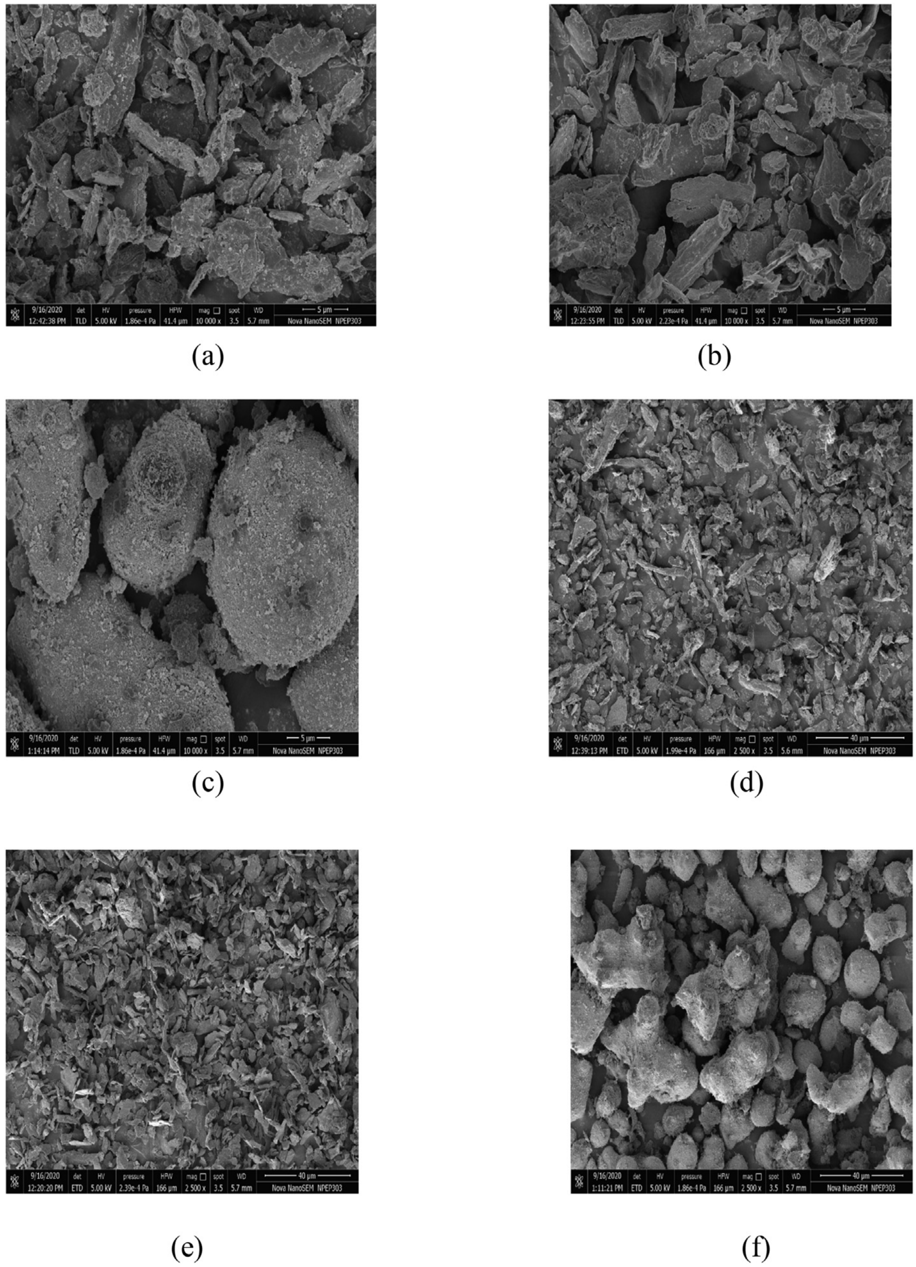


Fig. 5. SEM images of magnetic particles of MRFs (a) Sample A at 10000x, (b) Sample B at 10000x, (c) Sample C at 10000x, (d) Sample A at 2500x, (e) Sample B at 2500x, (f) Sample C at 2500x.

Table 4
Type of MR Fluids.

MR Fluid	Base fluid	Additives	Magnetic particles and coating
MR Fluid1 (MRF 1)	Paraffin oil	Grease + Oleic acid	Carbonyl Iron+ Guar Gum Powder
MR Fluid 2 (MRF 2)	Paraffin oil	Grease + Oleic acid	Carbonyl Iron+ Xanthan Gum powder
MR Fluid 3 (MRF 3)	Synthetic oil	Grease+ Stearic acid	Carbonyl Iron+ Guar Gum Powder
MR Fluid 4 (MRF 4)	Synthetic oil	Grease+ Stearic acid	Carbonyl Iron+ Xanthan Gum powder
MR Fluid 5 (MRF 5)	Paraffin oil	Grease + Oleic acid	Atomized Iron dust + Guar Gum Powder

(a) (b) (c)

Fig. 6. Sedimentation study (a) and (b) Visual measurement, and (c) Diagrammatic representation.

time intervals to find thesettling rate of iron particles. Fig. 6 shows a reprequationesentative experiment performed for the sedimentation study. Eq. (1) shows calculations for obtaining percentage sedimentation. Where R represents the sedimentation ration and Hd + Hs represents total height of the MR fluid.

$$\%R = \frac{H_d}{H_d + H_s} \times 100 \tag{1}$$

All the prepared MR Fluids were poured into 50 ml cylinder as seen in Fig. 6b and observed for time in hours. Fig. 6a shows the volume of magnetic particles settled at the bottom. Diagrammatic representation shows the height of dispersed phase (H_d) and height of settled phase (H_s).

It is observed in the Fig. 7 that MRF 5 fluid has greater sedimentation ratio than others. Atomized iron dust settled down rapidly in the MRF 5 and reached 64 %. Subsequently, the sedimentation ratio of Carbonyl iron coated with xanthan gum powder in MRF 2 became slow as compare to other fluids. As the shear stress change of Paraffin oil with grease and oleic acid (MRF 2) is more and density of Carbonyl Iron coated with Xanthan Gum powder is low, settling speed of MRF 2 is slowed down.

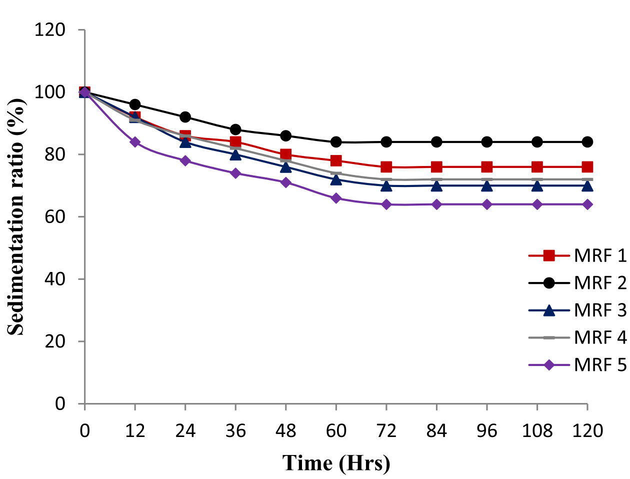


Fig. 7. Sedimentation versus Time in hours.

5. Magnetic flux density study

The efficient working of MR damper counts on the flow of magnetic field. Hence required damping force of MR damper is dependent on the magnetic flux density of magnetic piston. The magnetic permeability is the important property to increase magnetic flux density and magnetic force of MR damper. Absolute permeability (μ) is given by Eq. (2) and magnetic flux density is calculated with the help of Eq. (3). Relationship values between input electric power in ampere and output magnetic flux density in Tesla are given in Table 5.

$$\mu = \mu r \times \mu 0 \tag{2}$$

where,
μ_0 = permeability of the free space.
= $4\pi \times 10^{-7}$(Henries per meter).
μ_r = relative permeability of material.
$\mu = \mu_r \times \mu_0 = 200 \times 4\pi \times 10^{-7}$

$$\text{Magnetic flux density} = B = \mu r \times \mu o \times H(Tesla) \tag{3}$$

H = Magnetic field intensity = NI/l.
Number of turns are = N = 320.
I = current in Ampere.
Length of iron core solenoid = length of magnetic circuit (l) = 26 mm = 0.026 m.

It is examined from the Fig. 8, that the magnetic flux density increases with increment in current of magnetic coil. Magnetic flux density increases linearly up to 1 A current and saturation point

Table 5
Magnetic flux density measurements.

Sr. No.	Current (A)	Magnetic flux density (T)
1	0	0
2	0.2	0.62
3	0.4	1.23
4	0.6	1.85
5	0.8	2.47
6	1	3.09
7	1.2	3.58
8	1.4	3.91
9	1.6	4.21
10	1.8	4.42
11	2	4.54

occurs at 1.8 A. Hence MR fluid is activated from current 0.1 A to 2 A.

6. Results and discussions

Apparent viscosity of all five fluids for different magnetic flux densities is measured using Brookfield DV-E viscometer. Results of apparent viscosity vs the magnetic flux densities for all five MR fluid samples are shown in Fig. 9. MRF2 sample shows a high apparent viscosity compared to others. Apparent viscosity of MRF2 is more than 35 Pa-s at 600 mT magnetic flux density. Current in ampere for all fluids was increased gradually and viscosity was measured. MRF5 fluid showed low amount of viscosity than other four fluids. It shows that MRF2 can be transformed from low viscosity fluid into a semisolid state in a few milliseconds and when the magnetic field is removed, the fluid reverts back to its natural free-flowing state.

Rheological measurements of developed MR fluids were carried out by applying the magnetic field with the assistance of current in ampere. In the vicinity of magnetic field, the rheology of MR fluids instantly changes from a free flowing liquid state to a semi solid state with controllable yield strength. As Shown in Fig. 10, MR fluids offer high yield strength in the presence of a magnetic field and low yield strength in the absence of a magnetic field. MR fluid with paraffin oil as base oil, mixed with additives grease and oleic acid and xanthan gum coated carbonyl iron (MRF2) can develop the yield stresses above 50 kPa, while MR fluid with synthetic oil as base oil, mixed with additives grease, stearic acid (MRF 3 and MRF 4) couldn't exceed 48 kPa. MRF 1 shows rheological properties near to MRF 2 but is lower than it.. MR fluid with synthetic oil as base oil, mixed with additives grease and stearic acid and guar gum coated carbonyl iron (MRF2) has low yield stresses for all magnetic flux densities.

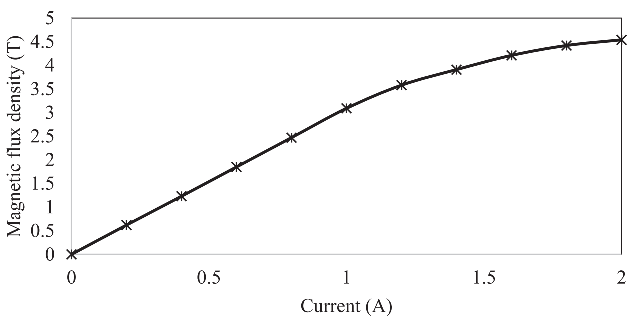


Fig. 8. Relationship between magnetic flux density and current.

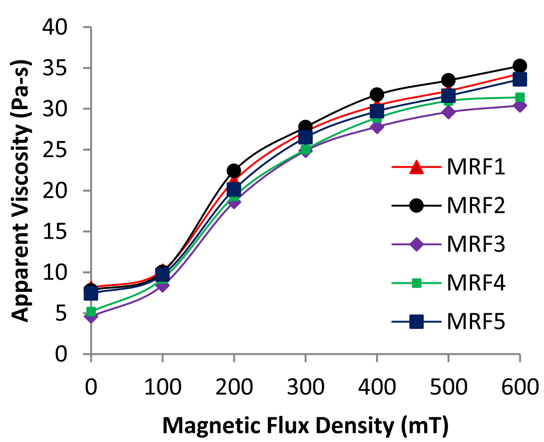


Fig. 9. Apparent viscosity vs magnetic flux density for five MR fluid samples.

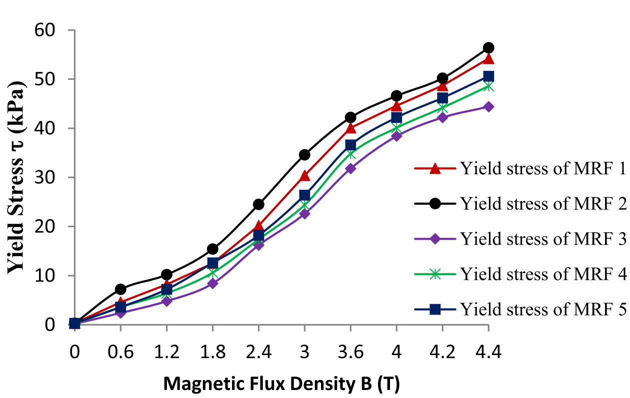


Fig. 10. Yield stress change with varying magnetic flux density.

7. Conclusions

The experimental investigation of sedimentation, magnetic flux density, and change in apparent viscosity with variable magnetic flux densities are the main areas of research in this publication. Yield stress analysis is observed for five MR fluid samples. Samples are prepared by combining carrier fluids (Paraffin oil and synthetic oil), magnetic particles (Carbonyl Iron and Atomized Iron Dust), and additives. It is found that MRF1 and MRF2 with Paraffin as carrier fluid contain less sedimentation ratio than other fluids. Also, the magnetic flux density increases with the rise in current. For all samples, viscosity increases with an increase in current. Desirable shear stress up to 300 Pa was observed in Paraffin oil mixed with grease and oleic acid. Silicone oil was not considered further for the synthesis of MRF as it has a shear stress of less than 100 Pa. In comparison to other samples, the MRF2 and MRF1 samples show a higher apparent viscosity. Morphology images of carbonyl iron coated with guar gum and xanthan gum powder showed a fiber-like structure, which increases the surface area with fluid. Hence MRF 2 with paraffin oil as base oil, mixed with xanthan gum coated carbonyl iron illustrated yield stress of more than 50 kPa. This fluid property of high yield stress and apparent viscosity helps in increasing the resistance force of the MR damper. Paraffin-based MR fluids outperformed other fluids together in sedimentation and yield stress development.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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