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PERFORMANCE CHARACTERIZATION AND SELECTION OF ELECTRORHEOLOGICAL FLUID FOR DAMPER, USEFUL FOR RECOIL MINIMIZATION IN HEAVY-DUTY APPLICATIONS

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ABSTRACT

A detailed process of synthesis, characterization and selection of Electro Rheological (ER) fluid specifically for damper of recoil system of an artillery gun has been performed. Significant research efforts have been devoted and incorporated to develop suitable smart fluid damping system for heavy duty applications. In view of controlled damping system, the ER fluid is required to exhibit necessary characteristics like high viscosity; high yield strength, low sedimentation rate etc. are listed in the beginning. In this work, nine samples are synthesized by varying concentration and physical structure of ER fluid ingredients. The main ingredients preferred are barium titanyl oxalate powder particles with and without Urea or Acrylamide coating as polarizable particles, silicon oil as carrier fluid along with oleic acid as additives. The bare barium titanyl oxalate (BTO) powder particles are directly procured from market hence its average particle size and urea or acrylamide coating size is determined by using scanning electron microscopy (SEM). The XRD and BUTR characterization is performed to check presence of respective ingredient in synthesized material. The prepared ER samples are characterized for rheological and electric properties. The selected ER fluid sample has reported yield stress of 20 kPa at 3 kV/mm with very low sedimentation rate as per the requirement proposed in damping system application of recoil mechanism of artillery gun

Keywords: Acryamide coated, Barium titanyl oxalate, Electrorheological fluid, Urea coated, Yield stress.

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1. INTRODUCTION

Modern artillery guns are powerful long-range guns and lighter weight as compared conventional artillery guns. These types of guns transported without difficulty as compared to tanks. The most vital point of alarm with these guns is its recoil mechanism. Smart fluids like Electro-rheological (ER) and Magneto-rheological (MR) whose properties (for example the viscosity) can be altered by applying an electric field and a magnetic field respectively and can be used as a fluid in damper for the recoil system. The use of smart fluids in the damper of an Artillery gun recoil system can reduce the recoil stroke length and recoil time as compared to the conventional dampers. This can reduce the size and cycle time of the system which provides performance improvement to the artillery guns. Quicker response and higher yield strength of ER fluids make them ideal choice over MR fluids for the gun recoil application. Recent year's substantial researches in MR fluid have been conducted. Weijia wen et al. [1] studied effects of viscosity and longer chain of base fluid on yield strength and sedimentation of resulting BUTR based ER fluid. Lei Shi et al. [2] proposed that urea coating over powder particles leads to improve polarizability, which in turn increases the yield strength of resulting ER fluid significantly. Zhang Xu-ping et al. [3] stated that not only long chain-like molecular structures and surface (interface) activity but also the concentration of dissolving particles and the effect of temperature on mechanical properties are equally important to increase ER effect. Tom a. s. Belza et al. [4] studied dynamic properties of urea coated silica nanoparticles based ER fluid with and without electric field. Urea coating over silica particles is assured by thermogravimetric technique. M. A. Ning et al. [5] observed that the performance of hydroxyl oil based ER fluids is far better than hydrogen oil based and the methyl oil based ER fluid at same viscosity as it reduces the aggregation of the particles because of strong links among particles and weak steric hindrance effect. XU Ling-li et al. [6] synthesized titania coated montmorillonite powder based ER fluid. samples by varying concentration in methyl-silicon oil. The maximum yield stress recorded is 4.28 kPa, which is larger than that of bare montmorillonite powder based ER fluid. Bera and Sarkar [7] synthesized Barium titanate powder by a semi-oxlate method that uses barium oxalate and TiO2 precursors, instead of titanyl oxalate. Kunquanlu et al. [8] concluded that the pre-treatment of electrodes and the contrivance of new measuring procedures are desirable for the characterization of material. Tan et al. [9] presented the result of finite element analysis that the two adjacent Polar Molecule Dominated Electro-Rheological (PMER) particles have orientational polarization at the outer shells. Wen et al. [10] have presented synthesis and characterization of giant ER fluid, whose static yield stress is 130 KPa at 5 kV/mm. Li et al. [11] have reported improved properties like maximum yield stress of 195 kPa and very low sedimentation rate for multiwall carbon nanotubes based ER fluid compared to bare BTO based ER fluid. Cheng et al. [12] have synthesized acetamide modified TiO_2 nanoparticles based ER fluid that exhibit large shear stress of 47 KPa at 5 kV/mm. The sol-gel method assured the uniform size of 30 nm of TiO_2 nanoparticles with acetamide coating by different self-assembled processes. KE Zhang et al. [13] have proposed a generalized yield stress equation to show direct relation between yield strength and electrical field. Tian Hao et al. [14] have presented review study on changes in rheological behavior of different ER fluid under the application of electric field.

In this work, based on the literature gap and present practices different attempts are made to improve the performance of ER fluid by using nano-size polarizable powder particles coated with polarizing agents like urea or acrylamide, low viscous base fluid and surfactants. The best suitable ER fluid sample is selected to use in recoil system of a gun subjected to impact force of 460 kN upon firing. The main objective of the work is to minimize gun firing recoil distance and to maximize firing rate of weapon at different possible firing angles ranging from 0^0 to 80^0. For such heavy duty application it is necessary to use ER fluid with desirable properties to achieve optimum damping in order to meet the objectives.

The paper is organized as follows. Sec. 1 presents the introduction. Selection of ER fluid compositions as per required properties for the proposed heavy duty application is discussed in Sec. 2. In Sec. 3 synthesis of different ER samples in systematic manner is presented. Performance testing of prepared samples is presented in Sec. 4. Thereafter, an analysis of the characteristics is conducted. Finally, discussion and conclusions are provided.

2. ELECTRO RHEOLOGICAL FLUID

The proposed damper of 155 mm howtizer artillery gun recoil system incorporates with ER fluid as a working fluid. Upon application of external field, the characteristic changes in fluid are viscosity, yield strength and chemical structure of the fluid, which produce the ER effect and hence required damping, could be achieved. The ER fluid is comprises of carrier fluid, polarizable particles and additives. The careful selection of these materials to achieve high ER effect for resulting ER fluid is necessary. The yield strength is the main rheological characteristic which plays vital role in selection of ER fluid for proposed application is calculated as,

$$F_{ER} = \frac{(2L_o\tau_y A_p)}{h} \quad (1)$$

Where, L_0 = Length of ER channel, τ_y= Yield strength of ER fluid, A_p = Area of piston, h = Gap size of ER channel (0.7 mm). As per the dynamics of recoil system, the required ER damping force is 92 kN to recoil back barrel mass of gun system within permitted length of 150 mm. In Eq. (1), using the values of L_0, $F_{ER,}$ A_p and h, the yield stress is calculated as 14 kPa.

To achieve such high yield strength it is necessary to apply high voltage as yield strength is linearly proportional to electric field and keep polarizable particle size to micro or nanoscale as yield strength is inversely changing with particle size.

2.1. Selection of ER fluid compositions

The ER effect of ER fluids mainly depends upon important parameters like the liquid medium used, significance of water, change in temperature, particle volume fraction and particle dielectric property etc. The important guidelines required to follow for selection of appropriate compositions to achieve high yield strength are as given below.

2.1.1. The liquid medium

The liquid medium is a non-conducting liquid should have low viscosity at zero field. The ideal liquid medium should exhibit properties like high density that should not match with density of solid material, withstand a high electric field, high boiling point & low solidifying point, high chemical stability and hydrophobicity. It is a major constituent of ER fluid (50 to 60 %). Many liquid medium are available like silicon oil, mineral oil, vegetable oil, paraffin, kerosene, chlorinated hydrocarbon, transformer oil to synthesize ER fluid. Based on the required properties silicon oil is the most prominent carrier fluid to use in ER fluid as it has

very low viscosity of 0.1 mPas and disposal of it is not major concern as in case of transformer oil.

2.1.2. Solid Particulate

The yield stress and the apparent viscosity of an ER suspension are largely dependent on the particle volume fraction and particle size. Generally, the particle concentration varies from 5 % to 50 % to achieve required ER effect. In ER fluid upon application of electric field, the induced polarization forms chain like structure is termed as ER effect. The thin dielectric layer coated conducting particles helps to enhance ER effect significantly. For proposed application to achieve minimum yield strength of 14 kPa, urea/acrylamide coated barium titanyl oxalate (BTO) powder particles are selected of average size as calculated using Eq. (2),

$$\tau_y \sim \frac{F_{m-e}}{3} \qquad \text{Where, } F_{m-e} = \frac{3\emptyset}{2\pi r^2} N f_{m-e} \qquad \text{Where, } f_{m-e} = \frac{e\mu}{2\pi\varepsilon_o\varepsilon_f d_{m-e}} \qquad (2)$$

The other terms are, $\emptyset$ = volume fraction of particles in suspension (30 %), μ = Dipole moment of polar molecule, ε_0= Dielectric constant of vacuum, ε_f = Dielectric constant of fluid, e = Fundamental unit charge of particle, d_{m-e} = Diameter of dipole, r = Radius of particle. Putting all known values in Eq. (2), the particle size calculated is 40 nm for minimum yield stress of 14 kPa. The required thickness of urea coating [15] is given as,

$$U_{ad} = \frac{\mu^2}{4\pi\varepsilon_o d^3} \qquad (3)$$

Where, μ = Dipole moment of urea, ε_0= Dielectric constant of vacuum, d = Size of the molar molecule. The thickness of the coating has been approximated as $\frac{r}{20}$. Hence coating thickness is 1 nm.

2.1.3. Additives and Surfactants

The additives are used to promote uniform solution of ER fluid. It is generally used to improve flow properties of base fluid. Surfactants are added to ER fluid to accelerate ER effect. The particle strength can be increased by suitable surfactant to support ER effect. The surfactant may directly added to base fluid or coated over particles by using chemical doping or gas dispersoid method. Later technique is most general. Many additives serves the purpose of surfactant too. The oleic acid is of this category selected for proposed application.

3. SYNTHESIS OF ER FLUIDS

For the development of different ER fluid samples, the BTO powder particles with different concentrations are added to silicon oil and oleic acid mixture. The blend is obtained by sonication method. The silicon oil with dynamic viscosity 342 mPas and density 0.973 is procured from market. The BTO particles with nanoscale size are selected to add as polarizable particles in silicon oil. In first attempt, it is decided to prepare BTO particles with required nano-size and purity. However, due to time-consuming preparation process it is further decided to procure it from direct market with required size. Out of several preparation methods, Direct Synthesis from Solution (DSS) method [16] is selected for the preparation of ER particulate as it gives particles size within the calculated limit. The barium titanate powder particles are prepared as shown in fig. 1 (a) and further urea coating over bare particles is done as elaborated in fig.1 (b),

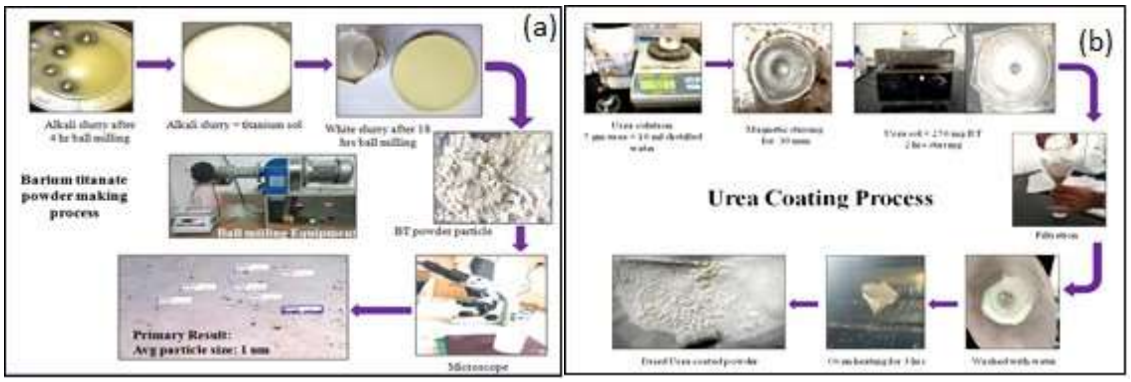

Figure 1 (a) Preparation process of bare barium titanate powder particles (b) Process of urea coating over bare barium titanate powder particles

The size obtained for bare particles is less than 1 μm and with urea coating it is about 1 μm. The particle size is to the micro level and quantity could be able to produce by DSS method is only few grams (less than 5 gms per day) and required quantity for proposed application is high around 600 gms, hence, it is decided to procure powder of BTO with average particle size of less than 100 ηm from market. The 1 kg of powder with average particle size of 100 ηm is purchased from Nanoshell, NewDelhi.

3.1. Urea/Acrylamide coating over bare BTO powder particles

To increase the polarazibility of BTO particles, the coating of urea/ acrylamide is carried out. To develop 10 gms of urea coated BTO particles, first mix 10 gms of bare BTO particles to 500 ml distilled water and stir it with teflon coated magnetic stirrer for two hours. After two hours, the aqueous solution of urea (10 % wt.) is added slowly by using dropper to the resulting mixture and it is stirred for 16 Hours. After allowing the solution to settle for 2 hours, it is filtered using Wattman filter paper as shown in fig 2 (a). Then, the filtered powder is dried in an oven for 6 hours at 150^{o}C, it is removed from the filter paper using a spatula and collects it in a petre dish. The resulting powder is grinded in a mortor pistol until a fine powder is obtained and checked it for agglomeration of particles if present, and then broke them by grinding again with Mortor pistol as shown in Fig. 2 (b). Thus fine particles of urea coated BTO are prepared, similarly acrylamide coated BTO particles have been prepared.

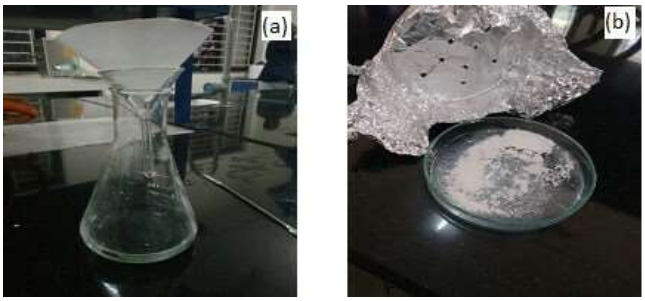

Figure 2 Instrumentation for powder preparation method (a) Filtration, (b) Mortar Pistol

3.2. Characterization of prepared BTO powder particles

Thus synthesized urea-coated or acrylamide coated BTO powder particles have been tested to know average size by using scanning electron microscope, confirm presence of functional group by using Fourier Transform Infra-red Spectroscopy (FT-IR) technique and check thermal stability using thermo-gravimetric analyzer (TGA). The results of all tests are presented as below,

3.2.1. Scanning Electron Microscopy (SEM)

The SEM images of BTO powder particles are as shown in fig. 3 (a), (b) & (c). It is observed that bare BTO powder particle size ranges from 124 nm to 161 nm with an average size of 142.5 nm, while the urea coated nanoparticles size ranges from 160 nm to 179 nm, the average particle size of 184.75 nm and coating thickness of around 40 nm. The acrylamide-coated sample is in the size range of 162 nm to 196 nm, with an average particle size of 185.4 nm and coating thickness of around 42 nm.

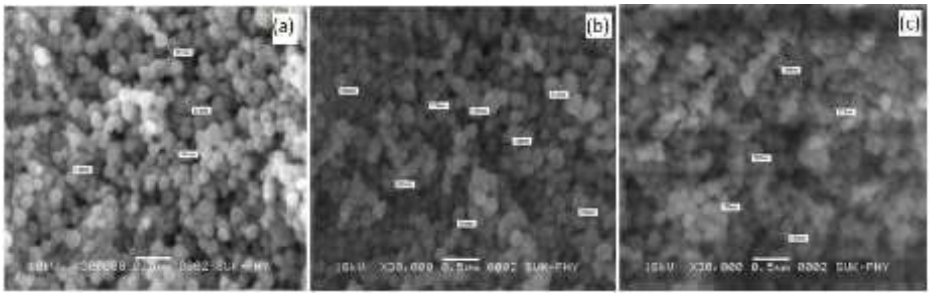

Figure 3 SEM Images of the (a) Bare BTO nanoparticles (b) Urea-coated BTO nanoparticles (c) Acryamide-coated BTO nanoparticles.

3.2.2. Fourier Transform Infra-red Spectroscopy (FT-IR)

The FT-IR test results obtained for wave-number cm^{-1} presented in fig. 4 (a), (b) and (c) are compared with standard range of wave number considered from literature as shown in table 3 to assure presence of respective functional group.

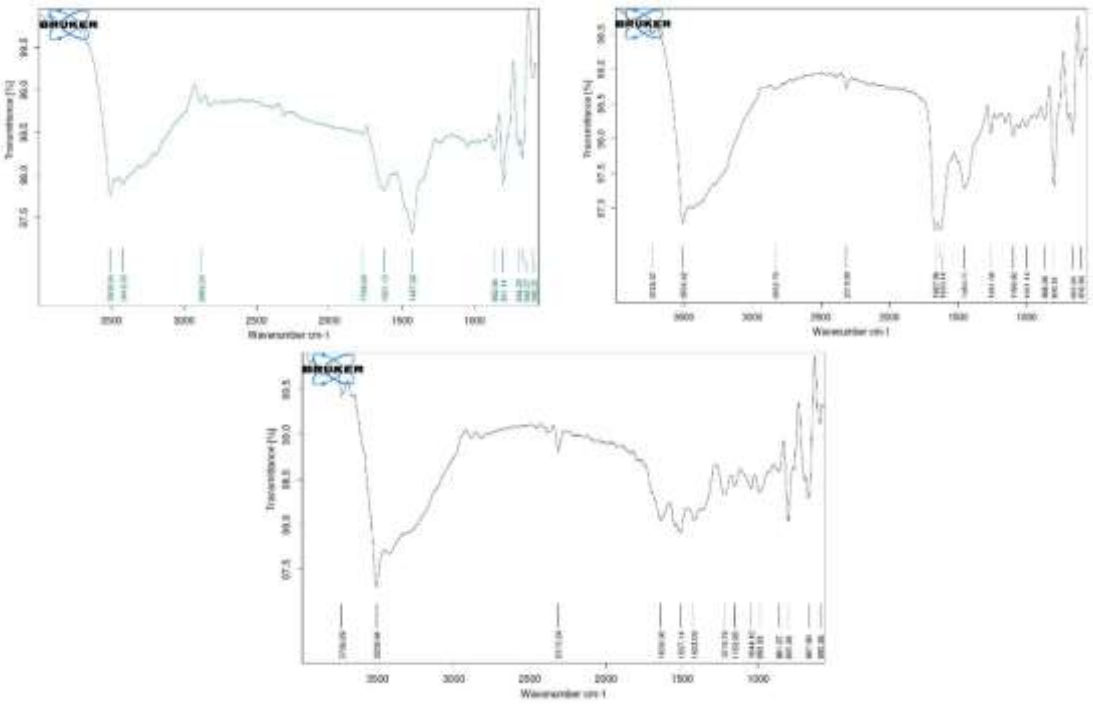

Figure 4 (a) FT-IR of bare BTO powder (b) FT-IR of Urea coated BTO powder (c) FT-IR of Acryamide coated BTO powder

Table 3 Comparison of wave numbers to check the presence of a functional group

Wavenumber Range/peak(cm^{-1})	Wavenumber by Test(cm^{-1})	Functional Group	Remark
For bare BTO particles			
1658	1667	C=O of BaTiO3	$BaTiO_3$ material
3436	3508.54	Water in $BaTiO_3$	$BaTiO_3$ material
1418 and 1273	1454.11 and 1261.08	C-O in $BaTiO_3$	$BaTiO_3$ material
Urea-coated BTO powder			
1623 and 3412(peaks)	1630 and 3506(peaks)	N-H of urea	Urea coating present on BTO Powder
Acrylamide-coated BTO powder			
1675	1639.6	C=O of acrylamide	Acrylamide coating present on BTO Powder
3353	3508.94	Solid NH_2	Acrylamide coating present on BTO Powder

As presented in table 3, the wave-numbers obtained by tests are closely matching with respective standard wave-numbers of materials assured the presence of respective BTO material, urea and acrylamide.

3.2.3. Thermo-gravimetric Analysis (TGA)

The TGA is used to check thermal stability of the BTO particles. The powder sample (6.757 mg) was heated in furnace until 1000^o C with heating rate of 10^0 C/min in air medium. The TGA results obtained for bare BTO, urea coated BTO and acrylamide coated particles is as shown in fig. 5 (a), (b) and (c) respectively.

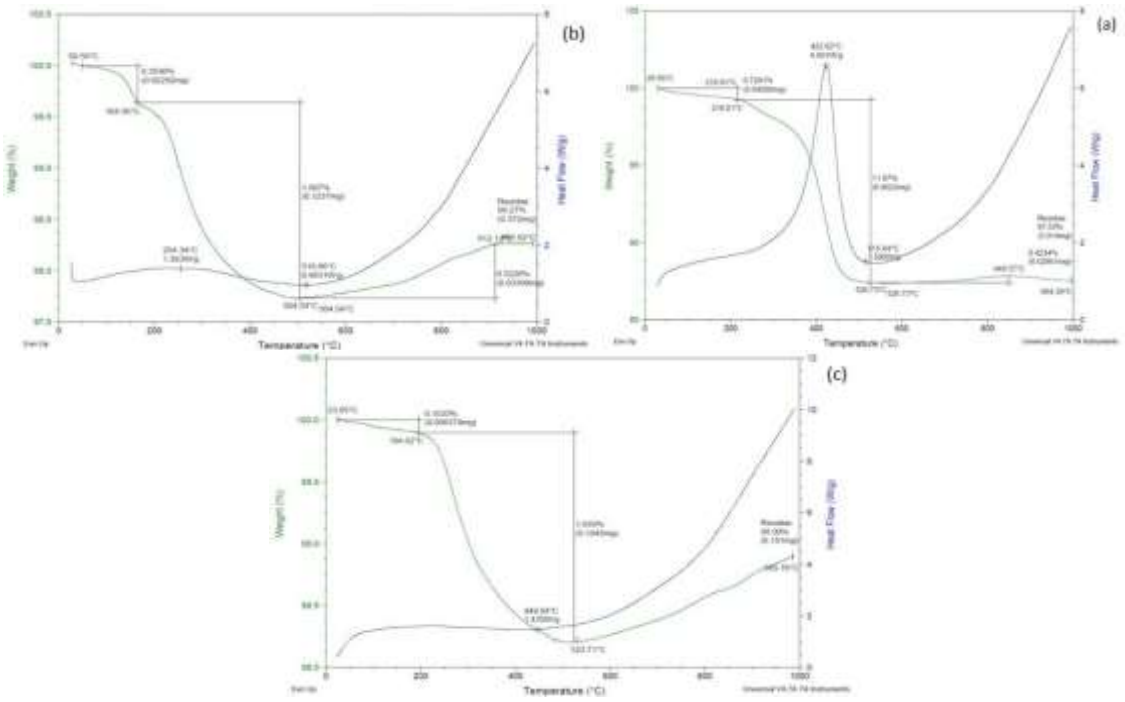

Figure 5 Weight vs. Temperature (a) Bare BTO (b) U-BTO and (c) A-BTO

The thermal stability and percentage weight change of respective material is as presented in table 3. The percentage weight change of acrylamide coated BTO powder is less and its

thermal stability is higher compared two other two samples. However, there is no significant difference between the U-BTO and A-BTO powder in thermal stability.

Table 3 Thermal analysis of BTO samples

BTO Sample	Weight change (%)	Thermal stability (^{0} C)
Bare BTO	12	422.82
Urea-BTO	2.2	518.66
Acryamide-BTO	1.8	523.71

3.3. Preparation of ER fluid

The ER Fluid preparation is carried out using weight-by-weight (W/W) percentage method. The weighed powder is mixed with preheated silicone oil (up to 150^o C in an oven to remove any moisture content) in a 100 ml beaker using a glass rod. The oleic acid (1 % w/w) is added to resulting mixture that is stirred continuously. To get uniform solution of ER fluid sample, the mixture is kept for 18 hour in an ultrasonic sonicator (water is changed every 30 minutes to maintain the temperature of the ER fluid and to avoid sticking of the BTO powder to the glass bottom). The mixture is grinded in mortar pistol to break the agglomeration of the ER Fluid particles if any as shown in fig. 6 (a).

Figure 6 (a) Removing agglomeration in ER fluid using Mortal Pistol (b) ER Fluid Samples.

Using this preparation process, the nine samples have been prepared as Shown in fig. 6 (b). Three samples of each bare BTO, U-BTO and A-BTO powder particles with concentration of 15, 20 and 25 % are prepared. Weighing calculations of sample 1 (*25 % w/w Bare BTO powder*) are as presented in table 4.

Required amount of sample = 50 ml approx. or more.

A: BTO powder (25% w/w), B: Silicone Oil (74% w/w), C: Oleic acid (1% w/w)

W/W percentage of solute A (X_A) = (Mass of solute A) / (Mass of Solute A + Mass of solvent B + Mass of solvent C)

$$X_A = (16.66) / (16.66+50+0.66) = 24.7\ \% \sim 25\ \%$$

Table 4 Bare BTO 25% w/w ER Fluid component details

Material	Quantity(W/W Method)	Theoretical Material Percentage	Actual weight (Put in ER Fluid)	Actual Material percentage
BTO Powder	16.66gm	24.7474%	16.676gm	24.7574
Oleic acid	0.66gm	0.9803%	0.669gm	0.9932%
Silicone oil	50gm	74.2721%	50.0124gm	74.2493%
TOTAL		**100%**		**100%**

The appearance of resulting ER fluid samples differs according to the concentration of powder particles. The appearance of the ER Fluid with 25% concentration is muddy and extremely viscous, while the ER Fluid with 15% concentration is more consistent.

4. TEST APPARATUS AND RESULTS

The performance of ER samples in terms of yield strength is determined using rotational modular compact rheometer (MCR-52) as shown in figure 7.

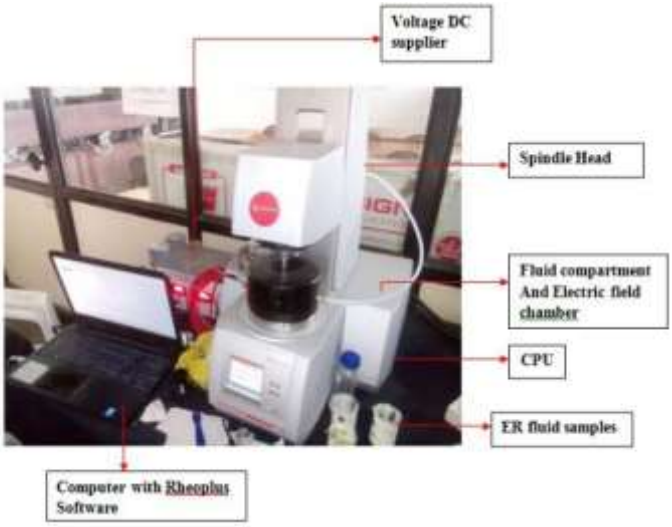

Figure 7 The experimental set-up with MCR-52

The sample 1 tested on MCR-52 exhibit 1.5 kPa yield stress at zero field and maximum yield stress of 4.75 kPa at 3 kV/mm as shown in fig. 8.

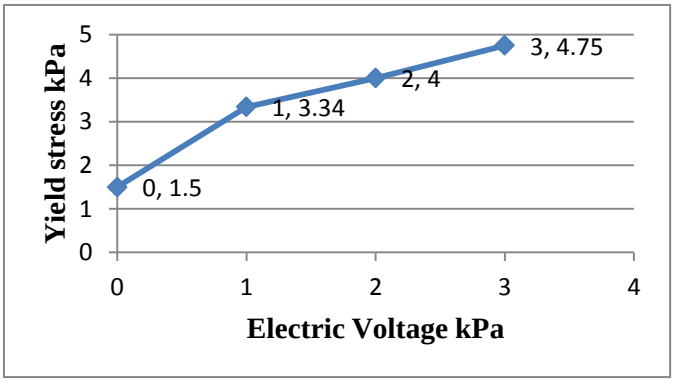

Figure 8 Dynamic yield strength (kPa) vs. applied electric voltage (kV/mm)

Similarly, the results obtained for other samples are compared as shown in figure 9 to identify ER sample with maximum yield strength.

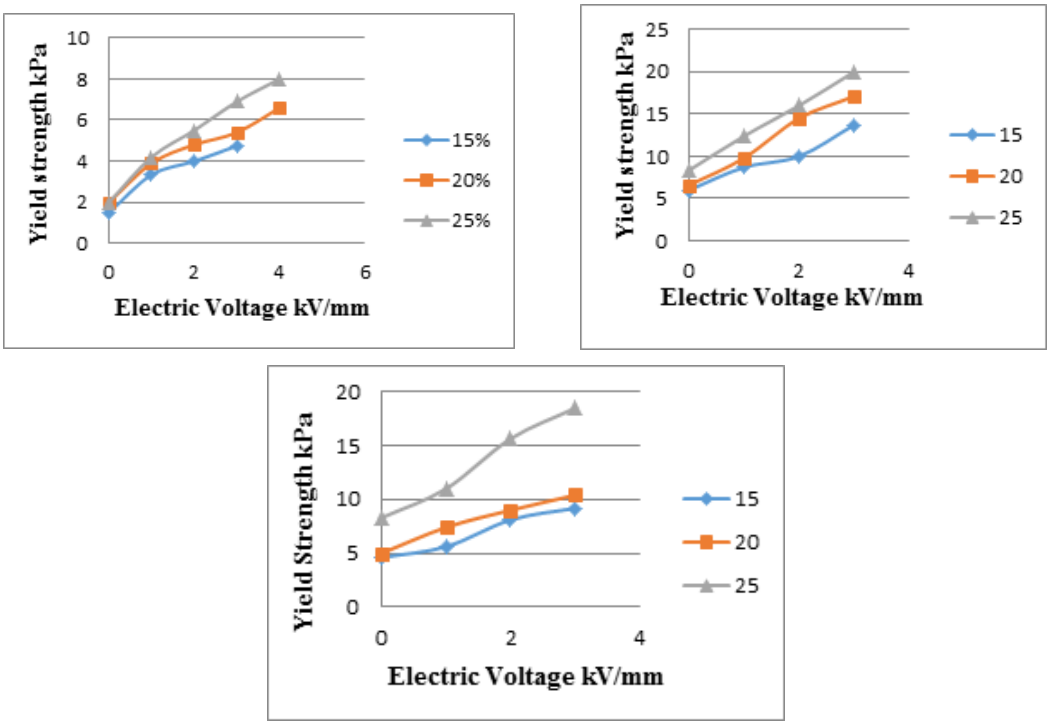

Figure 9 Yield stress (kPa) vs. electric Voltage (kV/mm) for ER fluid samples with concentration 15%, 20% and 25% of (a) Bare BTO (b) Urea coated BTO (c) Acrylamide coated BTO

From the figure 9 (a), (b) and (c), it is clear that maximum yield strength is 20 kPa at 3 kV/mm for sample 6. This is urea coated BTO based ER fluid prepared with 25 % concentration.

The breakdown voltage of the ER Fluid samples is independent of the particle type (bare or coated) and the particle concentration as the breakdown voltage of all the samples is between 3 to 4 kV/mm. The largest breakdown voltage recorded for sample 9, Acrylamide based ER fluid is 6 kV/mm.

To determine the sedimentation rate, the samples were kept without disturbing them for one month. During the test, it has been observed that how much time the respective sample took to settle down completely. The urea coated BTO based ER samples never showed sedimentation, while as bare BTO ER samples settled down very rapidly within two days and Acrylamide coated ER samples exhibit high settling rate however they settled down within one month.

4.1. Selection of ER fluid for proposed damper

The selection of appropriate ER fluid sample for proposed application of ER damper in recoil system is done based on their properties obtained yield strength, breakdown voltage and sedimentation rate. Based on the results obtained, the sample 6 (urea coated BTO based ER sample with 25 % concentration) exhibits high yield strength with high breakdown strength. In addition to this the sample 6 exhibit very low sedimentation rate. Hence it is decided to select urea coated BTO based ER sample with 25 % concentration for proposed application of ER damper in recoil system.

5 CONCLUSIONS

The preparation of different ER fluid samples and characterization of them were conducted. The suitability of ER fluid sample in proposed recoil damper is checked. The following lists the pertinent findings from the present work.

- A twin tube type of ER damper was used so that electric voltage can be applied between the annular gaps of the two cylinders inside the damper to get ER effect flow. This, damper provides 'flow mode' type of ER flow which gives higher pressure drop than other modes and brings considerable reduction in cycle time of recoil system.
- For the synthesis of ER fluid, based on the key role parameters, the silicon oil with very low viscosity as 0.1 mPas is selected as base fluid, bare BTO or urea/acrylamide coated BTO powder particles are selected as polarizable particles with the concentration of 15%, 20% and 25%. For homogeneous mixture and improved ER effect oleic acid with concentration of 1% is added.
- For the proposed application of ER damper, the minimum yield strength of ER fluid calculated is 14 kPa. For such high yield strength, powder size selected is in nanometre.
- The bare powder particles are showed average size of 142.5 nm and when coated with urea or acrylamide it showed 184.75 and 185.4 nm respectively under scanning electron microscope.
- The wave-numbers obtained by FT-IR tests are closely matching with respective standard wave-numbers of materials assured the presence of respective BTO material, urea and acrylamide.
- Based on the results of TGA it has been concluded that the thermal stability of the A-BTO powder is good compared to the bare BTO and U-BTO powder however there is not any significant difference between the U-BTO and A-BTO powder in thermal stability.
- The nine ER fluid samples were prepared using different concentrations of 15%, 20% and 25% for bare BTO, urea coated BTO and acrylamide coated BTO. These samples were tested for yield strength, breakdown voltage and sedimentation rate. The sample prepared with urea coated BTO based ER fluid with 25% concentration exhibit high yield strength of 20 kPa at 3kV/mm breakdown voltage with very low sedimentation rate compared all other samples. The sample is selected as it fulfils all the requirements of proposed application of ER damper in recoil mechanism.
- In a broader view, this research work has contributed some study to the area of preparation, characterization and selection of ER fluid for heavy duty applications.

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