INVESTIGATION AND OPTIMIZATION OF PARTICLE-REINFORCED RUBBER COMPOSITES FOR ENHANCED MECHANICAL AND WEAR PROPERTIES

THESIS SUBMITTED IN PARTIAL FULFILLMENT
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SUBMITTED BY

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CERTIFICATE APPROVAL*

This foregoing thesis entitled **"Investigation and optimization of particle-reinforced rubber composites for enhanced mechanical and wear properties"** is hereby approved as a credible study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

Committee
On Final Examination for
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1) ______________________________

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CERTIFICATE OF RECOMENDATION

This is to certify that the thesis entitled, **"Investigation and optimization of particle-reinforced rubber composites for enhanced mechanical and wear properties"** which is being submitted by **Mr. Sagar Kumar Barman** in the partial fulfillment of the requirements for the award of degree of Master of Mechanical Engineering of Jadavpur University, Kolkata – 700032 during the academic year 2021 – 2023, is the record of student's own work carried by him under the supervision of **Prof. Nipu Modak and Prof. Dulal Krishna Mondal**.

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as a part of his Master of Mechanical Engineering studies.

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by this rule and conduct, I have fully cited and referred all material and results that are not original to this work.

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Dedicated to
My Parents,

C O N T E N T S

ABSTRACT

Particle reinforced rubber composites offer a promising avenue for developing materials with improved mechanical and wear properties, catering to a wide range of applications. This thesis aims to investigate the influence of particle fillers on the mechanical and wear behavior of rubber composites, while optimizing the composite formulation and processing parameters to achieve superior performance. The research encompasses a comprehensive analysis of various particle types, concentrations, and manufacturing techniques, with a focus on enhancing the composite's strength, stiffness, and resistance to wear. Experimental characterization methods, such as tensile testing, hardness measurement, and wear analysis, will be employed to evaluate the performance of the developed composites. The findings from this study will contribute to the understanding of particle-reinforced rubber composites and facilitate the development of advanced materials for demanding applications.

Chapter 1

Introduction

1.1 Background

Rubber is a versatile material with a wide range of applications. However, the mechanical properties of pure rubber are not adequate to meet the present need. Particle-reinforced rubber composites offer a way to improve the mechanical and wear properties of rubber, making it suitable for more demanding applications including tires, seals, gaskets, and bearings. They are also being investigated for use in new applications, such as artificial joints and medical implants. In a particle-reinforced rubber composite, particles of a reinforcing material, such as carbon black, silicon carbide, silicon, titanium oxide, magnesium hydroxide, aluminium oxide etc. are added to a rubber matrix. The particles are dispersed throughout the matrix, forming a network that helps to improve the strength and wear resistance of the composite. A composite material can be defined as a combination of two or more chemically distinct constituents, on a macro-scale, having a distinct interface separating them. One or more discontinuous phases are therefore embedded in a continuous phase to form a composite, **Agarwal et al. [1]**.

The type, size, and concentration of the reinforcing particles can be varied to optimize the mechanical and wear properties of the composite. For example, carbon black particles are more effective at improving the tensile strength of rubber composites, while silica particles are more effective at improving the tear strength.

The most common reinforcing particles used in rubber composites are carbon black, silica, and glass fibers. Each type of particle has its own advantages and disadvantages. Carbon black is the most effective at improving the tensile strength of rubber composites, while silica is the most effective at improving the tear strength. Glass fibers are the most effective at improving the stiffness and strength of rubber composites.

The size of the reinforcing particles has a significant impact on the mechanical and wear properties of the composite. Smaller particles are more effective at improving the tensile strength and tear strength, while larger particles are more effective at improving the abrasion resistance.

The concentration of the reinforcing particles also has a significant impact on the mechanical and wear properties of the composite. With increasing concentration, the mechanical properties of the composite improve, but the processability and flexibility of the composite decrease.

In recent years, there has been a growing interest in the use of recycled rubber powder as a reinforcing agent in rubber composites. Recycled rubber powder is a low-cost, environmentally friendly alternative to virgin rubber. It has been shown to be effective at improving the mechanical and wear properties of rubber composites.

The development of particle-reinforced rubber composites is an ongoing area of research. As research continues, it is likely that the performance of these composites will continue to improve, making them even more suitable for demanding applications.

1.2 Objectives

Based on the aim of the research, the objectives are outlined to accomplish the goals as mentioned below

- To fabricate the particle reinforced rubber composites considering different types of particles.
- To study mechanical properties like hardness and strength of particle reinforced rubber composites.
- To study tribological behaviour (wear and friction) of the particle reinforced rubber composites.
- To optimize parametrically the tribological behaviour of the particle reinforced rubber composites.
- Investigate the effects of different types of reinforcing particles on the mechanical and wear properties of rubber composites.
- This objective will be achieved by conducting of experiments to measure the tensile strength, hardness, wear and coefficient of friction of particle reinforced rubber composites.

The research findings will be useful for the design and development of particle reinforced rubber composites with enhanced mechanical and wear properties for a variety of applications.

1.3 Scope and Limitations

Scope:

The scope of this research will be limited to the following:

- Particle reinforced rubber composites considering different types of filler particles like silicon metal powder, silicon carbide, magnesium hydroxide, aluminum oxide and titanium oxide are to be fabricated.
- Mechanical and tribological characterization of the particle rubber composites are to be performed.
- The effects of types of particles on the mechanical properties of the rubber composites are to be investigated experimentally.
- The effects of types of particles on the tribological behaviour of the rubber composites are to be investigated experimentally.

Limitations:

The following are some of the limitations of this research:

- The research will be limited to the mechanical and wear properties.
- The research will be conducted using a limited number of reinforcing particles, sizes, and concentrations.
- The research will not address the environmental impact of particle-reinforced rubber composites.
- The type of rubber matrix used may affect the results of the research.
- The processing conditions used to produce the rubber composites may also affect the results of the research.
- The research may not be able to account for all of the factors that affect the mechanical and wear properties of rubber composites.

The research findings will be useful for the design and development of rubber composites with enhanced mechanical and wear properties for a variety of applications.

1.4 Thesis Organization

The present thesis is organized as follows:

Chapter 1: Includes General Introduction, Objectives, Scope and Limitation to the subject designed to provide a summary of the basic understandings already available involving the issues of interest. It presents the research work on particulate reinforced rubber composites by various investigators.

Chapter 2: Includes the Literature Review on Mechanical and Tribological Behaviours of the raw materials used for the processing of Particulate and Fiber Reinforced Rubber Composites. It presents the type of fillers, effect of particulate fillers on rubber composites. It contains the methods involved for mechanical and tribological characterization of the composites under investigation.

Chapter 3: Presents the Materials and Method of particle reinforced rubber composites and also mentioning the physical and mechanical properties of the composites under study.

Chapter 4: Includes the Results and Discussion of particle reinforced rubber composites with the curve, bar diagram and optimization technique.

Chapter 5: Provides Summary of the findings of this research work outlines specific conclusions drawn from the experimental investigation and suggests ideas and directions for future research.

Chapter 2

Literature Review

2.1 Particle-Reinforced Composites

Particle Reinforced rubber composites have been largely used in applications like aerospace, automotive, marine, and other civil structures, where mechanical and tribological properties are of prime consideration. In this section, a comprehensive literature review on the mechanical and tribological behaviour of rubber composites based on particle reinforced is introduced. The effects of physical characteristics of different types of particle reinforced rubber composites on the mechanical and tribological properties of several thermoset and thermoplastic rubbers are addressed. Also, the effects of the tribological operating parameters such as applied load, sliding velocity, samples and sliding distance on the frictional and wear performance of particle reinforced rubber composites are demonstrated. The data and analyses available in the literature revealed that the type of treatment and physical characteristics of the reinforced particle significantly influence the mechanical and tribological behaviour of composites. The most influence key in designing reinforced particle/rubber composite is the interfacial adhesion of the particle with the matrix. Frictional characteristics of the reinforced particle rubber composites are poor and solid lubricants are recommended to reduce the friction coefficient of the materials.

Presently, it is rare to employ the rubber polymer in its natural unfilled condition. Most of the engineering rubber has various ranges of particulate additives during manufacture, such as fillers. Different types of particulate fillers (carbon black, silica and zinc oxide etc.) are added for several reasons, for instance reinforcing the elastomers, reducing the material cost and supporting the processing. Consequently, the final rubber products can attain longer life time, higher strength and more satisfied modulus of elasticity. **Agarwal et a**l.**[1]** produced rubber composites based on acrylonitrile-co-butadiene rubber (NBR) reinforced with particulate fillers (carbon black and silica) and short fibre (aromatic polyamide, Kevler). Mechanical properties of these composites were determined and compared with unfilled rubber vulcanisate. The effect of surface treatment on the improvement of strength, in case of Kevlar, was considered. **Martins and Mattoso [2]** prepared composites made from powdered tire rubber and sisal fiber by hot-press molding and investigated the effects of fiber length and content, chemical treatments, and temperature on dynamic mechanical and tensile properties. **Laura et al**.**[3]** analyzed the effects of rubber type and particle size on the mechanical properties of glass fiber reinforced blends of nylon 6 and EPR/EPR-gMA or SEBS/SEBS-g-MA. **Zhang et al**.**[4]** developed and manufactured a series of rubber composites by mixing a nano-magnesium hydroxide powder and three kinds of micro-$Mg(OH)_2$ having different particle sizes with ethylene–propylene–diene monomer rubber (EPDM). The results showed that the mechanical properties of composites improved with decreasing particle size. **Zhao et al**.**[5]** fabricated silica- and carbon-filled styrene butadiene rubber (SBR) composites and investigated the influence of particle type and silane coupling agent on cure characteristics, physical and dynamic mechanical properties of particle-reinforced SBR. The authors showed that tensile strength was improved more and more by increasing the filler content. **Chen et al.[6]** carried out methodically the tensile and tear tests based on silicone rubber composites reinforced by silica particles ranging from tens of to hundreds of nanometers (nano-scale to submicro-scale). The ultimate strength, fracture toughness and the fracture tensile strain of the composites are determined and analyzed. The morphology and evolution of the composite microstructures are also carefully characterized. **Arani et al.[7]** studied experimentally the erosion of rubber particle-reinforced epoxy composites by angular silicon carbide particles. The erosion rates were found to be considerably lower than the pure epoxy for all experimental conditions. **Liu et al**.**[8]** developed a bulk modification method to attain a novel nanoparticle-reinforced silicone rubber composite having high strength and strong adhesion. The tensile strength and shear adhesive strength of the new composite can reach up to 10.4 MPa and 90 kPa, respectively, both of which are much higher than their counterparts in the popular silicone rubber product Sylgard184. In rubber composites, some commonly used conventional reinforcing fibers are aramid, glass, carbon, metallic, ceramic fibers etc. Apart from this, other type commonly used fibers are natural fibers for rubber reinforcements such as short jute, short coir, bamboo, sisals, hemp, grass, pineapple leaf etc. A number of research work available on the conventional and natural fiber reinforced rubber composites. **Irez et al**.**[9]** fabricated the epoxy-rubber composites reinforced with alumina fibers (Al_2O_3) using powder metallurgy technology and evaluated their mechanical properties employing drop weight tests, three-point bending tests and nanoindentation techniques. The authors used scanning electron microscope

(SEM) to examine fracture surfaces and the microstructure of the composites. **Kabakci et al**.**[10]** designed and manufactured economical devulcanized recycled rubber based composites reinforced with glass bubble microspheres, short glass fibers and fine gamma alumina fiber (γ-Al_2O_3). The authors analyzed thoroughly the related toughening mechanisms for the most appropriate reinforcements and some mechanical and physical properties were estimated by means of fracture toughness experiments. **Gao et al.[11]** predicted the mechanical properties of rubber composites reinforced by short aramid fiber under large deformation using finite element based numerical and experimental approaches. In their work, the effects of the fiber volume fraction, fiber length, and fiber elastic modulus on the mechanical response were discussed. **Yin et al.[12]** performed the fatigue crack growth tests under variable fatigue strain loadings and analyzed the influence of aramid fibres (AFs) on the crack growth of reinforced styrene-butadiene rubber/CB composites (SBR/CB/AF) in the fatigue process. The behaviour and mechanism of the fatigue crack growth in aramid-fibre reinforced styrene–butadiene rubber were discussed. In a similar study. **Zhang et al.[13]** investigated the true stress evolution of aramid fiber (AF) reinforced styrene butadiene rubber (SBR)/carbon black (CB) composites having different interface characteristics in the fatigue failure procedure. The authors found the significant reduction in the fatigue crack growth rate of the rubber composites reinforced by a coated fiber with a flexible interface layer was significantly reduced. **Ji et al**.**[14]** studied effect of surface treatment of aramid fiber (AF) on the properties of reinforced aramid fiber/carbon black/butadiene benzene ethylene rubber (AF/CB/SBR) composites. The results signified that compared with that of the composite with untreated AF, the interfacial bonding between the treated AF and the rubber matrix was enhanced, particularly for tensile modulus elongations of 100% and 300%. **Zhang et al**.**[15]** fabricated the carbon fiber natural rubber composites and studied the mechanical and thermal properties experimentally. The authors found that the addition of carbon fiber resulted in the significant improvement of the mechanical properties of rubber composites. The addition of carbon fiber would improve the aging resistance of rubber and maintain the property of rubber matrix. The addition of carbon fiber could improve the decomposition temperature effectively and enhance the heat-conducting property. **Mahesh et al**.**[16]** designed and fabricated a novel composite prepared from naturally available jute fiber and rubber matrix material using compression moulding machine to carry out physio-mechanical analysis and wear characterization. The tensile, tear, specific wear rate and hardness were found to better with a composite having minimum number of plies. **Ferreira et al.[17]** manufactured scrap rubber/epoxy composites reinforced with Aluminium, Alumina Fibre and TiO2 particles and mechanical and tribological properties of these composites were investigated. The microstructure and matrix/reinforcement interface analyses were performed with the aid of Scanning Electron Microscope (SEM). The wear performance of hard particles reinforced composites were evaluated in view of micromechanical properties. **Patel et al**.**[18]** illustrated aluminum (Al) reinforced silicone rubber (SR) particles and mechanical and tribological properties of these composites were prepared, and the effects of the content, particle size, shape, and surface modification of Al particles on the dielectric properties and thermal conductivity of the Al/SR were investigated. Dielectric permittivity, dissipation factor and thermal conductivity of the Al/SR increase with increasing the filler content. Decrease in particle size and surface modification of Al can increase the dielectric permittivity and thermal conductivity of the Al/SR composites. Suggesting that the ternary composites has potential applications in electromechanical actuators because of their high dielectric permittivity and thermal conductivity but low dissipation factor, and good elasticity. **Han et al.[19**] obtained and introduces silicone rubber (SR) into high-density polyethylene/magnesium hydroxide (HDPE/MH) composites by melt blending, and the electron beam irradiation was used to prepare the irradiation crosslinked flame retardant HDPE composites. The changes of properties of the samples were investigated by melt index test (MI), mechanical property test, thermal stability test (TG/DTG), oxygen index test (LOI) and cone calorimetry (CCT). MI test results indicated that SR can increase the internal lubricity of HDPE composites. **Duan et al**.**[20]** improved mechanical, thermal conductivity and low heat build-up properties of natural rubber composites with nano-sulfur modified graphene oxide/silicon carbide when SiC/GO-S (SG-S) filler was added to NR, the tensile strength, thermal conductivity and low heat generation properties are higher than those of NR/GO rubber by 22.5%, 21.2% and 8.3%. **Kulkarni et al.[21]** investigated the prepared natural rubber composites using silicon carbide and titanium dioxide as filler in different proportions. Curing characteristics were investigated as a function of filler loading and filler proportion. Mechanical properties like tensile strength, tear strength, hardness, elongation at break and modulus were determined. Both tensile strength and modulus were found to increase with SiC (Silicon carbide) content which may be due to the restrictions offered by filler particles to the rubber chain mobility. Cure properties also support the reinforcing capacity of SiC filler in the natural rubber matrix.

Naphon et al.[22] obtained the TiO_2 nanoparticles have a significant effect on the increasing thermal conductivity while the electrical resistivity tends to decrease with increasing nanoparticle content. However, the tensile stress of the rubber compound tends to increase. The results obtained from this study disclose different properties that influence the strength, thermal and electrical resistance of latex rubber based composites reinforced by surface unmodified and modified nanoparticles. **Patil et al.[23]** investigated the incorporation of nano filler Mg(OH)2 particle reinforced rubber nano composites improved the properties of Polymers are often filled with particulate fillers in order to improve the stiffness, to enhance barrier properties, to enhance resistance to fire and ignition, or simply to reduce the cost. **Agrawal et al.[24]** discussed the innovation, characterization, and execution of low density, corrosion resistant and low cost raw material and manufacturing of polymer based composite materials. Based on that, a series of novel flexible hybrid composites consisting of aluminium oxide (Al2O3) and solid glass microspheres (SGMs) in an epoxy matrix for high performance microelectronic components are designed and fabricated. Their physical, mechanical, thermal, and dielectric properties are studied. The measured thermal conductivity values are compared with calculated values obtained from the already established mathematical model and are found to be in good agreement with experimental findings. Result indicates that compared with raw epoxy, effective thermal conductivity and dielectric constant increases with Al2O3 content and decreases with SGM content. Meanwhile, glass transition temperature increases whereas coefficient of thermal expansion decreases with either of the filler content. **Kumar et al.[25]** fabricated rubber composites of hybrid filler with few-layer grapheme along with the particle titanium dioxide and another particle iron oxide shows in the experiments the inclusion of iron oxide (Fe3O4) or TiO2 fillers in RTV-SR improves mechanical, actuation, and magnetic properties. **Cheng et al.[26]** illustrated alumina/silicone rubber composites were prepared using thermally conductive alumina as fillers and their thermal conductivities were measured as a function of alumina loadings. The effects of phases and morphologies of fillers on the thermal conductivity were studied. Under a low filling fraction, porous sintered a-Al2O3 has a more distinct effect to enhance the thermal conductivity of composite, compared with c-Al2O3 and spherical solid aAl2O3. Owing to its spherical morphology of solid aAl2O3, the highest filler loading can be achieved, under a mass content of 82 % delivering a thermal conductivity of 1.41 W/(m K), 6 times higher than pure silicone rubber. Meanwhile, the thermal stability of the silicone rubber composites is also increased with a high alumina loading. Both phase and shape of filler particles are important for the fabrication of alumina/silicone rubber composite.

2.1.1 Types of Particle Fillers

Singh et al.[27] review the use of different fillers with natural fiber hybrid composites and their response on mechanical properties. The various fillers like Titanium Oxide (TiO_2), Aluminum Oxide (Al_2O_3), Calcium Carbonate ($CaCO_3$), Silicon carbide (SiC), Zinc Oxide (ZnO) , Zirconium Oxide (ZrO_2) in varying ratios improves mechanical characters of natural fiber composites. Chi et al. [28] SiC filler can significantly improve the electrical conductivity of SiR-based composites compared to pure SiR and induce excellent nonlinear conductivity, and the thermal and mechanical properties of the resulting SiR-based composites are improved, accompanied by a decrease in breakdown strength. The nonlinear coefficient and thermal conductivity of the composites increased with increasing filler content, the maximum nonlinear coefficient and thermal conductivity were 0.69 and 0.229 W/(mK), respectively, and the breakdown strength decreased significantly. **Chen et al.[29]** found that, when the particle content is fixed, the ultimate strength, fracture toughness and fracture tensile strain of the composite exhibit monotonic increase with the decrease of particle size. In the composite filled with monodispersed submicro-particles, the improved strength is due to the hindering effect of particles on the crack propagation and the strong interface bonding between particles and matrix, while the improved toughness is mainly resulted from the crack-pinning around particles. the composite filled with small nano-nanoparticles shows remarkably improved mechanical properties in comparison with the composite filled with submicro-particles. The present work should provide insights for optimally designing a flexible composite with both desirable strength and toughness. **Gao et al.[30]** investigated and conducted systematically to measure the effective thermal conductivities of composite materials made of methyl vinyl silicone rubber and spherical Al_2O_3 particles of four different mean diameters (3, 10, 35, and 75mm), with volume fractions ranging from 0.05 to 0.62. The results show that for each particle size, effective thermal conductivity of composite increases with increasing particle volume fraction and the rate of change in effective thermal conductivity increases with increasing volume fraction. This suggests that the higher the volume fraction, the more particles per unit volume are in contact to form conducting network. With regard to a fixed volume fraction, effective thermal conductivity of composites increases with increasing mean particle diameter, which suggests that thermal tortuosity increases with the decrease in mean particle diameter, equivalently with the increase in specific area. The results of this study clearly indicate that the contact between particles is a very important mechanism that affects effective thermal conductivity of composites with particle fillers. **Debnath et al.[31]** illustrated the effective bonding between the filler and matrix components typically improves the mechanical properties of polymer composites containing inorganic fillers. The aim of this study was to test the hypothesis that composite flexural modulus, flexure strength, and toughness are directly proportional to filler–matrix interfacial shear strength. **Chattrairat et al.[32]** investigated comprehensive assessment of the tensile, compressive, and hardness properties of the examined composites was conducted, and they were compared with the properties of human biological skin. The results exhibited that the elastic moduli and the hardness of all composites increased with the concentration of both reinforcements. While integrating only the bioglass particles had the advantage of an insignificant effect on the hardness change of the silicone matrix, the composite with polyethylene fibres possessed superior tensile elastic modulus and tensile strength compared to those of the bioglass reinforced composite. The composites with 5% untreated polyethylene fibres, $KMnO_4$ surface-treated fibres, and bioglass reinforcements enhanced the tensile elastic moduli from the pure silicone up to 32%, 44%, and 22%, respectively. It reflected that the surface treatment of the fibres promotes better interfacial adhesion between the silicone matrix and the fibres. Moreover, the smaller bioglass particle had a greater mechanical contribution than the larger glass particle. Systematically characterised for the first time, the developed composite skin simulants demonstrated essential mechanical properties within the range of the human skin and constituted better skin alternatives than pure silicone for various biomedical applications.

2.1.2 Effects of Particle Fillers on Rubber Composites

Agarwal et al.[1] found that both particulate fillers and short fibres can improve the mechanical properties of rubber composites. Particulate fillers, such as carbon black and silica, can increase the stiffness and tear strength of the composites. Short fibres, such as Kevlar, can further improve the tensile strength and impact strength of the composites. **Debnath et al.[31]** carried out effective bonding between the filler and matrix components typically improves the mechanical properties of polymer composites containing inorganic fillers. The aim of this study was to test the hypothesis that composite flexural modulus, flexure strength, and toughness are directly proportional to filler–matrix interfacial shear strength.

2.2 Mechanical Properties of Particle-Reinforced Rubber Composites

Debnath et al.[31] carried out the Effective bonding between the filler and matrix components typically improves the mechanical properties of polymer composites containing inorganic fillers. The aim of this study was to test the hypothesis that composite flexural modulus, flexure strength, and toughness are directly proportional to filler–matrix interfacial shear strength. **Khan et al.[33]** illustrated the filler material used for the enhancement of mechanical and thermal properties are Aluminium oxide (Al_2O_3), Zinc oxide (ZnO), Silicon carbide (SiC), Silica (SiO_2) and carbon black (CB). Different filler concentrations of particles were used in SiR polymer matrix and their effect on the mechanical and thermal properties were evaluated and to do the research on Numerical analysis, Filler concentration, Filler material, Polymer composites.

2.2.1 Tensile Strength and Modulus

Lee Dong-Joo.[34] investigated the measured tensile strength increased with increasing particle loading and decreased with increasing particle size. The measured fracture toughness increased with increasing particle size. A fracture mechanical model to predict the tensile strength was developed to better understand the reinforcing effects of the particle and to provide a criterion for a better composite. The tensile strength as a function of the measured fracture toughness (J value) and the modulus of the matrix can be calculated by comparing the energies. The predicted tensile strength decreased with increasing particle size in a similar manner to the experimental results. **Debnath et al.[31]** carried out effective bonding between the filler and matrix components typically improves the mechanical properties of polymer composites containing inorganic fillers. The aim of this study was to test the hypothesis that composite flexural modulus, flexure strength, and toughness are directly proportional to filler–matrix interfacial shear strength.

2.2.2 Hardness

Chattrairat et al.[32] conducted comprehensive assessment of the tensile, compressive, and hardness properties of the examined composites and they were compared with the properties of human biological skin. The results exhibited that the elastic moduli and the hardness of all composites increased with the concentration of both reinforcements. While integrating only the bioglass particles had the advantage of an insignificant effect on the hardness change of the silicone matrix, the composite with polyethylene fibres possessed superior tensile elastic modulus and tensile strength compared to those of the bioglass reinforced composite. The composites with 5% untreated polyethylene fibres, $KMnO_4$ surface-treated fibres, and bioglass reinforcements enhanced the tensile elastic moduli from the pure silicone up to 32%, 44%, and 22%, respectively. It reflected that the surface treatment of the fibres promotes better interfacial adhesion between the silicone matrix and the fibres. Moreover, the smaller bioglass particle had a greater mechanical contribution than the larger glass particle. Systematically characterised for the first time, the developed composite skin simulants demonstrated essential mechanical properties within the range of the human skin and constituted better skin alternatives than pure silicone for various biomedical applications. **Debnath et al.[31]** carried out effective bonding between the filler and matrix components which are typically improves the mechanical properties of polymer composites containing inorganic fillers. The aim of this study was to test the hypothesis that composite flexural modulus, flexure strength, and toughness are directly proportional to filler–matrix interfacial shear strength.

2.3 Wear Behavior of Particle-Reinforced Rubber Composites

Hu et al.[35] deduce the dependence of erosion on impact angle for Si showed a typically brittle response while that for RB-SiC/Si showed a semi-brittle response when using small particles, but displayed a typically brittle response when using large particles. Particular attention should be paid to the synergistic effect between the material microstructure and employed particle size, which has an inherent correlation to the shift in maximum erosion from 90° to 75°/80°. Achieved erosion information may provide reference for the jet machining of composite materials and the design of functional materials with erosion-resistant structure in the future. **Prabanjan et al.[36]** found that the corrosion performance is to be increased. Particle Reinforced Metal Matrix Composite (PRMMC) is an emerging technology in hardfacing that will enhance the tribological performance of the components by adding hard metal or ceramic particles in the existing alloys. Tungsten Carbide (WC) is often selected as reinforcement in PRMMC to improve the wear and erosion behavior.

2.3.1 Wear Mechanisms

Khafidh et al.[37] carried out a pin-on-disc tribometer and a microscope which are used to analyze the friction and wear mechanisms of the elastomeric composites in sliding contact with a granite counter surface. The results show that the coefficient of friction of the composites consists of different stages, these stages are influenced by the wear processes during sliding. For elastomers which are reinforced by short-cut aramid fibers and silica, a higher energy input is needed to achieve all stages since the presence of silica in the elastomer matrix increases the resistance of matrix particle detachment. A general friction behavior of short-cut aramid fiber and silica reinforced elastomers is proposed. **Ala-Kleme et al.[38]** attributed to the different wear mechanics and consequently wear mechanisms in the two tests. In the dry sand rubber wheel abrasion test abrasion and detachment of the reinforcements are the major wear mechanisms while in the cone crusher abrasion with rock sliding and pure indentation are the major wear mechanisms. The differences in wear mechanisms result from differences in abrasives (type, size and hardness) and other wear conditions. It is concluded that dry sand rubber wheel abrasion test should not be used for screening materials for rock crushing applications as far as metal matrix composites are concerned.

2.3.2 Factors Influencing Wear Resistance

Prabhu et al.[39] developed a wear model based on the discrete lattice spring–mass approach to study the effects of particle volume fraction, size, and stiffness on the wear resistance of particle reinforced composites. The model predicts that (i) increasing volume fraction, reducing particle size and increasing particle stiffness enhance the wear resistance of the particle reinforced composites, (ii) the particle stiffness is the most significant factor affecting the wear resistance of the composites, and (iii) the wear resistance reduced above the critical volume fraction (Vc), and Vc increases with increasing particle size. Finally, we have qualitatively compared the model results with our previously published experimental results to prove the effectiveness of the model to analysis the complex wear systems. **Ulfah et al.[40]** studied the mechanical properties such as hardness, abrasion resistance and tensile stress at 300% elongation. In the hardness and abrasion resistance measurement, the higher ratio CB/Si decrease contribution of silica, which resulting smaller of hardness value. Ratio CB/Si 40/20 gives an optimum filler blended. It is also clearly understood that higher abrasion resistance mainly due to the lower hardness value under the same condition. The tensile stress at 300% elongation of rubber compound increased with the increasing carbon black filler.

2.4 Current Manufacturing Techniques for Particle-Reinforced Rubber Composite

Bhudolia et al.[41] investigated the static indentation properties of composite laminates toughened by the addition of core-shell (C/SH) particles at the interfaces of non-crimp carbon fibre (NCCF)/Elium® composite laminate. NCCF/Elium® composite exhibited improved static indentation performance with an increase in the feed rate. There is a 19.6% and 13.5% increase in peak load with no particle reinforcement and 5% C/SH respectively when the feed rate was increased from 1 mm/min to 10 mm/min. **Chattrairat et al**.[32] studied the various factors, including filler concentration, KMnO4 surface treatment of the polyethylene fibre, and particle size. A comprehensive assessment of the tensile, compressive, and hardness properties of the examined composites was conducted, and they were compared with the properties of human biological skin. The results exhibited that the elastic moduli and the hardness of all composites increased with the concentration of both reinforcements.

2.4.1 Mixing and Compounding Methods

Yang et al.[42] illustrated the modified silica slurry which was prepared in cyclohexane with an interfacial modification technology, and the mixing between the silica and rubber molecular chains was completed in the organic phase. Favorable processing properties were confirmed using the Mooney viscosity test. Compared with the in situ modified silica/NR composites made using dry blending, the silica/NR composites made via solution compounding had better filler dispersion, better mechanical properties, lower tanδ and lower rolling resistance. Thus, the preparation of a silica/NR masterbatch using solution compounding provides a new procedure for the preparation of silica/NR compounds with excellent performance for "green tires. **Yan et al**.[43] studied the experimental results and finds that the theoretical models of Halpin–Tsai–Nielsen and Nicolais–Narkis can be used to predict the tensile moduli and the tensile strengths, respectively, for the particulate reinforced composites produced by the rotational moulding process when uniform distribution of reinforcement is achieved. The scanning electron microscopic images show that an even distribution of particles within the product wall can be achieved in two ways: direct manual mixing method for bigger sized particles (90–240 μm) and melt compounding method for smaller particles (6.5–35 μm). It is also found that with around 2 vol% of the smallest Spheriglass 5000 beads added by the melt compounding method, the tensile strength remains almost the same and the tensile modulus reaches a 20% improvement above that of pure LMDPE and also Compared to direct mixing, melt compounding has been shown to be a better method for preparing the charge material for rotational moulding when fine glass beads. **Peng et al**.[44] found that MWCNTs are homogenously dispersed in the natural rubber (NR) latex as individual nanotubes since strong self-aggregation of MWCNTs has been greatly depressed with their surface functionalization. The well-dispersed MWCNTs produce a remarkable increase in the tensile strength of NR even when the amount of MWCNTs is only 1 wt.%. Dynamic mechanical analysis shows that the glass transition temperature of composites is higher and the inner-thermogenesis and thermal stability of NR/MWCNT composites are better, when compared to those of the pure NR. The marked improvement in these properties is largely due to the strong interfacial adhesion between the NR phase and MWCNTs. **Zeng et al.[45]** studied the ceramic/polymer composites with co-doped TiO_2 particles embedded into the silicone rubber matrix were prepared by mechanical mixing and hot-pressing method. With surface modification of the co-doped TiO_2 particles by H_2O_2 activation and silane coupling agent, SEM observation confirms the well dispersion of these particles in the silicone rubber matrix, TGA results suggest that the fabricated composites have good thermal stability up to 400 °C.

2.4.2 Curing Techniques

Kulkarni et al.**[21]** illustrated the natural rubber composites which were prepared using silicon carbide and titanium dioxide as filler in different proportions. Curing characteristics were investigated as a function of filler loading and filler proportion. Mechanical properties like tensile strength, tear strength, hardness, elongation at break and modulus were determined. Both tensile strength and modulus were found to increase with SiC (Silicon carbide) content which may be due to the restrictions offered by filler particles to the rubber chain mobility. Cure properties also support the reinforcing capacity of SiC filler in the natural rubber matrix. **Parvathi & Ramesan**.**[46]** focused on the enhancement of these properties in natural rubber (NR) using zinc ferrite ($ZnFe_2O_4$) nanoparticles were prepared by a simple two-roll mill mixing technique. Structure, morphology, crystalline nature, cure characteristics, swelling, thermal and mechanical properties of the NR composites containing $ZnFe_2O_4$ were analysed in detail. FTIR and UV analysis proved the interaction of zinc ferrite with the macromolecular chain of NR. The XRD patterns of composite films revealed a decrease in amorphousness of NR with well-dispersed crystalline peaks of nanoparticles in the polymer. SEM images evidenced the morphological changes caused by dispersing zinc ferrite in the NR matrix. TEM analysis showed the uniform attachment of nanoparticles in the polymer. Glass transition temperature obtained from DSC was improved with the addition of zinc ferrite. The mechanical properties of rubber nanocomposites showed that the addition of $ZnFe_2O_4$ improved their modulus, tensile strength, hardness, abrasion resistance and heat build-up, whereas the elongation at break and resilience decreases. **Theppradit et al.[47]** evaluated the efficiency of modified silica (SiO_2) particles in the reinforcement of natural rubber (NR) vulcanizates. NR vulcanizates filled with modified SiO_2 particles were prepared and the mechanical, thermal and dynamic mechanical properties of composites were investigated. The morphology of composite materials was also investigated by scanning electron microscopy. The modified SiO_2 particles were well dispersed in the NR matrix leading to the good compatibility between the rubber and filler, and so an improved cure, mechanical, thermal and dynamic mechanical properties of the composite vulcanizate materials.

Chapter 3
Materials and Methods

This chapter describes the materials and methods used for the fabrication of composites and investigations carried out under this study. It also presents the details of the testing, optimization procedure and characterization of the composite specimens. The methodology of the optimization based on Taguchi L25 design of experiment is elaborated. The contribution of the control parameters on the results is also analysed through analysis of variance.

3.1 Materials

3.1.1 Matrix Materials

Among different types of matrix materials, rubber matrices are the most commonly used one because of its cost efficiency, ease of fabricating with less tooling cost and due to its excellent behaviours at room temperature. This acted as the motivation to select rubber under this current investigation. There are different polymer matrices like thermoplastic or thermoset are widely used in composite fabrication. The most commonly used thermoset resins are epoxy, vinyl ester, polyester and phenolics. The epoxy resins are being widely used for many advanced composites due to their excellent adhesion behaviour with a wide variety of fibers, good performance at elevated temperatures and superior mechanical and electrical properties. In addition to that they have low shrinkage upon curing and good chemical resistance. Due to several advantages over other thermoset polymers as mentioned above, epoxy (LY 556) is chosen as the matrix material for the present research work. It chemically belongs to the 'epoxide' family and its common name of epoxy is Bisphenol-A-Diglycidyl-Ether.

3.1.2 Particulate Filler Materials

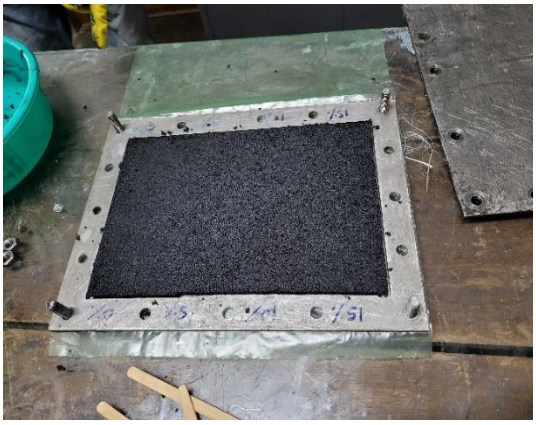
Particulate filler plays an important role for the improvement of performance of polymers and their composites. Various types of fillers like natural or synthetic, both organic or inorganic is already being used as reinforcement in polymeric composites. Among them, alumina (Al_2O_3), silicon carbide (SiC), silica (SiO_2), titania (TiO_2) etc. are most widely used as conventional fillers. Generally, Al_2O_3 is an inorganic material that has the potential to be used as particulate filler material in various polymer matrices.

3.2 Composite Fabrication

In this study, particle of Mg $(OH)_2$, TiO_2, Al_2O_3, SiC, Silicon Metal Powder (SMP) are considered as reinforcement materials. The epoxy resin and the hardener are supplied by Ciba Geigy India Ltd. Mg $(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder (SMP) powders are obtained from NICE Ltd India in a range of 80-100 μm. A stainless-steel mould having dimensions of 457× 304×7.5 mm^3 is used for composite fabrication. Disposal rubber and Mg $(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder (SMP) powder particulates are mixed with epoxy resin by the simple mechanical stirring and the mixture is poured into various moulds conforming to the requirements of various testing conditions and characterization standards. The composite samples of five different compositions (**Sample 1** to **Sample 5**) are prepared in which no particulate filler is used. A releasing agent is used to facilitate easy removal of the composite from the mould after curing. The entrapped air bubbles (if any) are removed carefully during the composite preparation with a sliding roller and the mould is closed for curing at room temperature i.e. 30°C for 24 h at a constant load of 50.8 kgf. After curing, the specimens of suitable dimension are cut for mechanical and Tribo tests. The composition and designation of the composites prepared for this study are listed in **Table 3.1.**

Table 3.1 Composition and Designation of Composites

Sample	Composites	Compositions
1	Mg $(OH)_2$	Rubber: Epoxy: Mg $(OH)_2$ =50:40:10=275gm:220gm (210gm + 21gm):55gm
2	TiO_2	Rubber: Epoxy: TiO_2 =50:40:10=275gm:220gm (210gm + 21gm):55gm
3	Al_2O_3	Rubber: Epoxy: Al_2O_3 =50:40:10=275gm:220gm (210gm + 21gm):55gm
4	SiC	Rubber: Epoxy: SiC =50:40:10=275gm:220gm (210gm + 21gm):55gm
5	Silicon Metal Powder (SMP)	Rubber: Epoxy: SMP =50:40:10=275gm:220gm (210gm + 21gm):55gm



(a) Sample Preparation with Die

(b) Sample Preparation with Die

(c) Sample Preparation by compaction.

(d) Specimen for tensile test, hardness test and Tribo test

Figure 3.1 Particle reinforced rubber composite samples and specimen preparation.

The rubber is used as matrix material that holds the reinforcement particles together. The properties of the rubber matrix may affect the mechanical and tribological behaviour of the composites. The reinforcement particles are the materials that are added to the rubber matrix to improve its mechanical and tribological behaviours. The variation in type and size of the reinforcement particles may also affect the mechanical and tribological behaviours of the composites. The curing agent is the chemical that is used to harden the rubber matrix. The type and amount of curing agent will affect the mechanical and tribological behaviours of the composites.

The first step for fabrication of composites is mixing of reinforcement particles with the rubber matrix and curing agent in a mixing machine. The mixing process is important to ensure that the reinforcement particles are evenly distributed in the rubber matrix. The mixture is then poured into a metal die as per the required size and shape. The composite mixture then compressed manually by placing some weight over it and kept some time to become compact and solid. The time for which it is allowed to become solid is called curing time. The curing process is important to ensure that the rubber matrix is hardened and the composite is able to withstand the desired loads and stresses. The same composite material is cut and shaped as per the standard test specimen based on the tests to be carried out.

3.3 Characterization

The next step after composite fabrication is to understand the composition and surface morphology of the composites which may impact its behaviours. The presence of different elements added into it and their distribution also plays an important role to decide its behaviours. Hence, the surface morphology of the composited made with five different reinforcement materials are studied using an optical microscope. The surface morphology images of the composites are taken at different resolution. It helps to visualize the distribution of the filler particles in the rubber matrix and to identify any defects in the composite.

3.4 Tensile Testing

Tensile testing is a common method for measuring the tensile strength and modulus of elasticity of a material. In tensile testing, a specimen is subjected to a tensile load and the stress-strain response is measured. The tensile strength is the maximum stress that the specimen can withstand before it breaks. The modulus of elasticity is the slope of the stress-strain curve in the linear elastic region.

The tensile test was performed on all the five different categories of the composites as per ASTM D3039-76 test standards. The tensile test is generally performed on flat specimens. A uniaxial load is applied through the ends. The ASTM standard test recommends that the length of the test section should be 100 mm with fibers parallel to the loading direction and the specimen should have a width of 11.5 mm. The tensile tests were carried out using a Universal Testing Machine (UTM, Model:5582, Make: INSTRON, Germany) with a uniformly increasing load from 0 to 0.908 KN with a loading rate of 10E-4/s. The UTM set up utilized to carry out the tensile tests are displayed in figure 3.2. The test set up is accompanied by a dedicated system which was used to record the data. The recorded datas were utilized to calculate the tensile strength and elastic modulus of the test specimens. The category of tests is carried out for at least three samples. The average of the obtained results is presented in this report.

Figure 3.2 UTM Machine Setup

3.5 Hardness Measurement

Hardness is a measure of the resistance of a material against permanent indentation due to indentation or scratch. Hardness testing is a common method for evaluating the mechanical properties of materials. There are many different hardness testing methods available, but the most common method for measuring the hardness of particle-reinforced rubber composites is the Vicker’s hardness test.

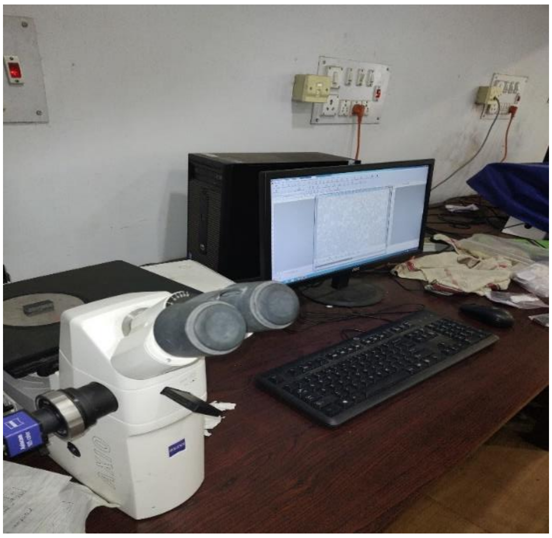


Figure 3.3: Vicker’s Hardness Tester with dedicated set up.

Vicker’s micro-hardness tester is used for micro-hardness measurement on composite samples. A diamond indenter in the form of a right pyramid of a square base of an angle 136° between opposite faces is forced under a load 2000 Kgf into the sample. After removal of the load, the two diagonals of the indentation (X and Y) left on the surface of the sample are measured and their arithmetic mean L is calculated. The load considered in the present study is 2000Kgf and Vickers hardness is calculated using the following equation:

$$H_v = 0.1889\ F/L^2 \text{ --------------------------------(i)}$$

$$\text{and} \quad L = (X+Y)/2 \text{ ------------------------------------ (ii)}$$

where F is the applied load (N), L is the diagonal of square impression (mm), X is the horizontal length (mm), Y is the vertical length (mm).

3.6 Tribological Test and Optimization

3.6.1 Design of Experiment

Experimental design is the process of planning and conducting experiments in a way that ensures that the results are valid and reliable. In the context of particle-reinforced rubber composites, experimental design was used to conduct the experiments and optimize the control parameters for a suitable operating condition to manufacture these composites. The current study involves three different control parameters namely reinforcement particle, sliding speed and applied load. Each control parameters have five levels. Therefore, as per full factorial design of experiments total of 5^3 = 125 set experiments need to carried out which is laborious and time consuming. Hence, Taguchi's L25 orthogonal array (OA) was selected to carry out the experiments. The selected control parameters and their levels are presented in the table 3.2.

Table 3.2. Tribological Test Parameters and their Levels

Design Factors	Units	Levels				
		1	**2**	**3**	**4**	**5**
Reinforcement Particle	-	Al_2O_3	SiC	TiO_2	$Mg(OH)_2$	SMP
Applied Load	N	0.5	1.0	1.5	2.0	2.5
Sliding Speed	cm/sec	100	125	150	175	200

3.6.2 Tribological Test

The tribological tests are carried out using a pin-on-disc type tribo tester. The detailed test process is explained through the flowchart given in figure 3.4. Each of the tests are conducted for at least 3 times and the test datas were recoded using a computer attached with the tribo-tester which was also used to monitor and control the test parameters. The average of the recorded datas is presented in this report. Moreover, the pin samples were measured prior and after the tribological test using a weighing balance. The difference between the weights before and after the test indicates the measure of worn-out mass during the tribological test. The same worn-out mass was utilized to calculate the specific wear rate of the as-deposited coatings.

The below mentioned formula was employed for the calculation of specific wear rate (Ws in kg/N.m).

$$Ws = (M.L)/N \text{ -- (iii)}$$

where M is the worn-out mass in kg, L is the travel distance in meter and N is the applied load in newton.

The travel distance covered by the specimen was calculated considering the track dia, disc rotation speed in rpm and total time duration for the complete test

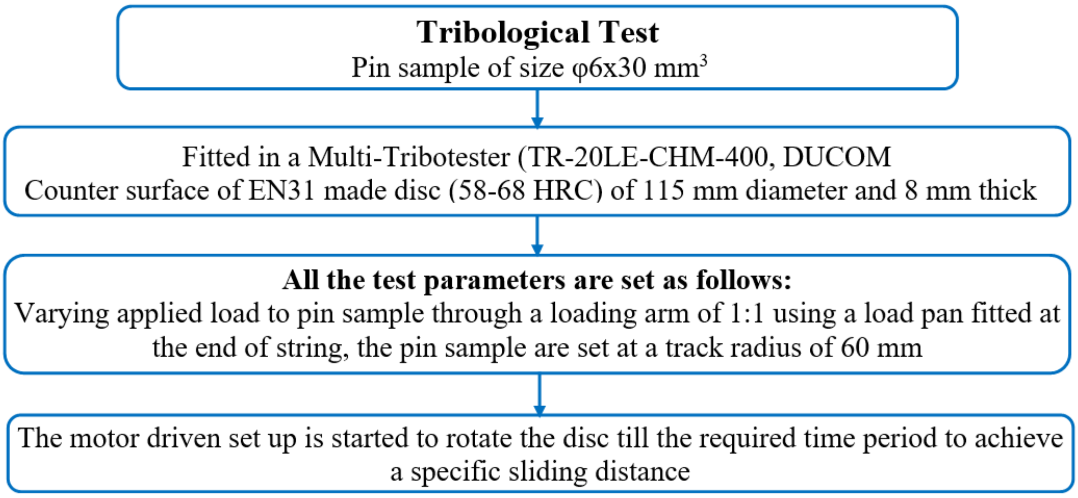


Figure 3.4 Tribological Test Procedure

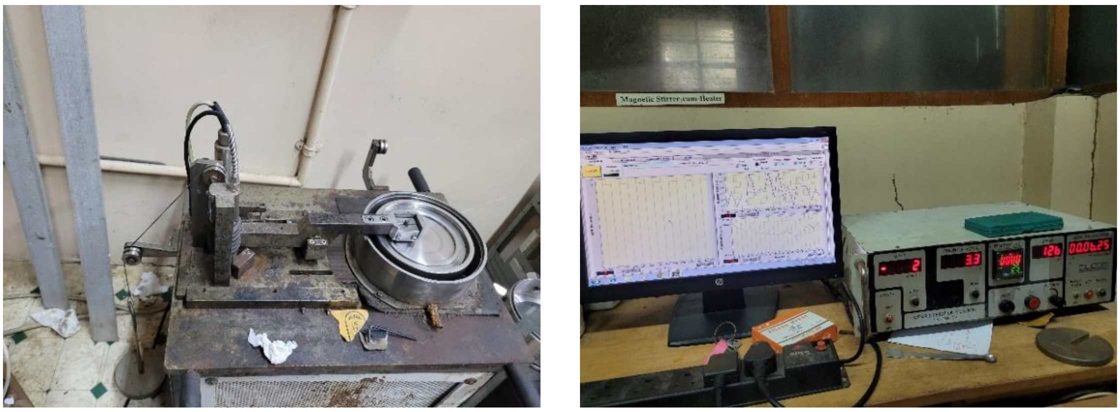


Figure 3.5. Pin-on-disc Tribo-Tester with dedicated setup.

Table 3.3 Orthogonal Array for Taguchi Method.

Sl. No.	A	B	C	Reinforcement Particle	Applied Load	Sliding Speed
1.	1	1	1	$Mg(OH)_2$	0.5	100
2.	1	2	2	$Mg(OH)_2$	1	125
3.	1	3	3	$Mg(OH)_2$	1.5	150
4.	1	4	4	$Mg(OH)_2$	2	175
5.	1	5	5	$Mg(OH)_2$	2.5	200
6.	2	1	2	TiO_2	0.5	125
7.	2	2	3	TiO_2	1	150
8.	2	3	4	TiO_2	1.5	175
9.	2	4	5	TiO_2	2	200
10.	2	5	1	TiO_2	2.5	100
11.	3	1	3	Al_2O_3	0.5	150
12.	3	2	4	Al_2O_3	1	175
13.	3	3	5	Al_2O_3	1.5	200
14.	3	4	1	Al_2O_3	2	100
15.	3	5	2	Al_2O_3	2.5	125
16.	4	1	4	SiC	0.5	175
17.	4	2	5	SiC	1	200
18.	4	3	1	SiC	1.5	100
19.	4	4	2	SiC	2	125
20.	4	5	3	SiC	2.5	150
21.	5	1	5	SMP	0.5	200
22.	5	2	1	SMP	1	100
23.	5	3	2	SMP	1.5	125
24.	5	4	3	SMP	2	150
25.	5	5	4	SMP	2.5	175

3.6.3 Optimization using SN Ration

Taguchi's design and analysis are a powerful tool for designing high quality systems based on Taguchi's L25 orthogonal array (OA), **Panja & Sahoo [48].** In this method, the use of a loss function i.e., S/N ratio is suggested based on performance measures such as higher-the-better, lower-the-better and nominal-the-best, **Goyal et al.[49**]. In S/N ratio, mean and standard deviation denotes signal and noise, respectively. A higher value of S/N ratio is desired which indicates that the experiment is less susceptible to noise which affects the system performance. In the present work, the considered responses are friction and wear. A lower friction value denotes smooth and compact surface. Hence friction value is to be minimized. Similarly, less wear rate is better for application of composites and it is also to be minimized. So, for friction and wear both, a lower-the-better quality characteristic is used and the S/N ratio (in dB) is obtained as:

$$S/N \;=\; -10\log\left(\frac{1}{n}\sum_i^n y_i^2\right) \text{ -------------------------- (iv)}$$

For higher-the-better quality characteristic is used since it is to be maximized and S/N ratio is computed as follows:

$$S/N \;=\; -10\log\left(\frac{1}{n}\sum_i^n \frac{1}{y_i^2}\right) \text{ --------------------------- (v)}$$

where n is the total number of trials for an observation and y is the observed i^{th} result. From the results, main effects plot is obtained which gives the optimal setting of parameters.

It would be interesting to note at this point that the first process parameter that has been considered is reinforcement particle type which is qualitative. By reinforcement particle type, the fabrication process used different types of reinforcement particles i.e., Al_2O_3, $Mg(OH)_2$, TiO_2, SiC and SMP. One of the important features of Taguchi's optimization technique is the ability to use qualitative variables as parameters since the optimization is independent of the quantitative measures of the process parameters. In fact, the use of qualitative variables has been demonstrated in previous works, **Gupta & Sood [50**]. Therefore, the use of qualitative parameter i.e., reinforcement particle has been possible due to the use of Taguchi's optimization technique.

3.6.4 Significance and Contribution through ANOVA

Moreover, the statistical significance of the considered design parameters in controlling friction and wear is obtained from ANOVA. The results are based on F-ratio which is the ratio between regression mean square and mean square error. At any particular confidence level, if the obtained F-ratio is higher than the tabulated values, then the parameter is considered to be statistically significant.

Finally, a confirmation test is carried out to validate the optimization results. This is done by comparing the predicted result of responses from Taguchi analysis with experimentally obtained values at the optimal combination of process parameters. The predicted S/N ratio is obtained from the following relation:

$$\hat{\gamma} = \gamma_m + \sum_i^0 (\overline{\gamma_i} - \gamma_m) \text{ ----------------------- (vi)}$$

where $\hat{\gamma}$ denotes the predicted S/N ratio, γ_m is the mean value of S/N ratio while $\overline{\gamma_i}$ denotes mean value of S/N ratio at optimal level and the total number of process parameters is denoted by o. The optimal results of S/N ratio are also compared with the responses obtained at initial test condition. The improvement in S/N ratio at the optimal setting of process parameters compared to the initial test run is noted. The steps followed for Taguchi's optimization process is sequentially depicted in Figure 3.6.

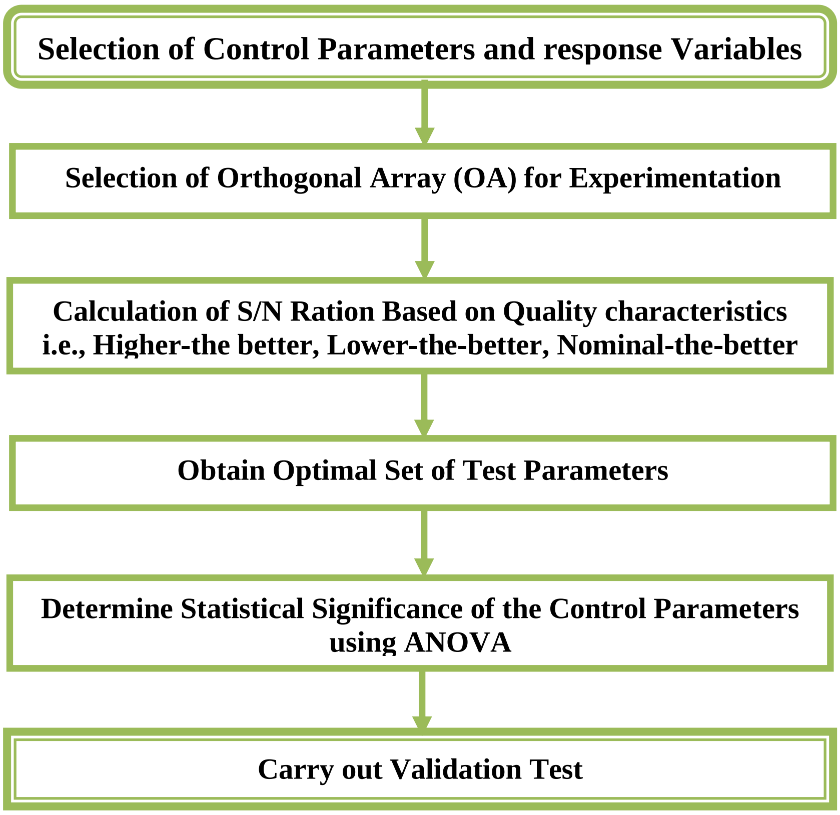


Figure 3.6 Flowchart of Optimization Process

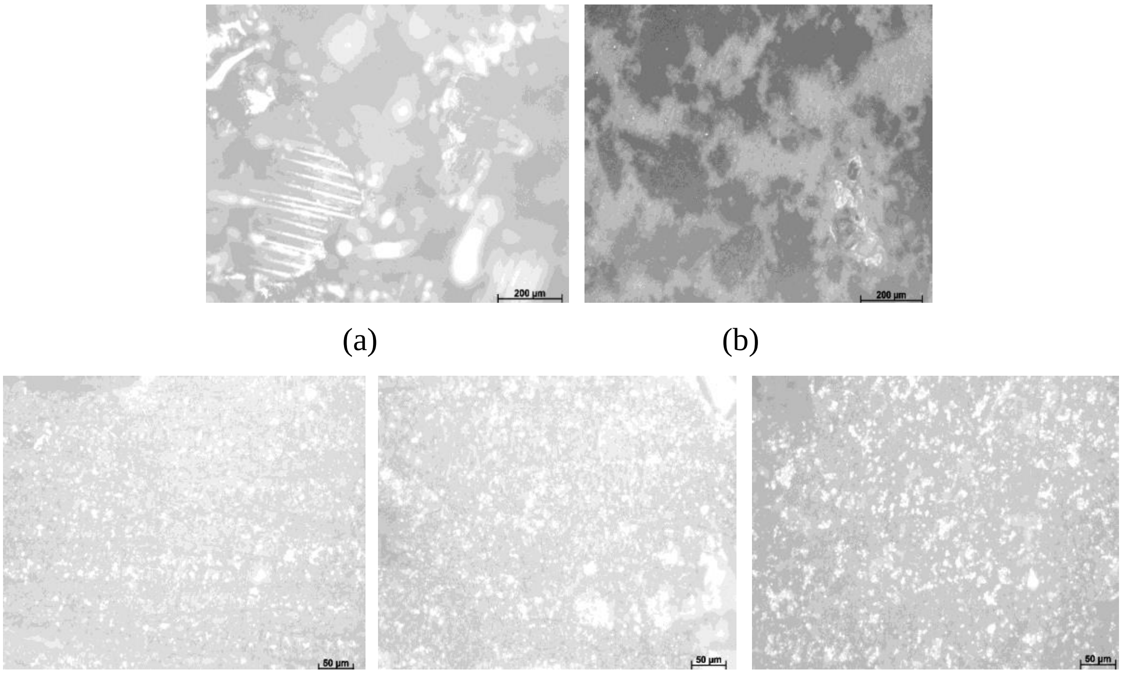
Chapter 4

Experimental Results and Discussions

This chapter presents the results of mechanical and tribological properties of particle reinforced rubber composites. This chapter consists of two parts, in the first part the results of mechanical behaviour of particle reinforced rubber composites and in the second part tribological behavior of particle reinforced rubber composites is presented.

4.1 Surface Morphology and Characterization

The surface morphology of the composites is studied using an optical microscope. The images of the surface obtained from the microscope is presented in figure 4.1. The figure 4.1 represents the surfaces of the composites obtained from different reinforcement materials which show a compact and uniform morphology. The morphology also shows the uniform distribution of particles throughout the surface. The compact surface usually leads to better tribological and mechanical behaviours.



(a) (b)

(c) (d) (e)

Figure 4.1 Surface Morphology of the Composites obtained with Reinforcement Material (a) Mg $(OH)_2$, (b) TiO_2, (c) Al_2O_3, (d) SiC and (e) Silicon Metal Powder

4.2 Mechanical Properties

4.2.1 Micro-hardness

The surface hardness of the composites is determined through a micro-hardness tester with a constant load of 2000Kgf. The indentation-based hardness is measured on five different locations along a line on the surface of the composite specimens and the average of the results are presented in this report. The micro-hardness (HV0.1) values of rubber composites marked as sample 1, 2, 3, 4 and 5 represents the specimens prepared with reinforcement particles $Mg(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder (SMP), respectively. The obtained results from the experiments are presented in the table 4.1. The hardness values are also presented through the bar chart in the figure 4.2. The results show that the composite specimen prepared with SMP reinforcement exhibit highest hardness value. The reinforcement of small particles makes the surface compact and pore free. The compact surface and uniform distribution of particles might have led to an improvement in surface hardness value of the composites obtained with SMP particles.

Table 4.1 Average hardness values of different five samples

Sample	Particle Reinforced rubber composites	Average Hardness value (HVO.1)
1	Mg $(OH)_2$	19.32
2	TiO_2	17.53
3	Al_2O_3	17.73
4	SiC	22.67
5	**Silicon Metal Powder (SMP)**	**24.79**

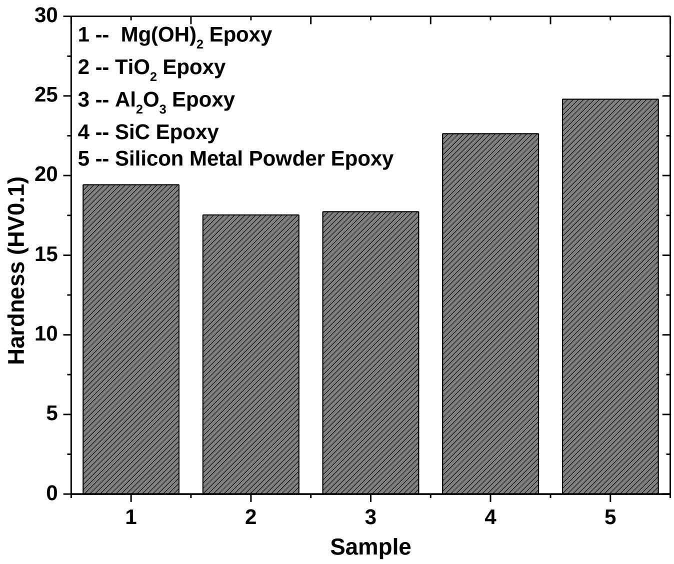
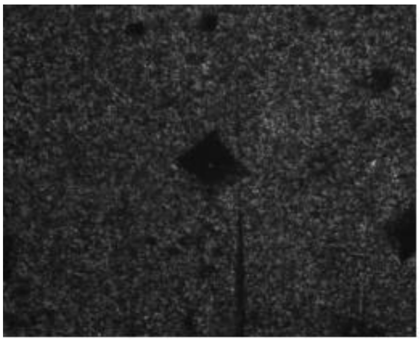
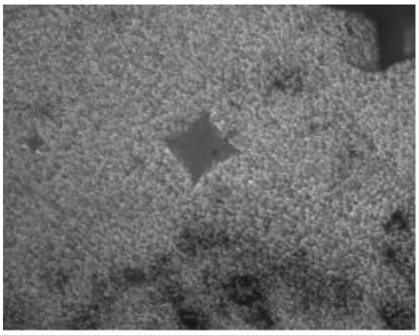


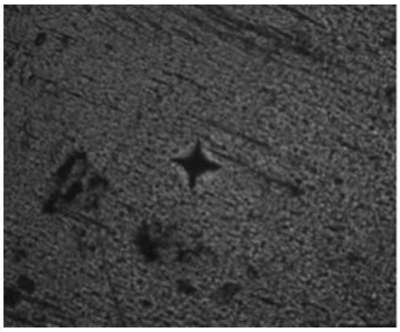
Figure 4.2 Hardness for different particle reinforced rubber composite.



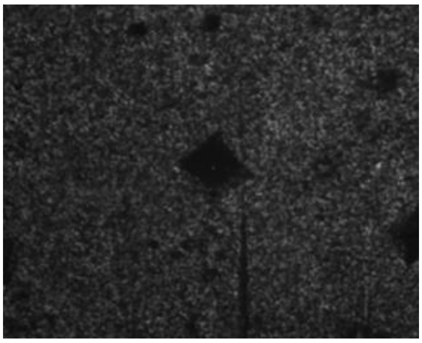
a. $Mg(OH)_2$ epoxy



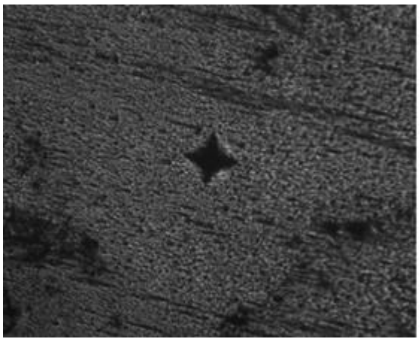
b. TiO_2 epoxy



c. Al_2O_3 epoxy



d. SiC epoxy



e. Silicon Metal Powder epoxy

Figure 4.3 Images of the samples after hardness test of $Mg(OH)_2$ epoxy, TiO_2 epoxy, Al_2O_3 epoxy, SiC epoxy and Silicon Metal Powder epoxy composite.

The image of the indented surface with prominent indentation is presented in figure 4.3. The diagonals of the permanent indentation marks are measured and it is utilized to calculate the Vickers hardness value. The more the hardness of a surface will require more force to make same indentation or the same load will make small impression on the hard surface. The figure 4.3 also shows that the permanent indentation mark on the surface is least on the specimens obtained with SMP particles. Hence, this also confirms the better hardness value of composites obtained with SMP particles. This fact may also be due to the inherent hardness properties of the particles and bonding between the particles and the matrix. For instance, Silicon Metal Powder is the hardest particles among five particles within the particles considered under the current investigation. This completely agrees with the current investigation results.

4.2.2. Tensile Behaviour

The tensile tests are carried out as per ASTM D638 – 14 Standards for all the specimens. The dimensions of the specimens used for the tensile test are displayed in table 4.2. The specimens before and after the test are displayed in figure 4.4.

a. Specimen before Test.

b. Specimen after Test.

Figure 4.4 Specimens of before and after Tensile Test.

Table 4.2 Dimensions of specimens for Tensile Test with Results

Specimens	Width (mm)	Thickness (mm)	Length (mm)	Tensile stress at breaking Point (MPa)	Tensile strain at breaking point (%)
Mg $(OH)_2$	13	7.5	57	3.87718	1.45655
TiO_2	13	7.49	57	4.6991	1.36184
Al_2O_3	13	7.51	57	7.9827	2.10994
SiC	13	7.05	57	5.7.418	1.72057
Silicon Metal Powder	**13**	**7.14**	**57**	**9.78794**	**2.17770**

The effect of particle filler type on the stress strain relationships considering $Mg(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder are illustrated in figure 4.5. It is evident from the figure 4.5 that for a particular tensile strain (upto 0.012) for the rubber composite reinforced with silicon metal powder possess highest value of tensile stress among five categories and followed by Al_2O_3, $Mg(OH)_2$, TiO_2 and SiC. Also, the tensile stress at breaking point is found maximum (9.78794 MPa) for Silicon Metal Powder epoxy while the minimum (3.87718MPa) tensile stress at breaking point is evident in case of the Mg $(OH)_2$ epoxy.

The tensile stresses at the breaking point of the remaining particle reinforced rubber composites are in the order of Al_2O_3 epoxy (7.9827 MPa), SiC epoxy (5.71418 MPa) and TiO_2 epoxy (4.6991MPa). Furthermore, the tensile strain at breaking point is found maximum (2.17770 %) for Silicon Metal Powder epoxy while the minimum (1.36184%) tensile strain at breaking point is evident in case of the TiO_2 epoxy. The tensile stresses at the breaking point of the remaining particle reinforced rubber composites are in the order of Al_2O_3 epoxy (2.10994%), SiC epoxy (1.72057%) and Mg $(OH)_2$ epoxy (1.45655%).

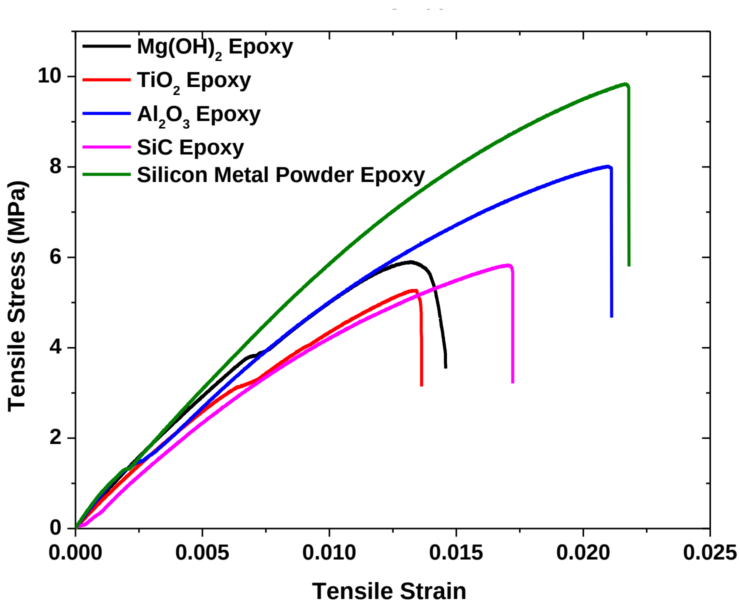


Figure 4.5 Tensile stress - strain diagram for different particle reinforced rubber composite

Figure 4.6 demonstrates the test values of Young's Modulus for five particle reinforced rubber composites namely, Silicon Metal Powder reinforced rubber composite**,** Silicon carbide reinforced rubber composite, Magnesium hydroxide reinforced rubber composite, Aluminum Oxide reinforced rubber composite, and Titanium Oxide reinforced rubber composite.

Table 4.3 Young's Modulus (MPa) for different particle reinforced rubber composite.

Sample	Particle Reinforced rubber composites	Young's Modulus (MPa)
1	Mg $(OH)_2$	776.82627
2	TiO_2	712.59947
3	Al_2O_3	744.39949
4	SiC	502.63537
5	**Silicon Metal Powder (SMP)**	**878.61346**

It can be seen that the values of Young's Modulus from highest to lowest are in the order of Silicon Metal Powder reinforced rubber composite, Magnesium hydroxide reinforced rubber composite, Aluminum Oxide reinforced rubber composite, Titanium Oxide reinforced rubber composite and Silicon Carbide reinforced rubber composite.

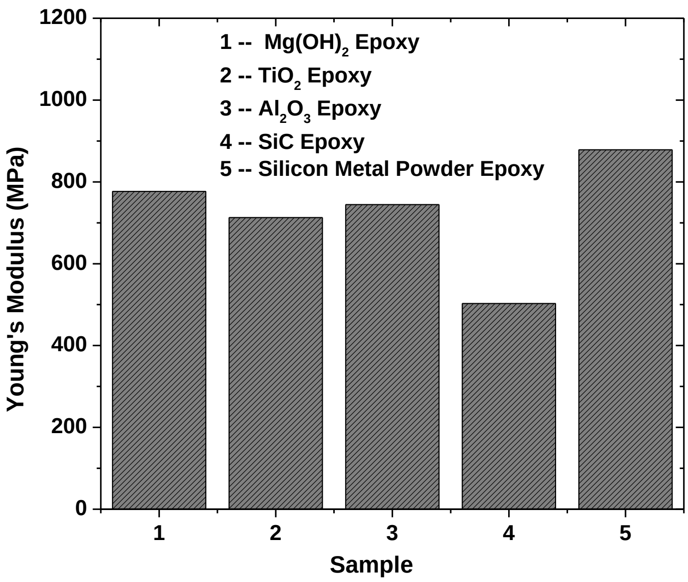


Figure 4.6 Young's Moduli for different particle reinforced rubber composite

Table 4.4 Tensile Strength (MPa) for different particle reinforced rubber composite

Sample	Particle Reinforced rubber composites	Tensile Strength (MPa)
1	Mg $(OH)_2$	5.90336
2	TiO_2	5.26853
3	Al_2O_3	8.01570
4	SiC	5.83019
5	**Silicon Metal Powder**	**9.84007**

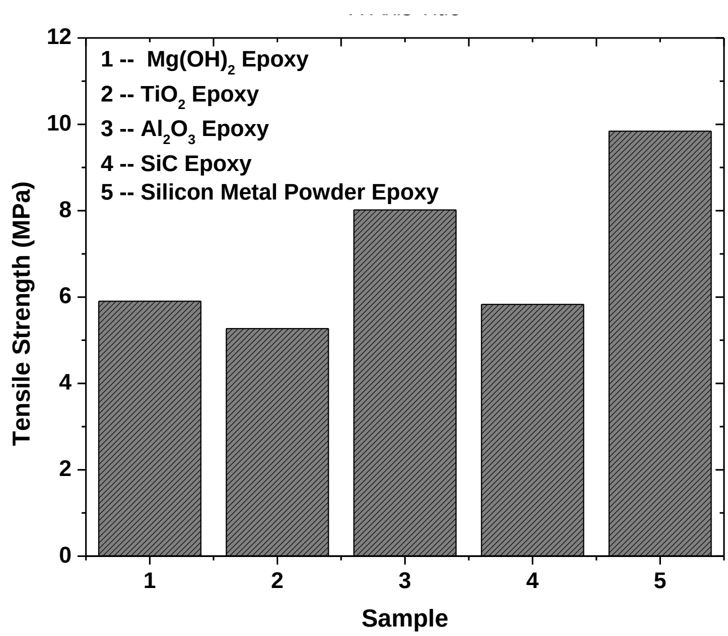


Figure 4.7 Tensile Strength Bar diagram for different particle reinforced rubber composite.

The tensile strengths of the particle reinforced rubber composite considering five different particles Silicon Metal Powder, Al_2O_3, Mg $(OH)_2$, TiO_2 and SiC are shown in Figure 4.7. It is evident from the figure that the tensile strength of Silicon Metal Powder epoxy is maximum among the five considered particle reinforced rubber composites while the tensile strength of Tio_2 epoxy is the minimum. The tensile strength of the remaining particle reinforced rubber composites is in the order of Al_2O_3 epoxy, Mg $(OH)_2$ epoxy and SiC epoxy respectively.

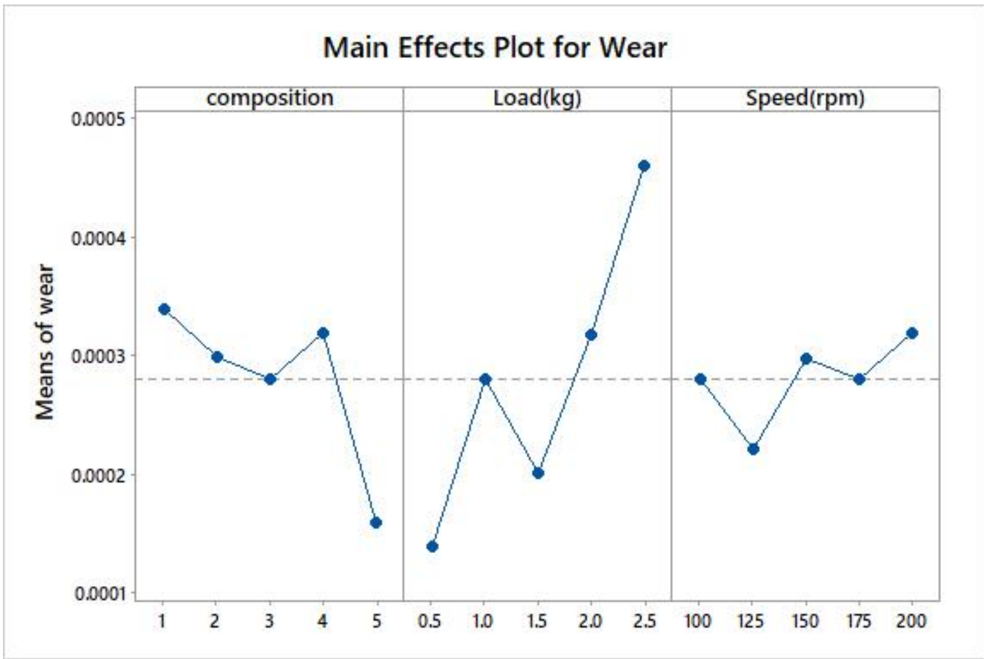
4.3 Tribological behaviours

4.3.1 Wear Behavior Analysis

Table 4.5 Wear of particles (1) Mg $(OH)_2$ epoxy, (2) TiO_2 epoxy, (3) Al_2O_3 epoxy, (4) SiC epoxy and (5) Silicon Metal Powder epoxy with respect to load and speed.

Sample	Load (kg)	Speed (rpm)	Wear (gm)
1	0.5	100	0.0001
1	1	125	0.0002
1	1.5	150	0.0002
1	2	175	0.0006
1	2.5	200	0.0006
2	0.5	125	0.0004
2	1	150	0.0005
2	1.5	175	0.0004
2	2	200	0.0002
2	2.5	100	0.0006
3	0.5	150	0.0002
3	1	175	0.0002
3	1.5	200	0.0003
3	2	100	0.0003
3	2.5	125	0.0004
4	0.5	175	0.0002
4	1	200	0.0004
4	1.5	100	0.0003
4	2	125	0.0003
4	2.5	150	0.0004
5	0.5	200	0.0001
5	1	100	0.0004
5	1.5	125	0.00011
5	2	150	0.00019
5	2.5	175	0.0003

The wear specimens are tested for a fixed sliding distance of the experiments found on Pin-on-disc Tribo tester for measuring the wear with respect to the varying load and speed of individual specimen of particles considering Mg $(OH)_2$ epoxy, TiO_2 epoxy, Al_2O_3 epoxy, SiC epoxy and Silicon Metal Powder epoxy. The table 4.5 shows the wear results. The same results are utilized to determine a suitable set of parameters to get an optimized wear. The same results are also used to determine the significance of the control parameters on the response through SN ratio. The calculated SN ratios of wear are displayed in table 4.6. The same SN ratios are utilized to draw the main effect plots. The main effect plots of wear are displayed in figure 4.8. The SN ratio results shows that the composition is the most significant parameter to decide the wear behaviour of the composites. The stiffness of the main effect plot is highest which is the confirmation for the highest significance of composition.



Note:1--$Mg(OH)_2$ epoxy;2--TiO_2epoxy; 3--Al_2O_3 epoxy; 4--SiC epoxy; 5--Silicon Metal Powder epoxy.

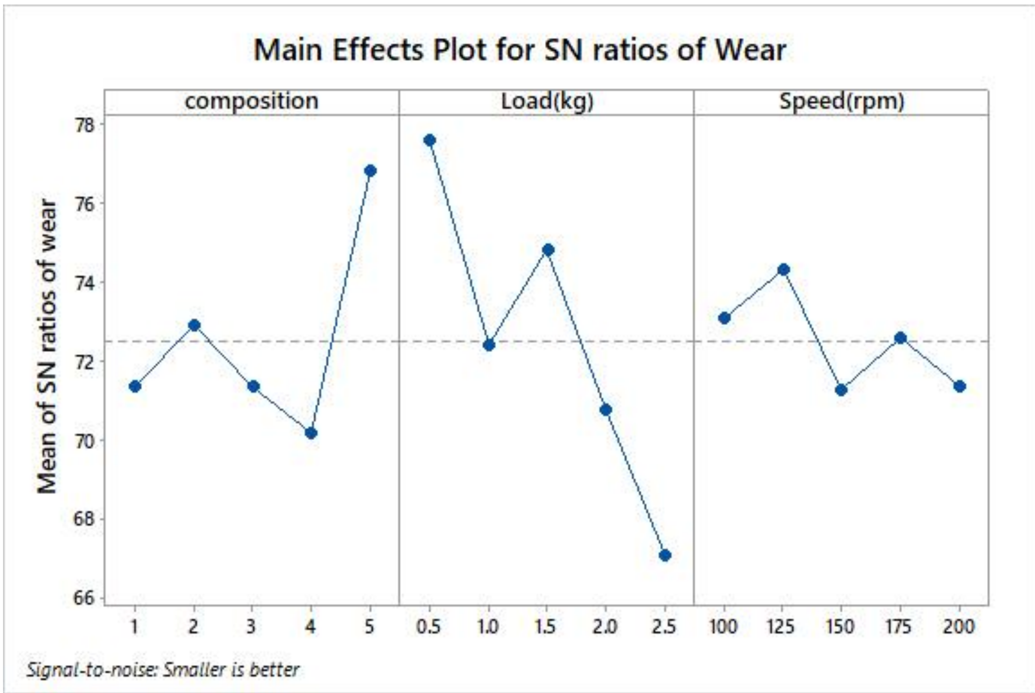
Figure 4.8. Plot Means of wear Vs Composition, Load, Speed**.**

In the 2nd plot indicates the wear loss against load. Wear loss shows the typical trend with the increase in load. It observed that Minimum wear loss at lower load (0.5kgf) and maximum wear loss at higher load (2.5kgf). This particular trend follows Archard's wear law. In the 3rd plot indicates the wear loss against speed. This plot indicates typical nonlinear trend at varying speed. The wear loss is minimum at 125 rpm and highest at 200 rpm.The obtained trend is mainly based on mean values considering the particles Mg $(OH)_2$ TiO_2, Al_2O_3, SiC and Silicon Metal Powder through Taguchi method. Thus, the wear loss variation against load and speed doesn't follow the peculiar trend. However, wear loss variation against load is quite linear.

Table 4.6 SN Ratio of wear of particle (1) Mg $(OH)_2$ epoxy, (2) TiO_2 epoxy, (3) Al_2O_3 epoxy, (4) SiC epoxy and (5) Silicon Metal Powder epoxy with respect to load and speed.

Composition	Load (Kg)	Speed (rpm)	SNR of Wear
1	0.5	100	80.0000
1	1	125	73.9794
1	1.5	150	73.9794
1	2	175	64.43697
1	2.5	200	64.43697
2	0.5	125	80.0000
2	1	150	66.0206
2	1.5	175	80.0000
2	2	200	73.9794
2	2.5	100	64.43697
3	0.5	150	73.9794
3	1	175	73.9794
3	1.5	200	70.45757
3	2	100	70.45757
3	2.5	125	67.9588
4	0.5	175	73.9794
4	1	200	67.9588
4	1.5	100	70.45757
4	2	125	70.45757
4	2.5	150	67.9588
5	0.5	200	73.9794
5	1	100	70.45757
5	1.5	125	70.45757
5	2	150	64.43697
5	2.5	175	63.09804

In the Table 4.6 indicates the individual particles considering the SN ration of wear with respect to the load and speed which is distributed by the taguchi method . The particle reinforced rubber composite considering Mg $(OH)_2$ epoxy, TiO_2 epoxy, Al_2O_3 epoxy, SiC epoxy and Silicon Metal Powder are the different particle oriented epoxy which shows the result of SN ration of wear for every step of DOE matrix.



Note: 1. $Mg(OH)_2$ epoxy; 2. TiO_2 epoxy; 3. Al_2O_3 epoxy; 4. SiC epoxy; 5. Silicon Metal Powder epoxy.

Figure 4.9 Plot Means of SN ratios of wear Vs Composition, Load, Speed.

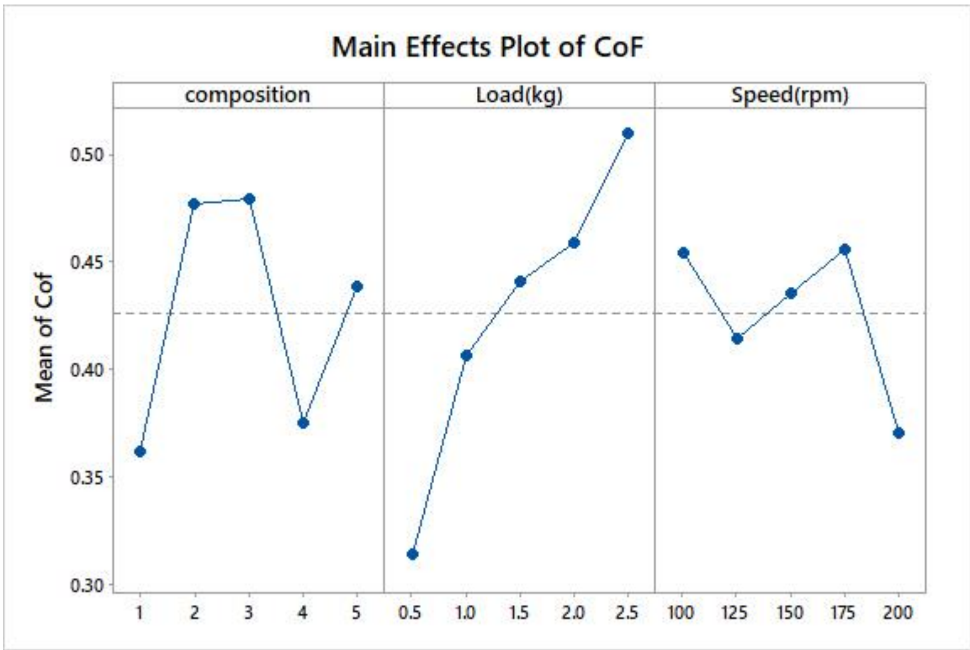
4.3.2 Friction Behavior Analysis

In this test coefficient of friction (COF) values of rubber composite considering the particles Mg $(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder epoxy have been obtained experimentally in the Table 4.7. In Pin-on-disk, the coefficient of friction (COF) value measurement has been taken by using Taguchi optimization method and their average value is calculated. COF trend obtained against particle considering $Mg(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder epoxy does not follow a particular trend. The lowest COF value is reported for sample (1) $Mg(OH)_2$ epoxy. However, sample no. (3) Al_2O_3 reported the highest COF value in Figure 4.10.

In the 2nd plot indicates the variation of COF against load in Figure 4.10. The existing plot almost exhibit the linear trend with the increase in load where the minimum value obtained for lowest load (0.5kgf) and COF value is maximum at higher load (2.5kgf). The 3rd plot depicts the variation of COF against sliding speed in Figure 4.10. Here also the trend is linear between 125rpm to 175rpm. However, at lower speed(100rpm) the COF value is appearing the higher and the higher speed (200rpm) the COF value is minimum. Lowest COF value may have occurred due to minimum point of contact at higher speed between Pin and Counter disk.

Table 4.7 COF of particle (1) Mg $(OH)_2$ epoxy, (2) TiO_2 epoxy, (3) Al_2O_3 epoxy, (4) SiC epoxy and (5) Silicon Metal Powder epoxy with respect to load and sliding speed.

Composition	Load (Kg)	Speed (rpm)	COF
1	0.5	100	0.34898
1	1	125	0.36629
1	1.5	150	0.353787
1	2	175	0.354406
1	2.5	200	0.387109
2	0.5	125	0.300162
2	1	150	0.48515
2	1.5	175	0.595038
2	2	200	0.484694
2	2.5	100	0.519217
3	0.5	150	0.331327
3	1	175	0.497513
3	1.5	200	0.44519
3	2	100	0.565663
3	2.5	125	0.555308
4	0.5	175	0.285909
4	1	200	0.231492
4	1.5	100	0.385034
4	2	125	0.427697
4	2.5	150	0.543548
5	0.5	200	0.305442
5	1	100	0.453545
5	1.5	125	0.423387
5	2	150	0.463069
5	2.5	175	0.545233



Note: 1--$Mg(OH)_2$ epoxy; 2--TiO_2 epoxy; 3--Al_2O_3 epoxy; 4--SiC epoxy; 5--Silicon Metal Powder epoxy.

Figure 4.10 Plot Means of Coefficient of Friction (Cof) Vs Composition, Load, Speed.

In this SN Ration of coefficient of friction (COF) values of rubber composite considering the particles Mg $(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder epoxy have been obtained experimentally in the Table 4.8. SN Ration of COF trend obtained against particle considering $Mg(OH)_2$, TiO_2, Al_2O_3, SiC and Silicon Metal Powder epoxy does not follow a particular trend. The lowest SN Ration of COF value is reported for sample (3) Al_2O_3 epoxy. However, sample no. (4) SiC epoxy reported the highest SN Ration of COF value in Figure 4.11.

In the 2nd plot indicates the variation of SN Ration of COF against load in Figure 4.11. The existing plot almost exhibit the linear trend with the increase in load where the minimum value obtained for highest load (2.5kgf) and SN Ration of COF value is maximum at lowest load (0.5kgf). The 3rd plot depicts the variation of SN Ration of COF against sliding speed in Figure 4.11. Here also the trend is linear between 125rpm to 175rpm. However, at lower speed (100rpm) the SN Ration of COF value is appearing the lowest and the higher speed (200rpm) the SN Ration of COF value is maximum.

Table 4.8 SN Ratio of COF of particle (1) $Mg(OH)_2$ epoxy, (2) TiO_2 epoxy, (3) Al_2O_3 epoxy, (4) SiC epoxy and (5) Silicon Metal Powder epoxy with respect to load and sliding speed.

Composition	Load (kg)	Speed (rpm)	SNR of COF
1	0.5	100	9.143999
1	1	125	8.723497
1	1.5	150	9.025166
1	2	175	9.009989
1	2.5	200	8.243338
2	0.5	125	10.45289
2	1	150	6.282485
2	1.5	175	4.509106
2	2	200	6.290649
2	2.5	100	5.693028
3	0.5	150	9.594876
3	1	175	6.063916
3	1.5	200	7.029102
3	2	100	4.94884
3	2.5	125	5.109318
4	0.5	175	10.87545
4	1	200	12.70928
4	1.5	100	8.290018
4	2	125	7.37728
4	2.5	150	5.295244
5	0.5	200	10.30142
5	1	100	6.867587
5	1.5	125	7.465256
5	2	150	6.687077
5	2.5	175	5.268354

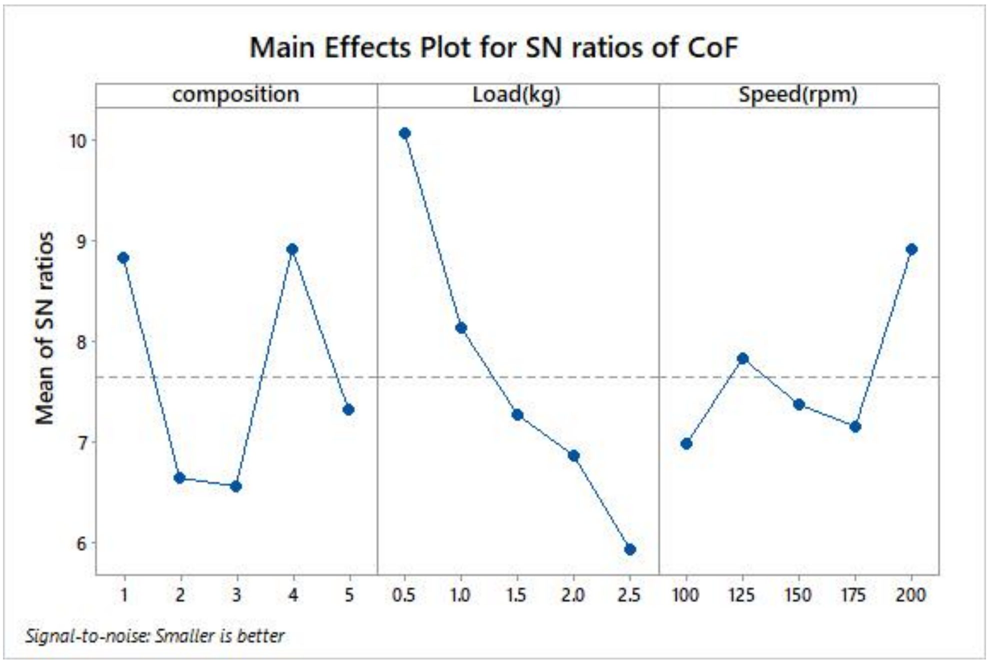


Figure 4.11 Plot Means of SN ratios of CoF vs Composition, Load, Speed.

4.3.3 Significance and Contribution through ANOVA

The test results analyzed using S/N Ratio were again analyzed by using ANOVA (Analysis of Variance) for identifying the significant factors and their relative contribution on the outcome or results. By using S/N Ratio it is not possible to judge and determine the effect of individual parameter where by using ANOVA percentage contribution of individual parameters can be determined. The analysis was carried out with a confidence level of 95% (α = 0.05) which means we are 95% sure that our prediction is right or in the other hand there is a chance of type-1 error is only 5% which means rejecting null hypothesis while it is true. Our null hypothesis is that the control parameters are not significant. Therefore, alternative hypothesis is that they are influencing the outcome.

The decision rule for accepting the null hypothesis or rejecting is that – at a α level of confidence,

Reject H_0 if $P(F_{k-1,\, n-k} > F_{computed}) < \alpha$

Do not reject if H_0 if $P(F_{k-1,\, n-k} > F_{computed}) > \alpha$

Statistically the two hypotheses can be written as

H_0 = null hypothesis = control factors are not significant = 0

H_A = alternative hypothesis = control factors are significant $\neq 0$

Effect of each parameter can be determined by extraction of average SN ratio values at each level from the table 4.6 and table 4.8. The average values obtained at each level are used to calculate the delta values for each parameter. The delta values are the difference between the maximum and minimum average values among the five levels of each parameter. The delta value indicates the significance of the different parameters. The significance of the control parameters is determined from the SN ratios for wear and friction which are displayed in table 4.9 and table 4.11. Similarly, the experimental datas are also used to determine the significance of the control parameters and their contributions to decide the response through ANOVA. The ANOVA results for wear and friction are displayed in table 4.10 and table 4.12.

Table 4.9 Significance of Control Parameters on wear using SN Ratio

Level	Composition	Applied Load	Sliding Speed
1	71.36	76.382	71.156
2	72.884	70.472	71.964
3	71.358	73.064	69.268
4	70.154	68.746	71.092
5	68.478	65.57	70.154
Delta	4.406	10.812	2.696
Rank	**2**	**1**	**3**

Table 4.10 ANOVA Results for Wear

Factors	DOF	Seq. SS	Adj. SS	Adj. MS	F Value	P	Contribution
Composition	4	0.0000002	0.0000002	0.0000001	11.04	0.001	40%
Applied Load	4	0.0000002	0.0000002	0.0000000	13.70	0.000	40%
Sliding Speed	4	0.0000001	0.0000000	0.0000000	1.76	0.203	20%
Error	12	0.0000000	0.0000001	0.0000000			
Total	24	0.0000005					

S= 0.0000653962 R-sq = 89.83% R-sq (Adj.) = 79.66%

From the table 4.10, it may be seen that the applied load is the most significant parameter with a contribution of 40% to decide the wear behaviour of the composites, followed by composition. From the values of P values, it can be concluded that applied is (p=0.000) is more significant factor than the composition (p=0.001), which again validate the findings of Taguchi S/N ratio conclusions. As the p value of both the factors is less than the (0.05) value so it can be said that these factors are statistically significant.

Table 4.11 Significance of Control Parameters on friction using SN Ratio

Level	Composition	Applied Load	Sliding Speed
1	8.8240	10.07	6.984
2	6.6438	8.124	7.82
3	6.5488	7.258	7.372
4	8.9040	6.856	7.138
5	7.3120	5.916	8.91
Delta	2.36	4.154	1.926
Rank	**2**	**1**	**3**

From the table 4.12, it may be seen that the applied load is the most significant parameter with a contribution of 44.94% to decide the wear behaviour of the composites, followed by composition and sliding speed. From the values of P values, it can be concluded that applied is (p=0.003) is more significant factor than the composition (p=0.024) and sliding speed (p=0.215), which again validate the findings of Taguchi S/N ratio conclusions displayed in table 4.11. As the p value of the factors is less than the (0.05) value so it can be said that these factors are statistically significant.

Table 4.12 ANOVA Results for Friction

Factors	DOF	Seq. SS	Adj. SS	Adj. MS	F Value	P	Contribution
Composition	4	0.061257	0.061257	0.015314	4.19	0.024	25%
Applied Load	4	0.106035	0.106035	0.026509	7.26	0.003	44.94%
Sliding Speed	4	0.043839	0.043839	0.003653	1.70	0.215	18.58%
Error	12	0.024780	0.024780	0.006195			
Total	24	0.235911					

S= 0.0604422 R-sq = 81.42% R-sq (Adj.) = 62.83%

Another term appeared in the ANOVA table is R-Sq & R-Sq (adj) where R-sq is a statistical measure of how close the data are to the fitted regression line. This is also known as co-efficient of determination or the co-efficient of determination for multiple regressions. R-sq. is always between 0% to 100%. 0% indicates that the model explains none of the variability of the response data around its mean and 100% indicates that the model explains all the variability of the response data around its mean. In general, higher the R-sq. better the model fits your data. R-Sq(adj) is the modified version of R-sq. that has been adjusted in for the number of predictors in the model. The adjusted R-sq increases only if the new term improves the model more than would be expected by chance. It decreases when a predictor improves the model by less than expected by chance. The R-squared can be negative, but usually not. It is always lower than the R-squared.

Chapter 5
Conclusions and Future Work

5.1 Summary of Findings

The various fillers like Titanium Oxide (TiO2), Aluminium Oxide (Al2O3), Silicon carbide (SiC), Silicon Metal Powder, Magnesium Hydroxides ($Mg(OH)_2$)with several type improves mechanical characters of particle reinforced rubber composites. The mechanical characterization also affected by the parameters like dispersion of fillers, interfacial bonding between filler and rubber matrix and distribution of fillers.

5.2 Contributions to the Field

The field of "Investigation and Optimization of Particle-Reinforced Rubber Composites for Enhanced Mechanical and Wear Properties" has made significant contributions to materials science and engineering. This area of research focuses on enhancing the mechanical strength and wear resistance of rubber materials through the incorporation of reinforcing particles. Here are some of the key contributions of this field:

1. Improved Material Performance:

One of the primary contributions is the development of rubber composites with superior mechanical properties. By incorporating various types of reinforcing particles such as nanoparticles, It has been able to significantly enhance the tensile strength, modulus, and toughness of rubber materials. This has expanded the range of applications for rubber-based products in industries like automotive, aerospace, and construction.

2. Wear Resistance Enhancement:

The field has led to innovations in improving the wear resistance of rubber composites. By carefully selecting and optimizing the type, sizes, and concentration of reinforcing particles, have developed rubber materials that can withstand abrasive wear, erosion, and friction better than traditional rubber compounds. This is particularly valuable in applications where durability and longevity are critical, such as in conveyor belts, tires, and seals.

3. Sustainability and Cost-Efficiency:

The field has also explored environmentally friendly approaches by investigating sustainable reinforcing materials and manufacturing processes. By using recycled or renewable resources for reinforcing particles, it has contributed to more sustainable rubber composites. Additionally, optimizing the production process has led to cost-efficient manufacturing methods, reducing the overall cost of producing high-performance rubber materials.

In summary, the investigation and optimization of particle-reinforced rubber composites have made substantial contributions by enhancing the mechanical and wear properties of rubber materials, expanding their applications, improving sustainability, and fostering collaboration between about this research and industry professionals. These advancements have had a positive impact on numerous sectors, ranging from transportation to manufacturing, ultimately benefiting society through improved product performance and durability.

5.3 Limitations and Recommendations for Future Research

5.3.1 Limitations:

1. Complex Material Interaction: Particle-reinforced rubber composites involve intricate interactions between the rubber matrix and reinforcing particles. Understanding these interactions comprehensively can be challenging due to the complex nature of rubber materials.

2. Optimization Challenges: Achieving the optimal combination of reinforcing particles, their size, distribution, and concentration, as well as the processing conditions, can be a time-consuming and resource-intensive task.

3. Environmental Concerns: While there is a growing emphasis on sustainability, some reinforcing particles, such as certain nanoparticles or exotic materials, may raise environmental and health concerns during manufacturing and disposal.

4. Scale-Up Issues: Transitioning from laboratory-scale research to large-scale production can be difficult. Scaling up the manufacturing processes while maintaining consistent material properties and quality can be a limitation.

5. Cost Considerations: The addition of high-performance reinforcing particles can increase the overall cost of rubber composites, making them less economically viable for some applications.

5.3.2 Future Scope:

1. Nano materials Integration: Further research can focus on the integration of advanced nano materials, such as graphene or carbon nanotubes, to enhance mechanical and wear properties. Understanding their dispersion and the potential for cost-effective production methods will be crucial.

2. Multi-Functional Composites: Future work can explore the development of particle reinforced rubber composites that offer multiple functionalities, such as self-healing properties, electrical conductivity, or thermal resistance, in addition to enhanced mechanical and wear properties.

3. Sustainable Reinforcements: Investigating sustainable and eco-friendly reinforcing materials, like natural fibers or biodegradable nanoparticles, can be a promising avenue to address environmental concerns.

4. Advanced Characterization Techniques: Advancements in analytical and characterization techniques, such as in-situ microscopy and spectroscopy, can provide deeper insights into the material interactions at the nanoscale and help optimize composite formulations.

5. Machine Learning and Computational Modeling: Leveraging machine learning and advanced computational modeling to predict the behavior of particle-reinforced rubber composites can accelerate the development process and reduce experimentation time.

In conclusion, the future of research on the investigation and optimization of particle-reinforced rubber composites holds great promise, with opportunities for innovation in materials, processes, and sustainability. Overcoming current limitations and addressing emerging challenges will lead to the development of advanced materials with enhanced properties for a wide range of applications.

5.4 Concluding Remarks

- In conclusion, the field of "Investigation and Optimization of Particle-Reinforced Rubber Composites for Enhanced Mechanical and Wear Properties" has made significant strides in advancing the performance and versatility of rubber materials. Through extensive research and innovation, this area has led to the development of rubber composites that exhibit superior mechanical strength and wear resistance, thereby expanding their utility across diverse industries.
- However, it is important to acknowledge the existing limitations, including the complexity of material interactions, optimization challenges, environmental concerns, scale-up issues, and cost considerations. These challenges highlight the need for continuous exploration and innovation in this field.
- The wear rate of particle reinforced rubber composites strongly depends on the experimental test parameters i.e. process parameters – compositions, load, speed, sliding distance and time.
- Wear and friction showed an tendency to increase in time , load and sliding velocity. But CoF value is maximum at higher load (2.5kgf) for the particle composition of Silicon Metal Powder. On the other hand CoF value is minimum at lower load (0.5kgf) for the particle composition of $Mg(OH)_2$. In case of wear where wear loss shows the typical trend with the increase in load. It observed that Minimum wear loss at lower load (0.5kgf) and maximum wear loss at higher load (2.5kgf).
- In the Micro-Hardness test results as indicate that Silicon Metal Powder (SMP) reinforced rubber composite possesses highest hardness value (24.79 HV0.1) among five considered particle reinforced rubber composites and followed by Silicon carbide reinforced rubber composite , Magnesium hydroxide reinforced rubber composite, Aluminum Oxide reinforced rubber composite, Titanium Oxide reinforced rubber composite. So Silicon Metal Powder (SMP) is the hardest particles among five particles consider in the test.
- In the Tensile test, the tensile stress at breaking point is found maximum (9.78794 MPa) for Silicon Metal Powder epoxy while the minimum (3.87718MPa) tensile stress at breaking point is evident in case of the $Mg(OH)_2$ epoxy. On the other hand, the tensile strain at breaking point is found maximum (2.17770 %) for Silicon Metal Powder epoxy while the minimum (1.36184%) tensile strain at breaking point is evident in case of the TiO_2 epoxy. So the Silicon Metal Powder (SMP) is the more strength particles among five particles consider in the test.

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