ROLLING RESISTANCE OF ELECTRORHEOLOGICAL COMPOSITES

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ROLLING RESISTANCE OF ELECTRORHEOLOGICAL COMPOSITES

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Thesis

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ABSTRACT

Even with highly efficient future cars in sight, along with improved fuel efficiency, rolling resistance still contributes to 6 – 10% of the overall fuel consumption. Rubbers exhibiting tenability thus arouses substantial interest to solve the problem of further increasing the fuel efficiency of vehicles. This research aims to explore electrorheological enriched composites that can be combined into rubber tires with tunable rolling resistance. The rolling resistance will be a function of applied electric field. Tests are conducted using poly(vinylidene fluoride) (PVDF) as a polymeric base.

Experiments are carried out using latex and silicone rubber to show electrically active rubber composites. Rolling resistance properties are measured using a wooden roller based closely on the invention of Dr. Alan Gent.
ACKNOWLEDGMENTS

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CHAPTER I
INTRODUCTION

1.1 Overview of Electrorheological Composites

Electrorheology [1-13] can be described as the change in viscosity upon the application of electric field [14]. ER fluids or smart fluids as they are well known in the scientific fraternity have been around since decades but the giant ER effect was reported only around 2003. Since then researchers across globe are busy exploring applications of smart fluids in day to day life. To fully understand the behavior of ERF and get a real life application as basic as a self-tuning car tire is a real challenge. Use of ERF in creating composite. The integration of ERF into polymeric or rubber composites is one of the key steps in developing such advanced materials. Imagine a car going uphill which will require higher traction value as opposed to running on expressways. Tunable rolling resistance of such composites will not only result in a substantial fuel saving but will also ensure greater control in varying driving conditions.

1.2 Goal of Research

The primary goal of this research is to develop ER composites with silicone rubber and latex rubber. Integration of ERF into composites is the primary focus point of the experiments. Use of polymeric fibers for composite development will be pursued. This
study will establish the responsiveness of composites which can be further developed for industrial applications. This study is focused on the concept development of ER composites. Industry will benefit the tire industry in developing self–tuning rolling resistance tire composites.
CHAPTER II
LITERATURE REVIEW

2.1 Rolling Resistance

Rolling resistance is defined as the energy consumed by a tire per unit of distance covered [15]. Rolling resistance has become quintessentially important due to its linkage with the fuel consumption of a vehicle. The ever increasing pressure from the scientific fraternity which lays importance on reducing the rolling resistance of tires has garnered a significant amount of interest in this field. Green tires and allied technological concepts make it worth the effort in discovering solutions for the future generation cars. Rolling resistance amounts to almost 6 – 10% of the fuel consumption and reducing it is the only green option and a way forward to a cleaner and greener society.

2.1.1 Industrial Rolling Resistance Measurement Device

A typical setup to measure rolling resistance of a passenger car tire is shown in the figure. To put it in a simple way, a tire is mounted on a free rolling spindle and then it is loaded against a test drum which has a fairly larger diameter. The test drum is externally powered as can be seen in the figure. NHTSA has described two methods for measuring the rolling resistance viz. force method and torque method.
Figure 2.1 A typical rolling resistance measurement setup.

Under test condition the radius of the tire is measured with other testing parameters being constant. ISO 28580 has prescribed the method to calculate the rolling resistance with the use of following equation:

\[ F_r = F_t [1 + (r_L/R)] - F_{pl} \]

Where, \( F_t \) is spindle force, \( r_L \) is ratio of the loaded tire radius, \( R \) is \( F_{pl} \) is the skim load.
Torque method employs a torque cell which measures the torque required for drum rotation. As shown in the Figure XZ the drum is connected to the motor via torque cell. These methods are used to measure the rolling resistance at the industrial level. The capital involved in setting up such huge lab is huge and hence they are not recommended for laboratory setup at University level research.
2.1.2 Rolling Resistance Measurement Device for Laboratory Purpose

U.S. patent [52] describes the use of hydrostatic bearing and a belt which is pressed against the tire. The pressure differential is used to determine the rolling resistance of the tire. This method is preferred for direct application to the vehicles running on the highway. Gent 2002 [53] came up with a simplified apparatus to measure the rolling resistance of surfaces. The apparatus comprises of a heavier steel roller to be kept in contact with the material under consideration. This heavier roller is connected through an arm to a small weight which can swing like pendulum. The pendulum is set in motion with the help of a small control arm which is also used to set the initial position. An acoustic emission device is used to measure the frequency of rotation and hence the damping of the roller.

![Figure 2.4 Schematic showing the use of pendulum rolling resistance device [53]](image)

Figure 2.4 Schematic showing the use of pendulum rolling resistance device [53]
Figure 2.4 shows the basic use of the rolling resistance measurement device. The acoustic emission device is connected to a computer where it records the sound waves reflected from the pendulum attached to the roller. The waveform is recorded and then the damping of the signal is calculated to determine the rolling resistance. The equation used to calculate damping is

\[ \zeta = \frac{\log \left( \frac{Y(t_i)}{Y(t_j)} \right)}{\Delta t \ast \omega_0} \]

where \( \zeta \) is the normalized damping coefficient of the system, \( Y(t_i) \) the displacement envelope of the pendulum oscillations, \( \omega_0 \) the natural frequency of the pendulum evaluated by transforming the oscillations in the frequency domain, \( \Delta t \) the time change between time \( t_j \) and \( t_i \).

2.2 Silicone Rubber

Silicone rubber has been widely used across the medical field for various applications ranging from reconstructive surgeries to drug carrying tubes. The use of silicone rubber family gives the advantage of varying physical properties due to its heat resistance and inertness.

In 2003 Waters reviewed a range of properties of silicone rubber in an attempt to validate the properties of silicone rubbers as compared to the other commercially available options. It included the study of PDMS combined with silica fillers as maxillofacial prosthetic materials for replacement of facial parts which were lost in trauma or through disease. Although, none of the commercial silicone rubbers studied were found to possess ideal properties, the tear strength, softness and ease of manipulation was regarded as
important for carrying out such activities. Waters concluded that due to the absence of ideal properties in any of the readily available silicone rubber, a new array of materials is needed for medical purposes.

Wang et al. 2002 worked upon increasing the thermal conductivity by about 2 W/mK deploying an increased total volume fraction of the filler alongside an adequate filler distribution [16]. Results of this nature encouraged us to use ER fluid as a filler and develop an electrorheological composite with evenly distributed ER particles.

The silicone rubber used for the experimentation purpose goes by the chemical name organopolysiloxane mixture as per the data sheet provided by the supplier. They are also known as polydimethylsiloxane with chemical formula \( \text{CH}_3[\text{Si(CH}_3)_2\text{O}]_n\text{Si(CH}_3)_3 \) where \( n \) is the number of repeating monomer [SiO(CH\(_3\)_2] units. The Wikipedia page shows the chemical structure of the silicones as following

![PDMS structure via www.wikipedia.org](www.wikipedia.org)

Lotters [56] found out that silicone rubbers can be used as flexible top elastomer without compromising the device sensitivity. It can also be used as a material that can be used to make flexible encapsulation for sensors so that they could be physically and chemically decoupled from the environment without affecting its functional properties.
Even though a range of medical grade silicone rubbers are deemed suitable for plastic surgery for replacement of soft tissues and cartilage there are issues reported where the bodily fluids get absorbed when they are used to carry fluids. Fatty acids have been reported to get absorbed into artificial valves and caused heart failure [57]. Researchers tried to resolve this problem using various combinations of fillers to eliminate the absorption of fluids.

Kastsuno and Motojima [58] carried out a series of experiments to determine the change in electrical properties viz. impedance, phase angle, resistance and capacitance with the help of carbon micro coils. The effect is reported due to the touching carbon micro coils in the silicone – rubber matrix composite.

2.3 ER Fluids

Around 1939, researchers begin to report an interesting observation wherein certain kinds of particles when suspended in low viscosity oil and subjected to electric field demonstrated a phenomenon of forming oil – occluding mass [17]. This interesting phenomenon was further deliberated and due diligent progress was made in developing electrorheological fluids which showed giant ER effect under the application of electric field. The mechanism is elaborated further in 2.4.2.
Figure 2.6 Images of nanoparticles in GER suspensions. (a) TEM image of coated nanoparticles. Urea coatings are clearly seen. (b) Optical microscopic image of a sample prepared in epoxy, solidified under an applied field of 2 kV/mm. Columns aligned along the field direction are visible. (c) TEM image of a section of the column shown in (b). The arrows indicate one of the flattened interfaces [18].

2.3.1 ER or Smart Fluids

Electrorheological fluids can be defined as a type of “smart” colloid which is capable of varying its viscosity or even solidify with change in the applied electric potential [19]. The transition from liquid to solid state and vice versa is in the order of milliseconds. The giant electrorheological effect [20, 21] gave a platform to inventors for applying smart fluids to a range of mechanical equipment like clutches, valves, dampers etc. with a flick of a switch. This has led to a complete paradigm shift in the development of novel products.

2.3.2 The ER mechanism

Even though the discovery of ER effect is widely credited to Winslow [], the curiosity and realistic research started only around 1980’s. The renewed theoretical and experimental advances laid the foundation of the use of ER fluids for application purpose. The dielectric constant contrast between the solid particles and the liquid colloid under the applied electric field gives rise to an effective dipole moment. This results in the formation of columns as seen in the Figure 2.7 which explains the increased viscosity of the ER fluid as a whole [22-28].
Figure 2.7 The structural evolution of dielectric microsphere under an increasing electric field, from (a) no field, to (b) a moderate field of 500 V mm\(^{-1}\), to (c) a strong field of 900 V mm\(^{-1}\). Here the ER fluid consists of 1.5 micron glass spheres suspended in silicone oil.

Parthasarathy [29] reviewed a range of proposed mechanisms to find out the driving force behind the ER effect. The idealized electrostatic polarization model predicted that the ER response is a function of electrostatic interactions and repulsive interactions when applied to small particle separations. This model was generalized to get a better understanding of the Maxwell – Wagner model which deciphers the behavior of high dielectric constant particles like barium titanate that shows increased activity at increasing field frequency as compared to a DC field.

Hao [30] examined a range of properties to determine the mechanism behind the ER effect. The interfacial polarization can be attributed to ER effect. The assumption of large interfacial polarization producing large surface charges which helps in particles to form fiber like structures is found to be valid under the suggested framework.

Wen [31] reported that by decreasing the size of urea coated barium titanyl oxalate nanoparticles the ER effect can attain a yield stress in excess of 250 kPa. The experiments proved that the ER effect is sensitive to the volume fraction of the solid particles.
2.3.3 ERF properties

ER fluid operates under the influence of applied electric field. For a range of applications a strong electric field is required (>1000 Vmm\(^{-1}\)) for the desired ER effect to exist. This makes it pertinent for ER fluid to have excellent electrical properties and temperature stability for any application under consideration.

The practical applications of ER depends on a number of parameters like high yield stress under the applied electric field, low yield stress when the field is removed, excellent dispersion properties, low current density, low thermal degradation, low on toxicity, non–abrasive, non–flammable [73]. The scaling up of commercial ER production is not the design of the ER fluids but the availability of predictable and consistent performing ER fluids [73]. An articulate evaluation of the properties of ER fluids for a majority of applications has been carried out and represented in Table 2. [73 – 75].

It is possible to increase the stress level in an ER fluid by including more active particles but this will tremendously increase the off state viscosity of the fluid and blur the difference between the off state and the on state [73]. An ideal ER fluid having showing stress – shear rate behavior is illustrated in Figure 2.
Table 2.1 Ideal properties of ER fluids for practical application [73 – 75].

<table>
<thead>
<tr>
<th>ER property</th>
<th>Recommended minimum value</th>
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<tr>
<td>Dynamic yield stress at 4.0 kV mm(^{-1})</td>
<td>&gt;3.0 kPa</td>
</tr>
<tr>
<td>Current density at 4.0 kV mm(^{-1}) at 25 °C</td>
<td>&lt;10 (\mu)A cm(^2)</td>
</tr>
<tr>
<td>Zero field viscosity at 25 °C</td>
<td>0.2–0.3 Pa s</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-40–200 °C</td>
</tr>
<tr>
<td>Dielectric breakdown strength</td>
<td>&gt;5.0 kV mm(^{-1})</td>
</tr>
<tr>
<td>Particle size</td>
<td>~10 (\mu)m</td>
</tr>
<tr>
<td>Stability</td>
<td>Low sedimentation</td>
</tr>
<tr>
<td></td>
<td>No dynamic separation</td>
</tr>
<tr>
<td></td>
<td>No electrophoresis</td>
</tr>
<tr>
<td></td>
<td>No chemical changes</td>
</tr>
<tr>
<td></td>
<td>Low volatility</td>
</tr>
<tr>
<td>Other properties</td>
<td>Non-abrasive</td>
</tr>
<tr>
<td></td>
<td>Non-toxic</td>
</tr>
<tr>
<td></td>
<td>Non-corrosive</td>
</tr>
<tr>
<td></td>
<td>Non-flammable</td>
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</table>

The Bingham behavior under the field is evident with region 1 showing solid state. Region 2 is the onset of flow at static yield whereas region 3 shows the retention of an enhanced field induced stress in all regions of flow for an ideal case.
Conrad et al 1991 [55] found out that the strength of the ER fluid increases with the increase in temperature. Also the dielectric constant along with conductivity increases with temperature to about 100°C.

Figure 2.8 Stress–shear rate behavior of an ideal ER fluid [75].
Figure 2.9 Stress vs temperature for E = 1 and 2 kV/mm. Shear strain $\gamma = 5$ and shear strain rate $\dot{\gamma} = 0.085$ s$^{-1}$[55].

2.3.4 Applications based on ERF

Owing to the outstanding properties of electrorheological fluid, a variety of applications have been developed over year. The application are not only limited to heavy machinery but also the subtle and complex medical field has also shown interest in utilizing the ER effect. Few of the applications are discussed here.

2.3.4.1 ER based damper

Makris, Burton and Taylor [76] designed a prototype damper that could absorb the seismic energy in the case of earthquake. The schematic of their prototype is shown in the Figure 2.10. The idea behind the damper is to eliminate the use of moving parts to
control the inexpensive fluids like ERF and MRF. Their proposed ER damper showed satisfactory behavior under different deformation rates.

![Schematic of prototype damper](image)

**Figure 2.10 Schematic of prototype damper [76].**

**2.3.4.2 ER valves**

Yoshida [77] published a paper in 2002 describing the use of ER fluids in making valves to be used in micromechanics. The miniature sized ER valves were fabricated using micromachining technologies. The paper describes use of several two – port micro ER valves with varying electrode gaps. Also a three – port micro ER valve is used to ascertain the controllable pressure change rate of 60% of supply pressure and 0.2 s response time. The author has validated the operational properties by controlling position of a bellows micro actuator [77]. Homogeneous ER fluid was used for the experimentation purpose.
Figure 2.11 Micro valve using homogeneous ER fluids [77].

Figure 2.12 Driving method of a bellows micro actuator with three – port micro ER valve:
(a) expansion; (b) contraction [77].
2.3.4.3 ER fluid assisted polishing

Kuriyagawa [78] used ER fluid in developing a new machining method for polishing of smaller sized three-dimensional parts. The method developed was capable of micro-polishing and micro-grinding as described by the author. The principle of operation in a simplified form is shown in the Figure. The ERF is used to host ultra-fine abrasive particles. These particles polarize with the application of electric field and form a chain of ER particles as expected. The radiating electric force near the tip of tool align the abrasive particles which assists in removing the material directly from the exposed work piece surface giving polish [78].

Figure 2.13 Principle of electrorheological fluid – assisted polishing [78].
2.4 ERF composites

A range of applications have been developed with the use of ER as the primary component. The unique feature of its reversibility upon the removal of electric field makes it interesting. Applications ranging from dampers to actuator, sensors, brakes, vibration control devices etc. have been developed by researchers.

Sirivat [32] demonstrated at very low volume fractions ERF can be used as an agent to generate a dipole moment. This filler in acrylic rubber matrix can store additional elastic energy under the influence of applied electric field.

Zhao [33] in 2013 developed electrorheological elastomers with tunable stiffness designs by incorporating theoretical and numerical modelling. The emphasis of their work is the utilizations of mesostructured electrorheological elastomers in attaining tunable stiffness under the influence of applied electric field. The underlying principal used is the change in microstructural orientations due to elastomer deformation inducing variance in the electrostatic potential energies and hence the tunable stiffness.

Jinsong and Yanju [34] coupled ERF and fiber optic senor to develop vibration monitoring sensor for smart composite structures. The primary purpose of ERF was to act as actuators owing to its fast and reversible change in rheological properties.

2.5 Magnetorheological fluids

Magnetorheological fluid, as described by Genc and Phule [58], is a meso – scale dispersion of ferromagnetic and ferromagnetic particulates in carrier liquid. A range of ceramic, alloy and metals can be used to prepare MR fluids as long as the materials depict
negligible or low magnetic coercively. Iron penta – carbonyl (Fe(CO)$_5$) is the most commonly used material for this application which gives high purity iron powder after decomposition [58].

![Figure 2.14 SEM images of spherical shape (left) and onion – rings like structure (right) carbonyl powder (image adapted from BASF website (2015)).](image)

Osama [59] has defined MR fluids as stable suspensions of non – colloidal ferromagnetic particles in an insulating carrier medium demonstrating controllable rheological properties under the influence of applied magnetic field. The composition of MR fluids has been described to comprise of three important components: ferromagnetic dispersed particles, a carrying fluid and a stabilizer. The dispersed particles provide resistance to the flow of overall material and act as a chain upon the application of field. The carrying fluid continuously provides insulating medium while the stabilizer keeps the particles suspended by either providing agglomerative stability or sedimental stability as per the application in context.

MR fluids have also been termed as intelligent materials which change viscosity to several orders of the applied magnetic field of order 1 T [60]. Leveraging this remarkable
property, innovative minds have been able to use MR fluids in applications like shock absorbers, control valves, clutches, brakes, vibration dampers to name a few. They have been further discussed in the literature.

2.5.1 MR fluids properties and mechanism

The yield stress development has been correctly attributed to the formation of chain like structures of the suspended particles in the carrier medium. Field induced yield stress is shown in the schematic Figure 2.15. The ferromagnetic particles lay dormant in the medium as seen in Figure 2.15 (a), when there is no magnetic field. With the application of magnetic field, the particles begin to align themselves in line with it as seen in Figure 2.15 (b). Figure 2.15 (c) shows the ultimate alignment of the particles with the flux direction creating a resistive path for the motion of the fluid. This results in the development of yield stress in the fluid. Entire process takes place in the order of milliseconds [61].

Figure 2.15 Activation of MR fluid: (a) no magnetic field applied; (b) magnetic field applied; (c) ferrous particle chains have formed [61].

The development or formulation of every MR fluid is directed towards achieving high levels of yield stress. A keen observation of the applications using MR fluids reveal
that even though on – state is desired, the application more often than not operates in an off state. This implies that the viscosity of the fluid should return to low levels as soon as the magnetic field is removed. This gives an imperative meaning to the application which can rely on the fluid to remain in its low viscosity state till the time its MR feature is not desired.

The characteristic stiffening of MR fluid can also be explained by Bingham model as shown in Figure 2.16. The Bingham model explains the behavior of MR fluid as a solid in the absence of shear rate.

![Bingham Model](image)

Figure 2.16 Bingham model [62].

Turn – up ratio as defined by Genc [62] is the ratio of “on – state” yield stress to the “off – state” viscosity. When the magnetic field is applied to the MR fluid the state is referred to on – state. The yield stress depends on the magnetic properties and volume fraction of the participating magnetic phase. Off – state as the name suggests is the value when there is no magnetic field. They further found out that the MR fluids are anisotropic
As the particles lined up in the direction of the applied magnetic field as shown in Figure 2.17. This revelation is important from the application point of view as the yield stress will be dependent on the orientation of the magnetic field.

Figure 2.17 Effect of magnetic field direction on the yield stress of MR fluids (adapted from Genc [62])

As seen in the Figure 2.17, the yield stress will depend on the direction of the applied magnetic field and the shear direction. Brakes, clutches and dampers employ the y – direction scenario whereas for optical polishing application z – direction scenario is preferred [79 from 62]. Shorey and co – workers also found out that yield stresses were comparable in magnitude but slightly higher for Figure 2.x C than Figure 2.x B and concluded that this may be due to the internal structure formation. They chose the latter two cases due to the orthogonality of field orientation to the flow direction.
The effect of viscosity on the yield stress was duly studied and the results were documented in the work of Foister [63]. He showed that even though the yield stress grows rapidly with the increase in volume fraction as shown in Figure 2.18 it is coupled with the decrease in the off–state viscosity as can be seen in Figure 2.18. It can be seen in Figure 2.18, for a growing volume fractions, the viscosity grows at a faster rate than the yield stress. This will result in lower turn–up ratio.
Figure 2.18 Magnetorheological fluids (Foister 1997).
2.5.2 MR fluids applications

The applications of MR fluids is based on its operation in parallel, shear or squeeze mode. Figure 2.x show a schematic of the operational MR fluids.

![Diagram of MR fluids operational modes](image)

Figure 2.19 Typical operational mode of MR fluids (a) flow (b) shear and (c) squeeze mode [64].

In flow mode, the MR fluid is allowed to flow between two stationary plates by the means of pressure drop. The flow resistance can be altered by altering the magnetic field strength. In shear mode the surfaces in context are moving with respect to each other and the magnetic field is perpendicular to the motion of the sliding or rotating surfaces. The squeeze mode employes the distance between the surfaces changes which causes a squeeze flow.

2.5.2.1 MR fluid damper

MR damper has been recognized as one of the most appropriate application to reduce structural vibration. Yang et. al. [66] studied the dynamic performance of MR dampers and provided algorithms to optimize the dynamic response. Owing to the simplicity, lower power consumption and robustness, the MR dampers are very promising.
for civil engineering applications. In their study a 20 – ton MR damper (shown in Figure 2.20) providing semi – active damping for structural applications has been constructed. For design purposes, they provided two – quasi static models, an axisymmetric and a parallel – plate model.

Figure 2.20 Schematic of large scale 20 – ton MR fluid damper [66].

The dynamic response time is addressed in their research by the means of a current driver. Experimental results suggest that a parallel connection is preferred over a series connection of damper coils for faster response time.
2.5.2.2 MR Clutch

Torque control requires devices having a better level of sophistication than the regular servo motors. To address this issue, Shafer [67] designed a prototype MR clutch which is well suited for human–friendly torque control applications. Apart from achieving an output capacity of 75Nm, they were able to achieve lower values of mass and output inertia which allowed its integration with human involved actuation systems.

Figure 2.21 Experimental setup used to verify the prototype of MR clutch [67].
2.5.2.3 MR Brake

Park [68] proposed a brake based on MR fluid. The design consisted of multiple rotating disks immersed in the MR fluid which in totality are enclosed in an electromagnet. The varying magnetic field create enough yield stress to generate breaking torque. The research was not able to produce sufficiently high levels of breaking torque to be implemented in automotive industry but their design confirmed with the theoretical predictions and could be leverage for using extra disks for generating the desired breaking torque.

![MR Brake Diagram](image)

Figure 2.22 MRB based on design criteria [68].

2.6 Comparison between ERF and MRF
Selection of either of the responsive fluids highly depends on the intended application. It will always be the case when ERF will be suited for a certain application where magnetic force may interfere with the primary function of the application and then there would be applications which will require a small power supply for operation. Permanent magnets or electromagnets may pose to be cumbersome in designing the application due to the complexity involved for a sophisticated device. On the other hand a high voltage supply integration with the application may incur additional control and instrumentation parameters making the application lose focus from the intended purpose. Owing to these reasons, a careful consideration of the fluids is important for a state of art device configuration.

Working at the US National Bureau of Standards in 1940s Jacob Rabinov was discovering the effects of MRF at around the same decade Winslow was occupied with the developments in electrorheological fluids. There are some similarities between MRF and ERF but then MRF uses a voltage range of 2 to 24V whereas ERF requires DC source in the range of kV. The electrorheological effect depends on the electrostatic field whereas the magnetorheological effect depends on the magnetic field as the name suggests [65]

The control over ERF with respect to contaminations is quite poor as compared to MRF which has good stability. The MRF developed in USA, Europe and Japan diligently addressed the issue of sedimentation and abrasive behavior which has helped researchers facing problems to apply MRF in developing dampers, clutches, brakes discussed earlier in this section [65].
A brief comparison of some of the properties of electrorheological and magnetorheological fluids is summarized in Table 2.x. These are not absolute and as the field advances there are additions to the existing properties and their applications.

Table 2.2 Comparison of some of properties of MR and ER fluids [69].

<table>
<thead>
<tr>
<th></th>
<th>MR Fluids</th>
<th>ER Fluids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate Material</td>
<td>Zeolites,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Iron, ferrites, etc</td>
<td>Polymers, SiO₂,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BaTiO₃</td>
</tr>
<tr>
<td>Particle size</td>
<td>0.1-10µm</td>
<td>0.1-10µm</td>
</tr>
<tr>
<td>Suspending fluid</td>
<td>Nonpolar oils,</td>
<td>polar liquids,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>water and other</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>3-5</td>
<td>1-2</td>
</tr>
<tr>
<td>Off viscosity (mPa·s)</td>
<td>100-1000</td>
<td>50-1000</td>
</tr>
<tr>
<td>Required field</td>
<td>∼ 3 kOe</td>
<td>3kV/mm</td>
</tr>
<tr>
<td>Field Induced changes</td>
<td>τₓ (B) ∼ 100kPa</td>
<td>τₓ (E) ∼ 10 kPa</td>
</tr>
<tr>
<td>Device excitation</td>
<td>Electromagnets or permanent magnets</td>
<td>High voltage magnets</td>
</tr>
</tbody>
</table>
2.7 Incorporating ERF into composites and tires (Wong 2013)

In an attempt to redefine the viscoelasticity of tires after they have reached a consumer as a product, scientists have led the research in developing articles which can exhibit tunable properties. The change in elastic modulus as a function of time or completely independent of it provides a fascinating opportunity to explore the area. This section elaborates an approach in the same direction.

Rolling resistance is an important factor that dictates the consumption of fuel in a vehicle. It is estimated at 6 – 10% of the overall consumption of fuel in a vehicle. A small decrement in the value of rolling resistance can lead to a substantial saving of fuel on road. The idea however is restricted by a small setback as to providing tires with lower rolling resistance or higher rolling resistance will not fulfill the primary objective of the vehicle that is transportation in varying road conditions. For example, tires with lower rolling resistance will provide good traction and significantly higher torque when the vehicle is climbing a mountain. The extra frictional force will be a plus for the stated purpose. Therefore, there is a need in developing the art of tire making with the luxury of altering elastic modulus and the time-dependent elasticity at the consumers will.

ER fluid as discussed earlier is the suspension of colloidal particles in a carrier medium which can tune its viscosity under the influence of change in electric field. The change in viscosity is reversible with the removal of electric field. The original viscosity is regained in a matter of milliseconds. The sharp response time gives the transition of fluid to solid-like state of ERF and vice-versa. The homogeneity of this characteristic shear yield property makes the use of ERF an obvious choice.
The manufacturing methods for incorporating electrorheological fluids into polymeric materials or rubber composites for that matters is highly dependent on the fact that the electric field doesn’t alter the carrying part of the composite. The patent discusses a range of ideas for the purpose. One of the ideas discusses about the integration of rubber part with woven or non–woven fabrics carrying ERF. The integration is achieved using composite processing. Use of fiber preforms or chopped strands and discontinuous fibers has also been discussed. Other idea explores the use of articles discussed earlier to be used as a ply for the tires which can then change viscoelasticity and rolling resistance as the function of electric field. Another idea explores the use of pockets in the polymeric medium to carry electrorheological fluids. The pockets can be partially filled as per the need of the application. There are a range of ideas that can server the purpose of attaining variable viscoelastic properties and tunable rolling resistance by the incorporation of electrorheological fluid. Few of them are discussed below.

A simplified method of incorporating a fiber mat with electrorheological fluid that will be rolled as an impregnated tow is shown in the figure 2.x. A choice of fiber in the form of fabric, either woven or non–woven, is fed alongside a polymeric carrier mat to the pinch roll. The function of the pinch roll is to combine these two mats into a composite material by applying pressure. The composite material obtained from the pinch role is then fed to a bat filled with electrorheological fluid. The composite material is guided to the bath with help of a guide roller. Inside the bath there are a set of rollers submerged in the electrorheological fluid. The positioning of the rollers is set in a way that the path of the composite material from the guide rollers has to travel thorpoug the bath of electrorheologcaol fluid. This will ensure a complete soaking of electrorheolocial fluid in
to the composite material. This operations creates a final electrorheological composite material.

After the electrorheological composite mat leaves the ERF bath, it is guided to a set of pinch rollers. The pinch roller again compresses the carrier mat and the electrorheological composite. This final product is then guided to form ERF impregnated tow which is done in a continuous rolling process. The ply thus obtained can be used for articles like tires.

Figure 2.23 A general schematic of an exemplary method of creating polymeric article employing a fabric to receive electrorheological fluid [70].

Another method for incorporating electrorheological fluid into fibers can be seen in the Figure 2.x This exemplary methods utilizes multiple tows of fibers which are fed through tensioners to the electrorheogcial fluid bath. The ERF bath is set in a manner that allows ample time for the fibers to be impregnated with ER fluid and thus obtain a stream of coated fibers. When the ER fluid coated fibers exit the ERF bath, they are guided through an aperture on to a moving platform. The moving platform provides a rotating mandrel for
the collection of coated fibers. The moving platform has a lateral motion with respect to the rotating mandrel, ensuring a winding of ERF coated fibers in the form of tows or any other suitable means for final use. It also give a uniformity in the fiber collection. The fibers thus collected can be then selectively used as woven or non-woven form for applications like tires.

Figure 2.24 A general schematic of an exemplary method for creating electrorheological fluid bearing tows for use in this invention.

Alternative method is provided in Figure 2. This method involves the movement of a carrier mat from a carrier mat roller underneath a sprayer. The sprayer mounted over the path sprays chopped fibers on the surface of the carrier mat. As the carrier mat advances,
its surface is coated with chopped strands. Then the mat is subjected to a set of rollers which compresses the strands on the carrier mat. Then it is guided to a bath filled with electrorheological fluid which again submerges the mat into it. Thus a coated strands of fibers with ERF fluid are obtained which is then collected as a final composite material. They can be employed for the purpose of tire application.

Figure 2.25 A general schematic of an exemplary method of creating a polymeric article in employing chopped fibers to be immersed in electrorheological fluid [70].

As the field of electrorheology advances, there will be a further advancement in the composition of the ER fluids and their subsequent properties. A certain application will require a specific property of ER fluids which will differ from other application. Every ER fluid will have a certain a field strength range which will activate its change in viscoelastic modulus. Thus a range of ER fluids will be employed for a host of applications involving
ER fluids as a prime component. Figure 2 represents a schematic of application of this invention in tire application.

Figure 2.26 A general schematic representation of the application of this invention in a tire [70].

The Figure 2 simplifies the modus operandi of a practical application in tires. It is an exaggerated diagrammatic perspective of the application which assumes the suspend electrorheological particles in a tire. The power supply is used to change the field strength by varying the electric voltage. As the field strength changes the particles align themselves
in the direction of the field strength increasing the elastic modulus of the tire. This results in a harder tire with a defined range of voltage. Again with the variation of the electric field strength the tier can be made softer or stiffer as per the requirement of the consumer. All these operations are controllable by a switch.

Another conceptual model involves the use of piezoelectric material for the voltage generation purpose. A piezoelectricity means the generation of electricity by the application of pressure. There are certain materials in nature that exhibit this unique property wherein a pressure difference creates a voltage difference which can be used to complete a circuit. Crystals, ceramics, stones have been known to exhibit this property. An extension of this property have been discussed in patents [71, 72].

Figure 2.27 A schematic of using piezoelectric polymers/ ceramics to create ER effect [70]

Hollow tubes of piezoelectric polymer are filled with ER fluid. These carrier tubes are not supplied with any external potential difference. During normal operation, the tubes will be carrying ER fluid in its liquid state. The arrows represents the application of pressure on the tubes and due to the application of this constituting pressure on the hollow
carrier tubes the pressure is piezoelectrically converted into potential difference. Due to the difference in the polarity, the potential difference is generated between the applied pressure points. The potential difference creates electric field which triggers the electrorheological effect turning the liquid ER fluid into solid like gel. This in turn increases the elastic modulus without the application of external field. Regardless of phase transformation, the increase in viscosity is bound to provide stiffness and additional contact stress to the tubes carrying them. These materials can be incorporated into rubber tires as a whole which can change the way a car tire reacts to a pothole or bump. An increase in the stiffness while hitting irregular terrain will be advantageous with respect to the driving conditions and overall life of the tires.

2.7 Electrospinning Process

Electrospinning is a uniquely simplified method wherein nanofibers are produced with diameters of the order of a few micrometers to nanometers [35]. This method was brought to limelight upon the first U.S. patent grant in 1934 [36]. Since then over 30 U.S. patents have been granted related to electrospinning and the process development. Although the Formhals [36] introduced electrospinning, the revival and development of the technology is attributed to Reneker [37, 38].

The process consists of using high voltage of the range of 10 – 25kV to produce ultra – fine nanofibers. Figure 2.8 elucidates a schematic of basic setup used to produce electrospun fibers. Almost every electrospinning setup consist of a pipette or a syringe filled with polymeric solution, a high voltage power supply and a conductive collector plate which is grounded. The syringe needle acts as an electrode to charge the solution. In
addition to these there is a metering pump which is used to control the flow rate of the polymeric solution.

Figure 2.28 Schematic of a basic electrospinning setup; (b) non-aligned polymer fibers produced by electrospinning.
Under the influence of strong electrostatic force, the polymeric solution at the tip of the needle is accelerated towards the collecting conductive plate. This is mainly due to electric field surpassing the surface tension of the pendent of droplet formed at the tip of the needle and forming conical shape [39, 40]. This phenomenon will not occur at low electric fields due to the surface tension of the polymeric solution.

Figure 2.29 Schematic illustration of the Taylor cone formation: (A) Surface charges are induced in the polymer solution due to the electric field. (B) Elongation of the pendant drop. (C) Deformation of the pendant drop to the form the Taylor cone due to the charge-charge repulsion. A fine jet initiates from the cone. [Baji 2010]

Process parameters like the strength of the field, the distance of needle from the collector, viscosity of the solution, etc. play a very important role in the overall morphology
of the electrospun nanofibers. By altering the diameter of the nanofibers and aligning them a combination of desired properties can be attained.

2.7.1 Electrospun fiber collection methods

Recent studies have concluded that the nature of collector has a significant role on the morphological properties and physical properties of the electrospun nanofibers [41, 42]. A non–conducting collector will result in retained charges and hence the repulsion of fibers which eventually would lead to a sparsely packed fibers on the collector. On the other had a conducting collector will facilitate the discharge of charges held and eliminate repulsion giving closely packed fibers. A number of methods for collecting fibers have been developed over years. Following are some of the frequently used methods.

2.7.1.1 Rotating drum collector

The most common method to collect aligned electrospun fibers is shown in the figure XXX. It is known as rotating drum collector. As shown in the schematic (see figure XXX) the assembly consists of a cylindrical shaped drum for collecting the fibers. The drum can rotate at a few 1000 rpm which is sufficient for the process. The deposition of the fibers is along the circumference of the drum. The diameter of the fibers can also be controlled by controlling the speed of the rotating drum [41]. It has been concluded in many researches that the linear speed of the rotating drum should be matched with evaporation rate of the solvent. This allows the fibers to be deposited on the surface of the rotating drum. Alignment of the fibers also depend on the rotational speed of the drum. Randomly oriented fibers are obtained at low rotational speed than the fiber take–up velocity. At slightly higher speeds, a circumferential centrifugal force elongates the fibers. At extremely higher speeds, fiber breaks before deposition.
Figure 2.30 Schematic of the rotating drum used for fiber collection. The inset SEM micrograph shows the aligned fibers obtained using the rotating drum.

2.7.1.2 Rotating disk collector

The rotating disk collector is basically a variant of drum collector wherein a sharp edged disk is used as a collector. The schematic for such a setup is shown in the Figure XXX. The fibers deposited using this setup are highly aligned. In this setup the jet while transforming into fiber takes a conical path and then an inverted conical path towards the
rotating disk. There is a point above the disk the loop decreases in its diameter resulting in the inverted conical shape. As the charge is applied to the edge of the disk, the fibers are pulled towards the edge of the disk. There is a further stretching of the fiber resulting in reduced diameter and a fine quality of aligned fiber [Baji].

![Schematic of disk collector](image)

Figure 2.31 Schematic of disk collector [Baji 2010].

2.7.1.3 Static parallel electrodes

The simplicity of this setup lies in the way single fibers can be collected for mechanical testing. Excellent quality of alignment can be obtained using this technique. The fiber alignment is achieved by the residual electrostatic repulsive forces between the electrospun fibers, which ultimately aids in their alignment [5, 47-49 Baji].
Figure 2.32 Schematic of static electrodes used for collecting aligned fiber bundles. The optical micrograph shows the aligned fibers collector using this technique [Baji 2010].

2.7.2 Parameters affecting electrospinning

Fiber geometry, texture and size can be clinically altered or controlled using some of the parameters involved in the electrospinning process such as the viscosity, temperature, distance between needle and the collector, applied voltage and solvent used.

2.7.2.1 Viscosity of the Solution
Viscosity of the solution plays a very important role in with reference to beads formation. A solution which is less viscous is likely to give beads or droplets in the electrospun fibers. A viscous solution holds on a perfectly surface tension to form the Taylor cone and hence resulting in fine fiber geometry. Figure XXX shows too the effect of low viscosity PVDF solution on the fibers.

Figure 2.33 SEM micrographs showing the effect of viscosity on electrospun fibers.
2.7.2.2 Applied electric voltage

Shi [43] observed that the applied voltage during electrospinning plays a crucial role in the fiber morphology. A voltage of 14kV resulted in solution dripping which led to poor electrospinning. Higher voltage of 23kV resulted in further unstable electrospinning. So a stable electrospinning was observed at a voltage range of 14kV to 22kV.

Figure 2.34 SEM micrographs showing the effect of applied voltage on fiber diameter [43].

The increase in fiber diameter with the increase in electrostatic forces have been reported by researchers [44]. This is mostly attributed to the increase in the flow rate of the polymeric solution owing to the increased field strength.

2.7.2.3 Effect of solution concentration

Supaphol and Kohn [44] studied the effect of multiple concentration solutions of poly(DTE carbonate) and found out that with lower solution concentration, the jet stream would break down due to the Columbic stress acting on them. This resulted a break in fiber continuity and formation of bead in the fibers collected. The fibers smoothed out when the concentration was gradually increased.
Figure 2.35 SEM images (500×) of as-spun fibers from (a) 5, (b) 10, (c) 15 and (d) 20% (w/v) solutions of poly(DTE carbonate) in dichloromethane. The applied electrostatic field strength was 20 kV/10 cm and the collection time was 30 s [44].

Bead formation has also been attributed to the viscoelastic relaxation and the reduced electrostatic forces once the fiber is in contact with the grounded collector [44, 45].

2.7.3 Applications of electrospun fibers

Due to its unique nanostructural properties coupled with tunable sizes, nanofibers find a range of applications where potential advancements can be made for a thriving research and development team. The applications which find the use of nanofibers start from nano – sensors to cosmetic skin grafting and are not limited to the life sciences but
go beyond the drug delivery system to wound dressings. A schematic depicting the potentials of electrospun fibers is shown in the following figure.

Figure 2.36 Schematic showing the potential applications of electrospun nanofibers [54].

Filtration is an area where the nanofibers find their obvious application. The porosity which can be controlled by electrospinning gives an added advantage to improve the efficiency of the filtration process.
Figure 2.37 The efficiency of filter increases with the decrease in fiber diameter [46]

A US patent [47] has claimed of a dust bag filter constituted of plurality of layers with at least one carrier material layer. The advancement in filters would result in reduced power of the vacuum cleaners without costing the cleaning capabilities [48].

In an attempt to develop hematopoietic stem/progenitor cell (HSPCs) colonies, Leong [49] demonstrated the use of electrospun fibers in proliferating and differentiating the cell colonies with improved adhesion which helped in the expansion.

Figure 2.38 SEM images of human cord blood HSPCs after a 10-day expansion culture on aminated PES nanofiber mesh (A–C) and on aminated PES film (D–F) at various magnifications. Abundant distinct, circular cell colonies are evident on the aminated nanofiber scaffold (black arrows). Filopodia extend from the cells and interact with the aminated nanofibers (white arrows). On aminated film, fewer cells are adherent without colony formation; cells appear to attach along cracks [49].
Leveraging the high surface to volume ratio of the electrospun fibers for an efficient drug delivery system Wang, Bochu [50] demonstrated that the encapsulating nanoparticles with loaded drugs in core region and sheath region can give an advantage of distinct release behavior.

Figure 2.39 a: LM image (40x) of Chitosan nanoparticles encapsulating Rhodamine B. b: The LM image (40x) of Chitosan nanoparticles/PCL composted core–sheath electrospun fibers, Chitosan nanoparticles encapsulating Rhodamine B (Core) and PCL embedding Naproxen (Sheath). c and d: The SEM image of Chitosan nanoparticles/ PCL composted core–sheath electrospun fibers. [50]
Figure 2.40  a: Fluorescent image of Chitosan nanoparticles-FITC/PCL core–sheath nanofibers. b: LSCM image of Chitosan nanoparticles-FITC/PCL core–sheath nanofibers; Chitosan nanoparticles labeled FITC shows green light [50]

The shapeability of electrospun PCL can be used as an advantage in the field of reconstructive surgery. The high porosity of ultrafine nanofibers and its slow degradation can be effectively used for the creation of a supporting atmosphere for cell cultivation. Vacanti [51] used electrospun PCL scaffolds to create an environment for mineralized tissue formation. This research can be further extended to treat bone defects.
Fig. 2.41 SEM micrographs of MSCs seeded on electrospun PCL scaffolds. (a) Scaffold prior to seeding. (b) Low magnification view of the cell-polymer constructs after 1 week of culture. (c) High magnification view of the cell-polymer constructs after 1 week of culture. (d) Low magnification view of the cell-polymer constructs after 4 weeks of culture.
(e) High magnification view of the cell-polymer constructs after 4 week of culture. Abundant calcification and collagen bundles are seen [51].

These are a handful of applications that find the use of electrospun fibers to a great extent. A number of patents has been awarded to researchers for developing a series of exceptional proof of concept prototypes. Although the field is exciting a great deal of work still demands the propagation of the technology from the lab set up to the commercial production stage. In future we can expect one of our gadgets or appliance using some of the electrospun fibers discussed here.
CHAPTER III
EXPERIMENTAL WORK

3.1 Materials

PVDF (Kynar761) was supplied by Arkema Incorporation and N, N-Dimethylformamide (DMF) and Acetone from Fisher Scientific are used to prepare two samples with different concentrations.

Liquid silicone rubber (Two component, copytex A and B ratio is 1:1) is ordered from YMOM. ERF was purchased from Smart Materials Laboratory Ltd, Hong Kong. Latex rubber was purchased from amazon dot com.

3.2 Electrospinning of PVDF

PVDF1 with 0.10 g/ml, PVDF2 with 0.15 g/ml and PVDF3 with 0.17 mg/ml are prepared by dissolving PVDF in DMF and acetone. The volume ratio is 7:3 at 40-50 °C. The samples are electrospun at 0.25 ml/h under an applied voltage of 20 kV with the help of a single syringe setup. The needle is positioned 15 cm from the collector i.e. aluminium foil and the samples are dried in a vacuum oven for 12 h at 50°C. ERF was purchased from Smart Materials Laboratory Ltd, Hong Kong. 0.5 g ERF was applied on fibers using a brush and allowed to dry at room temperature for 2 h. The setup used for electrospinning is shown in the Figure 3.1
3.3 Preparation of smart silicone rubber composite

The silicone rubber ordered from Make Your Own Molds Company arrived in two components. Part A is comprised of Vinyl dimethyl terminated polydimethylsiloxane(75%), silicon dioxide (25%) and Platinum dicarbonyl dichloride(0.01%), Part B is comprised of Vinyl dimethyl terminated polydimethylsiloxane(58.5%), Dimrthly siloxane fluid(13%), silicon dioxide (17.5%), Polymethyhydrogen siloxane(5%), Diatomaceous earth(5%) and Custom orange silicone pigment(%).

The Part A and Part B are mixed in equal proportions and 10% ERF by weight of the composite are thoroughly mixed. Due care to avoid air bubbles is taken and after 30
mins of mixing an overnight curing of the composite is allowed to take place. This allows ample time for the ERF to spread evenly and a smooth surface of smart silicone rubber is obtained. Figure 3.3 shows the pictures of the final product which are later cut into small sizes for experimentation.

![Figure 3.2. Smart silicone rubber composite.](image)

3.4 Perpetration of smart latex rubber composite

Latex rubber is comparatively easier to cure than the silicone counterpart. The latex rubber is mixed with 10% weight. The curing time is less than 3 hours. Increasing the percentage of ERF in the composite beyond 10% results in the disintegration of the composite.
3.5 Wooden rolling resistance measurement device

The device used to measure rolling resistance was adapted from the patent of Gent [. The device was improvised to be used under the influence of electric field. Wooden roller was constructed for the purpose as shown in the Figure 3.4

Figure 3.3 Smart latex rubber composite with ERF (left) and without ERF (right).

Figure 3.4 Wooden roller for measuring rolling resistance.
The wooden roller is setup on a platform to measure the rolling resistance. The following equation is used to compute the rolling force.

\[ Fr = mgL(\cos \Theta_{eval} - \cos \Theta_{st}) / d \]

where, \( \Theta_{eval} \) is the angular position of the pendulum bar after \( N \) oscillations, \( \Theta_{st} \) the angular position of the bar when pendulum is released, and \( d \) the distance covered in \( N \) cycles. Sample waveform generated during the rolling force measurement is shown in Figure 3.5

![Sample waveform generated during rolling resistance measurement.](image)

Figure 3.5 Sample waveform generated during rolling resistance measurement.

### 3.6 SEM Analysis

Surface topography is examined using a scanning electron microscope (SEM). Sample membranes are sputter coated with silver using (K575x, Emitech) for 1 min and 20 s at 55 mA.
Figure 3.6 Scanning electron microscopy.
CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 SEM analysis of responsive nano – fabrics

The morphology of responsive fibers was analyzed using SEM. Figure 4.1 shows the micrograph of electrospun PVDF with ERF particles adhered to it. The ER particles occupy the spacing between two adjacent fibers to bridge the gap. This moderately helps maintaining the current flow under the influence of applied electric voltage.
Figure 4.1 SEM micrographs of ERF adhered to PVDF fibers.

The three samples of PVDF viz. PVDF1, PVDF2 and PVDF3 were used to measure the rolling resistance as a composite after coating it with ERF. The results are discussed in later in this section. Change in concentration of PVDF helped in better alignment of fibers with PVDF3 giving the best alignment as seen in Figure 4.2. Better alignment of fibers is construed to be one of the factors affecting the improvement in the rolling resistance.
4.2 Rolling resistance of smart fabrics

When various samples of PVDF are infused with ERF, the interstitial spaces between fibers become infiltrated with nano ceramic particles. Under the influence of the applied electric field, the barium titanyl oxalates align themselves along the direction of the electric field as discussed in the ER mechanism previously, thereby increasing the stiffness of the fiber. Due to the decreased surface adhesion and increased overall stiffness, the fiber samples show improved rolling resistance as damping decreases. The non –
dimensional damping of the signal was calculated using equation X and Figure 4.3 represents the graph of the same.

![Graph of Damping Coefficient vs. Applied Voltage for PVDF 1, PVDF 2, and PVDF 3](image)

**Figure 4.3 Relationship between the damping coefficient and the applied voltage for PVDF 1, PVDF 2 and PVDF 3.**

As it can be seen in Figure 4.3, with the increase in the applied voltage from 0 KV to 20 KV, the damping coefficient reduces dramatically from 0.052 to 0.025 i.e. approximately 50% drop for PVDF 3 thereby exhibiting the responsive function of the phase transformation of ERF in reducing the damping of the overall composite system.

To calculate the coefficient of rolling resistance, equation X and X were used.

\[ C_r = \frac{F_r}{N} \]

where, \( C_r \) is the coefficient of rolling resistance, \( F_r \) the normalized rolling force and \( N \) the normal force.
Table 1 shows the change in the coefficient of rolling resistance as a function of applied electric field. A common trend of decreasing coefficient is evident as the applied voltage increases. As the voltage increases the nano particles align themselves to give increased stiffness to the composite.

**TABLE 4.1.** Coefficient of rolling resistance (C_r) of PVDF 1, PVDF 2 PVDF 3 as a function applied E-field strength.

<table>
<thead>
<tr>
<th>Applied Voltage(KV)</th>
<th>C_r for PVDF 1</th>
<th>C_r for PVDF 2</th>
<th>C_r for PVDF 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.002579</td>
<td>0.003731</td>
<td>0.002800</td>
</tr>
<tr>
<td>5</td>
<td>0.002431</td>
<td>0.003705</td>
<td>0.002668</td>
</tr>
<tr>
<td>10</td>
<td>0.002588</td>
<td>0.003477</td>
<td>0.002448</td>
</tr>
<tr>
<td>15</td>
<td>0.002396</td>
<td>0.003411</td>
<td>0.002030</td>
</tr>
<tr>
<td>20</td>
<td>0.001912</td>
<td>0.003140</td>
<td>0.001928</td>
</tr>
</tbody>
</table>

Figure 4.4 reconfirms the drop in C_r. This phenomenon clearly indicates that we can tune the damping as well as the coefficient of rolling force of the fibers impregnated with smart fluid suspensions by changing the applied voltage. The drop in rolling coefficients for PVDF 1, PVDF 2, and PVDF 3 are 26%, 16% and 32% respectively, implying that PVDF 3 with 0.17g/ml has the highest drop in the rolling coefficient for the given range of applied field strength.
Figure 4.4 Relationship between the coefficient of rolling resistance (Cr) and applied voltage for PVDF 1, PVDF 2 and PVDF 3.

A schematic representation of the activities taking place in the experiment is shown in Figure 4.5.

Figure 4.5 Schematic representation of ER fluid stiffening under applied electric field.

4.3 Preliminary Yield stress measurement of ERF
The preliminary yield stress of ERF was measured before proceeding for ER composites. The setup used for the measuring the preliminary yield stress of ERF comprised of an electrified copper channel which was filled with ER fluid as shown in Figure 4.6

![Setup used for measuring the yield stress (preliminary) of ERF. The encircled part (right) shows solidified ERF upon the application of voltage.](image)

Crocodile clips connected to the power supply were attached to the electrodes to generate electric field in the copper channel. A load cell was connected to a circular stub of 8mm which acts the receptor for the load cell. Every time the receptor makes a contact with ERF and subsequent downward motion, a corresponding value of load is generated with the help of load cell. The values obtained were in the order of kPa which shows that the final yield stress of the fluid was not reached. The graph of preliminary yield stress was plotted against the voltage/mm showed in the Figure 4.6
The values obtained and as shown in the graph above are a crude measurement of yield stress. Higher level of sophistication is needed to measure the yield stress with voltage ranging from 1000 – 1500 V/mm. The limitation of the device was also due to the dielectric breakdown occurring due to the proximity of electrodes which resulted in electric sparks at higher voltage ranges (> 20 kV).

4.4 Responsive nano – fabric experiment

Nano – fabrics were subjected to change in electric field to observe the responsiveness due to the ER fluid particles impregnated in them. The experimental setup as shown in the Figure 4.7 was established to prove the concept.
Figure 4.8 Experiment showing the shift in position of Responsive nano – fabric with impregnated ERF particles

With the increase in electric field, the fibers showed a shift in position. The fiber which was attached to a string is attracted to the electrodes in the Figure 4.7 above. This shift in position is related to the nano particles impregnated with ERF. Due to the applied potential difference between the electrodes the particles tend to move towards the electrodes. This phenomenon implies that with the ERF integration, smart fibers can be produced for various applications. The smart fibers can be used as responsive sensors with the added advantage of flexibility.

Figure 4.8 SEM pictures of responsive nano fibers impregnated with ERF.

4.5 Smart silicone rubber composite
Smart silicone rubber composite created by curing silicone rubber with ERF in the lab was subjected to change in electric field to observe its responsiveness. Small rectangular pieces of silicone composites were tied to thread and strung with a dial in the background as shown in the Figure 4.9.

![Smart silicone rubber composite](image)

Figure 4.10 Experiment showing smart silicone rubber composite responding to the change in electric field.

As seen in the Figure 4.9, when there is no application of the electric field, the smart composite holds its neutral position i.e. at 0kV there is no change in the position of the composite. But as soon as the electric field is increased to 5kV there is a shift in the position of the composite. This is due to the fact that the ER particles tend to align themselves to the change in voltage and thus responding by shift in position. As the voltage is increased further, the composite moves further closer to the electrode. At 15kV the composite comes in contact with the electrode as seen above. The exaggerated view of smart composite is shown in figure 4.10
The ER particles are hypothesized to move through the interstitial space within the vulcanized silicone composite. This movement of nano–ER particles upon the application of electric field is construed to be the reason for the movement of composite toward the electrode. The shift in position further corroborates the hypothesis. EDX was used to determine the dispersion of ERF in the silicone rubber and Figure 4.11 shows the images.

Figure 4.12 EDX micrographs showing the dispersed components in the composite.
4.6 Smart latex rubber composite

The silicone rubber composite concept was further extended to latex rubber and similar process was adopted to test the performance of the latex rubber composite. As the percentage of ERF increases in the latex rubber, the composite disintegrates abnormally. This deters the use of higher percentages of ERF into latex for further research purpose. Figure 4.11 shows the effect of electric field on latex rubber composite.

![Image of experiment showing smart latex rubber composite responding to the change in electric field.](image-url)

Figure 4.13 Experiment showing smart latex rubber composite responding to the change in electric field.

The latex rubber composite responds to lower range of electric field as contrasted to silicone composite. The composite cut out from a larger piece of composite moves completely towards the electrode at about 9kV of applied voltage between the electrodes. This can be attributed to the fact that the latex composite carries many nano – ER particles near the surface making it convenient to respond with the applied electric voltage. The only
limitation is the faster disintegration during curing process of latex making it difficult to increase the percentage of ERF in the composite.
CHAPTER V

CONCLUSIONS

5.1 Conclusions

The electrorheological fluid was studied alongside for potential applications of developing composites for tunable rolling resistance. Silicone rubber composite, latex rubber composite and PVDF impregnated ER composites were prepared in the lab for measuring the change in properties. A wooden roller was successfully crafted for measuring the rolling resistance of the ER composites. It was established that the rolling resistance of the fiber composite changes with the change in electric field. The silicone and latex rubber composites also showed promising results with respect to their responsiveness. This provides a concrete platform for future investigation of their properties.

5.2 Future work

With the development of promising composites containing ER fluids as a fundamental constituent, the research has laid a solid foundation for the further
investigation and incorporation of these products into commercial applications. The behavior of silicone rubber with respect to wear and abrasion resistance needs to be further studied to incorporate them in tires with tunable rolling resistance. The use of different fiber material in fiber composites can give a range of properties which can be leveraged for different applications.
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