Magnetorheological Fluid Preparation Using Various Carriers and Study of Their Properties with Decent Durability

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Abstract. *Sedimentation instability is a significant problem of magnetorheological fluid. In most situations, using different surfactants to coat iron powder is inadequate in maintaining a stable fluid and often leads to sedimentation within a few days. One of the ideal requirements for magnetorheological (MR) fluid is the preparation of a fluid with outstanding sedimentation stability. This research explores the use of several carrier fluids and techniques to achieve a more stable magnetorheological (MR) fluid. Orthogonal experiments are conducted to determine the most effective balance of carrier oil and additive substances. The new findings demonstrate that the most effective combination is achieved by using the produced MR fluid with the compound scheme. This final combination analyses indicate that at normal temperature the best choice has a viscosity of PaS value of 1.924 and a sedimentation rate of 1.51% after four weeks of installation. The optimal MRF exhibits superior sedimentation stability and fluidity over an extended duration.*

***Keywords**: Magento-Rheology, Viscosity, Sedimentation, Smart Fluid.*

1. Introduction

The Greek term 'Rheos' means to move or progress smoothly. Rheology is the scientific study of how materials flow when subjected to external forces. Magnetorheological (MR) fluid refers to a kind of fluid that experiences an increase in its apparent viscosity when there is a magnetic field employed on it. MR fluids, sometimes called magnetorheological fluids, consist of small particles that stay in a base fluid influenced by the magnetic field. The fundamental fluid is an oil variant. The MR fluid undergoes a rapid transition in its liquid state upon exposure to the applied magnetic field. This special feature facilitates a prompt and efficient connection between physical systems and electrical components. Magneto-rheological fluid has many applications in common industries like automotive, aerospace, hydraulics, and medical domains [1].

Following the resolution of certain industrial challenges, the potential advantages for different MRF applications, both in terms of technological and economic aspects, have proven highly promising. Consequently, the development of MRF is an ongoing and continual process. Around six decades ago, during the 1940s, Jacob Rabinov discovered the MR fluid effect while working at the institute known as the United States National Bureau (UNB) of Standards. Simultaneously, W. Winslow was engaged in the development of a rival technique known as electro-rheological fluid (ERF). Since their discovery in the late 1940s, more studies have been conducted on ERF than on MRF. Both systems need electricity, although there are some similarities and differences. The ERF technology requires thousands of volts and several milliamperes, whereas the MRF technology typically requires between two and twenty-four volts and a few amperes. Similarly, the electro-rheological (ER) consequence is contingent upon a field of electrostatic, whereas the MR effect relies on a field that depends on magnetic force [2].

In the last five years, there have been more publications on MRF than on ERF in the accessible domain. During the first stages of MRF development, many unexpected phenomena were documented, including thickening, sedimentation, and abrasion during use. The commercialization of the first MRF-based application, particularly for automotive use, encountered many difficulties. In recent years, several colleges and corporations in the United States, European nations, and Japan have conducted research on stability, sedimentation, and abrasive behaviour. Currently, MR fluid technologies used as dampers in vehicle clutches, and, in active bearings have either been introduced as a product or are close to the beginning of new production [3].

2. Concept of MR fluid

Rheology is the scientific discipline that investigates the behaviour of circulation and deformation. The examination of movement involves both elastic and plastic distortion, since they share similar characteristics and must be examined together. In a typical application using a standard liquid, such as a hydraulic pump or a damper, the primary characteristic of utmost significance is viscosity, which varies in response to temperature fluctuations. Consequently, temperature is often seen as an unmanageable characteristic. Dynamic or kinematic viscosity are the two forms of expression for viscosity. The definition of dynamic viscosity is as follows:

$$\dot{\eta} = \tau/\gamma^0 \tag{1}$$

where, share stress is τ in (N per mm2) and share rate is γ^0 in (1/s) and $\dot{\eta}$ in (Pa S). Similarly, kinematic viscosity can be explored as,

$$\vartheta = \dot{\eta}/\rho \tag{2}$$

here, ρ is the density (kg/m3) and ϑ in (m2/s).

The thermal dependence of a standard fluid, such as mineral oil or silicon oil, is obtained using the estimate:

$$\dot{\eta}(\text{Th}) = C.e^{b/(r+273)} \tag{3}$$

The variables C and b are determined from experimental measurements for certain liquids. When Newton examined the relationship amongst shear rate and shear stress for different substances. For water, this correlation is linear. A fluid with these characteristics is often referred to as a Newtonian fluid. For any Newtonian fluid, the dynamic viscosity remains constant. Figure 1 illustrates the usual connections among shear stress and shear rate, as well as the analogous connections involving dynamic viscosity as well as shear stress for different solutions. Furthermore, calculations have been established to precisely measure the correlations between these rheological characteristics, in addition to their pictorial depiction. The correlation among viscosity, shear stress as well as shear rate is contingent upon the nature of the liquid. The curve in black labelled using the little letter ‘a’ indicates that the fluid in curve is a ‘Newtonian fluid’. Its viscosity remains regular regardless of the varying the value of shear rate, but for the shear stress exhibits a straight correlation with the values of shear rate. Water is the prototypical fluid that exhibits this characteristic. For curves ‘b’ and ‘c’, the shear stress exhibits a diminishing ‘b’ or escalating ‘c’ correlation with the values of shear rate. Viscosity and shear rate have a comparable connection, whereby each of these fluid characteristics correlates to one another. The typical fluids exhibiting these characteristics are ketchup and toothpaste. The curve (d) exhibits behaviour that closely resembles that of an MRF. If there is no magnetic field applied, the rheological properties

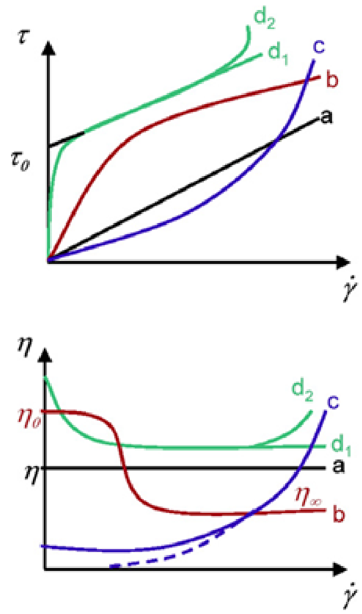

Fig. 1: Different types of fluids [4].

of any MR fluids closely resemble those of the fluids used as carrier, with the exception that the presence of iron particles in the MR fluid causes a modest increase in viscosity [2, 4].

In the figure 1 for Newton type fluid,

$$\dot{\eta} = \tau\dot{\gamma} \tag{4}$$

shown in the curve 'a'. For Yasuda type fluid,

$$\frac{\dot{\eta} - \dot{\eta}_\infty}{\dot{\eta}_0 - \dot{\eta}_\infty} = \left[1 + \lambda^\alpha \dot{\gamma}^2\right]^{\frac{n-1}{\alpha}} \tag{5}$$

represented by b. Ostwald type fluid is represented by

$$\tau = k\dot{\gamma}^n \tag{6}$$

Finally, another representation for Herschel-Bulkley for the equation,

$$\tau = \tau_0 + k\dot{\gamma}^n \text{ or } \tau = \tau_0/\dot{\gamma} + k\dot{\gamma}^{1-n} \tag{7}$$

3. MR fluid formation and sedimentation characteristics

The rheological state undergoes reversible transitions between liquid and solid phases. Most programs lack the ability to quickly manipulate these elements due to their fixed nature inside a certain context. For all fluids, the change in viscosity due to temperature is reversible. However, this does not facilitate easy control of viscosity. In the context of MR (magneto-rheological) materials, the fluid viscosity may be precisely regulated by manipulating the magnetic field. The reversible alteration of viscosity till reaching a solid state is a fundamental characteristic of MR fluid technology. The magneto-rheological fluid (MRF) effect refers to the disparity in rheological characteristics seen when there is a influence of magnetic field is employed compared to when it is absent. MR fluids in general contain of ferrous micro-magnetic elements suspended in a suitable liquid used as carrier, such as synthetic oil, water, or hybrid oil. The MR fluid consists of three primary constituents: The components of this mixture are as follows: 1) A fluid that serves as the base and carrier, 2) Metal particles that are capable of being magnetized, and 3) Additives that help stabilize the mixture [5].

Still, the significant disparity in concentration between particles as well as the fluid used as carrier results in a notable sedimentation issue for MR fluid. The limited sedimentation durability of MR fluid impedes its widespread use, particularly in material refining and damper applications. To prevent the settling of particles, several surfactants have been used to alter the surface characteristics of the particles, hence creating steric repulsion between them [6–8].

Furthermore, other techniques such as the use of core-shell soft magnetic particles [9, 10], the incorporation of special magnetic nanoparticles like carbon nanotube [11], and plasma processing have recently been employed [12]. The techniques have significantly enhanced the sedimentation consistency of the MR fluid. However, the issue of sedimentation has not been fully resolved. In addition, the inclusion of the chemicals leads to the emergence of additional issues, such as an increase in the zero-field viscosity of MR fluid. Hence, there is a need for further enhancements in sedimentation stability as well as zero-field viscosity. This work aims to enhance the performance of MR fluid by incorporating various surfactants into soft magnetic particles, resulting in improved stability, and reduced zero-field viscosity. To achieve this objective, we measured the sedimentation stability or zero-field viscosity of MR fluid using various surfactants, including both single surfactants and compound surfactants. We also analyzed the impact of surfactant material on the characteristics of the MR fluid and conducted research to determine the optimal relationship between surfactant compounds [13–19].

3.1. Materials and integration

Black iron oxide consists of 98% or more Fe3O4. Iron oxides serve as a highlight agent in Magnetic Resonance Imaging (MRI) by reducing proton relaxation durations. The superparamagnetic contrast agents consist of a magnetically crystalline core that is insoluble in water, often made of magnetite (Fe3O4). The average core diameter varies between 4 and 10μ. The crystalline core is often enveloped by a coating of dextrin or starch derivatives. The overall dimension of the particle is represented by the average diameter of the hydrated particle. Silicone oil, known for its elevated flash point and superior viscosity-temperature characteristics, is used as the carrier fluid. Alternatively, Castor oil has also been employed for this purpose. The surfactants used include oleic acid, sodium dodecyl benzene sulfonate (SDBS), and commercially acquired grease.

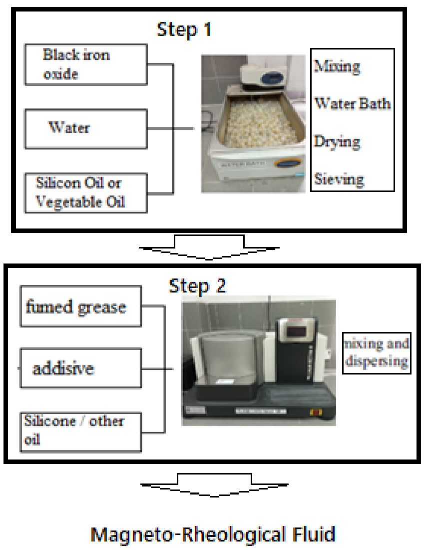

Fig. 2: Preparation of MRF.

The surfactant employed was a high-quality white grease. The grease was meticulously blended with a carrier oil for approximately 2 hours. Subsequently, black-iron particles were introduced into the mixture, which was then subjected to a water bath for an additional 2 hours. The resulting mixture was vigorously stirred for an additional hour using a planetary ball mixture machine at ambient temperature with 300 rpm speed. Therefore, we can get a uniform blend of MR fluid. Subsequently, it undergoes testing using the cup and bob style rheometer. The creation of magneto-rheological fluid is described in a separate article, and this process is almost similar [14, 15].

Tab. 1: Parameter of Black iron oxide.

Parameter	Black Iron
Molecular Weight	231.53
Appearance	Black powder
Bulk Density	1.1 g/mL
True Density	4.6 g/mL
Size Range	0.4-0.7 μ m
Average Particle Size	0.45-0.5 μm
Morphology	Spheroidal

The processed magnetorheological (MR) fluids are distributed evenly across four testing tubes, all test tube containing a volume of 10 cm^3 of MR fluid.

Tab. 2: Parameter of Commercial Grease.

Properties	Commercial grease
Appearance	An off-white grease, with a mild citrus odor
Specific Gravity	0.77 - 0.82
Active Content % m/m	30 - 40
Drop Temperature	$>$ 185^{o}C
Temperature Range	-20 to +140^{o}C

The test for sedimentation is conducted through visual observation. Therefore, it is advisable to do the test inside and ensure appropriate illumination to clearly observe the separation between the turbid and supernatant layers. Measurements are taken at regular time intervals to determine the distance between the clear fluid and the thick, cloudy MR fluid. Figure 2 depicts the configuration of the sedimentation test apparatus.

Tab. 3: Parameter of Carrier Oil.

Properties	Silicone Oil	Hybrid oil
Viscosity (Pa-s)	.37	0.048
Flash point	>295^{o}C	>270^{o}C
Fire point	>460^{o}C	>282^{o}C
Specific gravity	0.97	0.927
Density (g/cm^3)	1.07	0.914

An uncomplicated approach to assess the consistency of deposition in MR fluid involves monitoring the progression of particles. MR fluid specimens will be deposited in testing tubes for a duration of 14 days in this study.

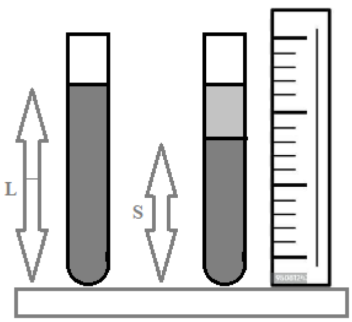

Fig. 3: Sedimentation test of MRF.

The sedimentation ratio is the ratio of the height of the carrier fluid-rich phase to the total height of the MR fluid. The zero-field viscosity of MR fluid is typically determined by the shear strain rate and can be measured using the NDJ-5S Viscosimeter (manufactured by Chongqing Drawell Instrument Co., Ltd). The measurement is conducted at a temperature of 25^{o}C and a shear velocity of 1.0 s^{-1}.

Prior to doing the zero-field viscosity measurement of the MR fluid, its flow capacity will be observed initially. Every measurement is replicated thrice, and the mean value is obtained. If the MR fluid has lost its ability to flow freely, it is not appropriate for use. Consequently, the viscosity of the fluid at zero magnetic field strength will not be measured using a viscosimeter. Prior to doing the zero-field viscosity measurement of the MR fluid, its flow capacity will be observed initially. If the MR fluid has lost its ability to flow freely, it is not appropriate for use. Consequently, the viscosity of the fluid at zero magnetic field strength will not be measured using a viscosimeter. As seen in figure 4, the samples are tested with time and the final state of the prepared fluid is found in the figure 4b. In

Tab. 4: Parameter of different types of samples.

Types	Diameter μm	Concentration Wt %	Carrier Oil	Additive Percentage
Sample 1	0.45-0.5	30	Silicon	0.05
Sample 2	0.45-0.5	30	Hybrid	0.05
Sample 3	0.45-0.5	40	Silicon	0.15
Sample 4	0.45-0.5	40	Hybrid	0.15

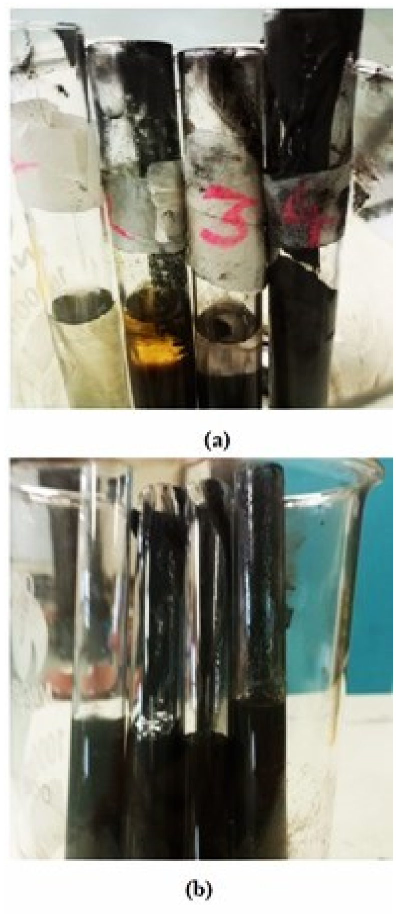

Fig. 4: Sedimentation test of MRF in Lab.

the figure 3, the MR fluid will clearly stratify after a lengthy placement period. The excess fluid makes up the top layer, and undifferentiated MRF makes up the bottom layer. The sedimentation rate R,

$$R = (S/L)^{*}100 \quad (8)$$

where L is the volume of suspension and L is the volume of MR fluid prior to implantation, is used to express sedimentation stability. Furthermore, viscosity is a crucial performance metric for MR fluid and should be monitored because it is influenced by different surfactants. The NDJ-5S viscometer measures the viscosity of MRF at 30 ± 1^{o}C.

4. Experimental results and discussion

To determine the properties of MR fluid and its long-term stability, samples are created by combining varying proportions of silicon oil and hybrid oil. All the samples have been retained for a duration of 3 days, and the sedimentation has been quantified by measuring the millimetre values from the test tube. The rate of sedimentation has also been quantified based on the available data. This research aims to determine the optimal choice for a stable mixture of MR fluid. In addition, various features have been measured to characterize MR fluids.

4.1. Case study with Silicon Oil

Initially, commercially acquired grease is combined with silicone oil. Next, the dispersion fluid is agitated using a rotary agitator at a speed of 300 revolutions per minute at room temperature. The MR fluid is prepared by dispersing black iron oxide particles in silicone oil. A total of eight types of magnetorheological (MR) fluids are created. The iron particle content is consistently maintained at 40% in all MR fluids. The additives they corresponded to varied in terms of their respective proportions. Table 1 displays the constituents of MR fluids. The sedimentation is quantified through visual examination of the displacement of the interface between the transparent and cloudy sections of the carrier oil. Figure 5 depicts the observation of sedimentation for particles with varying ratios of additives. An increased concentration of magnetic particles has a beneficial influence on the magnetorheological phenomenon. However, the impact of additions on the stability of the magnetorheological fluid has been examined by experimental investigation. The stability of the prepared sample has various values and undergoes temporal variations. The outcome was contingent upon the composition of the additive, iron particles, and the specific type of oil employed.

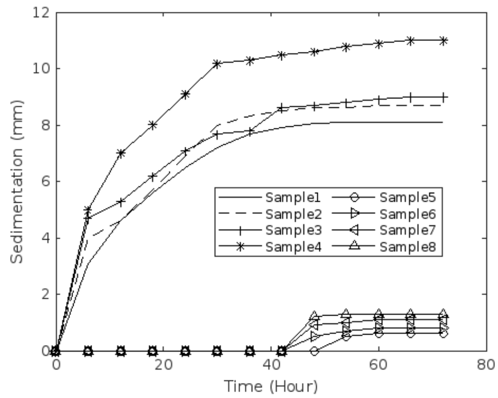

Fig. 5: Sedimentation test result for silicone oil carrier with time.

To enhance their stability, the percentage of additives has been modified employing MR fluid. MR fluid with reduced additive content is applied in the first four instances. In this scenario, the particles exhibit a faster settling rate in the fluid compared to the previous four scenarios, despite the presence of a higher concentration of additive. The graph displayed variance because of varying percentages of additives. Enhanced stability of the MR fluid can be achieved by augmenting the quantity of additives. Sample 8 had superior performance compared to the other samples.

4.2. Case study with Hybrid Oil

In this subsequent trial, MR fluids are formulated using varying proportions of hybrid oil as

Tab. 5: Mixture quantity of different types of samples with silicone oil.

Types	Black Iron	Oxide	Silicon Oil	Additive
	(μm)	(%)	(%)	(%)
Sample 1		23	75	2
Sample 2		28	70	2
Sample 3		33	65	2
Sample 4	0.45-0.5	38	60	2
Sample 5		21	75	4
Sample 6		26	70	4
Sample 7		31	65	4
Sample 8		36	60	4

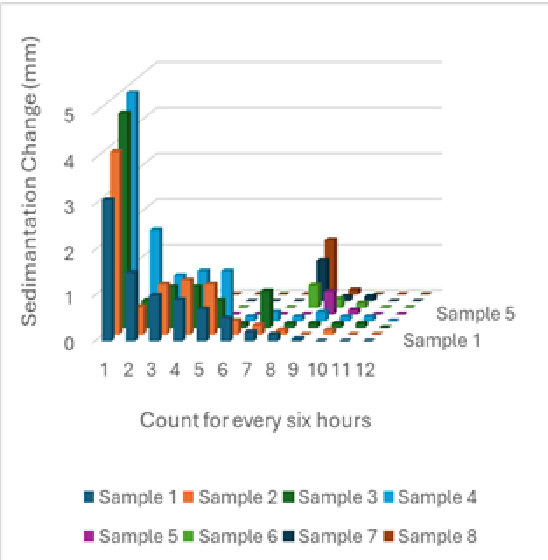

Fig. 6: Rate of change of sedimentation for silicone oil carrier with time.

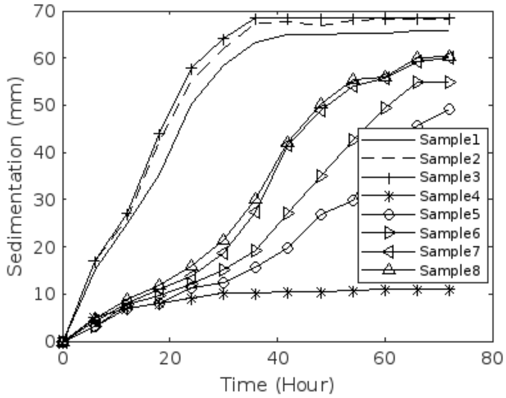

Fig. 7: Sedimentation test result for hybrid oil carrier with time.

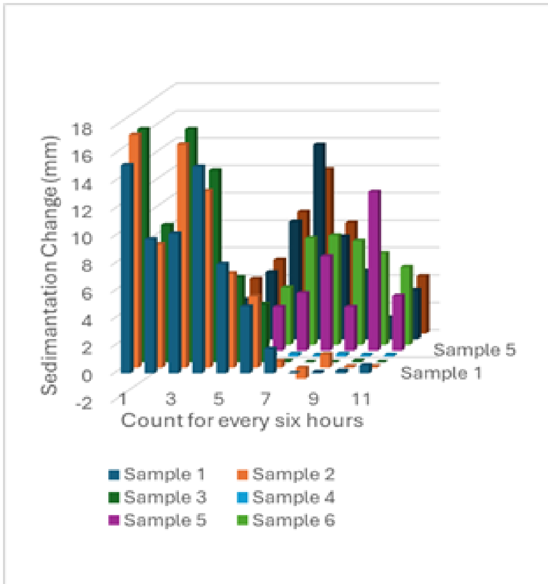

Fig. 8: Rate of change of sedimentation for hybrid oil carrier with time.

the carrier fluid. The research findings presented in figure 7 and Table 5 indicate that the composition of the hybrid oil and additive has been altered to achieve sedimentation stability using a surfactant. Hence, the examination will focus on the additive's content ranging from 2 to 4 percent and the ratio of carrier oil. Figure 7 illustrates the variation in the rate of sedimentation ratio of MR fluid when different amounts of individual surfactants are present.

As evidenced by the experimental figure, the sedimentation ratio consistently decreases as the surfactant content increases in all instances. When the amount of surfactant is reduced, there is no significant enhancement in the stability of sedimentation. This might be viewed as a partial coverage of the CIP surface by the surfactant. With an increased surfactant concentration, the sedimentation ratio drops because of the production of large, loosely bound floccules. These floccules have the potential to hinder the settling of particles.

Finally, it can be determined that with increment of additives and grease will improve the stability of MR fluid but as per previous research the MR fluid may lose the fluidity if the additive and iron particle get more than forty percent of total fluid [10, 11, 20, 21].

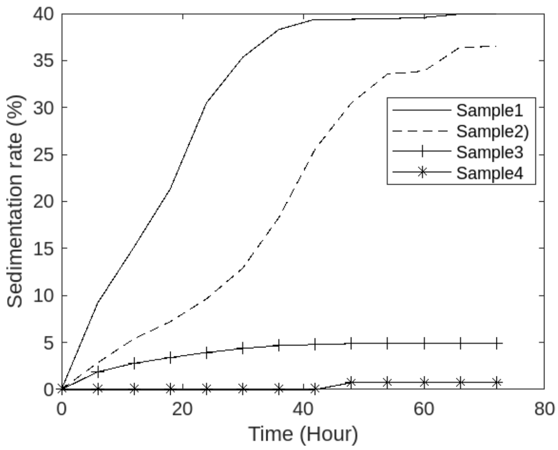

Fig. 9: Sedimentation test result Vs time.

4.3. Discussion and analysis

In this experiment, the content of MR VIF and sedimentation is expressed as percentage and for the different content of silicone oil and hybrid oil is expressed. Figure 7 displays the zero-field viscosities of the MR fluids with different compounding contents, and Figure 8 shows the sedimentation ratio of those fluids. Based on observations from Table 4 and Figure 4, the following phenomena are revealed:

- The zero-field viscosity is always lower, apart from situations in which the oil's percentage is kept at the maximum 40%. On the other hand, the funnelform viscosity testing instrument allows both components to flow freely. Moreover, viscosity exhibits a rising tendency when additive and iron particle concentrations rise.
- The zero-field viscosity is always lower, except for situations in which the oil's percentage is kept at the maximum 40%. On the other hand, the funnelform viscosity testing instrument allows both components to flow freely. Moreover, viscosity exhibits a rising tendency when additive and iron particle concentrations rise.
- Only for the hybrid oil does a drop in the additive amount, along with a change in the carrier oil, result in a decrease in the sedimentation ratio and settling time.

Moreover, the relative zero-field viscosity is between 2 and 0.3 Pa s, which is within the range needed by most magnetic resonance devices. The greatest yield stress of MR fluid measured with surfactant shows that at 0.43 T magnetic field, the yield stress may reach 55 kPa.

5. Conclusions

The impact of various surfactants on the carrier oil is assessed by evaluating the sedimentation ratio and zero-field viscosity of the MR fluid. The inclusion of a singular surfactant does not yield a high-performance magnetorheological (MR) fluid. The standard preparation technique involves the compounding of several surfactants. The research findings demonstrate that the MR fluid treated with a combination of silicone oil and black iron oxide compounding exhibits superior features, including enhanced sedimentation stability and improved zero-field viscosity. The optimal compounding concentration is determined to be 40 percent of additive black iron oxide. Simply put, the MR fluid exhibits optimal properties when the mass fraction of each surfactant is 4%. For final outcome it can be concluded for a longer period of time, the ideal MRF demonstrates better sedimentation stability and fluidity with black iron oxide and silica oil.

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Tab. 6: Zero field viscosity of different types of samples with hybrid oil.

Sl No	Black Iron Oxide	Carrier Oil	Addtive	Carrier Oil	Viscosity	Carrier Oil	Viscosity
	%	%	%		Pa S		Pa S
1	23	75	2		0.505		0.307
2	28	70	2		0.679		0.396
3	33	65	2		0.914		0.463
4	38	60	2	Silicon	1.31	Hybrid	0.506
5	21	75	4	oil	0.901	oil	0.417
6	26	70	4		1.407		0.681
7	31	65	4		1.819		0.719
8	36	60	4		1.924		1.103

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