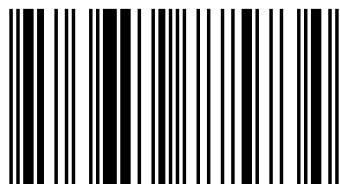


Magneto-rheological (MR) fluid technology has been proven for many industrial applications like shock absorbers, actuators, etc. In this research, electrolytic and carbonyl iron powder based MR fluids have been synthesized and characterized to identify their different properties especially to suit high yield stress applications like MR brake, MR clutch etc. Few MR fluid samples based on sunflower oil, which is bio-degradable, environmentally friendly and abundantly available have also been prepared. Different synthesis and characterization techniques have been presented to help the researchers to work further in this area. characterization results of locally made MR fluid samples and commercially available Lord Corporation's 132DG MR fluid have been compared and then suitability of particular MR fluid for high yield stress application has decided.



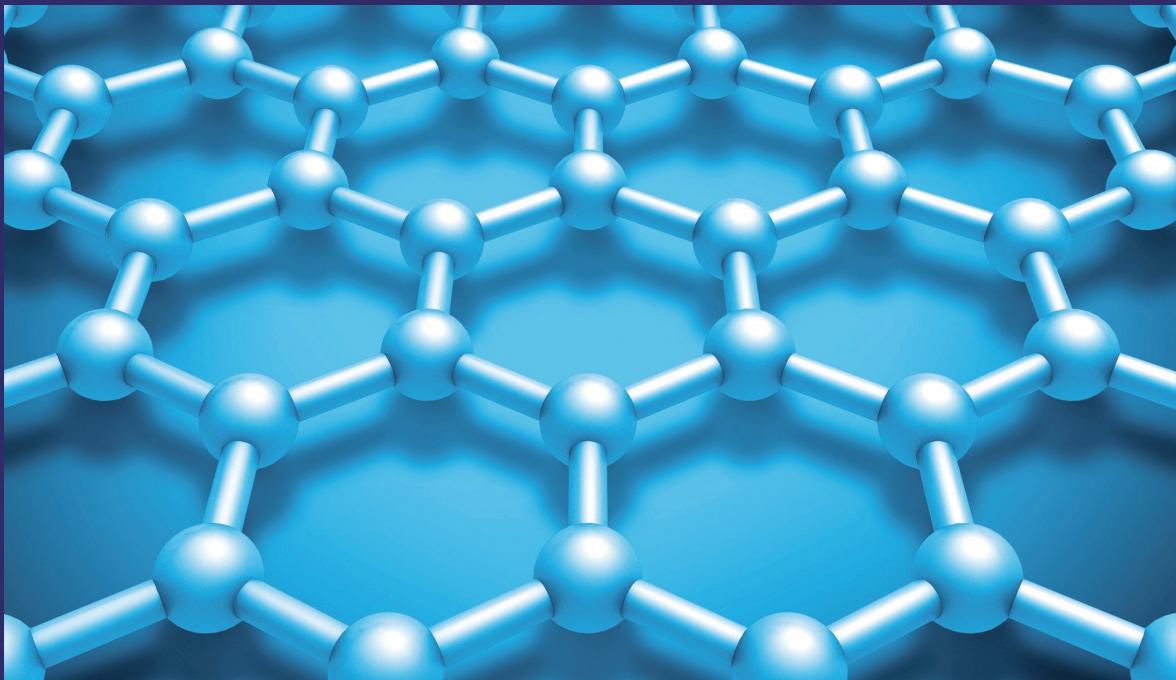
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Kumbhar

Magneto-Rheological Fluids



Bhau Kumbhar

Synthesis and Characterization of Magneto-Rheological Fluids

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1. INTRODUCTION AND MOTIVATION

The purpose of this chapter is to express the motivation for this work and to introduce the objectives. With the objectives identified, the means by which the objectives will be met are discussed. Finally, a discussion of the contributions of this work and an outline of this document conclude the chapter.

1.1 General

Science and Technology has made excellent developments by using different standard materials. Such materials have the ability to change their properties for example to change their shape or size when exposed to even a small amount of heat or to change the state from the liquid to a solid when exposed to a magnet. These materials are called as smart materials. Some of these materials are Shape-memory alloys, piezoelectric materials, electrostrictive and magnetostrictive materials, field responsive composites, electro-rheological fluids and solids, magneto-rheological (MR) fluids and solids, Ferro-fluids etc. [1].

Magneto-rheological (MR) fluid is a type of smart material whose rheological properties (e.g. viscosity) can be rapidly varied by applying a magnetic field. MR fluids are basically the suspensions of polarizable magnetic particles in the magnetically neutral carrier or base fluid. Under influence of magnetic field these suspended magnetic particles interact to form a chain like structure that resists shear deformation or flow. These chain-like structures restrict the motion of the fluid, thereby increasing the viscous characteristics of the suspension. The mechanical energy needed to yield these chain-like structures increases as the applied field increases resulting in a field dependent yield stress. This change in the material appears as a rapid increase in apparent viscosity or in the development of a semisolid state. Some additives and surfactants are also added in MR fluids in order to enhance their properties to suit the various industrial applications. The first development of

MR fluid was credited to Jacob Rainbow (1949) at the US National Bureau of Standards [2].

When a magnetic field is not present an MR fluid behaves like a Newtonian fluid. When a magnetic field is present, the MR fluid shows a characteristic of Bingham fluids. Newtonian fluids are basically those which obeys Newton's law of viscosity (Shear stress \propto time rate of deformations), have constant viscosity (Viscosity is independent of shear stress) and there will be linear relationship between shear stress and resulting rate of deformation.

It is recognized that the Bingham model is valid for use in describing the rheological features of an MR fluid. At zero shear rate there is some resistance to flow. The force causes a plastic deformation, but there is no continuous movement. In this condition, the maximum stress, which can be applied without causing continuous movement, is the yield stress and this is a function of the magnetic field strength [2].

1.2 Motivation for Present Work

Brake performance has direct bearing on road safety which is a key issue in India. Reduction in stopping distance and stopping time without sacrificing vehicle stability will help in great deal to improve the road safety. The response time of conventional hydraulic brake is around 200-300 ms; which if could be reduced, shall translate in reduction in stopping distance. Active control of brake system shall play an important role as well. Also, regular brakes which employ hydraulic fluids face the problem of fading, which reduces brake effectiveness.

MR brakes in motor vehicles may possibly provide some solutions to above mentioned problems and help to realize the objectives. MR brake's response time is 15-20 ms and active control is possible since it uses electromagnet for actuation of brakes.

Especially, when the number of electric and hybrid vehicles is on the rise on Indian roads, MR brakes and their adaptability for automotive braking requirements need some serious investigation.

MR brake mainly depends on the performance of the MR fluid which means the yield strength produced by it. Hence, as the major component of this MR brake operation is MR fluid, the research mainly emphasizes on the characterization and formulation of MR fluid. Rajarambapu Institute of Technology has identified ‘Smart Materials’ as a research area under Technical Education Quality Improvement Program (TEQIP). Also, **Industrial Metal Powders, Pune** have shown an interest in this research of formulation & characterization of MR fluids.

1.3 Aims and Objectives

This research intends to address the lack of awareness regarding the selection of effective MR fluid components. The Intention here is to provide a thorough investigation of the behavior of MR fluid in order to increase the yield strength which will be further helpful in shear mode applications.

The primary objectives of this research can be summarized as follows:

1. The main objective of proposed research study is to explore the potential of MR fluids for automotive MR brakes to be used as service brakes.
2. Application of MR fluid synthesis technology and knowhow
3. Synthesis and characterization of MR fluid by using electrolytic iron powder (locally made)
4. Synthesis and characterization of MR fluid by using carbonyl iron powder (Locally made)
5. Characterization of commercial MR fluid supplied by Lord Corporation, USA.
6. Comparative study between electrolytic iron powder based MR fluid and carbonyl iron powder based MR fluid.
7. Cost analysis of MR fluid made locally available.

1.4 Organization of Dissertation Work

The report of project work is organized as follow:

Chapter I-Introduction and Motivation

This chapter provides an idea of the research work which will be carried out in further studies. It also provides the base for this research.

Chapter II – MR Fluid and MR Brake

This chapter Introduces the basic concepts of MR fluid and MR brake. Furthermore, it elaborates the MR fluid technique, its working, components, properties and various modes of application.

Chapter III – Literature Survey

The extensive survey has been carried out on synthesis and characterization of magneto-rheological (MR) fluids and MR brake by referring earlier research works published in reputed journals. This has helped to develop a theoretical background required for the proposed work.

Phase IV –Synthesis of MR Fluids

MR fluid samples based on suitable compositions shall be formulated locally in order to evaluate their behavior and compare with commercial MR fluid characterized. The synthesis route has been defined for the same and proper selection of MR fluid components has been made.

Phase V –Characterization of MR Fluids

This chapter has presented the various techniques used for the characterization of MR fluid samples. It has also discussed the methodology of operation of these instruments and their specifications.

Phase VI –Results and Discussions

The results of characterization of MR fluid samples have been presented in this chapter. Based on these results, the comparative study of various properties of these MR fluid samples has been made. Also, the cost analysis for various MR fluid samples has been done.

1.5 Closure

The problems with the conventional hydraulic brakes have been presented in this chapter. Also, it mainly emphasizes on the motivation for the work and various objectives which need to be completed in further studies. The drawbacks of conventional brake used in an automotive brake can be eliminated with the use of magneto-rheological (MR) fluid brake. The next chapter elaborates the concept of MR fluid technology and MR brake in detail.

2. MR FLUID AND MR BRAKE

2.1 MR Fluid

Magneto-rheological (MR) fluids are a class of new intelligent materials whose rheological characteristics change rapidly and can be controlled easily in presence of an applied magnetic field. This chapter presents the introduction, working principle, rheology, various modes of operations and typical properties of MR fluid. [3]

2.1.1 Introduction

MR fluids consist of stable suspensions of micro-sized, magnetizable particles dispersed in a carrier medium such as silicone oil or water. As shown in figure 1, MR fluid is in a free-flowing liquid state in the absence of a magnetic field, but under a strong magnetic field its viscosity can be increased in a very short time (milliseconds) and it exhibits solid-like characteristics [1].

Magneto-rheological fluid (MRF) technology is an old “newcomers” coming to the market at high speed. Various industries including the automotive industry are full of potential MRF applications. MRF technology has been successfully employed already in various low and high volume applications. A structure based on MRF might be the next generation in design for products where power density, accuracy and dynamic performance are the key features [3].

Magneto-rheological (MR) fluids are a class of smart materials whose rheological characteristics change rapidly and can be controlled easily in the presence of an applied magnetic field. The devices based on MR fluids, including dampers, brakes, clutches, polishing devices and hydraulic valves, etc., have a very promising potential future; some of them have been used commercially in engineering applications such as automobiles, polishing machines and exercise equipments [4].

The strength of MR fluid can be described by shear yield stress. The change in viscosity is continuous and reversible i.e. after removing the magnetic field the MR fluid can revert to a free flowing liquid. Using these characteristics of MR fluids, MR

fluid devices have the ability to provide simple, quiet and rapid response [5]. Therefore, MR fluids hold great potential in many applications that require an electromechanical interface, such as clutches, brakes, valves, dampers and robotics. Another benefit is that its application can reduce the complexity of devices significantly [3]

2.1.2 Working Principle of MR Fluid

MR fluids consist of stable suspensions of micron-sized, magnetizable particles dispersed in a carrier medium such as silicone oil or water. As shown in Fig. 2.1, MR fluid is in a free-flowing liquid state in the absence of a magnetic field. When the MR fluid is subjected to a magnetic field, the particles become magnetized (induced dipoles) and they start to behave like tiny magnets. This is the ‘on’ or magnetized state of the MR fluid. The magnetic interaction, and with that the total potential energy, between these particles can be minimized if the particles line-up along the direction of the magnetic field lines. With the potential energy minimized the particles are in a stable position. The interaction between the resulting induced dipoles causes the particles to aggregate and form fibrous structures within the carrier liquid (chains or column-like structures, see Fig. 2.1), changing the rheology of the MR fluid to a near solid state. **These chain-like structures restrict the flow of the fluid, thereby increasing the viscosity of the MR fluid [6].**

The magnetic particles, which are typically micrometer or nanometer scale spheres or ellipsoids, are suspended within the carrier oil are distributed randomly and in suspension under normal circumstances. The change of behavior of MR fluid from liquid to solid occurs on the application of magnetic field as shown in Fig. 2.1.

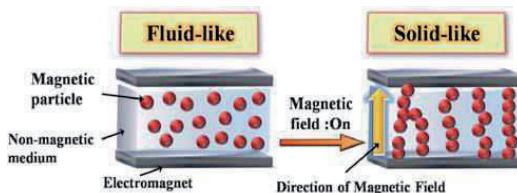


Fig. 2.1 Structural change in MR fluid [7]

Thus, in designing a MR device, it is crucial to ensure that the lines of flux are perpendicular to the direction of the motion to be restricted.

2.1.3 Rheology of MR Fluid

Rheology is the study of the deformation and the flow of the liquid. Basically three factors viscosity, shear stress and rate of strain are considered in the study of flow and deformation. In most of the fluid applications viscosity is an important property. In case of general fluids, viscosity changes with change in other physical properties such as shear stress, temperature etc. [8].

In most applications these physical properties cannot be controlled as they are governed by the working environment and hence the viscosity also cannot be controlled. In the case of MR fluid, the viscosity can be controlled with the help of magnetic field. Rheologically the MR fluid can change from a liquid state to a solid state by varying the strength of the magnetic field and this change is\ reversible. The rheological characteristics of MR fluid can be described effectively by using a Bingham plastic model. Fig. 2.2 shows the typical relationship between shear stress and shear rate for a Bingham fluid and compares this with a Newtonian fluid. It is recognized that the Bingham model is valid for use in describing the rheological features of an MR fluid [9].

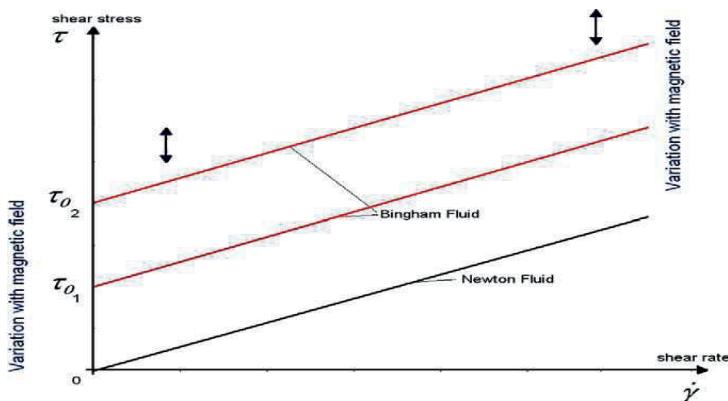


Fig. 2.2 Shear stress versus shear rate for Newton and Bingham model of MRF [9]

In the absence of magnetic field, MR fluid exhibits a Newtonian-like behavior, where the shear stress of MR fluids can be described as

$$\tau = \eta \dot{\gamma} \quad \dots \dots \dots \quad (2.1)$$

When the magnetic field is applied, the behavior of the controllable fluid is often represented as a Bingham fluid having variable yield strength [6].

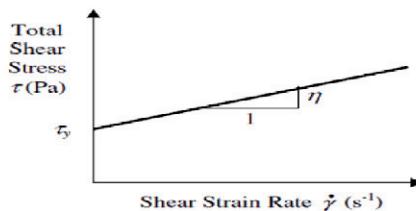


Fig. 2.3 Bingham Plastic Model [6]

In this model, the total shear stress τ is given by

$$\tau = \tau_H + \eta \dot{\gamma} \quad \dots \dots \dots \quad (2.2)$$

Where, τ_H is the yield stress due the applied magnetic field, η is the constant plastic viscosity, which is considered equal to the no field viscosity of the fluid and $\dot{\gamma}$ is the shear rate [7].

2.1.4 MRF Components

MR fluids are suspensions of micron-sized, magnetizable particles in a carrier fluid. They mainly consist of the following three components: base fluid, metal particles and stabilizing additives. These components are described below.

Carrier Fluid:

The carrier fluid serves as a dispersed medium and ensures the homogeneity of particles in the fluid [10]. For the highest MRF effect the viscosity of the fluid should be small and almost independent of temperature. In this way the MRF effect will be the dominant effect when it is compared with the natural physical viscosity varying with temperature and shear stress. There are different types of liquid which can be used as the carrier fluid i.e. hydrocarbon oils, mineral oils or silicon oils [11].

Metal Particles

The metal particles are usually made of carbonyl iron, or powder iron, or iron/cobalt alloys to achieve a high magnetic saturation. The amount of metal powder in MRF can be up to 50% by volume. Typically, the diameter of the magnetizable particles range from 3 to 10 microns.

Larger particles and higher fractions of powder in the MR fluid will provide higher torque in the on state, but at the same time the viscosity of the MR fluid in the off-state will also be higher under these conditions [3].

Additives and surfactants

The additives include stabilizers and surfactants. Additives are suspending agents, thixotropes, friction modifiers and anti-corrosion/wear components. Highly viscous materials such as grease or other thixotropic additives are used to improve settling stability. Ferrous naphthanate or ferrous oleate can be used as dispersants and metal soaps such as lithium stearate or sodium stearate as thixotropic additives. Additives are required to control the viscosity of the liquid and the settling rate of the particles, the friction between the particles and to avoid the in-use thickening for a defined number of off-duty cycles [3].

All three components define the magneto-rheological behavior of the MR fluid. The change of one of the MRF components will lead to rheological changes (in the off-state) and to magneto-rheological changes in behavior (in the on-state). Finally a trade-off between the achievable performances of all three components in combination is required in order to optimize a formulation [3].

2.1.5 Operational Modes of MRF

The modes of operation for MR fluid devices are flow mode (fixed plate mode, valve mode), shear mode (clutch mode), squeeze mode (compression mode) and any combination of these three.

Valve mode:

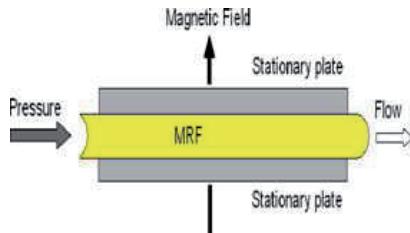


Fig. 2.4 Valve mode [12]

In the flow mode, MR fluid is made to flow between static plates by a pressure drop, and the flow resistance can be controlled by the magnetic field which runs normal to the flow direction. Examples of the flow mode include servo valves, dampers, shock absorbers and actuators [12].

Shear mode:

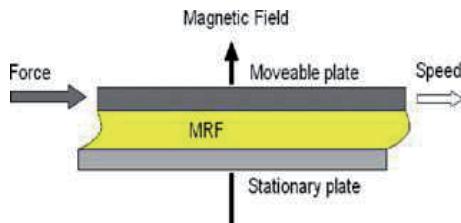


Fig. 2.5 Shear mode [12]

In the shear mode, the MR fluid is located between surfaces moving (sliding or rotating) in relation to each other with the magnetic field flowing perpendicularly to the direction of motion of these shear surfaces. The characteristic of shear stress versus shear rate can be controlled by the magnetic field. Examples of the shear mode include clutches, brakes, chucking and locking devices, dampers and structural composites [12].

Squeeze mode:

In the squeeze mode, the distance between the parallel pole plates changes, which causes a squeeze flow. In this mode relatively high forces can be achieved; this mode is especially suitable for the damping of vibrations with low amplitudes (up to a

few millimeters) and high dynamic forces. The squeeze mode has been used in some small-amplitude vibration dampers [12].

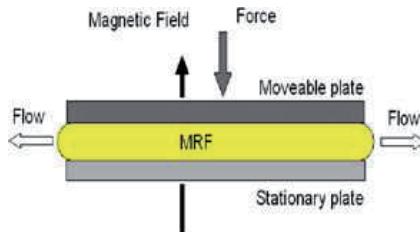


Fig. 2.6 Squeeze mode [12]

Some considerations should be made while designing of MR fluid devices such as minimum volume of active MR fluid and electrical power requirement. The rheological properties of MR fluids, the working mode and the design of the magnetic circuit all considerably influence the properties of the MR fluid device [12].

2.1.6 Properties of Typical MR Fluids

MR fluids possess different properties such as viscosity, density, yield stress, reaction time, working temperature, supply voltage and current. Some of MR fluids manufactured by Lord Corporation, USA formulated for general use in controllable, energy-dissipating applications such as shocks, dampers and brakes are LORD MRF-122EG fluid, LORD MRF-132DG and LORD MRF-140CG fluid. The typical properties of MR fluids are shown in Table 2.1.

Table 2.1 Properties of Typical MR fluids [6, 13]

Property	Typical Value
Initial viscosity	0.2 – 0.3 [Pa·s] (at 25°C)
Density	3 – 4 [g/cm ³]
Magnetic field strength	150 – 250 [kA/m]
Yield point	50 – 100 [kPa]
Reaction time	15 – 25 ms
Work temperature	-50 to 150°C
Typical supply voltage and current intensity	2 – 25 V, 1–2 A

The change in viscosity is continuous and reversible i.e. after removing the magnetic field the MR fluid can revert to a free flowing liquid. Using these characteristics of MR fluids, MR fluid devices have the ability to provide simple, quiet and rapid response [14, 15]. Therefore, MR fluids hold great potential in many applications that require an electromechanical interface, such as clutches brakes, valves, dampers and robotics. Another benefit is that its application can reduce the complexity of devices significantly. There have been a large number of studies on the application of MR devices in the automotive industry in order to replace traditional mechanical systems and some of them have been commercialized, such as the MR damper [4, 5].

2.2 Introduction to MR Brake

The MR brake operates in a direct-shear mode, shearing the MR fluid filling gap between the two surfaces [6]. The MR fluid brake is a device to transmit torque by the shear stress of MR fluid. MR rotary brake has the property that its braking torque changes quickly in response to an external magnetic field strength. As shown in Fig 2.7, MR brake consists of a rotating disk immersed in a MR fluid, enclosed in an electromagnet. The yield stress of a fluid varies as a function of magnetic field applied by electromagnet [10, 11].

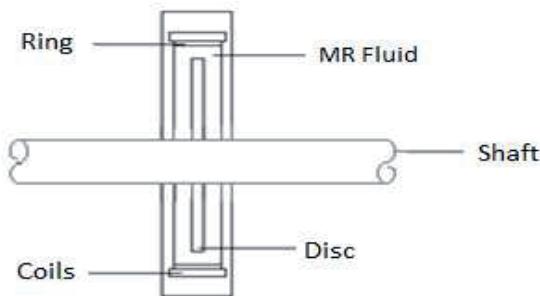


Fig. 2.7 Schematic of MR Brake

When electric current is put through the coil, a magnetic flux path is formed. As a result, the particles are gathered to form chain-like structures, in the direction of the magnetic flux path. These chain-like structures restrict the motion of the MR fluid, thereby increasing the shear stress of the fluid. The controllable yield stress causes friction on the disk surfaces which generates the retarding brake torque. The braking torque values can be adjusted continuously by changing the external magnetic field strength [7]. MR brake allows for continuous control of torque. When there is no magnetic field the torque is caused by viscosity of carrier liquid, bearings and seals. MR brake is especially well suited for a variety of applications including pneumatic actuator control, precision tension control and haptic force feedback in applications such as steer-by-wire [8].

The MRB is a pure electronically controlled actuator and as a result, it has the potential to further reduce braking time (thus, braking distance), as well as easier integration of existing and new advanced control features such as anti-lock braking system (ABS), vehicle stability control (VSC), electronic parking brake (EPB), adaptive cruise control (ACC), as well as on-board diagnostic features. There are important key features of MR brake system over the CHB system such as low power requirement, simple design & construction, hydraulic free: no hydraulic line & need less space requirement, no metal-with-metal friction, no brake pad needed, easy to control and fast response [8].

Controllable MR fluid-based brakes are already being used since 1995 in various types of fitness equipment and will soon be ready for successful employment in automotive applications. With the use of MR brake system, different limitations of conventional brake system can be eliminated.

Especially, when the numbers of electric and hybrid vehicles are run on Indian roads, MR brakes and their adaptability to automotive braking requirements need some serious investigation.

2.3 Closure

This chapter is focused on the MR fluid and MR brake. The working principle, MRF components, operational modes, typical properties of MR fluid have been described in this chapter. It also presents the concept of MR brake. Because of the advantages of MR brake over the CHB system, MR brake is one of the possibilities to replace a CHB. Recently there have been several studies on the design of MR brake systems for automotive application. Next chapter presents the literature review on MR fluids and MR brake systems.

3. LITERATURE REVIEW

3.1 General

This section includes the literature survey of earlier research work made by various researchers on magneto-rheological fluid. Various researchers presented the different results about the behavior of magneto-rheological fluids and analyzed the same but yet further efforts are needed in order to obtain even better results. This section presents the summary of these research works.

3.2 Classification of Literature Review

The literature is mainly classified into subgroups: MR fluid based literature and MR brake based literature review.

3.2.1 Literature Review on MR Fluid

Sarkar and Hirani (2013) discussed the synthesis of MR fluid and its application in brake. In MR brake, gap between stator and rotor was filled with low (off-state) viscosity MR fluid. On the application of magnetic field, MR fluid changed its state from liquid to semi-solid by aligning magnetic particles in chains. Due to such chaining action, yield strength of fluid increased, friction between stator and rotor increased and did fulfil the braking function. The strength of magnetic particle was the function of relative speed between stator and rotor, applied magnetic field and volume percentage of magnetic particle. In this study antifriction (off-state) and strong chain (on-state) CI based MR fluid were prepared by mixing oleic acid as antifriction additives and tetramethyl ammonium hydroxide as surfactant to reduce the agglomeration of the MR fluid. Yield strengths of the synthesized MR fluid in on-state and off-state were compared with commercially available MRF 241ES fluid. A flywheel based MR brake experimental setup was developed to analyze the performance of designed and developed MR brake. Results showed that the synthesized MR fluid was stronger and faster in response compared to MRF 241ES fluid.

Shetty and Prasad (2011) synthesized MR fluid 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 were prepared for comparing their rheological properties. An experimental setup consisting of a capillary viscometer with a pair of solenoid type of electromagnetic coils was developed.

The rheological properties of the proposed MR fluid were investigated under the application of different magnetic fields and the results were presented.

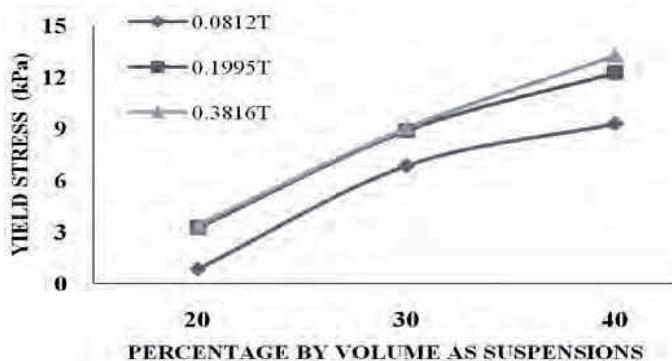


Fig. 3.1 Variation of shear stress with shear rate for 2.5 A current and 0.1995 T.

As shown in Fig. 3.1 it has 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.

Seval Genc (2002) synthesized MR fluids using different grades of iron powder (grade A, grade B) and surfactant A. Glycol ether based MR fluids were also synthesized. The difference in the redispersibility and stability of fluids with different grades of iron powder and carrier liquid and surfactants have shown. This attributed to the interactions of the iron surface with different surfactants as well as the particle size

differences. The saturation magnetization ($\mu_0 M_s$) for Grade A and Grade B grades of iron powder was found to be 2.03 and 1.89T respectively. The coercivities of these powders were measured as 30.51 and 14.22 respectively whereas the coercivity of bulk iron is 1.01 Oe.

One of the most important results of this research was the influence of the remnant magnetization on the magnetic dipole-dipole interaction energy of 33 vol% iron, MnZn ferrite, and NiZn ferrite based MR fluids and hence on the redispersibility of MR fluids. The redispersibility of the MR fluids enhanced by using additives that increased the interparticle distance. The off state yield apparent viscosity of MR fluids showed increase in the highest strain rate that could be measured with the rheometer by TA instruments. The off state apparent viscosity was 3.9 Pa·s at 50 s⁻¹, whereas for a regular MR fluid this value was ~2 Pa·s.

Kciuk et al. (2009) have presented the results of investigation of MR fluids composed of carbonyl iron (CI) particles and analyzed their flow behavior in terms of the internal structure formation by a control of applied external magnetic field. The morphology, magnetic properties, sedimentation stability, and magneto-rheological properties of the examined MR fluids were studied. Model MR Fluid was prepared using silicone oil OKS 1050 mixed with carbonyl iron powder CI. Furthermore, to reduce sedimentation aerosil 200 was added as stabilizers.

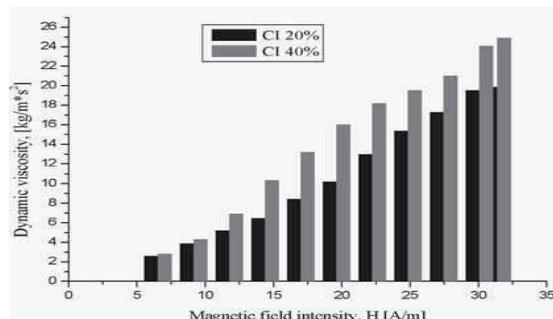


Fig. 3.2 Dependence of MR fluid (OKS 1050, 0.500 Pa·s) dynamic viscosity on the magnetic field intensity

In the purpose to determine the properties of the analyzed fluids the sedimentation and dynamic viscosity were investigated. As shown in Fig. 3.2 dynamic viscosity of investigated magneto-rheological fluids rapidly and reversibly change in response to the applied external magnetic field. Moreover added particles of fumed silica inhibited sedimentation of carbonyl iron particles. MR fluids offer an outstanding capability of active control of mechanical properties. But there are no systematic published studies of factors affecting the durability of MR fluids and devices.

Turczyn and Kciuk (2008) have developed the model magneto-rheological (MR) fluids. Basic properties of prepared MR fluids with their response to an external magnetic field and their stability were investigated. Moreover (furthermore) few results concerning stabilizing effect of various additives were presented. Model MR Fluid was prepared using three type of carriers: silicone oil OKS 1050, synthetic oil OKS 352, mineral oil OKS 600 mixed with carbonyl iron powder CI HQ. Furthermore, to reduce sedimentation Aerosil 200 and 972, Arsil 1100 and Arabic gum were added as stabilizers. MR effect was measured using device working as Couette's viscosimeter equipped with coil generating magnetic field.

Sedimentation was measured by simply observation of changes in boundary position between clear and turbid part of MR fluid placed into glass tube.

Influence of the additives presence on the MR effect was determined. The presence of additives did not diminish the magnetic effect but even increased the dynamic viscosity in existence of an external magnetic field. The stability of MR fluid was improved by adding additives to the formulation. Moreover, increasing stabilizer concentration further enhanced the MR fluid stability. The best result was achieved in case of Aerosil 9782 at 2 % content. However, due to sedimentation, MR fluid response to magnetic field is restricted and in an extreme situation could lead to the failure hence further efforts must be made in order to obtain even better results. This article has provided set of new data about improvement of MR fluid stability in the presence of selected stabilizers.

Yang et al. (2008) presented the work on characterization and synthesis of iron based alloy nano-particles for magneto-rheological fluids. The boro-hydride reduction method was used to synthesize the Fe-based alloy nanoparticles in an aqueous medium for MR fluids. The effect of ethanol content in the reaction medium on the synthesis of Fe–Co–B nanoparticles was studied first. With increasing the ethanol content from 0 to 40 vol. %, the average diameters of Fe–Co–B nanoparticles were decreased from 170 to 35 nm.

The possible mechanism for the effect of ethanol has been proposed. Among the four types of Fe-based alloys particles synthesized in this work, Fe–B had the highest magnetization saturation M_s , while M_s decreased in an order of Fe–B4Fe–Co–B4Fe–Cr–B4Fe–Ni–B. A magnetic field of 3000 Oe was able to increase M_s by about 5–6% for each type of iron-based alloy. Under a magnetic field, chain structures of nanoparticles were always formed. When a strong magnetic field such as 3000 Oe was applied, the particles were “squeezed” into chains.

Lim et al. (2005) developed carbonyl-iron (CI)-based magneto-rheological (MR) fluid containing submicron-sized additive particles. The flow behavior at a steady shear mode was investigated by comparing flow properties of CI-mineral oil suspensions with and without an additive under the magnetic field strength. To enhance the dispersion stability, submicron-sized organoclay was added to the CI suspensions. The submicron-sized particles, while preserving the magnetic properties, inhibited the sedimentation of the CI particles. In addition, with the precision control of magnetic field strength, they examined the novel features of submicron-sized particle-filled CI suspensions, especially under weak magnetic field strengths, in steady shear modes. A temporal decrease of steady shear viscosity was observed in sweeping magnetic field strengths.

Jolly et al. (2001) presented the rheological and magnetic properties of several commercial magneto-rheological (MR) fluids. These fluids were compared using appropriate figures of merit based on conventional design paradigms. Some

contemporary applications of MR fluids were discussed. These applications illustrate how various material properties may be balanced to provide optimal performance.

Premalatha et al. (2012) formulated MR fluids composed of iron particles and analyzed their flow behavior in terms of the internal structure, stability and magneto rheological properties. MR fluids were prepared using silicone oil mixed with iron powder. To reduce sedimentation, grease was added as stabilizer. The size of the particles was observed by Optical microscope and flow properties were examined by rheometer.

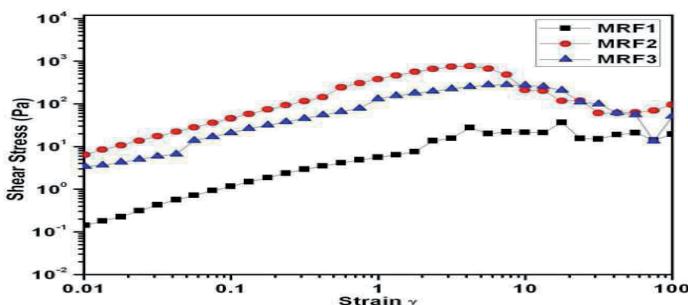


Fig. 3.3 Strain Vs shear stress for MRF1, MRF2, and MRF3

Three samples MRF1, MRF2, MRF3 were prepared by varying the percentage of additive. Strain and shear stress relationship for these MRF samples are as shown in Fig. 3.3. Sedimentation was measured by simple observation of changes in boundary position between clear and turbid part of MR fluid placed into glass tube. The various additive percentages also influenced the MR fluid's performances.

3.2.2 Literature Review on MR Brake

Karakoc and Park (2008) discussed the design considerations for building an automotive MR. The proposed brake consists of multiple rotating disks immersed in a MR fluid and an enclosed electromagnet. When current is applied to the electromagnet, the MR fluid solidifies as its yield stress varies as a function of the magnetic field applied. This controllable yield stress produces shear friction on the rotating disks, generating the braking torque.

In this work, practical design criteria such as material selection, sealing, working surface area, viscous torque generation, applied current density, and MR fluid selection were considered to select a basic automotive MR brake configuration. Then, a finite element analysis was performed to analyze the resulting magnetic circuit and heat distribution within the MR brake configuration. This was followed by a multidisciplinary design optimization (MDO) procedure to obtain optimal design parameters that could generate the maximum braking torque in the brake. A prototype MR brake was then built and tested and the experimental results showed a good correlation with the finite element simulation predictions.

However, the braking torque generated was still far less than that of a conventional hydraulic brake, which indicates that a radical change in the basic brake configuration is required to build a feasible automotive MR brake.

Sukhwani and Hirani presented (2007) described the design procedure of MR brake and discussed the effect of MR gap on its braking torque. Two brakes, Brake 1 with MR gap 1mm and Brake 2 with MR gap 2 mm were designed and fabricated. To generate magnetic field one central electro-magnet and two side electromagnets were suggested. To validate the theoretical design and its findings, prototyping, and experimental study of MR brake were performed.

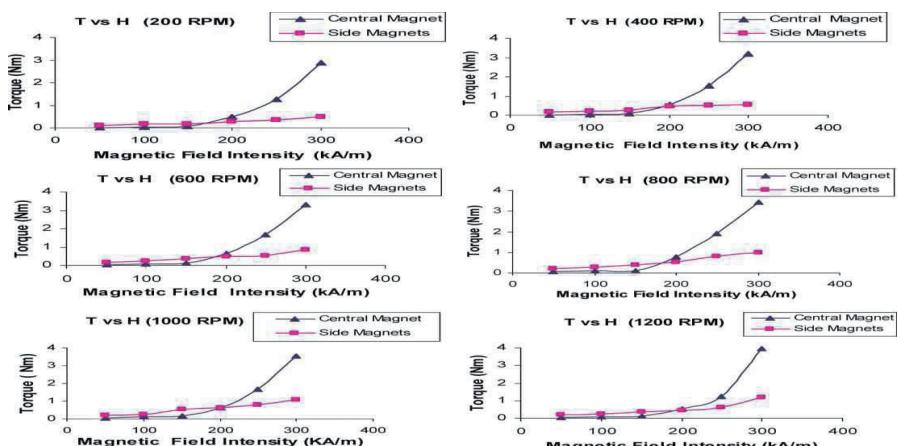


Fig. 3.4 Comparison of experimental torque for central and side electromagnets

An experimental test setup has been developed to measure the braking torque under various operating speeds (200 to 1200 r/min) and control currents (0.0 to 1.2 A). The effects of central and side electromagnets on braking torque have been examined. The observed results are presented in tabular and graphical form as shown in Fig.3.3. A close agreement between theoretical and experimental results has been noticed.

Park et al. (2007) developed a magneto-rheological brake (MRB) system that has performance advantages over the conventional hydraulic brake system. The proposed brake system consists of rotating disks immersed in a MR fluid and enclosed in an electromagnet, which the yield stress of the fluid varies as a function of the magnetic field applied by the electromagnet. The controllable yield stress causes friction on the rotating disk surfaces, thus generating a retarding brake torque. The braking torque controlled precisely by changing the current applied to the electromagnet.

In this paper, an optimum MRB design with two rotating disks was proposed based on a design optimization procedure using simulated annealing combined with finite element simulations involving magneto-static, fluid flow and heat transfer analysis. The performance of the MRB in a vehicle was studied using a quarter vehicle model. A sliding mode controller was designed for an optimal wheel slip control, and the control simulation results show fast anti-lock braking.

3.3 Literature Findings

The literature review reveals the following points:

1. MR fluids synthesized by the various researchers could not exceed the typical value of yield stress (100 kPa)
2. Very few researchers have tried to increase the yield stress produced by MR fluid which will particularly suit to the shear mode applications.
3. MR fluids have already been used for automotive suspension applications effectively.

4. Few efforts have been made to design and optimize an MR brake configurations.
5. However, increasing the braking torque and reducing the weight of the brake remain major challenges.
6. Also, not many reports or research articles are available on MR fluid brake application which means this area needs further exploration.
7. Braking torque delivered by an MR brake is only around 5% of the requirement of braking torque of a typical midsize car.
8. Cost of commercially available MR fluid (Lord Corporation MR Fluid) is also much more nearly 80,000 Rs. (Including all the Expenses) per liter.

Thus, the torque can be increased by increasing the yield stress produced by the MR fluid. Hence, in the current study the effort has been made to synthesize the MR fluid which shall produce the possible high yield stress.

3.4 Closure

This chapter presented literature review on MR fluids and its applications. It has also emphasized on the literature of MR fluid based brake designs for automotive application. In literature, for synthesis of MR fluid different proportions of materials have been used. The effect of varying percentage of base fluid, magnetic particles and various additives on the MR effect have also been discussed. This literature study has helped us to formulate MR fluid. Next chapter presents the research plan for synthesis of various MR fluid samples.

4. SYNTHESIS OF MR FLUIDS

4.1 General

The main objective of this chapter is to formulate the high yield strength MR fluids. The attempt has also made to produce the same with the reduced cost as compared to commercially available MR fluid (Lord Corp., USA MR Fluid).

4.2 Requirements of MR Fluid

It is necessary to improve certain properties of MR fluid so as to suit the MR brake application. The main properties of MR fluid which influences the MR brake performance are discussed as follows:

1] Off-state Viscosity

The field-independent viscosity (η) is the most critical off-state property of MR-fluids since it has a direct impact on the velocity-dependent minimum output force or torque of a given device in the absence of magnetic field. Furthermore, this viscosity is also responsible for the temperature dependence of the device output force or torque [16]. The MR-fluid viscosity is mostly influenced by two factors: the intrinsic viscosity of the carrier fluid and the particle volume fraction. Higher the particle, volume fraction, higher is the MR-fluid viscosity. At room temperature, most MR-fluid viscosities range from 50 to 200 MPa.s [9].

2] Yield Stress

The field-dependent maximum yield stress (τ_y) is the most critical on-state property of MR fluids since it has a direct impact on the maximum output force or torque of a given device. The material of the particles has an impact on the maximum yield stress since its value increases with the square of the saturation magnetization of the particles. A second factor influencing the maximum yield stress is the particle volume fraction [17]. An Increase in the particle volume fraction leads to an increase in the output torque of MR fluid brake. Since then, a number of researchers have studied this effect and have shown that the maximum yield stress increases non-linearly with

growing particle volume fraction. The off-state plastic viscosity also increases with particle volume fraction, at an even faster rate than the yield stress, leading to a decrease of the potential dynamic range (ratio between maximum and off-state force and torque) of a device using such fluids. An alternative way to increase the maximum yield stress is to increase the particle size distribution inside the MR-fluid [10].

3] Durability and In-Use-Thickening (IUT)

If an ordinary MR-fluid is subjected to high stress and high shear rate over a long period of time, the fluid will thicken. This phenomenon is called In-Use-Thickening (IUT). A MR-fluid initially exhibiting low off-state viscosity will progressively thicken until it eventually turns into a thick paste exhibiting a much higher off-state viscosity and making it unusable in most applications [18].

One of the causes of IUT is the fact that, when exposed to long periods of stress, the friable surface layer of the iron particles peals away and breaks into small pieces that separate from the primary particle.

This is particularly true for carbonyl iron particles exhibiting an onion skin structure. Solutions to this phenomenon include the use of particles exhibiting a higher hardness and/or the use of anti-wear and anti-friction additives (at levels of 0.5 to 3% by volume) [11].

4] Temperature Range

Literature review reveals that the synthesized MR fluids should work under different ranges of operating temperatures. If this could happen, the MR fluid can satisfactorily suit the shear mode applications where it demands the high temp. range. Bydon (2002) described the construction and operation of Lord MR brake, which offers maximum 5.65 Nm torque at operating speed 1000 rpm. The brake was restricted to be operated within temperature ranging between -30 °C to 70 °C. Thus, the base fluid should be carefully selected which will work under higher operating conditions [12].

4.3 Synthesis Route

In this section the route for the formulation of MR fluid has been presented. The synthesis of this MR fluid mainly consists of various stages which includes selection of MRF components and decision of synthesis route. The formulation of MR fluid involves:

1) Selection of components

- Selection of magnetic materials (carbonyl and electrolytic iron powder)
- Ball milling for reduction of size of EI powder, if necessary.
- Selection of suitable carrier fluids.
- Selection of suitable additives.

2) Coating of magnetic particles

3) Flow Chart

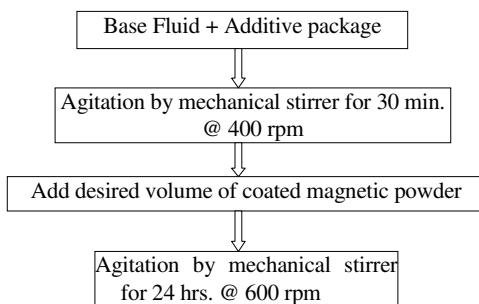


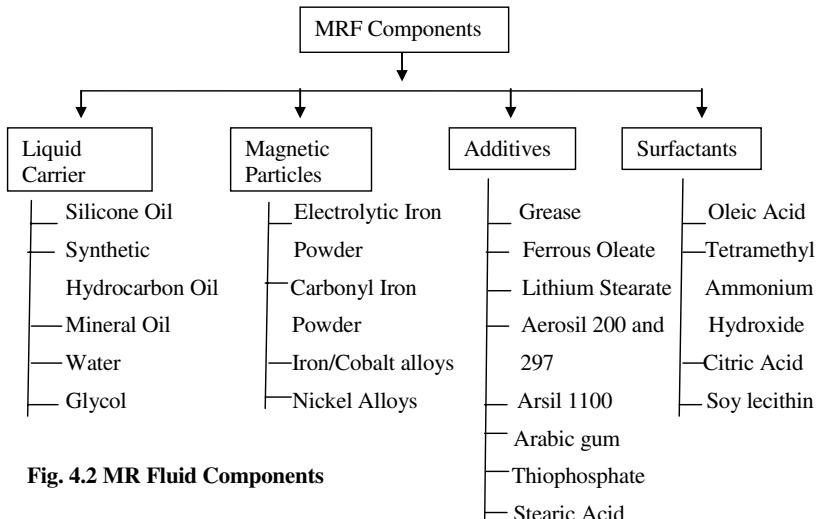
Fig. 4.1 Synthesis Route of MR Fluid

4.4 Selection of MR Fluid Components

The change in one or more components or in their properties affects the MR effect. Hence, need to study the various properties of these components which will help in the formulation of MR fluids to suit different industrial applications. There are basically three components in an MR fluid [6]:

- A. Liquid Carrier,
- B. Metal particles and
- C. Stabilizing additives

These various components are as shown in the Fig. 4.2 in detail:



4.4.1 Liquid Carrier

The liquid carrier or base fluid naturally combines lubrication (in combination with additives) and damping features. For the highest MRF effect the viscosity of the fluid should be small and almost independent of temperature [7].

The first consideration in the selection of MR fluid is the carrier fluid: synthetic hydrocarbon oil, silicone oil and mineral oil. Choose the liquid carrier depending on the environment or need of the application. Hydrocarbon based oil is always the best choice from a cost/performance perspective unless the MR fluid will be in contact with an organic rubber like natural rubber, or the temperature extremes are great [19]. If broad temperature-range performance is desired below 40°C and above 100°C, a silicone-based fluid may be appropriate. Carrier liquid is the major constituent of MR fluids (50-80 per cent by volume) which greatly influences the rheological properties of MR fluids [8].

The literature review reveals 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 tension, wets the clean surfaces quickly,

and makes it dirty. Synthetic oils are made artificially but cost more. Considering various other applications and their growing demands, the quantity of MR fluids 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 Sunflower 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.

Further it is non-volatile, thermally stable, and does not form sedimentation up to 80 °C and 50 hr of heating duration [9].

4.4.2 Magnetic Particles

Low coercivity, high saturation magnetization, high permeability, small remnance, small hysteresis loop, and high electrical resistivity are the characteristics of soft magnetic materials [20]. **In MR fluids, materials with lowest coercivity and highest saturation magnetization are preferred, because as soon as the field is taken off, the MR fluid should come to its demagnetized state in milliseconds. Due to its low coercivity and high saturation magnetization, high purity carbonyl iron powder appears to be the main magnetic phase of most practical MR fluid compositions** [11].

When a ferromagnetic material is magnetized in one direction, it will not relax back to zero magnetization when the imposed magnetizing field is removed. It must be driven back to zero by a field in the opposite direction. If an alternating magnetic field is applied to the material, its magnetization will trace out a loop called a hysteresis loop. The lack of retrace ability of the magnetization curve is the property called hysteresis and it is related to the existence of magnetic domains in the material. Once the magnetic domains are reoriented, it takes some energy to turn them back again. This property of ferromagnetic materials is useful as a magnetic "memory" [11].

4.4.2.1 The Hysteresis Loop and Magnetic Properties [21]

A great deal of information can be learned about the magnetic properties of a material by studying its hysteresis loop. A hysteresis loop shows the relationship

between the induced magnetic flux density (B) and the magnetizing force (H) as shown in Fig 4.3. It is often referred to as the B-H loop. An example of hysteresis loop is shown in Fig. 4.3.

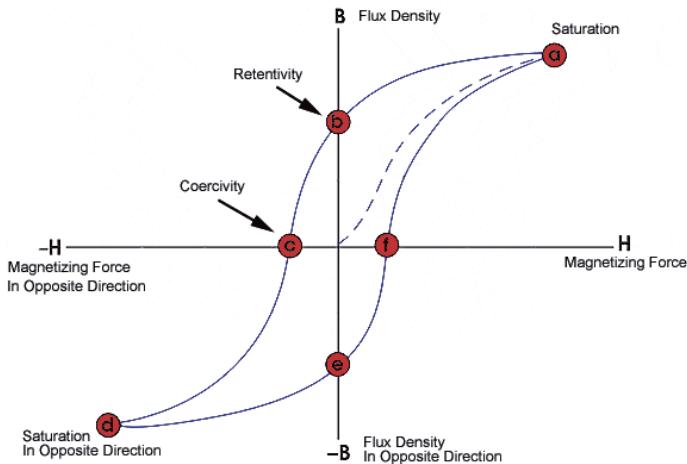


Fig 4.3 Hysteresis Loop and Magnetic Properties [21]

The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as H is increased. As the line demonstrates, the greater the amount of current applied ($H+$), the stronger the magnetic field in the component ($B+$). At point "a" almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux. The material has reached the point of magnetic saturation. When H is reduced to zero, the curve will move from point "a" to point "b." At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates the remanence or level of residual magnetism in the material. (Some of the magnetic domains remain aligned but some have lost their alignment.) As the magnetizing force is reversed, the curve moves to

point "c", where the flux has been reduced to zero. This is called the point of coercivity on the curve. (The reversed magnetizing force has flipped enough of the domains so that the net flux within the material is zero.) The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material [21, 22].

As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction (point "d"). Reducing H to zero brings the curve to point "e." It will have a level of residual magnetism equal to that achieved in the other direction. Increasing H back in the positive direction will return B to zero. Notice that the curve did not return to the origin of the graph because some force is required to remove the residual magnetism. The curve will take a different path from point "f" back to the saturation point where it will complete the loop. From the hysteresis loop, a number of primary magnetic properties of a material can be determined. [21, 22]

1. **Retentivity** - A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation. (The value of \mathbf{B} at point b on the hysteresis curve.)
2. **Residual Magnetism or Residual Flux** - the magnetic flux density that remains in a material when the magnetizing force is zero. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.
3. **Coercive Force** - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero. (The value of \mathbf{H} at point c on the hysteresis curve.)

4. **Permeability** - A property of a material that describes the ease with which a magnetic flux is established in the component.
5. **Reluctance** - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

4.4.2.2 Electrolytic and Carbonyl Iron Powders [3]

Iron powders made by the CVD decomposition of iron pentacarbonyl ($\text{Fe}(\text{CO})_5$) [7,8] are preferred as opposed to for example, those prepared using the electrolytic or spray atomization process. This is because carbonyl iron is chemically pure and the particles are mesoscale and spherical in nature in order to eliminate the shape anisotropy. The meso-scale particles are necessary since they have many magnetic domains. The high level of chemical purity ($\sim > 99.7\%$) means less domain pinning defects. The spherical shape helps minimize magnetic shape anisotropy. The impurities that cause magnetic hardness in metals also cause mechanical hardness, due to resistance to dislocation motion, and make the iron particles mechanically harder. In MR fluid based devices it is preferred to have particles that are non-abrasive. This is another reason why spherical, high purity iron powders are more appropriate for applications as a dispersed phase in MR fluids. Thus, carbonyl iron is chosen because of its high saturation magnetization (~ 2.1 Tesla, at room temperature) and magnetic softness [7].

4.4.3 Other Additives

To prevent gravitational settling and promote stable particles suspension, enhance lubricity and change initial viscosity of the MR fluids. The stabilizers serve to keep the particles suspended in the fluid, whilst the surfactants are absorbed on the surface of the magnetic particles to enhance the polarization induced in the suspended particles upon the application of a magnetic field [9]. Additives are suspending agents, thixotropes, friction modifiers and anti-corrosion/wear components. Highly viscous materials such as grease or other thixotropic additives are used to improve settling

stability [10]. Ferrous naphthanate or ferrous oleate can be used as dispersants and metal soaps such as lithium stearate or sodium stearate as thixotropic additives [4].

Additives are required to control the viscosity of the liquid and the settling rate of the particles, sedimentation the friction between the particles and to avoid the in-use thickening for a defined number of off-duty cycles [12].

In this study antifriction (off-state) and strong chain (on-state) iron based MR fluids have been prepared by mixing oleic acid as antifriction additives and **Guar gum powder** as surfactant to reduce the agglomeration of the MR fluid. By forming a coating layer over the ground CI powder, the guar gum improves the sedimentation stability and thixotropy of the MR fluid effectively. Wu, et al. (2009) presented CI powders coated with guar gum as magnetic particles in the MR fluid. Their experimental results showed that inducing a guar gum coating not only greatly improved the sedimentation stability but also strengthened the yield stress of the MR fluid. As per these experimental results as shown in Fig 4.4 the highest yield stress achieved is observed at 3% of the gaur gum powder to the total percentage of iron particles [13].

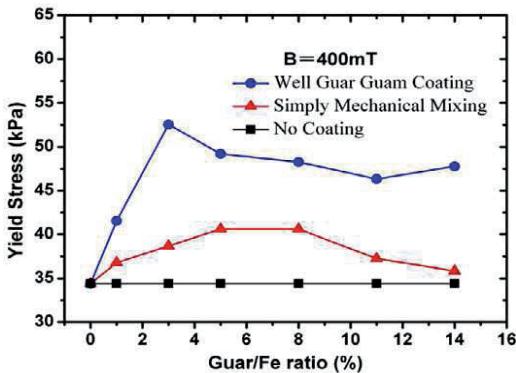


Fig. 4.4 The response of the shear stress for a MR suspension of 80% (by weight) Coating composite particles with different guar/Fe ratios (1%–14%) [10]

Similarly, as shown in Fig. 4.5 the lowest sedimentation ratio is observed to the 3% of the gaur gum powder to the total percentage of iron particles and hence for the present study 3% gaur/Fe ratio is considered as optimum [13].

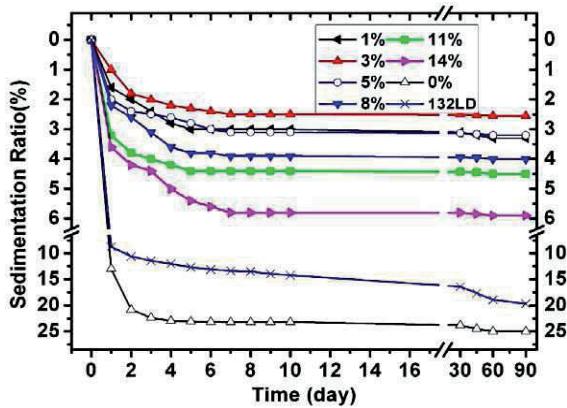


Fig. 4.5 Sedimentation ratios versus time; with certain guar/Fe ratio for each curve [10]

4.5 MR Fluid Synthesis Plan

In order to enhance the various properties of the MR fluid in the perspective of braking application the research plan for the synthesis has been prepared. The synthesis plan for different samples is prepared by varying the percentage of the specific components, whilst other components kept constant.

Part I

In the first part of the synthesis plan two samples shall be prepared. First sample contains electrolytic iron powder with silicone oil while other parameters kept constant. Similarly, next sample shall be prepared with carbonyl iron powder (refer Table 4.1).

Table 4.1 Synthesis Plan I

Samples No.	Carrier Fluid	Metal particles	Additive Package (Grease+Oleic Acid)	Surface Coating
1 (250 ml)	Silicone Oil [49% by vol.]	Electrolytic Iron Powder [50% by vol.] ~4µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder (0.75 % by volume)
2 (250 ml)	Silicone Oil [49% by vol.]	Carbonyl Iron Powder [50% by vol.] ~10µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder (0.75 % by volume)

In the research plan as shown in Table 4.1, the silicone oil is used to facilitate the fluid to work under high operating temperature. The increased fraction of iron powder is also used in order to increase the yield strength of MR fluid. The additive package which includes grease and oleic acid has been used. Grease improves the stability of the fluid while oleic acid helps to reduce the agglomeration of the particles.

Part II

In the second part of synthesis plan the similar samples of MR fluid shall be prepared only the difference is instead of silicone oil, synthetic oil is used which has been shown in Table 4.2

Table 4.2 Synthesis plan II

Sample No.	Carrier Fluid	Metal particles	Additive Package (Grease+Oleic Acid)	Surface Coating
1 (250 ml)	Synthetic Oil [49% by vol.]	Electrolytic Iron Powder [50% by vol.] ~4µm	Oleic Acid [0.5% by vol.]	Gaur Gum 3% to the amount of Iron Powder (0.75 % by volume)
2 (250 ml)	Synthetic Oil [49% by vol.]	Carbonyl Iron Powder [50% by vol.] ~10µm	Oleic Acid [0.5% by vol.]	Gaur Gum 3% to the amount of Iron Powder (0.75 % by volume)

Part III

The literature review reveals 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 tension, wets the clean surfaces quickly, and makes it dirty. Synthetic oils are made artificially but cost more.

The limitations of commonly used liquids have motivated to identify an alternative carrier liquid. In the present work, edible vegetable oil like Sunflower oil, which is bio-degradable, is environmentally friendly, and abundantly available in many parts is used as carrier liquid. Also there is no evidence in the literature regarding the use of this oil as carrier liquid. Thus, samples are prepared with sunflower oil as a carrier fluid and have been shown in the Table 4.3.

Table 4.3 Synthesis plan III

Samples No.	Carrier Fluid	Metal particles	Additive Package (Grease+ Oleic Acid)	Surface Coating
1 (250 ml)	Sunflower Oil [49% by vol.]	Electrolytic Iron Powder [50% by vol.] ~4µm	Oleic Acid [0.5% by vol.]	Gaur Gum 3% to the amount of Iron Powder (0.75 % by volume)
3 (250 ml)	Sunflower Oil [49% by vol.]	Carbonyl Iron Powder [50% by vol.] ~10µm	Oleic Acid [0.5% by vol.]	Gaur Gum 3% to the amount of Iron Powder(0.75 % by volume)

The nomenclature for MR fluid samples for the sake of the simplicity have been given in different fashion as shown in Table 4.4

Table 4.4 Nomenclature System

Sr. No.	Nomenclature	Elaboration
1	ESi 50%	50% Electrolytic iron powder and silicone oil
2	ESi 45%	45% Electrolytic iron powder and silicone oil
3	CSi 50%	50% Carbonyl iron powder and silicone oil
4	CSi 45%	45% Carbonyl iron powder and silicone oil
5	ESy 50%	50% Electrolytic iron powder and synthetic oil
6	ESy 45%	45% Electrolytic iron powder and synthetic oil
7	CSy 50%	50% Carbonyl iron powder and synthetic oil
8	CSy 45%	45% Carbonyl iron powder and synthetic oil
9	ESu 60%	60% Electrolytic iron powder and sunflower oil
10	ESu 50%	50% Electrolytic iron powder and sunflower oil
11	CSu 60%	60% Carbonyl iron powder and sunflower oil
12	CSu 50%	50% Carbonyl iron powder and sunflower oil

4.6 Modified Synthesis Plan

Previous research plan has been modified as per the off state viscosity results to meet the application requirements and the same is presented in this section. Actual synthesis of various MR fluid samples has been completed and the results are also discussed.

The off state viscosities of the Lord MR Fluid and the synthesized MR fluid samples have been measured with the help of Brookfield Viscometer. Primarily, by considering the highest percentage i.e. 50% by volume as mentioned in the previous research plan (refer Table 4.1, 4.2 and 4.3), some samples were synthesized. However, the results show that the off state viscosities exceed the specific value of 5 Pa.s and hence, the research plan has been modified. The samples prepared

previously with highest percentage of iron particles and their respected off state viscosities are presented in Table 4.5.

Table 4.5 OFF State Viscosities

Samples No.	Carrier Fluid	Metal particles	Additive Package (Grease+ Oleic Acid)	Surface Coating	Off State Viscosity (mPa.s)
MRF ESi 50% (250 ml)	Silicone Oil [49% by vol.]	Electrolytic Iron Powder [50% by vol.] ~4µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder	545
MRF CSi 50% (250 ml)	Silicone Oil [49% by vol.]	Carbonyl Iron Powder [50% by vol.] ~10µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder	570
MRF ESy 50% (250 ml)	Synthetic Oil [49% by vol.]	Electrolytic Iron Powder [50% by vol.] ~4µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder	510
MRF CSy 50% (250 ml)	Synthetic Oil [64% by vol.]	Carbonyl Iron Powder [50% by vol.] ~10µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder	520

The MR fluid samples are analyzed in order to find out their off state viscosities at Nikhil Analytical and Research Laboratory, Sangli (MH). The result for off state viscosity of MRF ESi 50% is as shown in Fig 4.6.

**CERTIFICATE OF ANALYSIS**

CH/P-1560	Bhau Kumbhar	13/02/2014	
Name/ Organisation			
Sample Description	MR Fluid		
Sample collected by	Party	Sample Received on 11/01/2014	
Sample Analysed by	Mrs. Bhagyshri	Analysis Completed on 13/02/2014	
Reference	RIT College Sakharale, Islampur.		
Sr.No.	PARAMETER	UNIT	VALUE
1.	Brookfield Viscosity Spindle No.4, 30 rpm, 25 °C	cP	545

Fig. 4.6 OFF State Viscosity - MRF ESi 50%

As per the research plan (refer Table 4.3), the samples with sunflower oil as a carrier fluid have also been synthesized and the results for the off state viscosities are analyzed (refer appendix A).

The off state viscosities for these samples i.e. MRF ES_U 50% and MRF CS_U 50% have seen to be very less as compared to other samples as shown in Table 4.6.

Table 4.6 OFF State Viscosities

Samples No.	Carrier Fluid	Metal particles	Additive Package (Grease+ Oleic Acid)	Surface Coating	Off State Viscosity (mPa.s)
MRF ES _U 50% (250 ml)	Sunflower Oil [49% by vol.]	Electrolytic Iron Powder [50% by vol.] ~4µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder	200
MRF CS _U 50% (250 ml)	Sunflower Oil [49% by vol.]	Electrolytic Iron Powder [50% by vol.] ~4µm	1% by vol.	Gaur Gum 3% to the amount of Iron Powder	205

Thus, in order to produce better yield stress and hence to satisfy various working conditions for the automotive braking application, the research plan has been modified.

Some synthesized MR fluid samples have shown the off state viscosity which exceeds a typical range of 5 Pa.s and hence, a need arise to work on modifications of this research plan. This modified research plan for the part I is as shown in Table 4.7.

Table 4.7 Modified Synthesis Plan I

Samples No.	Carrier Fluid	Metal particles	Additive Package (Grease + Oleic Acid)	Surface Coating
MRF ESi 45% (250 ml)	Silicone Oil [49% by vol.] 127.28 gram	Electrolytic Iron Powder [45% by vol.] ~12µm 135 gram	1% by vol. 2.2 gram	Gaur Gum 3% to the amount of Iron Powder 4.05 gram
MRF CSi 45% (250 ml)	Silicone Oil [49% by vol.] 127.28 gram	Carbonyl Iron Powder [45% by vol.] ~08µm 135 gram	1% by vol. 2.2 gram	Gaur Gum 3% to the amount of Iron Powder 4.05 gram

In this research plan, the percentage of iron powder has been reduced from 50% by volume to 45% by volume and the off state viscosities have been analyzed. These viscosities lie in between 2-5 Pa.s and hence, the percentage of particulars has been considered for synthesis.

The modified research plan for the part II is as shown in Table 4.8. In this research plan also the percentage of iron powder has been reduced from 50% by volume to 45% by volume and the off state viscosities have been analyzed. These viscosities also lie in between 2-5 Pa.s and hence, the percentage of particulars has been considered for synthesis.

Table 4.8 Modified Synthesis Plan II

Samples No.	Carrier Fluid	Metal particles	Additive Package (Grease+ Oleic Acid)	Surface Coating
MRF ESy 45% (250 ml)	Synthetic Oil [49% by vol.] 127.28 gram	Electrolytic Iron Powder[45% by vol.] ~12µm and 135 gram	1% by vol. 2.2 gram	Gaur Gum 3% to the amount of Iron Powder 4.05 gram
MRF CSy 45% (250 ml)	Synthetic Oil [49% by vol.] 127.28 gram	Carbonyl Iron Powder [45% by vol.] ~08µm 135 gram	1% by vol. 2.2 gram	Gaur Gum 3% to the amount of Iron Powder 4.05 gram

The modified research plan for the part III is as shown in Table 4.9. In this research plan unlike part I and II, the percentage of iron powder has been increased from 50% by volume to 60% by volume because the prior results have shown that the off state viscosities (considering 50 by volume) for these samples were far less.

Table 4.9 Modified Synthesis Plan III

Samples No.	Carrier Fluid	Metal particles	Additive Package (Grease+ Oleic Acid)	Surface Coating
MRF ESu 60% (250 ml)	Sunflower Oil [35.20% by vol.] 104.85 gram	Electrolytic Iron Powder [60% by vol.] ~12µm 180 gram	3% by vol. 6.6 gram	Gaur Gum 3% to the amount of Iron Powder 4.05 gram
MRF CSu 60% (250 ml)	Sunflower Oil [35.20% by vol.] 104.85 gram	Carbonyl Iron Powder [60% by vol.] ~08µm 180 gram	3% by vol. 6.6 gram	Gaur Gum 3% to the amount of Iron Powder 4.05 gram

Hence, the off state viscosities have been analyzed with increased percentage of iron powder. These viscosities also lie in between 2-5 Pa.s and hence, this percentage of particulars has been considered for synthesis.

4.7 Testing of MR Effect

While synthesis MR fluid samples, they were checked for MR effect. To test the MR effect the setup has been prepared which mainly consists of the DC power supply and coils as shown in Fig.4.7.



Fig. 4.7 MR Effect Testing Setup

The DC power supply used is capable of providing the voltage in range of 0 to 30 volts and current in between 0 to 5 ampere. The behavior of MR fluid when magnetic field is not there (OFF State) and under applied magnetic field (ON State) is as shown in Fig.4.8. This testing has been done at 12 V and 1.43 A.



(a) OFF State



(b) ON State

Fig. 4.8 Testing of MR Effect

4.8 Instrumentation for Synthesis

The instruments like high precision weighing scale and mechanical stirrer are used for the synthesis of MR fluids. Weighing scale model CA-402 is used which is manufactured by Contech Instruments Ltd. Precision Weighing Scale weighs even the slightest amount of weight hence it is demanded extensively by Laboratory and Research industry as every milligram of material used during research could drastically change the outcome. With Precision Weighing Scale one can get the accurate weight of chemicals and other such devices used in performing experiments. The least count of this instrument is 0.001 g and it is shown in the Fig. 4.9.



Fig. 4.9 Precision Weighing Scale

High speed stirrers are used in mechanical analysis and other laboratory applications where stirring is required. This high speed stirrer is manufactured to industry standards. This stirrer is made up of Stainless Steel. The motor connected to it which operates on 230-250 volts A.C. Very high speeds are obtained even under load. It is very popular in various laboratories for its trouble-free operation and its sleek looks. This mechanical stirrer is as shown in Fig. 4.10.



Fig. 4.10 Mechanical Stirrer

4.9 Synthesis Process

Some plates at the time of actual synthesis are captured and have presented under this section. Fig. 4.11 (a) shows gaur gum and water solution which is further used to coat the iron particles while Fig. 4.11 (b) indicates the setup prepared for the synthesis of MR fluid.



(a)



(b)

Fig. 4.11 Synthesis Process

4.10 Closure

This chapter has presented the methodology adopted at the time of synthesis of MR fluid samples. It has also discussed the research plan which has been adopted to synthesize the various MR fluid samples. The novelty of this work is also to formulate the MR fluid with biodegradable, environmental friendly vegetable oil (Sunflower Oil) as a base fluid. Next chapter presents the results of characterization of commercially available Lord Corporation MR Fluid and locally made MR fluid samples.

5. CHARACTERIZATION OF MR FLUIDS

MR fluid samples were characterized using rheometry, scanning electron microscopy and vibrating sample magnetometer. These characterization techniques have been presented in this chapter.

5.1 Characterization in General

Basically, the characterization refers to the use of external techniques to probe into the internal structure and properties of a material. Characterization can take the form of actual materials testing, or analysis. Characterization methods can be categorized into various general categories [13]. These include (but aren't limited to):

1. Physical: Determination of the structural, topographical, morphological state of the sample which includes Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM).
2. Chemical/Compositional: Characterization of the chemical elements or compounds present in the sample, possibly including location on the surface which includes X-Ray Diffraction (XRD).
3. Electrical: Measurement of the resistivity/conductivity of a sample, carrier concentration, mobility of charge carriers.
4. Optical: Measurement of the optical properties or behavior of the sample which includes ellipsometry, interference spectroscopy.
5. Magnetic: Measurement of the magnetic properties or behavior of the sample which includes Vibrating Sample Magnetometer (VSM), Hall.
6. Mechanical: Determination of the mechanical properties (strength, elastic modulus, etc) of the sample.

5.2 Characterization Requirements of MR Fluid Samples

MRF samples as well as Lord's 132DG MRF were characterized using rheometer, Scanning Electron Microscope (SEM) and Vibrating Sample Magnetometer (VSM). Rheological measurements include the determination of yield stress, viscosity, shear rates and were carried out using Parallel Plate Rheometer. Determination of the morphological state of the sample was done with the help of SEM. Magnetic properties like magnetic saturation (M_s), coercivity (H_c), retentivity (M_r), permeability were measured using VSM.

These results are then discussed in context of the braking application. Emphasis has been given on the yield strength produced by MR fluid and the stability of MR fluid as they affect the braking action to a greater extent. More is the yield strength produced by MR fluid, more is the torque generated by MR brake and hence, discussion is particularly made to correlate the suitability of the different MR fluid components and hence, MR fluid samples for braking action.

5.2.1 Rheometry

A rheometer is a laboratory device used to measure the way in which a liquid, suspension or slurry flows in response to applied forces. It is used for those fluids which cannot be defined by a single value of viscosity and therefore require more parameters to be set and measured than in case of a viscometer. It measures the rheology of the fluid [24].

Rheometry generically refers to the experimental technique used to determine the rheological properties of materials which is the quantitative and qualitative relationships between deformations and stresses and their derivatives. The selection of the adequate experimental technique depends on the rheological property which has to be seen. This can be the steady shear viscosity, the linear visco-elastic properties, the elongation properties, etc.

Rheometry is a specific concern for smart fluids such as magneto-rheological fluids and electro-rheological fluids, as it is the primary method to quantify the useful

properties of these materials. There are two distinctively different types of rheometers. Rheometers that control the applied shear stress or shear strain are called rotational or shear rheometers, whereas rheometers that apply extensional stress or extensional strain are extensional rheometers. Rotational or shear type rheometers are usually designed as either a native strain-controlled instrument or a native stress-controlled instrument [24,25].

As far as this research is concerned, for the characterization of the rheological properties a **parallel-plate rheometer** is constructed as shown in Fig. 5.1. The setup enclosed 5 major parts: a fixture for the MR fluid, a mechanical input, an electromagnetic circuit, a compression load cell and a data acquisition system.

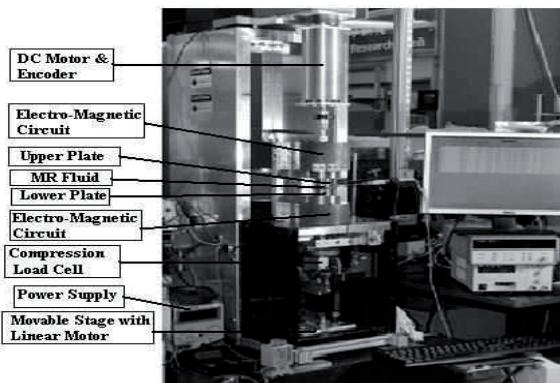


Fig. 5.1 Parallel Plate Rheometer

The fixture for the MR fluid consisted of 2 parallel plates. The lower plate was connected to a linear motor that adjusted the dimensions of the gap between the 2 plates. An optical laser sensor used to monitor the movement of the lower plate so as to ensure a constant gap throughout tests. Shear actions were produced by a D.C. servo motor. An optical encoder was used to measure the speed of the motor. An electromagnetic circuit with 3,500 turns of coil providing about 10mT to 1T was designed by using ANSYS. Magnetic pole radius was 20mm. A magnetometer was used to measure the magnetic field (B-field). However, magnetometer probe inserted directly into the MR fluid couldn't be used to measure the real magnetic field. Within

the MR fluid, it was inserted into the gap between the upper pole and also the upper plate. A calibration was done before the experiments were conducted. A compression load cell was fixed beneath the shaft of the lower plate to measure the normal force of the excited MR fluid. Signals from the load cell and the incremental encoder of the motor were captured by data acquisition units and recorded in a laptop for analyses.

Measuring procedure

Experiments were performed to study the responses of the MR fluid samples along the field direction. The specimen MR fluid contained in its original bottle was shaken and de-gassed in a vacuum before its use. A specific MR fluid quantity was taken onto the lower plate using a clean syringe. Elevation to the lower plate is then made to form a gap of 1 mm between the plates, which was monitored by the laser sensor. Pre-shearing was produced by revolving the upper plate with 2.2 s^{-1} was applied to the MR fluid for 10 minutes to ensure good dispersion. To start with, the readings for the load cell under no field and zero shear strain conditions were recorded for the first 3 min. The desired field was then applied and the normal force data were captured from the load cell with a sampling rate of 10 Hz for 30 mins. The experiment was carried at a constant shear rate of 100 s^{-1} which is imposed on the MR fluid by a motor. The normal force was first recorded for 5 min. After the experiments, the MRF was demagnetized by applying an inverse impulse magnetic field. The experiment was repeated for other magnetic fields.

5.2.2 Scanning Electron Microscopy (SEM)

The Scanning Electron Microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals those derive from electron-sample interactions reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample [26].

Morphology refers to the study of shape, size, texture and phase distribution of physical objects. The morphology of the particle is significantly related to physical properties like compactability, fluidity, magnetism and chemical reactivity i.e.

oxidation, catalysis and sintering. The disagreement arises from the relationship between the morphology of the powder particles such as surface state, size, aggregation and the principles on which size analysis is based.

In most applications, data is collected over a selected area of the surface of the sample, and a 2-dimensional image is generated that displays spatial variations in these properties. Areas ranging from approximately 1 cm to 5 microns in width can be imaged in a scanning mode using conventional SEM techniques (magnification ranging from 20X to approximately 30,000X, spatial resolution of 50 to 100 nm). The SEM is also capable of performing analyses of selected point locations on the sample; this approach is especially useful in qualitatively or semi-quantitatively determining chemical compositions, crystalline structure, and crystal orientations. Basically, the SEM appearance is as shown in the Fig. 5.2 [27].



Fig. 5.2 Scanning Electron Microscope

The basic steps involved in SEM sample preparation include surface cleaning, stabilizing the sample with a fixative, rinsing, dehydrating, drying, mounting the specimen on a metal holder, and coating the sample with a layer of a material that is electrically conductive [28]

Fundamental Principles of Scanning Electron Microscopy (SEM)

Accelerated electrons in an SEM carry significant amounts of kinetic energy, and this energy is dissipated as a variety of signals produced by electron-sample interactions when the incident electrons are decelerated in the solid sample. These signals include secondary electrons (those produce SEM images), backscattered electrons (BSE), diffracted backscattered electrons (used to determine crystal structures and orientations of minerals), photons (characteristic X-rays which are used for elemental analysis), visible light (cathode luminescence-CL), and heat [26].

Secondary electrons and backscattered electrons are commonly used for imaging samples: secondary electrons are most valuable for showing morphology and topography on samples and backscattered electrons are most valuable for illustrating contrasts in composition in multiphase samples (i.e. for rapid phase discrimination). X-ray generation is produced by inelastic collisions of the incident electrons with electrons in discrete shells of atoms in the sample. As the excited electrons return to lower energy states, they yield X-rays that are of a fixed wavelength (that is related to the difference in energy levels of electrons in different shells for a given element).

Thus, characteristic X-rays are produced for each element in a mineral that is "excited" by the electron beam. SEM analysis is considered to be "non-destructive"; that is, x-rays generated by electron interactions do not lead to volume loss of the sample, so it is possible to analyze the same materials repeatedly [26].

Essential components of SEM:

Essential components of all SEMs are Electron Source ("Gun"), Electron Lenses, Sample Stage, Detectors for all signals of interest and Display / Data output devices. Infrastructure Requirements: Power Supply, Vacuum System, Cooling system, Vibration-free floor, Room free of ambient magnetic and electric fields. The schematics of SEM is shown in Fig. 5.3

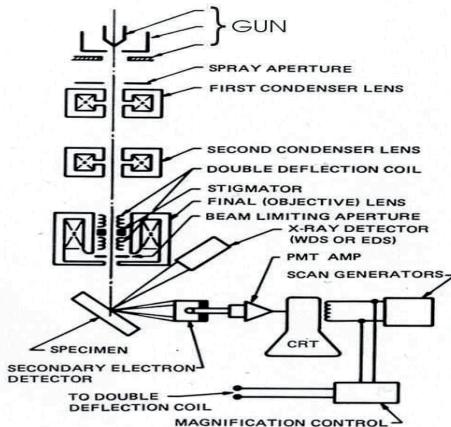


Fig. 5.3 Schematics of SEM [26]

SEMs always have at least one detector (usually a secondary electron detector), and most have additional detectors. The specific capabilities of a particular instrument are critically dependent on which detectors it accommodates.

Specifications

For morphological measurements of the coated and uncoated; electrolytic and carbonyl iron powders, **HITACHI S-4700 FE-SEM** is used which is available with Shivaji University, Kolhapur. Specifications for this SEM are given below [27]:

- The Field Emission SEM is capable of reaching a magnification of 500,000 times and a spatial resolution of up to 1.5 nm, making the FE-SEM a good choice for high magnification, high resolution imaging.

- In scanning electron microscopy, a thermionic electron source such as a tungsten filament is usually used.
- The Hitachi S-4700 FE-SEM, utilizes a cold cathode field emitter composed of a single crystal of tungsten etched to a fine point.
- The group of lenses contained in the column has one main goal: de-magnify the electron beam so that by the time it hits the specimen, the spot size (the diameter of the electron beam at the specimen) has decreased from ~ 50 μm to ~ 10 μm . That is the de-magnification of about 5,000 times.
- The FE-SEM is equipped with a special objective or focusing lens that projects the magnetic field below the lens. This simulates an in-lens SEM configuration and dramatically improves resolution. Spatial resolution in the S-4700 is, at best, ~ 1.5 nm at specified parameters (1 kV and 1 mm working distance [WD] as well as 20 kV and 12 mm WD).
- The S-4700 has no cathode ray tube (CRT) viewing screen and uses a flat screen LCD monitor
- FE-SEMs, as with all electron microscopes, operate in a vacuum environment, which removes air and its contaminants from the electron column
- A vacuum provides the needed insulation to prevent "arching" or jumping of high voltages in the electron gun [27].

5.2.3 Vibrating Scanning Magnetometer (VSM)

A vibrating sample magnetometer or VSM is a scientific instrument that measures magnetic properties, invented in 1955 by Simon Foner at Lincoln Laboratory MIT. A sample is placed inside a uniform magnetic field to magnetize the sample. The sample is then physically vibrated sinusoidally, typically through the use of a piezoelectric material. Commercial systems use linear actuators of some form, and historically the development of these systems was done using modified audio speakers, though this approach was dropped due to the interference through the in-phase magnetic noise produced, as the magnetic flux through a nearby pickup coil varies

sinusoidally [29]. The working principle of vibrating sample magnetometer is as shown in the Fig. 5.4.

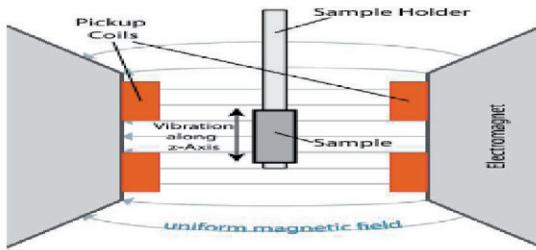


Fig. 5.4 Working Principle VSM [29]

The induced voltage in the pickup coil is proportional to the sample's magnetic moment, but does not depend on the strength of the applied magnetic field. In a typical setup, the induced voltage is measured through the use of a lock-in amplifier using the piezoelectric signal as its reference signal. By measuring in the field of an external electromagnet, it is possible to obtain the hysteresis curve of a material [29].

The actual testing of the magnetic properties like coercivity, saturation magnetization, retentivity, etc., has been carried out on the **Vibrating Sample Magnetometer (VSM) PAR 155** at Indian Institute of Technology, Madras (IITM). This VSM setup is as shown in the Fig. 5.5.

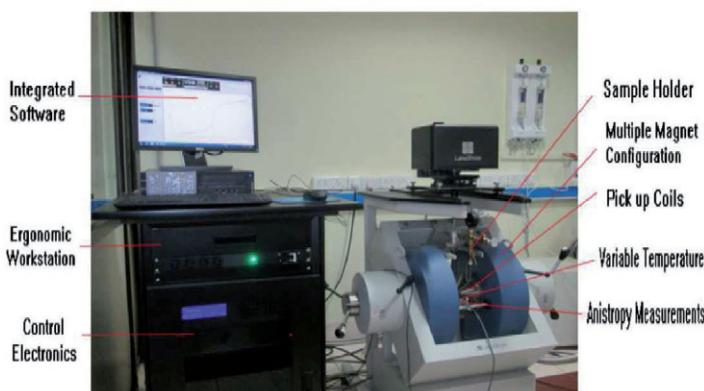


Fig. 5.5 VSM PAR 155

The magnetic properties of solids are very important, and attempts to understand them have led to a deep insight into the fundamental structure of many solids, both metallic and non-metallic. The VSM is the instrument used to measure the magnetic moment, the most fundamental quantity in magnetism, of solid samples.

When a sample material is placed in uniform magnetic field, a dipole moment proportional to the product of sample susceptibility and applied field is induced in the sample. If the sample is made to undergo sinusoidal motion as well, an electrical signal will be induced in suitable located stationary pick-coils.

This signal, which is at the vibration frequency, is proportional to the magnetic moment, vibration amplitude and vibration frequency. The instrument displays the magnetic moment in e.m.u. units.

Specifications for this VSM PAR 155 are as given below:

1. Range: 0.00001 to 10000 e.m.u.
2. Magnetic field: -10 to +20 kOe
3. Temperature range: 77 to 1050 K
4. Sample weight: Powder 20mg
5. Rotation: Up to 360° w.r.t magnetic field
6. Recording: X-Y/(t) Recorder
7. Sample size: Diameter 2.5mm, Length 1-2.5mm

5.2.4 Stability of MR Fluid

Stability of MR fluid samples depends on the content of iron particles and the type of the oil used. Sedimentation is one of the undesired properties of MRF which makes it unstable [9]. The sedimentation was measured by visual observation of the position changes of boundary between clear and turbid part of carrier oil. Prepared samples were placed into cylindrical glass test tubes (length 0.5 m, diameter 40 mm) for 3 days. As a result sedimentation ratio (R) was calculated.

Thus, sedimentation ratio can also be defined as a proportion between length of clear and turbid part of MR fluid as shown in equation 3:

$$R[\%] = \frac{A}{B} \times 100 \quad (3)$$

Where: R [%] - sedimentation ratio, A – length of the clear part,B – length of the turbid part.

5.3 Closure

This chapter has presented the various techniques used for the characterization of MR fluid samples. It has also discussed the methodology of operation of these instruments. Next chapter presents the results of the characterization of commercially available Lord Corporation MR Fluid and locally made MR fluid samples and the comparative study between them.

6. RESULTS AND DISCUSSIONS

The purpose of this chapter is to present the results of characterization of MR fluid samples. The characterization has been done for the procured Lord Corporation MR fluid and locally made MR fluid samples. The results displayed under this section include rheological properties, morphological properties and magnetic properties of MR fluid samples. Cost analysis for these samples has also been done. Comparative analysis of findings has been presented here.

6.1 Rheological Measurements

For the rheological measurements, Parallel Plate Rheometer is used. Rheological properties like yield stress, viscosity, temperature, shear rates have been observed and the graphical representation for the same has been discussed. The OFF state and ON state measurements for all the samples have been carried out. The Lord Corporation 132 DG MR fluid and MR fluid samples with highest percentage have been characterized.

6.1.1 OFF State Measurements

Though much of the success of MR fluids can be attributed to the controllable or on-state behavior of the fluid, the off-state behavior of the fluid cannot be overlooked. Much of the literature tends to focus on the behavior of the fluid when exposed to a magnetic field. However, the success of many MR fluid applications is highly dependent on the off-state behavior of the fluid.

Basically, Lord Corporation 132 DG MR fluid and locally made MR fluid samples have been tested on Parallel Plate Rheometer. The readings have been taken and the graphs like shear stress versus shear rate, viscosity versus shear rate, yield stress versus magnetic flux density have been plotted to evaluate various rheological properties. These separate readings for each sample have been assembled together and compared based on their rheological measurements. The shear stress is measured in these samples at various shear rates when there is no magnetic field applied to the fluid.

The results of off state viscosity rheological measurements have been shown in Table 6.1.

Data Series Information

Name:	Shear Stress with constant temperature
Number of Intervals:	1
Application:	RHEOPLUS/32 V3.62 21006567-33024
Device:	MCR52 SN81246380; FW3.70; Slot(2,-1); Adj(37,0)d
Measuring Date/Time:	3/22/2014; 1:27 PM
Measuring System:	PP25/P2-SN29511; [d=2.5 mm]
Accessories:	TU1=P-PTD200/AIR-SN81257379
Interval:	1
Number of Data Points:	30
Time Setting:	31 Meas. Pts.
Temperature:	30 °C

Table 6.1 Shear Stress with constant temperature

Shear Rate (1/s)	Shear Stress (Pa)							
	LORD MRF	MRF CSi 45%	MRF ESi 45%	MRF CSy 45%	MRF ESy 45%	MRF CSu 60%	MRF ESu 60%	
0	0	0	0	0	0	0	0	0
50	9.23	13.02	12.2	11.12	11.23	10.18	9.2	
200	31.34	28.12	36.09	35.34	33	28.03	32.45	
300	40.22	35.23	47.07	45.34	41.1	30.05	40.21	
400	49.45	50.45	58.12	53.54	49.12	39.61	50.25	
500	58.04	60	66.76	64.43	57.43	48.01	55.01	
600	61.22	68.18	68.23	65.13	63.03	57.10	56.12	
700	72.78	80.09	78.1	76.34	70.04	64.12	60.34	
800	80.76	90.36	86	83.6	78.34	70.91	62.76	
900	87.2	98.22	95.02	90.3	85.02	78.04	70.04	
1000	95	107	104.09	99.31	93.2	82	73	
1100	104.2	118.02	110.15	107.56	100.01	86.78	75.34	

The shear stress is then plotted against varying shear rate which is shown in Fig. 6.1

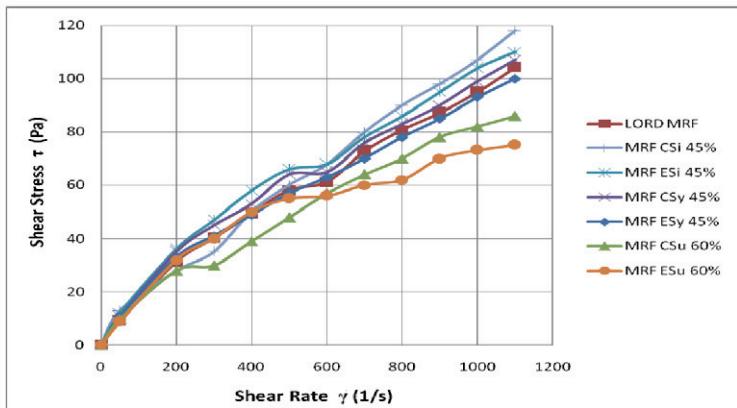


Fig. 6.1 OFF state shear stress change with varying shear rates

As shown in the Fig. 6.1, as the shear rate increases shear stress goes on increasing. In braking application, as rotor rotates, the MR fluid which is in contact with it also follows its motion and hence, shear rate also increases. This makes the fluid to offer more resistance with increase in shear rates. For the off state condition, this resistance means the yield stress produced by the MR fluid should be as low as possible.

The highest value of shear stress is found to be 118.02 Pa as in case of MRF CSI 45% while the value of Lord 132 DG MRF is 104.2 Pa. The MRF ESy 45% and MRF CSy 45% indicate the comparatively lowest shear stress values which lie in between 70-90 Pa. The shear stress value for MRF samples with electrolytic iron powder is always lagging to the same with carbonyl iron powder.

Similarly the OFF state viscosity is plotted against shear stress as demonstrated in Table 6.2.

Data Series Information

Name: Shear Stress with constant temperature
 Number of Intervals: 1
 Application: RHEOPLUS/32 V3.62 21006567-33024
 Device: MCR52 SN81246380; FW3.70; Slot(2,-1); Adj(37,0)d
 Measuring Date/Time: 3/22/2014; 2:38 PM
 Number of Data Points: 30
 Time Setting: 31 Meas. Pts.
 Temperature: 30 °C

Table 6.2 Viscosity with varying shear stress

Shear Rate (1/s)	Viscosity (Pa.s)						
	LORD MRF	MRF CSi 45%	MRF ESi 45%	MRF CSy 45%	MRF ESy 45%	MRF CSu 45%	MRF ESu 45%
0	0.22	0.422	0.352	0.386	0.352	0.302	0.284
100	0.216	0.42	0.35	0.37	0.338	0.28	0.276
200	0.211	0.389	0.348	0.358	0.33	0.272	0.27
300	0.21	0.376	0.342	0.362	0.326	0.27	0.268
400	0.198	0.365	0.34	0.342	0.32	0.263	0.262
500	0.196	0.358	0.335	0.322	0.3	0.256	0.25
600	0.196	0.35	0.34	0.32	0.28	0.246	0.235
700	0.192	0.32	0.32	0.285	0.278	0.235	0.21
800	0.188	0.3	0.3	0.265	0.26	0.21	0.19
900	0.186	0.28	0.3	0.245	0.24	0.202	0.182
1000	0.185	0.26	0.28	0.23	0.226	0.195	0.18
1100	0.184	0.26	0.28	0.21	0.22	0.18	0.175

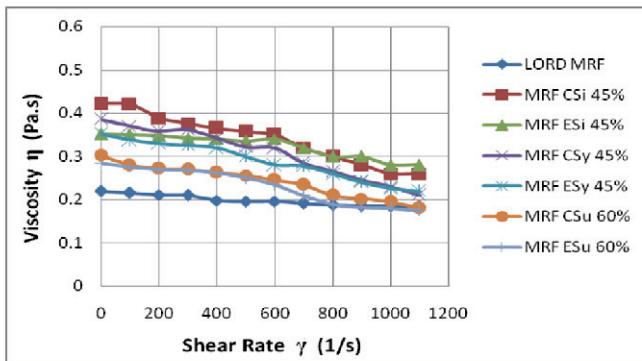


Fig. 6.2 OFF state viscosity change with varying shear rates

As shown in Fig. 6.2 the viscosity reduces with increasing shear rate. As in case of MRF 132 DG, this change is minimum which is desired but in case of other samples this change is bit higher.

In case of Lord MRF 132 DG, as shear rate increases viscosity value decreases from 0.22 Pa.s to 0.184 Pa.s. This total decrease in viscosity value is very less than only is 0.036 Pa.s but in case of other MRF samples this total decrease in viscosity value is even greater than 0.1 Pa.s. This change in viscosity as per shear rate should be as low as possible.

Stability of MR Fluid

Stability of prepared sample takes different values and it varies only within few minutes. It depends on the content of iron particles and also the type of the oil, which is used. Fig. 6.3 represents the sedimentation ratio of the particles for various samples with and without additives.

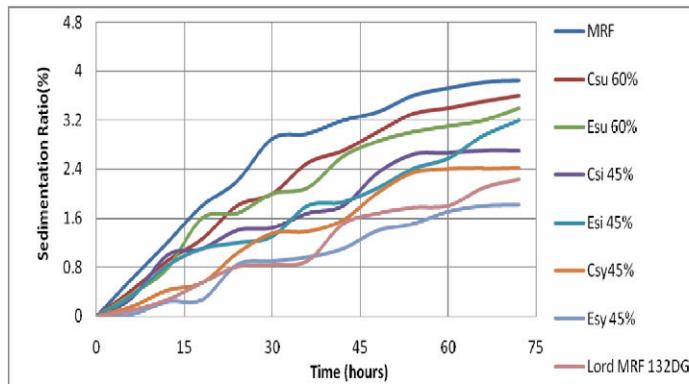


Fig. 6.3 Sedimentation ratios versus time

The combined effect of additive and gaur gum coating on the stability of the MR fluid is observed here. This effect could greatly reduce the sedimentation of MR fluid. MR fluid without additive is named as MRF. This MRF has the highest sedimentation ratio while the lowest sedimentation ratio is observed in case of ESy 45%. That means the additive and coating of guar gum improved the sedimental stability of the MR fluids.

Slightly higher sedimentation ratios are observed in case of MR fluid samples which employs sunflower oil as a carrier fluid. Sediment of the MR fluid should be as low as possible and which is preferred in braking application. Increased sedimentation of MR fluid particles directly affects the yield strength produced by MR fluid and hence, the torque produced. Thus, Lord MRF and MR fluid ESy 45% suits well for the braking application from sediment point of view

6.1.2 ON State Measurements

The rheological measurements have also been carried out after the application of magnetic field and that is termed as ON state. The yield stress has been calculated for MRF 132

DG and for the locally made MR fluid samples and the comparison has been made. These measurements are shown in Table 6.3.

Table 6.3 Yield stress at constant shear rate

Magnetic Field Strength B (T)	Yield Stress (kPa)						
	LORD MRF	MRF CSi 45%	MRF ESi 45%	MRF CSy 45%	MRF ESy 45%	MRF CSu 60%	MRF ESu 60%
0.1	10.23	15.23	13.23	11.23	10.39	7.21	6.89
0.2	22	23	22.2	20.38	19.24	15.12	13.24
0.3	32.02	37.23	34	30.52	32.56	19.13	20.13
0.4	44.23	48	41.24	41.24	43.21	22.34	23.67
0.5	52	59	50.21	51	57.45	26.78	32
0.57	61	70	62	58.82	60.1	33.45	35.23
0.65	67.67	79.23	72	66.23	66.34	40.12	41.23
0.68	71.12	84.12	76	70.86	69.13	43.24	41.78
0.72	80	92	80	73.2	72.34	45	41.78
0.78	83.32	92.34	87.54	76.43	74.1	45.28	41.78
0.84	83.32	92.34	87.57	76.43	76.4	45.28	41.78

The MRF samples with synthetic oil and silicone oil could develop the yield stresses above 70 kPa while the samples which uses sunflower oil as a carrier fluid couldn't exceed 45 kPa. As shown in Fig. 6.4, MRF CSi 45% shows the maximum yield stress of about 92.34 kPa whereas MRF ESu 60% shows the lowest yield stress which is 37.12 kPa.

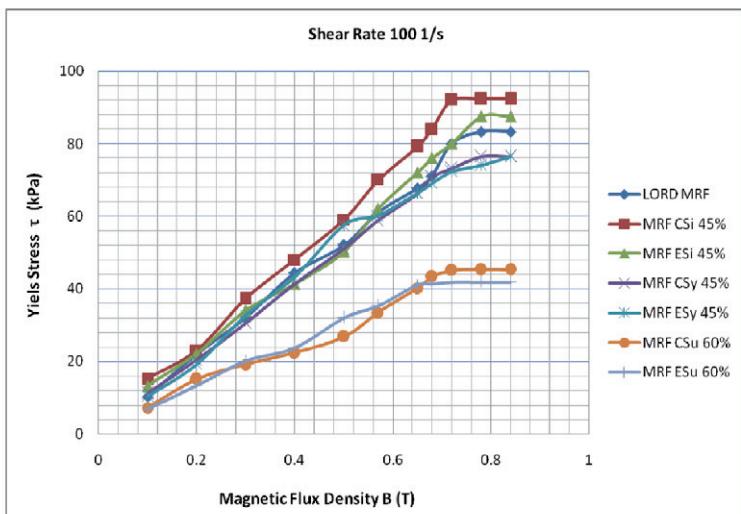


Fig. 6.4 Yield stress at constant shear rate

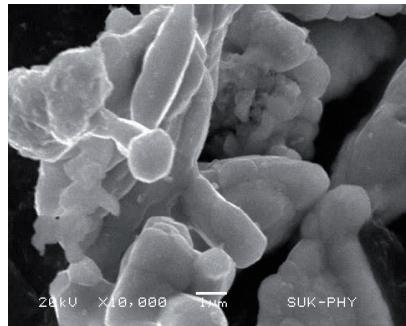
The yield stress produced by the MRF CSu 60% is 41.7 kPa which is slightly more than the yield stress produced by MRF ESu 60%. The samples which employs electrolytic iron powder has seem to be lagging in yield stress to those who employs carbonyl iron powder. The MRF samples CSu 60% and ESu 60% have shown the peak on the graph at about 0.68 T. This peak indicates the magnetic saturation for that material. The magnetic saturation is also higher as in case of MRF CSi 60% and which is at 0.72 T while LORD MRF 132 DG shows the point of magnetic saturation at 0.78 T. The magnetic saturation should be as more as possible since, it directly affects the yield stress produced by the fluid and hence, the braking torque.

6.2 Morphological Measurements

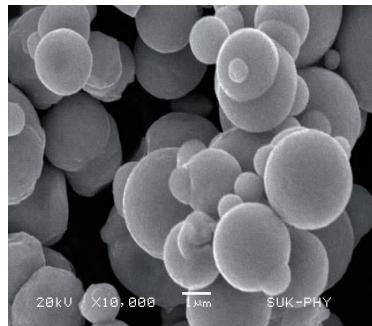
This section presents the results of morphological measurements of electrolytic and carbonyl iron powder. The appearance of coated electrolytic and carbonyl iron powders and uncoated electrolytic and carbonyl iron powders has been discussed.

Fig. 6.4 shows characteristic morphologies of pure electrolytic iron (Fig 6.5(a)) and carbonyl iron particles (Fig. 6.5(b)). The shape of the carbonyl iron powder seems to be spherical while electrolytic iron powder has no any specific shape. Also, the

carbonyl iron is chemically pure and the particles are mesoscale and spherical in nature in order to eliminate the shape anisotropy. The meso-scale particles are necessary since they have many magnetic domains. The spherical shape helps minimize magnetic shape anisotropy.



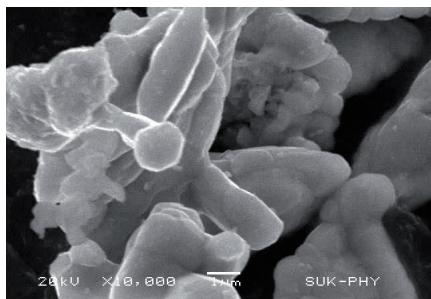
(a)



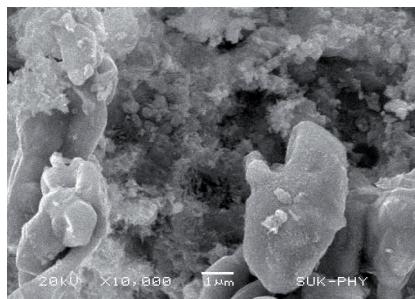
(b)

Fig. 6.5 SEM images of (a) Electrolytic iron powder (b) Carbonyl iron powder

Fig. 6.6 shows the difference between the morphology of uncoated electrolytic iron (Fig 6.6(a)) and coated electrolytic iron powders (Fig 6.6(b)). As shown in Fig. 6.6(b), the coating layer of gaur gum has been formed on the surface of the electrolytic iron particles.



(a)

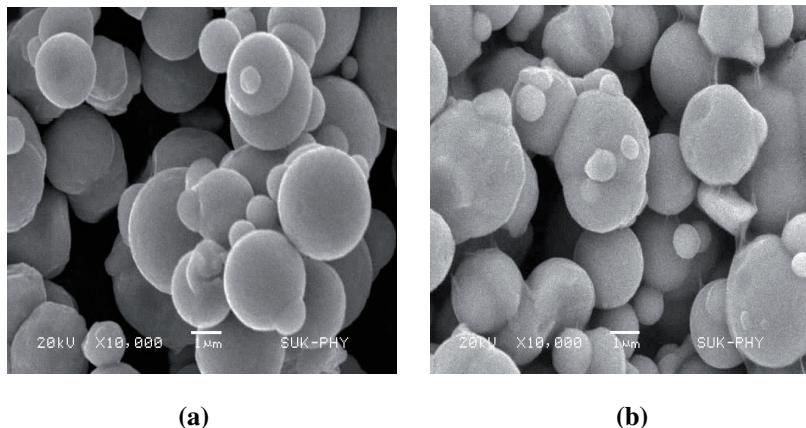


(b)

Fig. 6.6 SEM images of (a) Uncoated electrolytic iron powder

(b) Coated electrolytic iron powder

Similar to the electrolytic iron particles, Fig. 6.7 shows the difference between the morphology of uncoated carbonyl iron (Fig 6.7(a)) and coated carbonyl iron powders (Fig 6.7(b)). As shown in Fig. 6.7(b), the coating layer of gaur gum has been formed on the surface of the carbonyl iron particles.



**Fig. 6.7 SEM images of (a) Uncoated carbonyl iron powder
(b) Coated carbonyl iron powder**

6.3 Measurements of Magnetic Properties

The electrolytic and carbonyl iron powders used for formulation of MR fluid samples are analyzed for the measurements of magnetic properties like coercivity, retentivity, magnetic saturation on VSM. The measurements have been taken for the electrolytic iron and carbonyl iron powder at 300 K (27^0C) and 400 K (127^0C). These temperatures have been selected because the tests have been carried out at room temperature and highest temperature. Room temperature is considered as 300 K (27^0C) while the highest temperature involved in the braking application of two wheeler is considered as 400 K (127^0C).

Fig. 6.8 indicates the hysteresis (M-H) curve generated for the electrolytic iron powder at 300 K (27^0C) temperature.

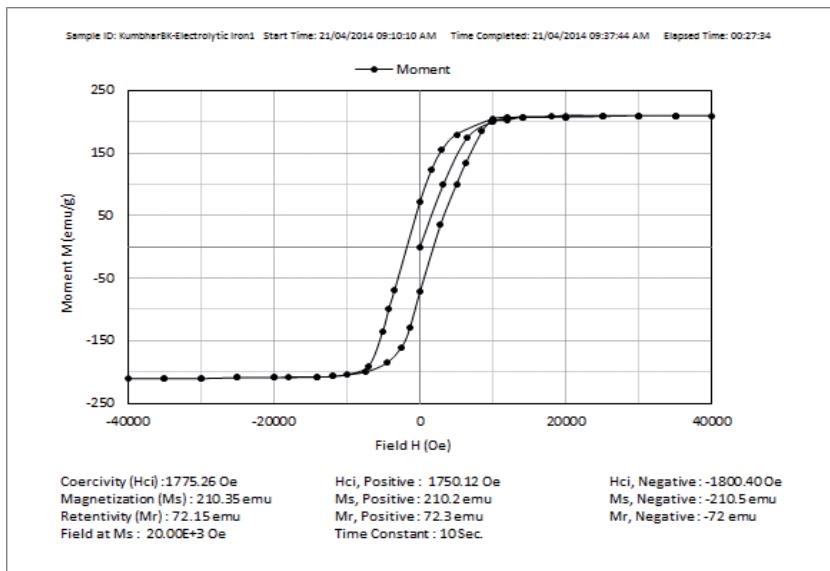


Fig. 6.8 Hysteresis Curve for electrolytic iron powder at 300 K (27°C)

By using this hysteresis loop the various magnetic properties of electrolytic iron powder have been analyzed. The saturation magnetization of electrolytic iron powder at 300 K (27°C) is obtained as 210.35 emu/g. Coercivity (Hci) is obtained as 1775.26 Oe while Retentivity (Mr) is 72.15 emu/g. As the retentivity is 72.15 emu/g, it is treated as a soft material because when it approaches to the 100 emu/g it becomes hard material.

The soft material is employed in MR fluid technology. Basically, low coercivity, low retentivity, high permeability and high saturation magnetization are the properties of ideal magnetic material used for the MR fluid technology.

Fig. 6.9 indicates the hysteresis (M-H) curve generated for the electrolytic iron powder at 400 K (127°C) temperature.

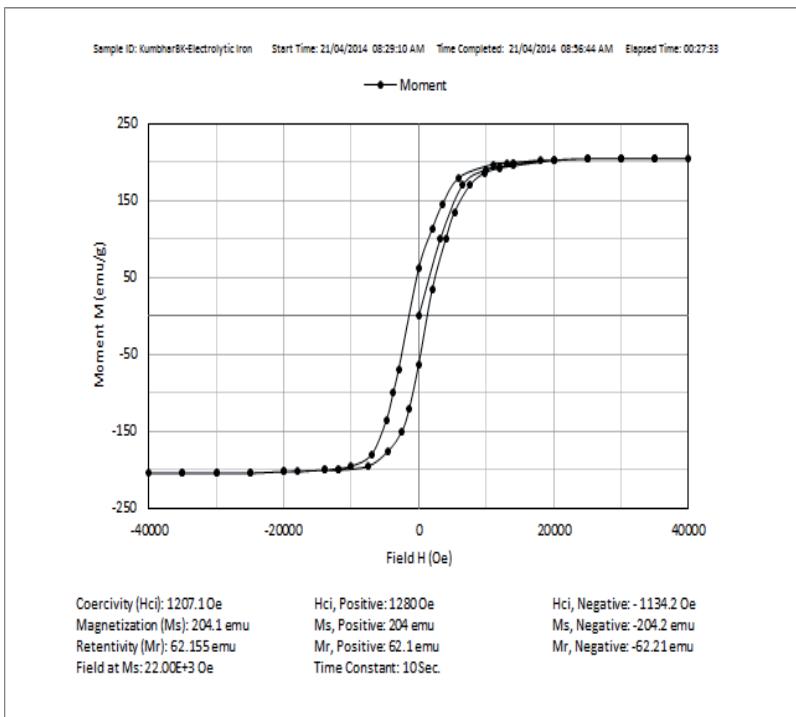


Fig. 6.9 Hysteresis Curve for electrolytic iron powder at 400 K (127°C)

The saturation magnetization of electrolytic iron powder at 400 K (127°C) is obtained as 204.10 emu/g. Coercivity (Hci) is obtained as 1207.1 Oe while retentivity (Mr) is 62.155 emu/g. The retentivity found in at this temperature is lower than it is found at 300 K (27°C) temperature. Field at the saturation magnetization is $22.00\text{E}+3$ Oe. This field should be as low as possible, this ensures the quick response of these powders to the magnetic field.

Fig. 6.10 indicates that the hysteresis (M-H) curve generated for the carbonyl iron powder at 300 K (27^0 C) temperature.

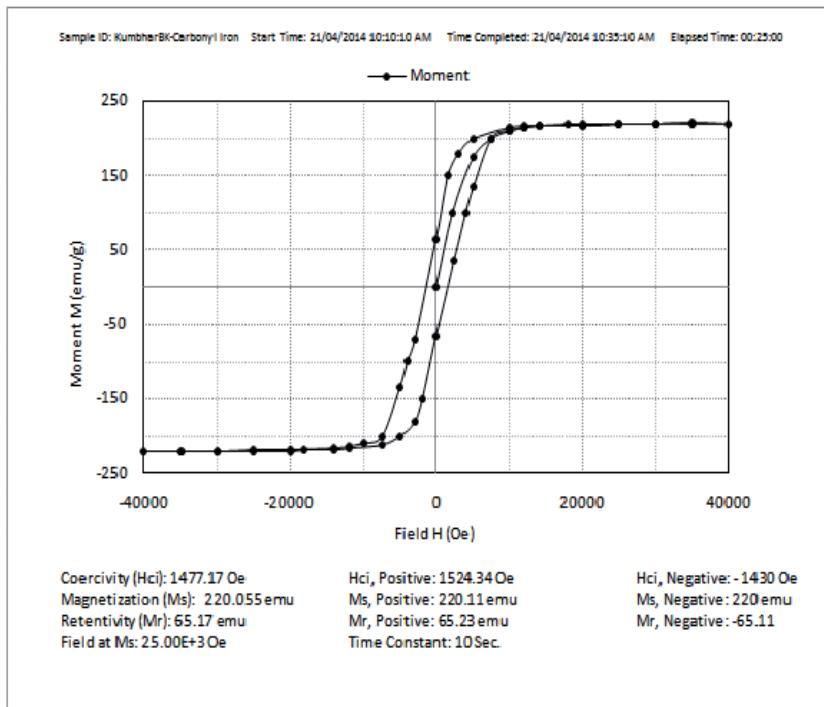


Fig. 6.10 Hysteresis Curve for carbonyl iron powder at 300 K (27^0 C)

The saturation magnetization of carbonyl iron powder at 300 K (27^0 C) is obtained as 220.055 emu/g. Coercivity (Hci) is obtained as 1477.17 Oe while retentivity (Mr) is 65.17 emu/g. Field at the saturation magnetization is 25.00E+3 Oe. The carbonyl iron powder is more soft as compared to the electrolytic iron powder.

Fig. 6.11 indicates that the hysteresis (M-H) curve generated for the carbonyl iron powder at 400 K (127^0 C) temperature.

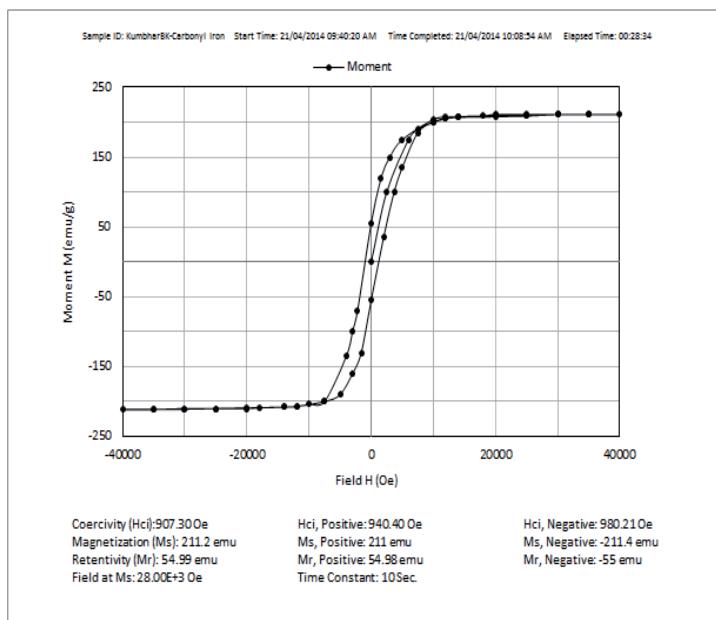


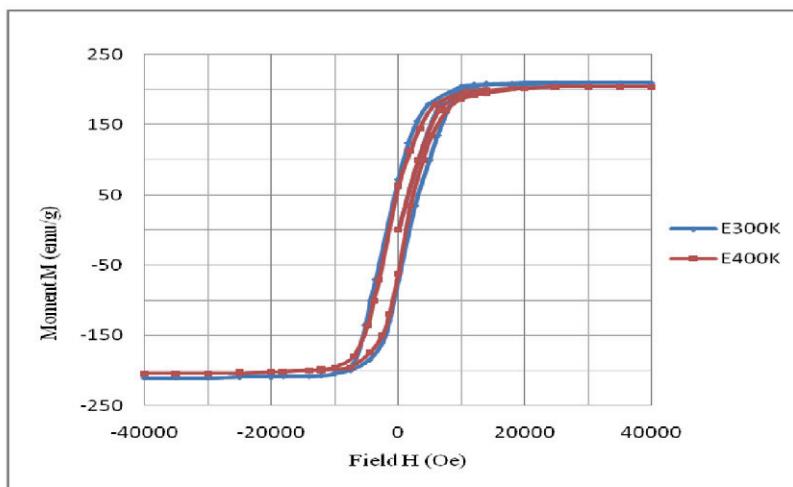
Fig. 6.11 Hysteresis Curve for carbonyl iron powder at 400 K (127^0 C)

The saturation magnetization of carbonyl iron powder at 400 K (127^0 C) is obtained as 211.2 emu/g. Coercivity (Hci) is obtained as 907.30 Oe while retentivity (Mr) is 54.99 emu/g. Field at the saturation magnetization is 28.00E+3 Oe. Small hysteresis loop is observed in case of carbonyl iron powder at 400 K (127^0 C) temperature.

Braking application demands quick response time which in turn requires as small hysteresis loop as possible. Hence, the loop produced by the carbonyl iron powder satisfies this requirement of braking application and may lead to increase the efficiency of MR brake. As it offers better magnetic properties even at higher

temperature, MR fluid technology prefers carbonyl iron powder instead of electrolytic iron powder.

The comparative study has been made based on the hysteresis loop and magnetic properties of electrolytic and carbonyl iron powder. Also, the magnetic properties of these powders at different temperatures have been analyzed. The hysteresis loops for the electrolytic iron powder at different temperatures (300 K (27^0 C) and 400 K (127^0 C)) are as shown in the Fig. 6.12.



**Fig. 6.12 Hysteresis Curves for electrolytic iron powder at
300 K (27^0 C) and 400 K (127^0 C)**

It is clearly seen that the small hysteresis loop is found when the same test is carried out with increased temperature. The saturation magnetization of electrolytic iron powder at 300 K (27^0 C) is 210.35 emu/g while at 400 K (127^0 C) it is found to be as 204.10 emu/g. It means that, the level of magnetic saturation is reduced with increased temperature.

The coercivity (H_{ci}) obtained in case of electrolytic iron powder at 300 K (27^0 C) is 1775.26 Oe while at 400 K (127^0 C) it is found to be as 1207.1 Oe. The value of

coercivity is also reduced with increased temperature. The lower value of coercivity and retentivity is preferred in MR fluid technology. The value of retentivity obtained for electrolytic iron powder at 300 K (27^0C) temperature is 72.15 emu/g while at 400 K (127^0C) it is found to be as 62.155 emu/g. The percentage increase or decrease in the magnetic properties at these temperatures has been given in Table 6.4.

Table 6.4 Percentage deviation in magnetic properties for electrolytic iron powder

Sr. No.	Magnetic Properties	at 300 K	at 400 K	% Increase or Decrease	Remarks
1	Saturation Magnetization (Ms) (emu/g)	210.35	204.10	2.97 % decrease	Unfavorable for braking application
2	Coercivity (Hci) (Oe)	1775.26	1207.1	32 % decrease	Favorable for braking application
3	Retentivity (Mr) (emu/g)	72.15	62.155	13.8% decrease	Favorable for braking application
4	Field at Saturation magnetization (Oe)	20.00E+3	22.00E+3	9.09 % increase	Unfavorable for braking application

Hence, as temperature is increased the value of retentivity is also increased. Thus, with increasing temperature, the magnetic properties of material become superior for MR fluid technology except the saturation magnetization goes on reducing.

The hysteresis loops for the carbonyl iron powder at different temperatures (300 K (27^0C) and 400 K (127^0C)) are as shown in the Fig. 6.13.

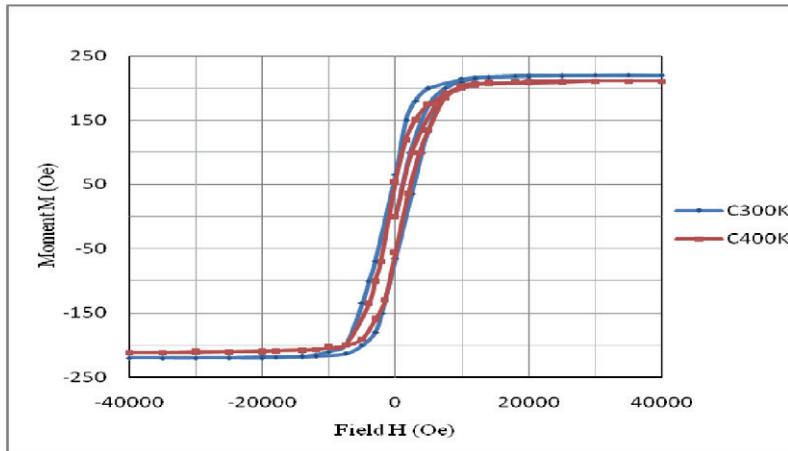


Fig. 6.13 Hysteresis Curves for carbonyl iron powder at 300 K (27°C) and 400 K (127°C)

The saturation magnetization of carbonyl iron powder at 300 K (27°C) is 220.055 emu/g while at 400 K (127°C) it is found to be as 211.2 emu/g. It means that, the level of magnetic saturation is reduced with increased temperature.

The coercivity (Hci) obtained in case of electrolytic iron powder at 300 K (27°C) is 1477.17 Oe while at 400 K (127°C) it is found to be as 907.30 Oe. The value of coercivity is also reduced with increased temperature. The lower value of coercivity and retentivity is preferred in MR fluid technology. The value of retentivity obtained for electrolytic iron powder at 300 K (27°C) temperature is 65.17 emu/g while at 400 K (127°C) it is found to be as 54.99 emu/g. The percentage increase or decrease in the magnetic properties at these temperatures for carbonyl iron powder has been given in Table 6.5.

Table 6.5 Percentage deviation in magnetic properties for carbonyl iron powder

Sr. No.	Magnetic Properties	at 300 K	at 400 K	% Increase or Decrease	Favorability for Braking Application
1	Saturation Magnetization (Ms) (emu/g)	220.055	211.2	4.02 % decrease	Unfavorable for braking application
2	Coercivity (Hci) (Oe)	1477.17	907.30	38.57% decrease	Favorable for braking application
3	Retentivity (Mr) (emu/g)	65.17	54.99	15.62% decrease	Favorable for braking application
4	Field at saturation magnetization (Oe)	25.00E+3	28.00E+3	10.7 % increase	Unfavorable for braking application

The magnetic behavior of electrolytic and carbonyl iron powders has been studied at different temperatures. Now, in this section, the comparative study in between electrolytic and carbonyl iron powders have been made based on the magnetic properties with the help of hysteresis loops. The hysteresis loops for these powders at a temperature of 300 K (27°C) have been shown in the Fig. 6.14.

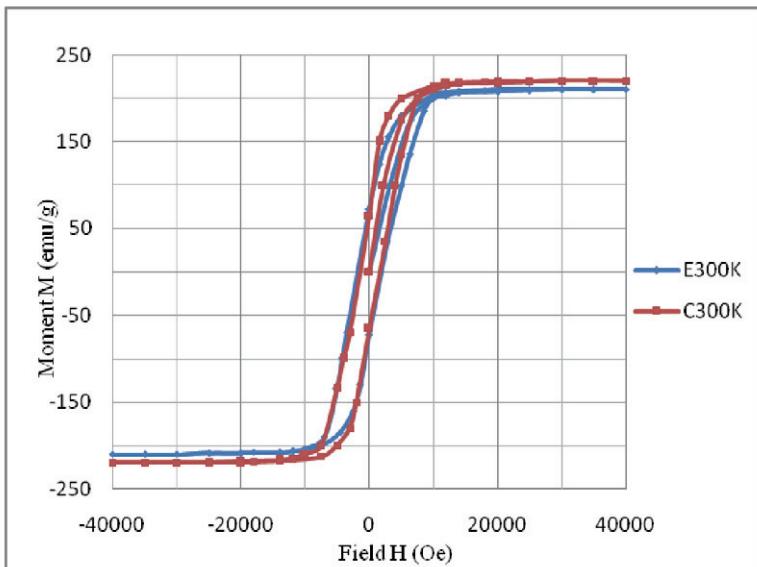


Fig. 6.14 Hysteresis Curves for Electrolytic and Carbonyl Iron Powders at 300 K (27°C)

The small hysteresis loop is found in case of carbonyl iron powder which is desired for the MR fluid technology. The saturation magnetization is also higher in case of carbonyl iron powder as compared to electrolytic iron powder. The magnetic saturation for electrolytic iron powder is 210.35 emu/g, while for carbonyl iron powder it is 220.055 emu/g.

The level of coercivity and retentivity is also low in case of carbonyl iron powder. The coercivity for the electrolytic iron powder is 1775.26 Oe while in case of carbonyl iron powder it is 1477.17 Oe. Also, the retentivity for electrolytic iron powder is 72.15 emu/g while for carbonyl iron powder it is only 65.17 emu/g. Thus the carbonyl iron powder yield better magnetic properties as compared to the electrolytic iron powder for the same temperature.

The percentage increase or decrease in the magnetic properties for electrolytic and carbonyl iron powders at 300 K (27°C) has been given in Table 6.6.

**Table 6.6 Magnetic properties for electrolytic and carbonyl iron powders at 300 K
(27°C)**

Sr. No.	Magnetic Properties	Electrolytic Iron Powder	Carbonyl Iron Powder	Favorability for Braking Application
1	Saturation Magnetization (Ms) (emu/g)	210.35	220.055	Unfavorable for braking application
2	Coercivity (Hci) (Oe)	1775.26	1477.17	Favorable for braking application
3	Retentivity (Mr) (emu/g)	72.15	65.17	Favorable for braking application
4	Field at saturation magnetization (Oe)	20.00E+3	25.00E+3	Unfavorable for braking application

As shown in Table 6.6 first three properties that is saturation magnetization, coercivity and retentivity help to produce small hysteresis loop as in case of carbonyl iron powder and hence, preferred in braking application. However, the last property shows slightly more field at saturation magnetization in case of CI powder which is unfavorable for braking application.

6.4 Cost Estimation

Cost analysis for the various MR fluid samples has been done in this section. Costing is basically the ascertainment of cost whether for a specified thing or activity. Costing is important to ensure that all expenses are covered and the group fixes a price that ensures a profit. Understanding costing assists in cost awareness, cost control / management. The constituents of the cost of a product or the cost elements are: Material cost, labour cost and expenses [30]. These elements have been discussed as follows:

6.4.1 Material Cost

Material is divided into the two basic categories: (a) Material for fabricated parts and (b) Standard purchased parts. The total cost of these two will give the material cost. Again there are two kinds of materials which comprise the factory cost of a product. These are direct material and indirect material.

(i) Direct Material

The direct material is the raw material which is processed in the plant to form final product. Any standard part which also becomes a part of the final product will also come in the category of direct material.

(ii) Indirect Material

Indirect materials are those which help in the processing of direct materials into the final product. These materials don't form a part of final product. Indirect material forms a part of oncost or overheads [30].

6.4.2 Labour Cost

Labour which enters into the manufacture of the product is of two categories: Direct labour and indirect labour

(i) Direct labour: The operator or operators which actually process the materials on machines or manually, form the direct labour

(ii) Indirect labour: All the staff except administrative and sales office staff, which helps in running the plant, comes under the category of indirect labour. Indirect labour includes: Foremen, supervisors, maintenance staff, stores personnel, time office staff, drawing office staff etc. Indirect labour forms a part of overheads [30].

6.4.3 Expenses

Total cost minus the costs of direct material and direct labour constituents the 'Expenses'. Expenses may also be direct or indirect.

(i) **Direct Expenses:** These materials like direct material and direct labour are directly chargeable to the final product. These are also known as chargeable expenses. These include [30]:

- (a) Cost of drawings or designs specifically prepared for a particular product which cannot be used for other purposes.
- (b) Cost of any experimental work done specially for particular product
- (c) Cost of inward carriage or freight incurred on supply of special material needed for the particular product.
- (d) Hire of special instruments or equipments for a particular product

(ii) **Indirect Expenses:** These are also called as ‘oncosts’ ‘Overheads’ or ‘Burden’. These include: cost of direct material, cost of indirect labour and other expenses that cannot be conveniently charged directly to a particular job.

Indirect expenses may be divided into [30]:

- (a) Factory expenses or overheads.
- (b) Office and administrative expenses or overheads
- (c) Selling and distribution expenses or overheads

Factory Expenses:

These expenses include: indirect materials, indirect labour, expenses insurance, maintenance and depreciation of machine, power etc.

Office and Administrative Expenses:

These expenses consist of all expenses incurred in the direction, control and administration of an undertaking. These expenses include: rent and rates of office premises, salaries of office staff, printing and stationery, postage and insurance on office equipments.

Selling and Distribution Expenses:

These expenses include: Salaries of sales staff, publicity and advertisement, catalogues, leaflets and price lists, packing and forwarding charges, godown rent, and

commission to salesmen etc. The overheads may be grouped into the two main categories [30]:

1. Fixed Overheads or Constant Overheads:

These are such items of indirect expenses which remain constant or fixed irrespective of volume of production. These items include: Salaries of higher officers (administrative and management's executives), capital taxes, insurance charges, depreciation of building, plant machinery etc., and rent of building [30].

2. Variable or Floating Overheads:

These are such items of overheads which vary with volume of production. Such items are: internal transport charges, power, fuel, store expenses, factory lighting and heating and sales office expenses and repairs of equipments or instruments.

Since fixed overheads remain constant irrespective of volume of the production, production should be increased to reduce the cost of the product. There should be some minimum production to meet the fixed expenses and start earning profit [30].

6.4.4 Cost Structure [30]

The elements of cost can be combined to give following types of cost:

1. Prime Cost: Prime cost or direct cost is given as:

$$\text{Prime cost} = \text{Direct material} + \text{Direct labour} + \text{Direct expenses (if any)}$$

2. Factory Cost: This cost is given as:

$$\text{Factory cost} = \text{Prime cost} + \text{Factory Expenses}$$

3. Manufacturing cost: Manufacturing cost or cost of production is given as:

$$\text{Manufacturing cost} = \text{Factory cost} + \text{Administrative Expenses}$$

4. Total Cost: Total cost is given as:

$$\text{Total cost} = \text{Manufacturing cost} + \text{Selling and Distribution overheads}$$

5. Selling Price: Selling price is given as:

$$\text{Selling price} = \text{Total cost} + \text{Profit}$$

6.4.5 Cost Estimation for MRF Samples

Cost analysis for one liter of various MR fluid samples has been carried out by considering various elements of costs and selling price for these samples is determined.

a) MRF ESi 45%

The cost elements for these samples are as follows:

1. Direct Material:

This includes the cost of material procured for the synthesis of MRF ESi 45%.

Table 6.7 shows the materials and respective costs.

Table 6.7 Direct Material

Sr. No.	Material	Cost/liter or kg (Rs.)	% by Weight (g)	Cost (Rs.)
1	Silicone Oil	1400	509.12	713
2	Carbonyl Iron Powder	2000	540	1080
3	Gaur Gum Powder	300	16.2	300
4	Oleic Acid	800	4.4	400
5	Grease	450	4.4	45
6	Ethanol	480	100	240
7	Acetone	800	400	400
	Total			3178/-

2. Direct Labour:

The salary of the labour working to synthesize the MR fluid sample is assumed to be 7000 Rs. per month. The time required for the agitation of MR fluid is 24 hrs. and

preparation of MR fluid setup and coating of magnetic particles is 8 hrs. The total time required to synthesize the MR fluid is 32 hrs.

$$\text{Cost of one day labour} = \text{Salary of labour}/\text{Working days}$$

$$= 7000/24$$

$$= 291.66 \text{ Rs.}$$

Thus,

$$\text{Cost of 4 days (32 hrs)} = 4 \times 291.66$$

$$= 1167 \text{ Rs.}$$

The direct labour cost is **1167 Rs.**

3. Direct Expenses:

The direct expenses for the MRF ESi are shown in Table 6.8:

Table 6.8 Direct Expenses

Sr. No.	Particulars	Cost (Rs.)
1	Cost of experimental work	500
2	Freight charges	2000
3	Hire of special instruments	2100
	Total	4600/-

Now, the prime cost can be determined.

$$\text{Prime cost} = \text{Direct material} + \text{Direct labour} + \text{Direct expenses}$$

$$= 3178 + 1167 + 4600$$

Prime Cost = 8945 Rs.

4. Factory Expenses

Basically indirect material, indirect labour, maintenance, depreciation of machine, power etc. falls under these expenses. These expenses are as given in Table 6.9.

Table 6.9 Factory Expenses

Sr. No.	Particulars	Cost (Rs)
1	Plastic bottles, Cloths, stirrer, filter papers.	500
2	Power, Maintenance	500
3	Supervisors, maintenance staff, stores personnel, time office staff	2000
	Total	3000/-

The factory expenses incurred are 3000 Rs.

Therefore,

$$\begin{aligned} \text{Factory cost} &= \text{Prime cost} + \text{Factory Expenses} \\ &= 8945 + 3000 \end{aligned}$$

$$\text{Factory Cost} = 11945 \text{ Rs.}$$

5. Administrative Expenses:

Consider the cost of these expenses is 2000 Rs. which includes rent and rates of office premises, salaries of office staff, printing and stationery etc.

Now, the cost of production is given as,

$$\begin{aligned} \text{Cost of Production} &= \text{Factory Cost} + \text{Administrative Expenses} \\ &= 11945 + 2000 \end{aligned}$$

$$\text{Cost of Production} = 13945 \text{ Rs}$$

Consider the cost of selling and distribution charges 1000 Rs. and hence, the total cost of the MR fluid sample is

$$\begin{aligned}\text{Total Cost} &= \text{Production Cost} + \text{Selling and Distribution overheads} \\ &= 13945 + 1500\end{aligned}$$

Total Cost = 15445 Rs.

If 10 % profit is considered then it becomes 1545 Rs. Therefore,

$$\begin{aligned}\text{Selling Price} &= \text{Total Cost} + \text{Profit} \\ &= 15445 + 1545\end{aligned}$$

Selling Price = 16990 Rs.

The selling price for MRF ESi 45% is 16990 Rs. In case of other MR fluid samples the total cost and selling price is almost same. Lord MR Fluid costs nearly 43830 Rs. per liter (excluding importing charges). Hence, the synthesized MR fluid could greatly reduce the cost of the MR fluid. This reduction is 26840 Rs. (61.23%) in the Lord Corporation MR fluid cost per liter.

The locally made MR fluid samples not only greatly reduce the cost of commercially available MR fluid but also increase the yield strength produced by it. The off state viscosity in case of Lord MR Fluid is low as compared to the synthesized MR fluid ESi 45%.

6.5 Closure

The results of characterization of MR fluid samples have been presented in this chapter. Based on these results, the comparative study of various properties of these MR fluid samples has been made. Also, the cost analysis for various MR fluid samples has been done and then it is compared with the cost of Lord Corporation MR Fluid.

7. CONCLUSIONS

In this research, MR fluids are synthesized using electrolytic and carbonyl iron powders with grease as an additive and oleic acid as a surfactant. The gaur gum coating is also introduced to enhance the polarization induced in the suspended particles. These MR fluids and commercially available Lord Corporation MR Fluid are characterized and comparative study based on their properties and costs is presented.

The synthesized MR fluids are as follows:

- CSi 45% 45% Carbonyl iron powder and silicone oil
- ESi 45% 45% Electrolytic iron powder and silicone oil
- CSy 45% 45% Carbonyl iron powder and synthetic oil
- ESy 45% 45% Electrolytic iron powder and synthetic oil
- CSu 60% 60% Carbonyl iron powder and sunflower oil
- ESu 60% 60% Electrolytic iron powder and sunflower oil

MR fluid sample CSi 45% exhibited the highest yield stress of about 92.34 kPa while the yield stress produced by the Lord MR fluid is 83.32 kPa. Hence, MR fluid CSi 45% can best suit for the braking application as it may produce the sufficient braking torque.

One of the aspect of this study is the formulation of MR fluids using Sunflower Oil which is biodegradable, environmental friendly and abundantly available. These samples CSu 60% and ESu 60% have produced the yield stress of about 45.28 kPa and 41.78 kPa respectively. However, the yield stress produced by these samples will not satisfy the torque requirements for the automotive braking application but these samples can be effectively used for the applications where the yield stress requirements are low such as shock absorbers, actuators, seat dampers etc.

The saturation magnetization (M_s) for electrolytic and carbonyl iron powders at 300 K (27°C) is found to be 210.35 and 220.055 emu/g respectively. The coercivities

of these powders are measured as 1775.26 and 1477.17 Oe respectively. A possible reason for the higher coercivity of the iron particles is the presence of impurities and defects in the particle. For braking application, small hysteresis loop is desired and which is achieved by higher magnetic saturation, lower coercivity and lower retentivity. Small hysteresis loop increases the particles response and higher magnetic saturation increases the yield stress produced by the MR fluid. Thus, carbonyl iron powder is best suit for the braking application as it has produced the small hysteresis loop.

The MR fluid sample without additive has shown the highest sedimentation ratios while due to the combined effect of additive and gaur gum coating, this ratio is significantly reduced. For braking application the sediment of MR fluid should be as low as possible since, it affects the response time of brake. ESy 45% has shown the lowest sedimentation ratio that means only 0.5% during 3 hrs and hence, it will best suit for the braking application from sediment point of view. But, from yield stress point of view CSi 45% suits for braking application as it produces highest yield stress while the yield stress produced by ESy 45% is only 76.4 kPa.

The cost analysis made for one liter of synthesized MR fluids has shown the significant difference as compared to the commercially available Lord Corporation MR fluid 132 DG. The cost for Lord MR Fluid 132 DG is Rs. 43830 per liter while the same for synthesized MR fluid is Rs. 16990 per liter. It means that the reduction in the Lord Corporation MR fluid cost is Rs. 26840 (61.23%) per liter. However, the off state apparent viscosity measured is \sim 4 Pa-s at 50 s^{-1} whereas for a Lord MR fluid this value is \sim 2 Pa-s. That means increased off state viscosity in case of synthesized MR fluid samples in not favorable for braking application because MR fluid offers more resistance to the rotation of disc and ultimately to the rotation of wheel which directly results into the power loss.

Thus, above conclusions can be summarized as follows:

1. MR fluid sample CSi 45% is the best choice for the automotive braking application from yield stress point of view, but it shows higher sedimentation ratio.
2. MR fluid sample ESy 45% suits well for the automotive braking application as it shows the lowest sedimentation ratio among all the samples.
3. MR fluid samples CSu 60% and ESu 60% cannot satisfy the requirements of automotive braking application but they can be used for low yield stress applications.
4. Carbonyl iron powder is the best choice for the automotive braking application as compared to the electrolytic iron powder as it produces small hysteresis loop and higher saturation magnetization
5. Synthesized MR fluids could reduce the overall cost of the Lord MR fluid by 61.23% but at the cost of increased off state viscosity.

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