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Synthesis and Analysis of MR Fluids for High Yield Stress

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Abstract—Magneto Rheological fluids consist of micron sized magnetizable particles dispersed in a carrier liquid. In the off-state, these MR fluids behave similar to Newtonian fluids, having an apparent viscosity in the range of 0.1 to 1 Pa-s. Under the application of external magnetic field the apparent viscosity of MR fluid changes significantly resulting in high yield stress. In the present research work, synthesis and on state rheological characterization of in house fabricated MR fluids is analyzed. The MR fluids samples are prepared using iron particles of 300- 500 mesh dispersed in a carried fluid like silicone oil or mineral oil along with suitable additive to inhibit sedimentation of the particles. The on state yield stress of the MR fluids is calculated with respect to applied magnetic field intensity using relative permeability approach. These values of yield stress are further analytically validated using Carlson approach. It has been concluded that yield stress of MR fluids increases from 26.9 to 50.1 kPa with the change in volume fraction of iron particles from 22 to 32%.Further, the yield stress becomes 1.05 times with a change in carrier fluid from silicon oil to mineral oil.

Keywords—Magneto-Rheological Fluids, Relative permeability, Yield stress, Carlson empirical relation

I. INTRODUCTION

Smart materials have the ability to change their (rheological) characteristics under the influence of external field. Magneto-rheological (MR) fluids falls under this category and are generally known as smart fluids. The MR fluids are the dispersions of micron size magnetizable particles in a non-magnetic carrier fluid. These MR fluids behave like a free flowing Newtonian fluid in the absence of magnetic field and have the consistency equivalent to motor oil. Under the application of magnetic field, the iron particles align themselves along the lines of magnetic flux which leads to the formation of strong chains. Due to such chaining action, there is a considerable increase in apparent viscosity and yield strength of a MR fluid. The on-state viscosity and yield strength of the MR fluid varies with the intensity of the applied magnetic field [1].

Main constituent of a MR fluid is iron or other magnetizable particle. High purity iron powder is widely used in the preparation of the MR fluids as it possesses high saturation magnetization. These iron particles are dispersed in a carrier fluid *e.g.* mineral oil, silicone oil and synthetic oil etc. The carrier fluid must be non-magnetic in nature and should not react with the particles. Silicone oil exhibits a good temperature stability and heat transfer characteristics [2] while mineral oil have high flash point and low vapor pressure. Being chemically inert, these can be used as an effective dispersion medium for the iron particles. Presence of a small amount of additives like tetra-methyl-ammonium-hydroxide and oleic acid helps to maintain the stability of the MR fluids by preventing/minimizing the settling down of particles in the carrier liquid. The tendency of settling down of particles can be reduced by increasing the percentage of additives in the MR fluid composition [3]. Fang [4] introduced the single walled carbon nano-tube in the carbonyl iron based MR fluids to reduce the sedimentation of particles. Zhao *et al.*[5] prepared MR fluids using the guar gum coated carbonyl iron particles. It was found that guar gum coating not only improves the sedimentation stability but also helps in increasing the yield strength of MR fluids.

Particle size, shape and its distribution have a great impact on the performance of MR fluids [6]. Larger the size of the particle more will be the yield strength of MR fluid [7]. Shah [8] reported that higher values of yield stress (nearly 15 times)can be obtained by using larger sized particles. Venkateswarlu and RajiniKanth [9] used different techniques like X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analysis (EDAX) to characterize the cobalt ferrite based MR fluids. Fernando [10] generated an empirical relation based on the Navier-Stokes equation for calculating the yield stress of a MR fluid as a function of applied magnetic field. Dang *et al.*[11] used a pressure-driven apparatus to measure the yield stress of a MR fluid as a function of the applied magnetic field, volume of carbonyl iron particles and the amount of surfactant present inside the fluid. Song Chen *et al.*[12]utilized the digital holographic microscopy technique and concept of volume fraction to study yield stress of MR fluids. Mangal and Kataria [13] prepared four different MR fluid samples using different weight percentage of iron particles, silicon oil and lithium grease. These samples were analyzed and tested for sedimentation characteristics under an off state condition. It was found that increase in the percentage of lithium grease provides better stability of the fluid. Mangal and Kumar [14] studied the rheological characteristics of MR Fluids and concluded that the apparent yield strength of these fluids can be changed significantly on the application of an external magnetic field. Further the yield strength of a MR fluid can be controlled with change in the magnitude of applied magnetic field. Mangal and Sharma [15] calculated the yield stress of commercially available Lord MRF-122EG fluid using different techniques. It was found that the yield stress of the Lord MRF-122EG fluid attains a maximum value of 34.86 Tesla at a magnetic field of 1.0 Tesla. Based on the literature review, it is evident that various researchers used different techniques to determine the yield stress of a MR fluid. In the present work, synthesis and on state rheological characterization of in-house developed MR fluids is carried out. The magnitude of on state yield stress of MR fluids with respect to magnetic field is calculated using the relative permeability approach. Further the values of yield stress are determined analytically using the Carlson equation [16].It has been found that yield stress of the MR fluids has increased significantly with an increase in volume fraction of iron particles. Further, the yield stress has also found to have increased by changing only in carrier fluid from silicon oil to mineral oil. These inferences can be used for by design engineer in the development of an effective MR damper.

II. SYNTHESIS OF MAGNETO RHEOLOGICAL FLUIDS

In the present work, synthesis and on state rheological characterization of in-house developed MR fluids is carried out to give higher yield stress. For this, six different MR fluid samples are prepared. The various components of the fluid are shown in Table 1.

TABLE 1. COMPONENTS USED FOR PREPARATION OF MRF SAMPLES

Material	Density (g/cm^3)
Iron powder(of 300/400/500mesh size)	7.86
Silicon oil /mineral oil	0.967/0.970
Oleic acid	0.890
Tetra-methyl-ammonium-hydroxide	0.866

The MR fluids are prepared by using silicon oil (66.5-76.9% by volume), iron powder (22-32% by volume), oleic acid (0.5-0.7% by volume) and Tetra-methyl-ammonium-hydroxide (0.6-0.8% by volume). The volume percentages of different components of the MR fluid samples, thus prepared, are shown in the Table 2.

TABLE 2.COMPOSITION OF MRF SAMPLES DEVELOPED

Sample no.	Carrier liquid (vol. %)	Iron particles (vol. %)	Oleic acid (vol. %)	Tetra Methyl Ammonium hydroxide (Vol. %)	Type of carrier liquid	Mesh Size of iron particles
1	76.9	22	0.5	0.6	Mineral oil	500 mesh
2	71.7	27	0.6	0.7	Mineral oil	400 mesh
3	66.5	32	0.7	0.8	Mineral oil	300 mesh
4	66.6	32	0.7	0.7	Silicone oil	500 mesh
5	76.7	22	0.5	0.8	Silicone oil	400 mesh
6	71.8	27	0.6	0.6	Silicone oil	300 mesh

The above MR fluids samples were prepared in-house by using the following procedure.
Firstly, the iron particles are mixed with the oleic acid using a stirrer at 400 rpm for 30 minutes.
The tetra-methyl-ammonium-hydroxide is poured next and again the mixture is stirred for 30 minutes at 400 rpm.

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Finally the carrier liquid *i.e.* silicon/mineral oil is poured gradually in the above mixture and it is stirred another one hour at 400 rpm.

III. DESIGN OF EXPERIMENTAL SET UP

The experimental set-up used to determine the yield stress of the above MR fluid samples is designed, developed and fabricated in-house and consists mainly the following four parts-

Electromagnets
DC regulated power supply
Perspex tube
Gauss meter

The developed electromagnet has 1800 turns of copper wire of 18 SWG and generates magnetic field up to 2.0 Tesla for an air gap of 18 mm. The electromagnet is made of soft iron poles with an input current capacity up to 6 A. The current is supplied to electromagnet through a DC regulated power supply. The perspex tube with external diameter of 18 mm is filled with the MR fluid. This tube is constricted between the poles of the electromagnet. The different values of magnetic field retained by the on-state activated MR fluid are measured using the gauss meter.

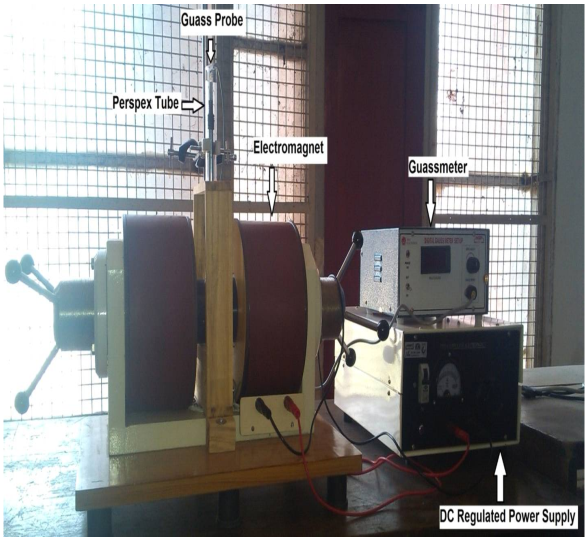

Fig. 1Design of Experimental set up

IV. TECHNIQUES USED FOR CALCULATION OF YIELD STRESS

For calculation of the yield stress of the synthesized MR samples, various techniques are employed. These are discussed in this section.

A. *Carlson Approach*

Carlson [16] has developed an empirical relationship to calculate the yield stress of the MR fluids. These relations correlate the yield stress & magnetic flux density with the volume fraction of the MR fluid and magnetic field intensity applied to the fluid. This approach is treated as analytical one. The relations are as follows:

$$\tau_y = \left(271.7 \times \phi^{1.5329} \times C\right) \tanh\left(6.33 \times 10^{-6} H_{mrf}\right) \quad (1)$$

$$B = 1.91\phi^{1.133}\left[1 - e^{(-10.97\mu_0 H_{mrf})}\right] + \mu_0 H_{mrf} \quad (2)$$

Equation (1) gives the induced yield strength (τ_y) as a function of the applied magnetic field intensity (H) and particle loading (ϕ), while the Eq. (2) gives the magnetic flux density (B).The magnetic field intensity (H) is varied to obtain the values of yield stress (τ_y) and magnetic field density (B). The constant C in Eq. (1) is a constant and depends on the type of carrier liquid used. The value of C is taken as 1 and 0.95 for mineral oil and silicon oil respectively. The values of particle loading for various samples are fixed as per

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Table 3. The different yield stress results obtained from Carlson equation are shown in Table 4.

TABLE 3. VALUES OF VARIOUS INPUT PARAMETERS FOR CARLSON EQUATION

Sample no.	Particle Loading (Φ)	Type of carrier liquid	Constant C
1	22	Mineral oil	1
2	27	Mineral oil	1
3	32	Mineral oil	1
4	32	Silicone oil	0.95
5	22	Silicone oil	0.95
6	27	Silicone oil	0.95

TABLE 4. VALUES OF YIELD STRESS OBTAINED USING CARLSON TECHNIQUE

Magnetic field intensity(H)	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6	
	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y
0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
25	0.13	4.2	0.16	5.8	0.18	7.5	0.18	7.1	0.13	4.0	0.16	5.5
50	0.23	8.3	0.28	11.3	0.32	14.7	0.32	13.9	0.23	7.9	0.28	10.8
75	0.32	12.0	0.37	16.3	0.43	21.2	0.43	20.1	0.32	11.4	0.37	15.5
100	0.38	15.1	0.45	20.7	0.52	26.8	0.52	25.5	0.38	14.4	0.45	19.7
125	0.44	17.8	0.51	24.4	0.59	31.5	0.59	30.0	0.44	16.9	0.51	23.1
150	0.49	20.0	0.57	27.3	0.65	35.4	0.65	33.6	0.49	19.0	0.57	26.0
175	0.53	21.7	0.61	29.7	0.70	38.4	0.70	36.5	0.53	20.6	0.61	28.2
200	0.57	23.1	0.66	31.5	0.74	40.8	0.74	38.8	0.57	21.9	0.66	29.9
225	0.61	24.1	0.70	32.9	0.78	42.6	0.78	40.5	0.61	22.9	0.70	31.3
250	0.65	24.8	0.73	34.0	0.82	44.0	0.82	41.8	0.65	23.6	0.73	32.3
275	0.68	25.4	0.77	34.7	0.86	45.0	0.86	42.8	0.68	24.2	0.77	33.0
300	0.71	25.9	0.80	35.3	0.89	45.8	0.89	43.5	0.71	24.6	0.80	33.6
325	0.75	26.2	0.84	35.8	0.93	46.3	0.93	44.0	0.75	24.9	0.84	34.0
350	0.78	26.4	0.87	36.1	0.96	46.7	0.96	44.4	0.78	25.1	0.87	34.3
375	0.81	26.6	0.90	36.3	0.99	47.0	0.99	44.7	0.81	25.2	0.90	34.5
400	0.84	26.7	0.93	36.5	1.03	47.3	1.03	44.9	0.84	25.4	0.93	34.7
425	0.88	26.8	0.97	36.6	1.06	47.4	1.06	45.1	0.88	25.5	0.97	34.8
450	0.91	26.9	1.00	36.7	1.09	47.5	1.09	45.2	0.91	25.5	1.00	34.9
475	0.94	26.9	1.03	36.8	1.12	47.6	1.12	45.2	0.94	25.6	1.03	34.9
500	0.97	26.9	1.06	36.8	1.15	47.7	1.15	45.3	0.97	25.6	1.06	35.0
525	1.00	27.0	1.09	36.8	1.18	47.7	1.18	45.4	1.00	25.6	1.09	35.0
550	1.03	27.0	1.12	36.9	1.22	47.8	1.22	45.4	1.03	25.6	1.12	35.0
575	1.07	27.0	1.16	36.9	1.25	47.8	1.25	45.4	1.07	25.7	1.16	35.0
600	1.10	27.0	1.19	36.9	1.28	47.8	1.28	45.4	1.10	25.7	1.19	35.1
625	1.13	27.0	1.22	36.9	1.31	47.8	1.31	45.4	1.13	25.7	1.22	35.1
650	1.16	27.0	1.25	36.9	1.34	47.8	1.34	45.4	1.16	25.7	1.25	35.1
675	1.19	27.0	1.28	36.9	1.37	47.8	1.37	45.5	1.19	25.7	1.28	35.1
700	1.22	27.0	1.31	36.9	1.40	47.8	1.40	45.5	1.22	25.7	1.31	35.1

B. Relative Permeability Approach As Experimental Technique To Calculate Yield Stress

Permeability may be defined as the measure of the ability of a material to support the formation of a magnetic field within itself. So,

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passage of magnetic field depends on the composition of fluids through which it is being passed. The relative permeability is designated as μ_r and is mathematically expressed as

$$\mu_r = \frac{B_{on}}{B_{air\ gap}} \tag{3}$$

Equations (1) yields

$$\phi = \left[\frac{\tau_y}{C \times 271.7 \times \tanh(6.33 \times 10^{-6} H)}\right]^{\frac{1}{1.5239}} \tag{4}$$

While Eq. (2) yields

$$\phi = \left[\frac{B_{on} - u_0 H}{1.91 \times \left(1 - e^{-10.97\, u_0 H}\right)}\right]^{\frac{1}{1.133}} \tag{5}$$

Comparison of Eqs. 4 and 5 gives

$$\left[\frac{\tau_y}{C \times 271.7 \times \tanh(6.33 \times 10^{-6} H)}\right]^{\frac{1}{1.5239}} = \left[\frac{B_{on} - u_0 H}{1.91 \times \left(1 - e^{-10.97 u_0 H}\right)}\right]^{\frac{1}{1.133}}$$

$$\left[\frac{\tau_y}{C \times 271.7 \times \tanh(6.33 \times 10^{-6} H)}\right] = \left[\frac{B_{on} - u_0 H}{1.91 \times \left(1 - e^{-10.97\, u_0 H}\right)}\right]^{\frac{1.5239}{1.133}}$$

$$\tau_y = 271.7 \times C \tanh(6.33 \times 10^{-6} H) \left[\frac{B_{on} - u_0 H}{1.91 \times \left(1 - e^{-10.97\, u_0 H}\right)}\right]^{1.345} \tag{6}$$

The magnetic flux density of the air gap can be given as
$B_{air\ gap} = \mu_0 H$

While magnetic flux density for on state MR fluid can be give as

$$B_{active\ MR\ fluid} = B_{on} = \mu_0 \mu_r H \tag{7}$$

Where, μ_0 is permeability of air and is equal to $4\pi\times10{-}7$ Henry/m. The μ_r is the relative permeability of the MR fluid. Using above in Eq. (6) gives

$$\tau_y = 271.7 \times C \tanh\left(6.33 \times 10^{-6} \frac{B_{on}}{12.56 \times \mu_r}\right) \left[\frac{B_{on}\left(1 - \frac{1}{\mu_r}\right)}{1.91\left(1 - e^{\frac{-10.97 B_{on}}{\mu_r}}\right)}\right]^{1.34501324} KPa \tag{8}$$

Equation (8) is used to find out the yield stress of MR fluids. This approach is treated as experimental one. To obtain the yield stress, two input parameter are required i.e. magnetic field intensity under on-state condition and relative permeability of the MR fluid (μ_r).In this experimental approach, the experiment is conducted in two stages. In the first stage, the empty cylindrical tube of 18 mm diameter is placed vertically and constricted between the poles of an electromagnet. The D.C. current is supplied to electromagnet ranging from 0.2 A to 5.6 A using D.C. regulated power supply. This current induces a magnetic field between the poles of the electromagnet. For a value of current fed to electromagnet, a generated magnetic field is measured by placing the gauss probe vertically inside the cylindrical pipe. This measured magnetic field is termed as $B_{air\ gap}$. Further, this cylindrical tube is now filled with the prepared MR fluid sample and is placed vertically between the poles of an electromagnet for calculating the on-state magnetic field values. This on-state magnetic field is termed as B_{on} and is measured again by placing the gauss probe vertically inside the activated fluid. The yield stress then can be calculated using the Eqs. (3) and (9). The values of the B_{on} and yield stress (τ_y)

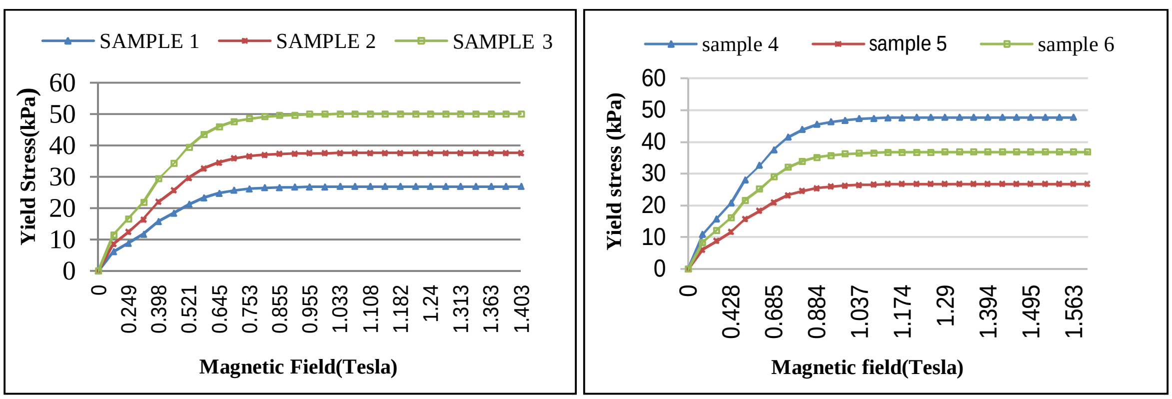
are tabulated in Table 5.

TABLE 5.EXPERIMENTAL RESULTS OF B_{ON} & τ_y BY VARYING THE CURRENT

Current	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6	
	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y	B_{on} state	τ_y
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.00
0.4	0.24	6.21	0.22	12.4	0.35	16.6	0.34	15.8	0.068	8.9	0.297	12.28
0.8	0.39	8.94	0.40	22.1	0.55	29.4	0.53	28.12	0.134	15.8	0.467	21.68
1.2	0.52	15.8	0.54	29.7	0.70	39.4	0.68	7.65	0.212	21.1	0.602	29.05
1.6	0.64	21.2	0.62	34.6	0.83	46.1	0.82	41.55	0.312	24.7	0.732	33.99
2	0.75	24.8	0.66	36.6	0.95	48.6	0.93	46.44	0.413	26.0	0.842	35.86
2.4	0.85	26.2	0.67	37.3	1.05	49.6	1.03	47.52	0.513	26.6	0.945	36.56
2.8	0.95	26.7	0.68	37.6	1.15	50.0	1.13	47.7	0.612	26.8	1.045	36.82
3.2	1.03	26.9	0.68	37.6	1.23	50.1	1.21	47.77	0.69	26.8	1.123	36.87
3.6	1.10	26.9	0.68	37.7	1.30	50.1	1.29	47.80	0.765	26.9	1.198	36.89
4.0	1.18	26.9	0.68	37.7	1.38	50.1	1.36	47.81	0.839	26.9	1.272	36.91
4.4	1.24	26.9	0.68	37.7	1.44	50.1	1.42	47.82	0.897	26.9	1.33	36.91
4.8	1.31	26.9	0.68	37.7	1.51	50.1	1.49	47.82	0.97	26.9	1.403	36.91
5.2	1.36	26.9	0.68	37.7	1.56	50.1	1.54	47.82	1.02	26.9	1.453	36.91
5.6	1.40	26.9	0.68	37.7	1.60	50.1	1.58	47.82	1.06	26.9	1.493	36.91

V. RESULTS & DISCUSSIONS

The variation of yield stress for MR fluid under the applied magnetic field using relative permeability approach is shown in Fig. 2. It can be seen from these graph that the yield stress of MR fluids increases from 26.9 to 50.1 kPa for mineral oil based MR fluid while the same parameter has increased from 28.9 to 47.8 kPa for silicon oil based MR fluid when volume fraction of the iron particles has increased from 22 to 32%.



(a) (b)

Fig. 2.Variation of yield stress with magnetic field (a) for samples 1-3 (mineral oil) (b) for samples 4-6(silicon oil) by relative permeability approach

The samples 3 and 4 have same volume fraction of iron particles of 32% but the sample 3 gives the higher values of yield stress 50.1 kPa as compared to 47.8 kPa for sample 4 (Table 5) or magnitude of yield stress of sample 3 is 1.05 times than that of sample 4. Thus, it can be concluded that the yield stress becomes 1.05 times on changing the carrier fluid from silicon oil to mineral oil. Further, Figures 3(a) to (f) shows the graphical comparison of the results obtained by using the two approaches adopted in this work *i.e.* experimental approach and Carlson approach. From this graph, it can be observed that results obtained from the two techniques are matching quite well with each other with a percentage error of less than 5%.

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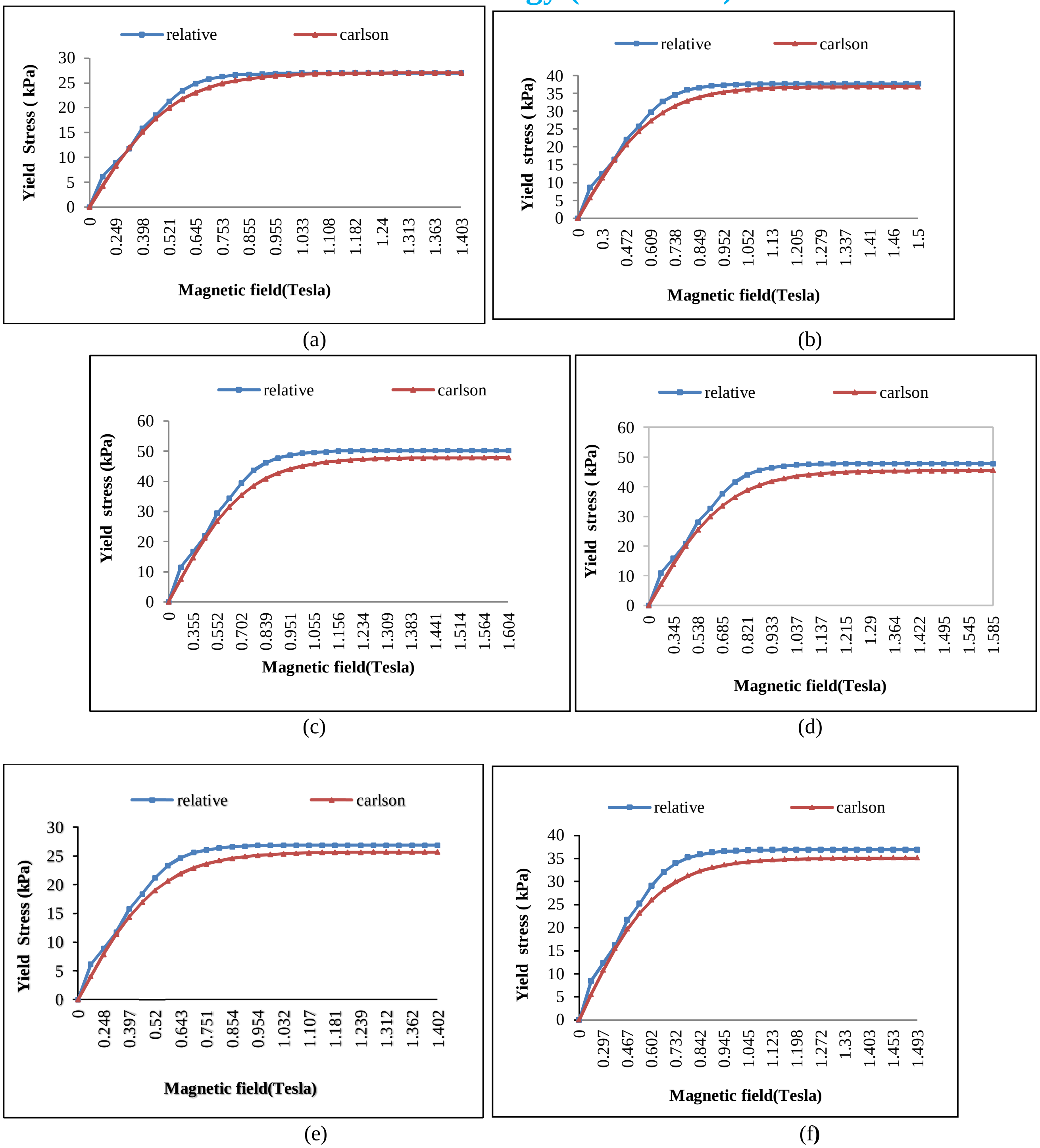

Fig 3: Comparison of Yield stress v/s Magnetic field obtained using two approaches for (a) Sample-1, (b) Sample-2 (c) Sample-3, (d) Sample-4, (e) Sample-5 and (f) Sample-6

VI. CONCLUSIONS

Magneto Rheological fluids consist of micron sized magnetizable particles dispersed in a carrier liquid. In the off-state, these MR fluids behave similar to Newtonian fluids, having an apparent viscosity in the range of 0.1 to 1 Pa-s. The MR fluid has wide industrial application e.g. semi-active vibration control strategies, braking system etc. In the present work, the yield stress of the MR fluid and their variation with externally applied magnetic field is evaluated. Six MR fluid samples are synthesized in which three have the mineral oil as carrier liquid while other three have silicone oil as carrier liquid. Experimentally, relative permeability approach is used to calculate the yield stress and relationship of yield stress with applied magnetic field using in-house developed experimental setup. Further, these values are also evaluated analytically using Carlson empirical equations. It has been observed that the results obtained by the two approaches are matching quite well with the maximum percentage error of less than 5%. Thus, it has validated the experimental set-up and the approach used in this work. It can be seen that yield stress of MR fluids increases with an increase in particle loading of the iron particles. The yield stress becomes 1.05 times its value for the MR fluids having mineral oil as carrier fluid in comparison to silicon oil for fluid formulation. It is recommended to use mineral oil rather than silicon oil in order to obtain high yield stress values. The above inferences can be used for by design engineer in the development of an effective MR fluid related device.

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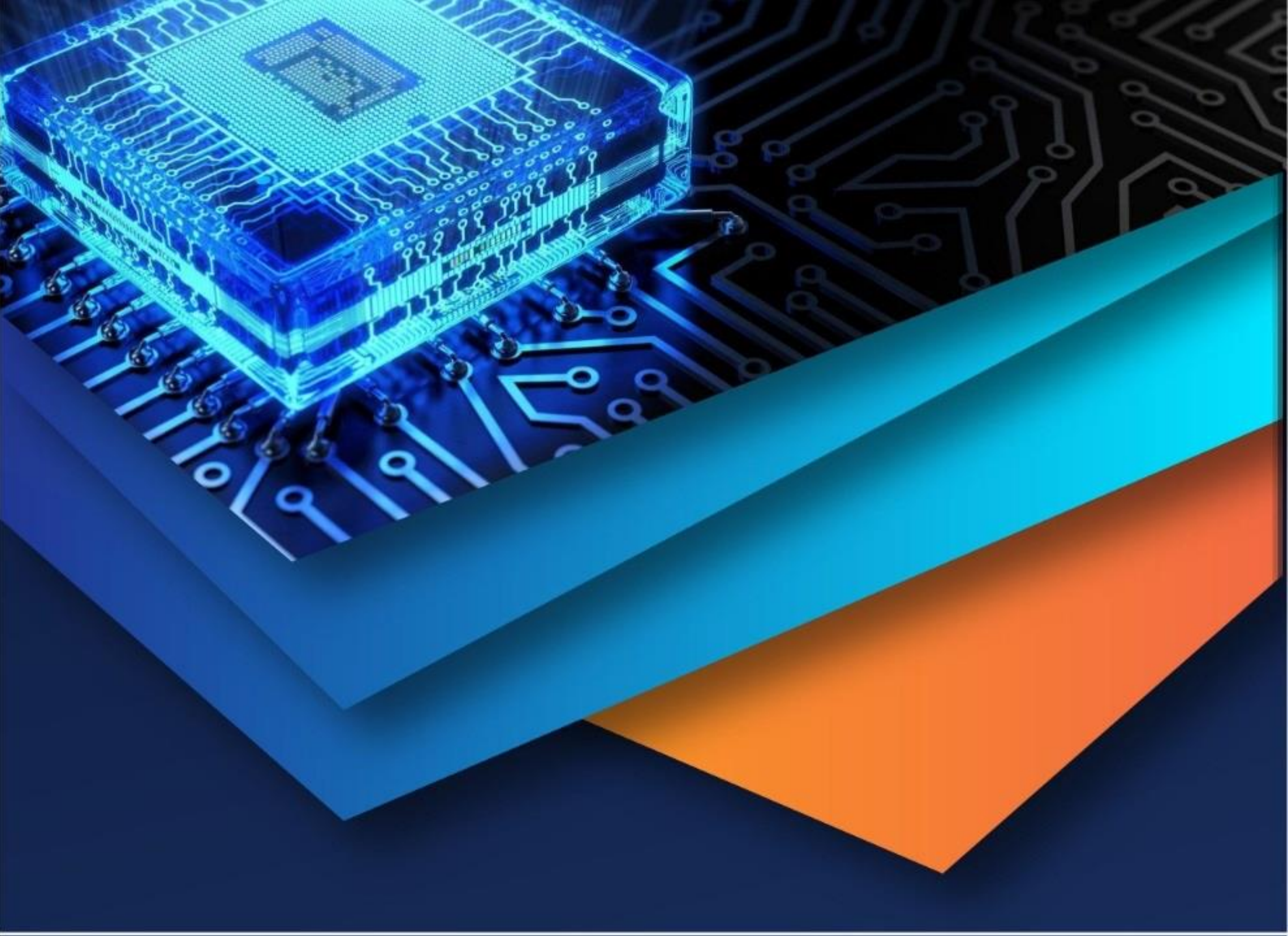

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