# DEVELOPMENT AND STUDY OF EROSION CHARACTERISTICS OF PEEK-GLASS FIBER COMPOSITES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

**Bachelor of Technology**
**In**
**Mechanical Engineering**

**By**

**PRIYA RANJAN PANIGRAHI**
**&**
**BIMAL KUMAR GOUDA**

**DEPARTMENT OF MECHANICAL ENGINEERING**
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Under the Guidance of
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# National Institute of Technology, Rourkela

## CERTIFICATE

This is to certify that the thesis entitled, “**Development and Study of Erosion Characteristics of PEEK - Glass Fiber Composites** ” submitted by **Sri Priya Ranjan Panigrahi** and **Sri Bimal Kumar Gouda** in partial fulfillment for the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

**Prof. Alok Satapathy**
Dept. of Mechanical Engineering
National Institute of Technology, Rourkela

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Date: - **Priya Ranjan Panigrahi** **Bimal Kumar Gouda**
Place:-

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# DEVELOPMENT AND STUDY OF EROSION CHARACTERISTICS OF PEEK-GLASS FIBER COMPOSITES

**PRIYA RANJAN PANIGRAHI & BIMAL KUMAR GOUDA**

Supervisor: **Prof. Alok Satapathy**

## ABSTRACT

The present work deals with the development and study of erosion wear behaviors of poly ether ether ketone(PEEK) - Glass-fiber (GF) and PEEK-GF-REDMUD composites. This work, study of its various mechanical properties like tensile strength, flexural strength and density. This work also includes erosion behaviors wrt. Varying Velocity and angle of impact of erodent. Comparison of properties of PEEK-GF and PEEK-GF REDMUD composites gives a detailed idea about the effect of REDMUD in PEEK-GF composites. For preparation of the composites clean glass plates were taken. Mould release sheets were placed on the plates. Mould release spray was applied on them. The catalyst and accelerator were added to the polyester in proportion 1.5% and 1% respectively and are thoroughly mixed. For preparation of different composites i.e. is neat PEEK-GF composite, Red mud filling PEEK-GF composite , this mixture was sprayed on the sheets to a thickness of about 2mm followed by a piece of glass fiber mat(cut in the shape of a rectangle). Again another layer of resin was sprayed .Thus a single layer of composite is formed. Load was applied on all these preparations and these were left for 48 hours for adequate curing and solidification. Then the mould release sheets were removed and molded composites were taken out. It may be mentioned that in all these composites the fiber orientation was set at $90^{0.}$

The important factors influencing the erosion rate of materials are the impact velocity, impact angle of erodent particles, the size, shape and hardness of eroding particles. This has been reported by a number of researchers for a wide range of materials and erodent .Many Investigators have used angular silica sand, alumina, corundum particles or irregular silicon Carbide abrasives. In the present study dry silica sand is used as erodent. Hence it is difficult to compare present erosion data precisely with literature data. It can be concluded that reinforcement of glass fiber into the PEEK matrix improves the flexural strength quite significantly, thus making them potential materials for structural applications. Addition of Red Mud to glass fiber reinforced composites also enhances the flexural strength, flexural modulus and tensile strength of the material. PEEK with glass fiber reinforcement exhibits better resistance to solid particle erosion in comparison to the un-reinforced PEEK resin. The rate of wear of the composite material is also greatly influenced by operational variables like impact angle and the velocity of impact. Further, material variables like erodent and type of composite also affect the erosion rate. The neat PEEK and 20% red mud filling of glass fiber reinforced PEEK composite exhibited maximum erosion rate at an impingement angle of $60^0$ under the present experimental conditions studied

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# CHAPTER 1

# INTRODUCTION

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Composites are combinations of two materials in which one of the materials, called the reinforcing phase, is in the form of fiber sheets or particles and is embedded in the other material called the matrix phase. The primary functions of the matrix are to transfer stresses between the reinforcing fibers/particles and to protect them from mechanical and/or environmental damage whereas the presence of fibers/particles in a composite improves its mechanical properties such as strength, stiffness etc. A composite is therefore a synergistic combination of two or more micro-constituents that differ in physical form and chemical composition and which are insoluble in each other. The objective is to take advantage of the superior properties of both materials without compromising on the weakness of either.

Composite materials have successfully substituted the traditional materials in several light weight and high strength applications. The reasons why composites are selected for such applications are mainly their high strength-to-weight ratio, high tensile strength at elevated temperatures, high creep resistance and high toughness. Typically, in a composite, the reinforcing materials are strong with low densities while the matrix is usually a ductile or tough material. If the composite is designed and fabricated correctly it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material. The strength of the composites depends primarily on the amount, arrangement and type of fiber and /or particle reinforcement in the resin

## 1.2 Merits of Composites

Advantages of composites over their conventional counterparts are able to meet diverse design requirements with significant weight savings as well as strength-to-weight ratio. Some advantages of composite materials over conventional ones are as follows:

- Tensile strength of composites is four to six times greater than that of steel or aluminium (depending on the reinforcements).

- Improved torsional stiffness and impact properties.

- Higher fatigue endurance limit (up to 60% of ultimate tensile strength).

- 30% - 40% lighter for example any particular aluminium structures designed to the same functional requirements.

- Lower embedded energy compared to other structural metallic materials like steel, aluminium etc.

- Composites are less noisy while in operation and provide lower vibration transmission than metals.

- Composites are more versatile than metals and can be tailored to meet performance needs and complex design requirements.

- Long life. Offer excellent fatigue, impact, environmental resistance and reduce maintenance.

- Composites enjoy reduced life cycle cost compared to metals.

- Composites exhibit excellent corrosion resistance and fire retardancy.

- Improved appearance with smooth surfaces and readily incorporable integral decorative melamine are other characteristics of composites.

- Composite parts can eliminate joints / fasteners, providing part simplification and integrated design compared to conventional metallic parts.

## 1.3 Classification

Broadly, composite materials can be classified into three groups on the basis of matrix material. They are:

a) Metal Matrix Composites (MMC)
b) Ceramic Matrix Composites (CMC)
c) Polymer Matrix Composites (PMC)

### 1.3.1 Metal Matrix Composites:

Metal Matrix Composites have many advantages over monolithic metals like higher specific modulus, higher specific strength, better properties at elevated temperatures, and lower coefficient of thermal expansion. Because of these attributes metal matrix composites are under consideration for wide range of applications viz. combustion chamber nozzle (in rocket, space shuttle), housings, tubing, cables, heat exchangers, structural members etc.

### 1.3.2 Ceramic matrix Composites:

One of the main objectives in producing ceramic matrix composites is to increase the toughness. Naturally it is hoped and indeed often found that there is a concomitant improvement in strength and stiffness of ceramic matrix composites.

### 1.3.3 Polymer Matrix Composites:

Most commonly used matrix materials are polymeric. The reason for this are two fold. In general the mechanical properties of polymers are inadequate for many structural purposes. In particular their strength and stiffness are low compared to metals and ceramics. These difficulties are overcome by reinforcing other materials with polymers. Secondly the processing of polymer matrix composites need not involve high pressure and doesn’t require high temperature. Also equipments required for manufacturing polymer matrix composites are simpler. For this reason polymer matrix composites developed rapidly and soon became popular for structural applications.

Composites are used because overall properties of the composites are superior to those of the individual components for example polymer/ceramic. Composites have a greater modulus than the polymer component but aren’t as brittle as ceramics.

Two types of polymer composites are:

- Fiber reinforced polymer ( FRP )
- Particle reinforced polymer ( PRP )

### 1.3.3.1 Fiber reinforced polymer:

Common fiber reinforced composites are composed of fibers and a matrix. Fibers are the reinforcement and the main source of strength while matrix glues all the fibers together in shape and transfers stresses between the reinforcing fibers. The fibers carry the loads along their longitudinal directions. Sometimes, filler might be added to smooth the manufacturing process, impact special properties to the composites, and / or reduce the product cost.

Common fiber reinforcing agents include asbestos, carbon / graphite fibers, beryllium, beryllium carbide, beryllium oxide, molybdenum, aluminium oxide, glass fibers, polyamide, natural fibers etc. Similarly common matrix materials include epoxy, phenolic, polyester, polyurethane, polyetherethrketone (PEEK), vinyl ester etc. Among these resin materials, PEEK is most widely used. Epoxy, which has higher adhesion and less shrinkage than PEEK, comes in second for its high cost.

### 1.3.3.2 Particle reinforced polymer:

Particles used for reinforcing include ceramics and glasses such as small mineral particles, metal particles such as aluminium and amorphous materials, including polymers and carbon black. Particles are used to increase the modules of the matrix and to decrease the ductility of the matrix. Particles are also used to reduce the cost of the composites. Reinforcements and matrices can be common, inexpensive materials and are easily processed.

Some of the useful properties of ceramics and glasses include high melting temp., low density, high strength, stiffness; wear resistance, and corrosion resistance.

Many ceramics are good electrical and thermal insulators. Some ceramics have special properties; some ceramics are magnetic materials; some are piezoelectric materials; and a few special ceramics are even superconductors at very low temperatures. Ceramics and glasses have one major drawback: they are brittle. An example of particle – reinforced composites is an automobile tire, which has carbon black particles in a matrix of poly-isobutylene elastomeric polymer.

Polymer composite materials have generated wide interest in various engineering fields, particularly in aerospace applications. Research is underway worldwide to develop newer composites with varied combinations of fibers and fillers so as to make them useable under different operational conditions. Against this backdrop, the present work has been taken up to develop a series of PEEK-GF based composites with glass fiber reinforcement and with fillers and to study their response to solid particle erosion.

## 1.4 Objectives

The objective of the present work can be stated as:

- To fabricate PEEK – glass fiber composites with single and multilayer fiber reinforcement.
- To fabricate Red mud filling PEEK-Glass fiber composites.
- To evaluate the resistance of these composites to solid particle erosion under different operational conditions.
- To analyze the experimental results by statistical techniques for identifying significant control factors affecting the wear properties of the composites.

This work is expected to introduce a new functional polymer composite suitable for tribiological applications.

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# CHAPTER 2

# LITERATURE SURVEY

# CHAPTER 2

## LITERATURE SURVEY

Composite materials offer exciting advantages over traditional monolithic materials. Modern advanced composites are a success story from the view point of their widespread applications, ranging from tennis rackets to advanced space vehicles. Aggressive research is being carried out worldwide to explore new composites with improved functional properties. This chapter outlines some of the recent reports published in literature on composites with special emphasis on erosion wear behavior of glass fiber reinforced polymer composites.

Polymers and composites are extensively used in tribo-applications such as bearings, gears etc. where liquid lubricants can not always be used because of various constraints [**1**]. Apart from adhesive wear mode, some polymers and composites have exhibited excellent tribo-potential in other wear situations also such as abrasive, fretting, reciprocating and erosive [**2**]. Comparatively less is reported on erosive wear performance of polymers and composites though some polymers such as rubbers have proved their superiority over metals [**3**, **4**]. Finnie [**5**, **6**] has done pioneering in the case of metals. Polymer and composites are increasingly being used in applications such as radomes, surfing boats, gas and steam turbine blades gears for locomotives, conveyor belts, helicopter blades, pump-impellers in mineral slurry processing, where the components encounter impact of lot of abrasives like dust, sand, splinters of materials, slurry of solid particles and consequently the parts undergo erosive wear. Hence, it becomes imperative to study erosive wear behavior of polymeric engineering materials in various operating conditions.

In general, the operating conditions and material properties decide the erosive wear performance of the material. Pool et al. [**7**] though have summarized some general trends about the influence of various factors such as hardness, ductility, brittleness, stress levels, surface finish of materials, erodent and operating conditions on erosive wear behavior of polymers, it is not necessarily true in the case of all polymers and composites.

Various researchers have correlated several properties such as hardness, brittleness index, resilience, fracture energy, etc. [**8-13**] with the erosive wear behavior of polymers and composites.

The erosion of materials caused by impact of hard particles is one of several forms of material degradation generally classified as wear. Bitter [**14**] defined erosion as “Material damage caused by the attack of particles entrained in a fluid system impacting the surface at high speed” while Hutchings [**15**] wrote “ Erosion is an abrasive wear process in which the repeated impact of small particles entrained in a moving fluid against a surface results in the removal of material from the surface”. Solid particle erosion is a serious problem in gas turbines, rocket nozzles, cyclone separators, valves, pumps and boiler tubes. Polymer composite materials are finding increased application under conditions in which they may be subjected to solid particle erosion. Examples of such applications are pipe lines carrying sand slurries in petroleum refining, helicopter rotor blades [**1, 2**], pump impeller blades, high speed vehicles, air-crafts operating in desert environments, water turbines, aircraft engine blades [**3**].

Many researchers [**16-38**] have evaluated the resistance of various types of polymers and their composites to solid particle erosion. Materials that have been eroded include nylon [**21**, **22**], epoxy [**34-36**], polypropylene [**28**, **3**], polyethylene [**29**], polyetheretherketone (PEEK) [**30**, **33**] ultra high molecular weigh polyethylene (UHMWPE) and various polymer based composites [**16**, **19**, **20**, **23-25**, **32-34**, **36**].

There are also several reports in the literature which discuss the erosion behavior of fibrous composites. These papers mainly showed, however, only the erosion behavior and performance to erosive damage. Although various types of fiber are used for reinforcing plastics, no paper has been published in which the effect of types of fiber, e.g. strand mat, woven cloth, unidirectional UD fiber, etc. on sand erosion damage have been discussed systematically. And no convenient method to predict the erosion rate has been reported anywhere.

Though some efforts have been focused on evaluation of erosion behavior of bulk polymers such as PE [**8**], Polyamides and their composites [**9]** and PEEK [**12**] very limited number of papers is available on systematic studies on erosive wear performance of a class of polymers with different mechanical properties.

It is often seen from the published reports that fiber reinforced composite materials compared to neat polymers present a rather poor resistance to solid particle erosion. In spite of this they are attractive for their high specific strength and are frequently used in engineering parts in automobile, aerospace, marine and energetic applications. Due to operational requirements in dusty environment, the erosion characteristics of the polymeric composites are of high relevance. As different mechanism of material removal seems to govern the erosion of polymer matrix composite, it is important to study the behavior of a specific composition in order to identify suitable application areas. Keeping this in mind, the present work has been undertaken to study the erosion wear pattern of polyester-glass-fiber-composites subjected to various experimental conditions.

Although large numbers of research papers are available in published literature, the author has not come across any work on ceramic filled fiber-reinforced-composites. In this investigation alumina powder is reinforced in polyester along with glass fiber. This new composite will be characterized with respect to its strength and erosive wear properties.

This work is expected to introduce a new class of functional composite that might find applications in erosive operational situations.

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# CHAPTER 3

# MATERIALS AND METHODS

# CHAPTER 3

# MATERIALS AND METHODS

## 3.1 Introduction

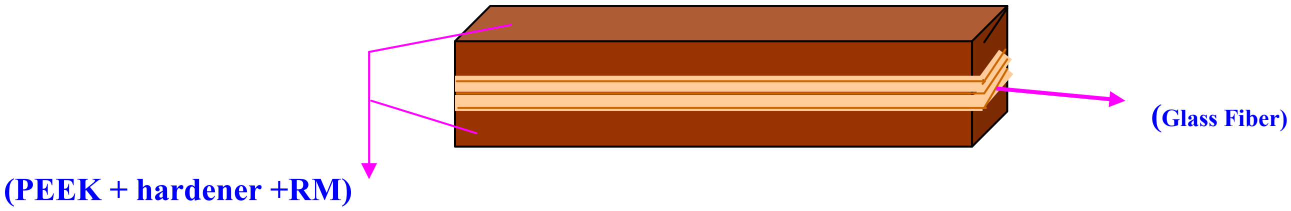
This chapter deals with the details of processing of the composites and the experimental procedures followed for their characterization and tribological evaluation. The raw materials used in this work are

1. PEEK - Resin
2. E-glass Fiber
3. Red mud Powder

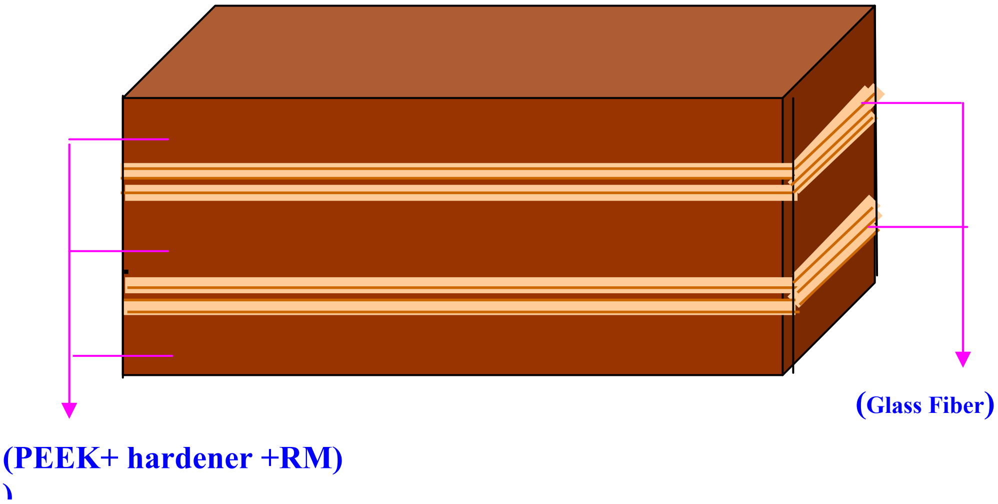
PEEK is the matrix material used in this work and is procured from CIBA GIEGY limited. Other chemicals used are cobalt acetate (Catalyst/Hardener) and accelerator compatible to polyester. Red mud powder in the particle size range about 500 micron procured from NICE has been used as the filler material. The reinforcing fiber is E-glass (360 Roving) taken from Saint Gobian.

## 3.2 Processing of the Composites :-

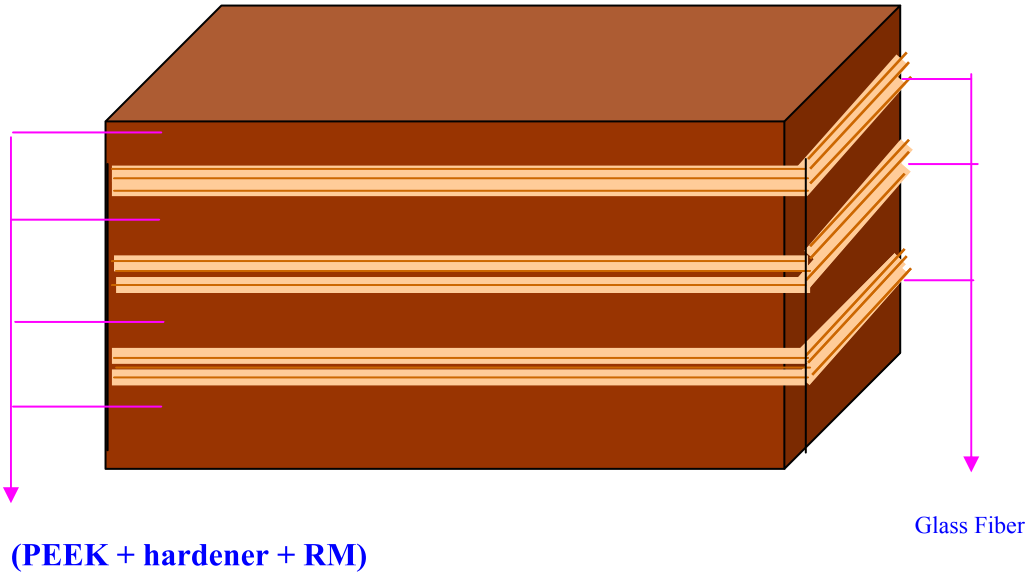
For preparation of the composites clean glass plates were taken. Mould release sheets were placed on the plates. Mould release spray was applied on them. The catalyst and accelerator were added to the polyester in proportion 1.5% and 1% respectively and are thoroughly mixed. For preparation of different composites i.e. is neat PEEK-GF composite ,Red mud filling PEEK-GF composite, this mixture was sprayed on the sheets to a thickness of about 2mm followed by a piece of glass fiber mat(cut in the shape of a rectangle). Again another layer of resin was sprayed .Thus a single layer of composite is formed. Load was applied on all these preparations and these were left for 48 hours for adequate curing and solidification. Then the mould release sheets were removed and molded composites were taken out. It may be mentioned that in all these composites the fiber orientation was set at $90^0$. Red mud powder was added and thoroughly mixed with the matrix base in a proportion of 20% by weight. Fig 3.1gives a schematic view of composites.



Single layer composite



Double layer composite



Triple layer composite

**Fig. 3.1 Schematic View of the Composites**

**Fig 3.2** Picture of the composites

### 3.3 Characterization of the Composites :-

The characterization of the newly developed composites includes the measurement of their density and evaluation of the flexural strength. From the compression moulded composite plates, test samples of approximately 70mm×40mm size were cut using a diamond cutter. The thickness of the samples of different composite were measured and recorded. Each sample is weighed using a precision electronic balance with ±0.001gm accuracy. The density of each composite sample was thus calculated by conventional method.

The determination of flexural strength is an important characterization of any structural material. It is the ability of a material to withstand the bending before reaching the breaking point. Conventionally a three point bend test is conducted for finding out this material property. In the present investigation also the composites were subjected to this test in a testing m/c INSTRON 1195. The photograph of the machine and the loading arrangement for the specimens are shown in fig 3.2 and fig 3.3 respectively. A span of 30mm was taken and cross head speed was maintained at 10mm/min. As for the mechanics of material the maximum shear stress that a material can withstand before rupture under bending is given by the equation

$$\mathbf{T = 3P / 4bh}$$

and the maximum tensile stress it can withstand before breaking is given by the equation

$$\sigma = 3PL / 2bh^2$$

Where $P$= applied central load (N)

$L$= test span of the sample (m)

$b$= width of the specimen (m)

$h$= thickness of specimen under test (m)

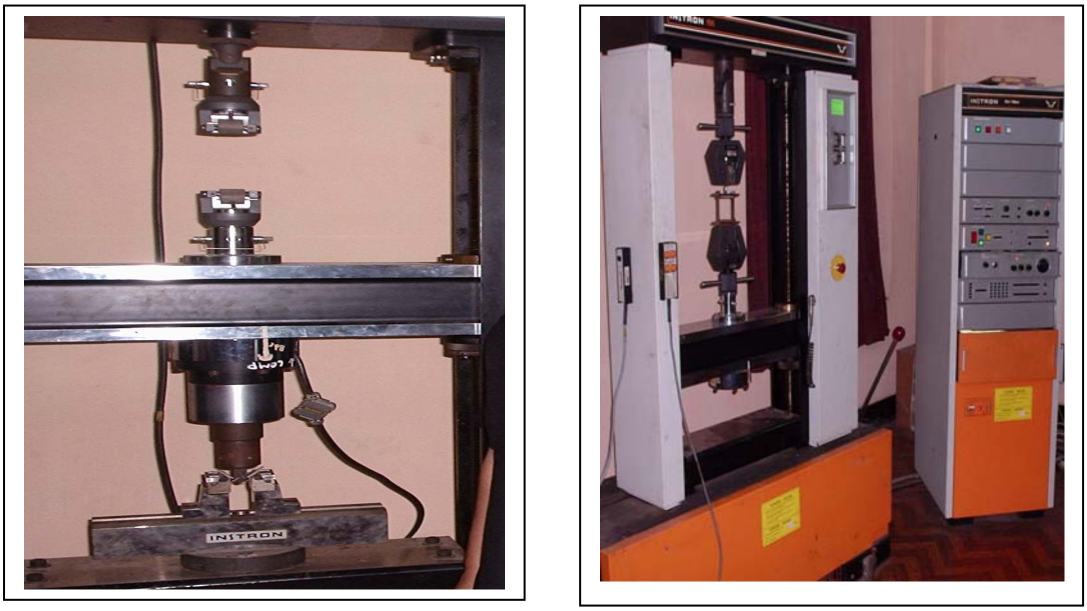


**Fig 3.3(a)** Photograph of the machine (Instron 1195) for 3 point bend test

**Fig 3.3 (b)** Loading arrangement for the specimens

This maximum tensile stress is taken as the flexural strength of the composite. In the present work the three point bend test was conducted in accordance with ASTMD790M-81 standard.

### 3.4 Study of Erosion Wear Behaviour of Composites :-

Solid particle erosion (SPE) is usually simulated in laboratory by one of two methods. The ‘sand blast’ method, where particles are carried in an air flow and impacted onto a stationary target and the ‘whirling arm’ method , where the target is spun through a chamber of falling particles.

In the present investigation, an erosion apparatus (self-made) of the ‘sand blast’ type is used (shown in fig 3.4). It is capable of creating highly reproducible erosive situations over a wide range of particle sizes, velocities, particles fluxes and incidence angles, in order to generate quantitative data on materials and to study the mechanisms of damage. The test is conducted as per ASTM G76 standards.

**Fig 3.4** Solid Particle Erosion Test Set Up

The jet erosion test rig used in this work employs one 80 mm long nozzle of 3 mm bore. This nozzle size permits a wider range of particle types to be used in the course of testing, allowing better simulations of real erosion conditions. The mass flow rate is measured by conventional method. Particles are fed from a simple hopper under gravity into the groove. Velocity of impact is measured using double disc method. Some of the features of this test set up are:

- Vertical traverse for the nozzle: provides variable nozzle to target standoff distance, which influences the size of the eroded area.
- Different nozzles may be accommodated: provides ability to change the particle plume dimensions and the velocity range
- Large test chamber with sample mount (typical sample size 40 mm x 60 mm) that can be angled to the flow direction: by tilting the sample stage, the angle of impact of the particles can be changed in the range of $0^0 – 90^0$ and this will influence the erosion process.

In this work, room temperature solid particle erosion test on an un-reinforced PEEK sample and on its various composites (with reinforcement) is carried out under different impact angles. The nozzle is kept at different stand-off distances from the target. 500 µm average size dry silica sand particles are used as erodent with three different velocities of 321m/s 45m/s and 58m/s. Amount of wear is determined on ‘mass loss’ basis. It is done by measuring the mass of the samples at the beginning of the test and at regular intervals in the test duration. A precision electronic balance with ± 0.1 mg accuracy is used for weighing. Erosion rate, defined as the coating mass loss per unit erodent mass (mg/g) is calculated.

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# CHAPTER 4

# MECHANICAL PROPERTIES

## CHAPTER 4

# MECHANICAL PROPERTIES

### 4.1 Introduction

In general, the various factors, which influence the erosive wear performance of polymers and their composites, are shown in **Fig 4.1**. The most important factor for design with composites is the fibre/filler content, as it controls the mechanical and thermo-mechanical properties. In order to obtain the desired material properties for a particular application, it is important to know how the material performance changes with the fibre content under given loading conditions.

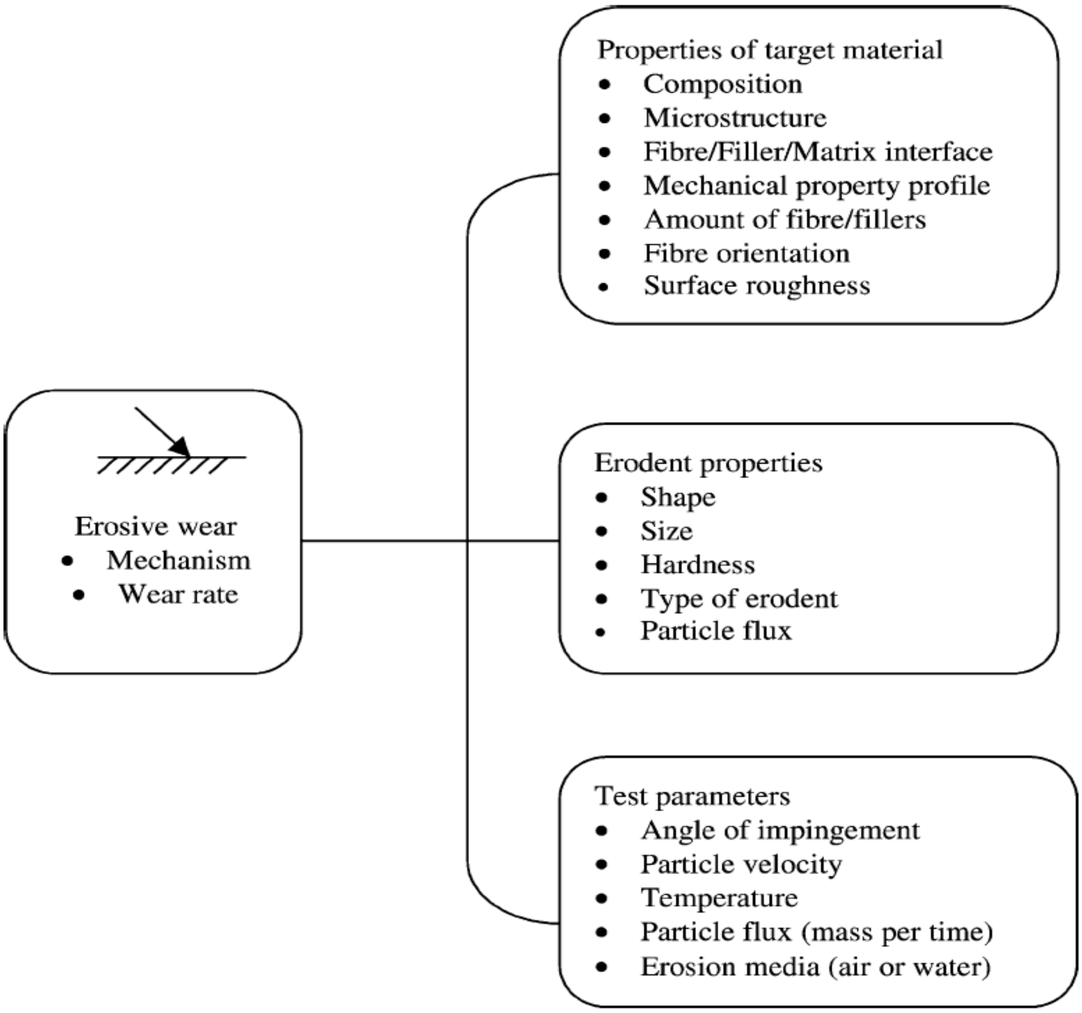


**Fig.4.1** Influence of material, erodent and test parameters on erosive wear performance of polymers and their composites.

## 4.2 Results

This work focuses on development of PEEK matrix composite with glass fiber reinforcement and on studying their response to solid particle erosion. A simple processing route has been adapted and its detail has already been described in the previous chapter. Some composite are also made with Red mud and SIC powder used as filler in them. This chapter presents the result of various tests which the composites are subjected to. The tests include evaluation of Tensile strength, flexural strength, Flexural modulus, measurement of density, and solid particle erosion test.

## 4.3 Evaluation of Tensile Strength

The tension test is generally performed on flat specimens. The most commonly used specimen geometries are the dog-bone specimen and straight-sided specimen with end tabs. A uniaxial load is applied through the ends. The ASTM standard test method for tensile properties of fibre–resin composites has the designation D3039-76. It recommends that the specimens with fibres parallel to the loading direction should be 11.5 mm wide and mode with 4-6 plies. Length of the test section should be 100 mm. The test-piece used here is of dog-bone type and having dimensions according to the standards. The tensile test was performed on the universal testing machine and results were analyzed to calculate the tensile strength of composite samples as show in **fig.4.2**

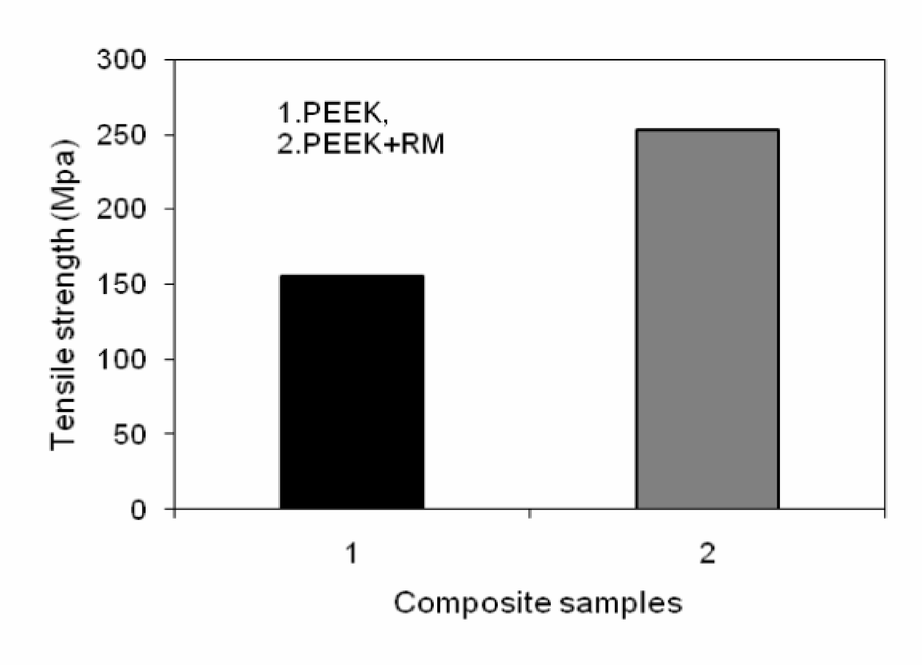


**Fig.4.2** Effect of Red mud on tensile strength of PEEK-GF composites.

## 4.4 Evaluation of Flexural Strength :-

The flexural strength is a measure of resistance of the composite to bending. It is the ability of the material to withstand bending before reaching the breaking point. 3 point bend test was conducted for all the 3 composites and the flexural strength for each of them was evaluated. Flexural Yield Strength is reported instead of flexural strength for materials that do not crack in the flexure test. The strength of a material in bending, expressed as the stress on the outermost fibers of a bent test specimen, at the instant of failure. In a conventional test, flexural strength expressed in Mpa is equal to:

$$\frac{3LP}{2bd^2}$$

Where P = the load applied to a sample of test length L, width *b*, and thickness *d*. Flexural modulus is the ratio, within the elastic limit, of the applied stress on a test specimen in flexure, to the corresponding strain in the outermost fibers of the specimen. The Flexural test measures the force required to bend a beam under 3 point loading conditions. The data is often used to select materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material's stiffness when flexed is shown in **fig 4.4**. Since the physical properties of many materials (especially thermoplastics) can vary depending on ambient temperature, it is sometimes appropriate to test materials at temperatures that simulate the intended end use environment. Most commonly the specimen lies on a support span and the load is applied to the center by the loading nose producing three point bending at a specified rate. The parameters for this test are the support span; the speed of the loading; and the maximum deflection for the test. These parameters are based on the test specimen thickness, and are defined differently by ASTM.

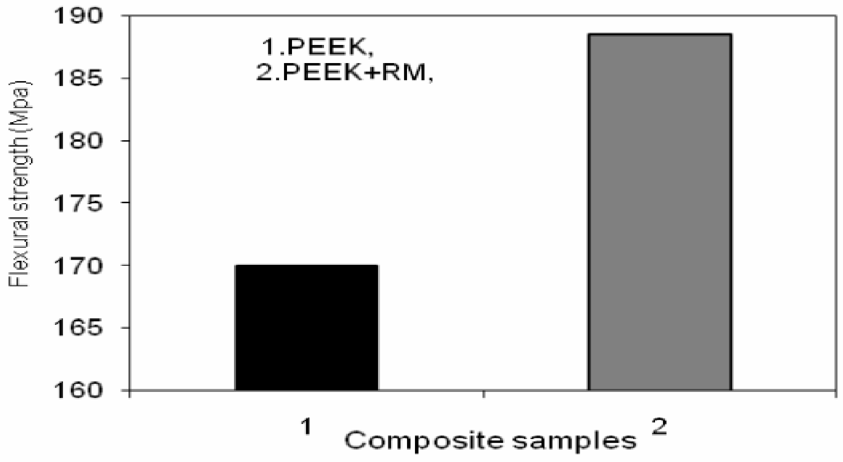


**Fig.4.3** Effect of Red mud on flexural strength of PEEK-GF composites.

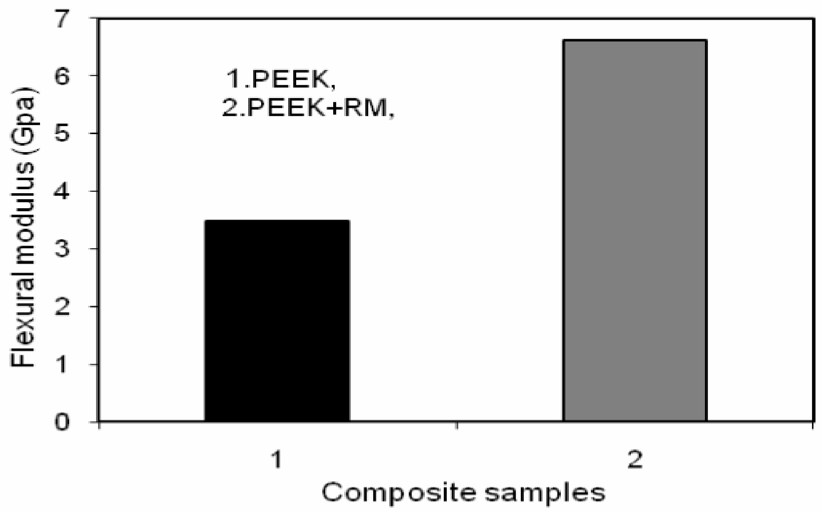


**Fig.4.4** Effect of Red mud and SIC filler on flexural modulus of PEEK-GF composites.

### 4.5 Evaluation of density

The mass density of all the 3 composites is tabulated in **Table 4.1**. It is seen in the **Fig 4.5** that the density of each sample is different from the rest. The fiber content and the ceramic filler content in the composites affect their density which is obvious.

| Type of composite | Density(gm/cc) |
|---|---|
| PEEK Composite | 1.608 |
| PEEK+RM Composite | 1.498 |

**Table 4.1** Density Values of Composites

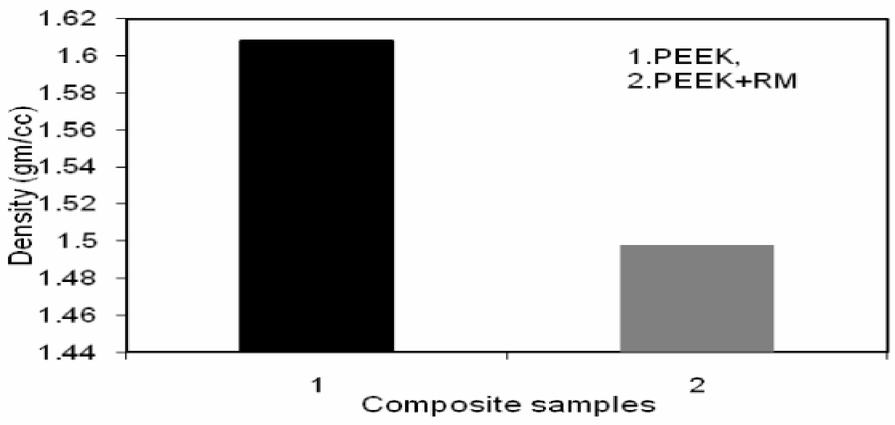


**Fig.4.5** Comparison of the density of some of the composite sample with and without Red mud powder filling.

# CHAPTER 5

# EROSION CHARACTERISTICS

# CHAPTER 5

# EROSION CHARACTERISTICS

## 5.1 Introduction

Different composites respond to solid particle erosion differently. They are affected largely by the reinforcement material, main matrix resin the erodent material and also by the operational variables. The results of erosion test on the composites are presented below:

## 5.2 Influence of erodent doze on wear behaviour

The doze of erodent to achieve steady state value varied with materials. Moreover, the nature of curves also varied from material to material. **Fig 5.1** – **Fig 5.5** show the variation of erosion rate of the composites as a function of the erodent doze for impact angles of $30^0$ - $90^0$ and velocity of 58 m/s respectively. It is seen that with increasing number of GF layers i.e. the fiber loading the erosion wear rate decreases for any amount of erodent strike. For a particular composite the wear rate shows either an increasing or a decreasing trend initially but with increase in the cumulative weight of erodent attains an almost steady value. These curves are drawn for composites of PEEK-GF and PEEK-GF with Red mud filler material.
The response of the materials to the weight of erodent was acceleration, peaking, deceleration and stabilization. All composite samples show similar behaviour of a typical brittle material in which the erosion rate increases with increase of cumulative weight of impinging particles. PEEK-GF sample shows higher value of erosion rates than the 20%Red mud filled PEEK-GF composites. The comparisons of Figures indicate that a strong dependence of the erosive wear exists as a function of the relative microstructure of the composites this is because of the fact that when a composite surface is eroded by solid particles, the material lost is composed of fibre and matrix.

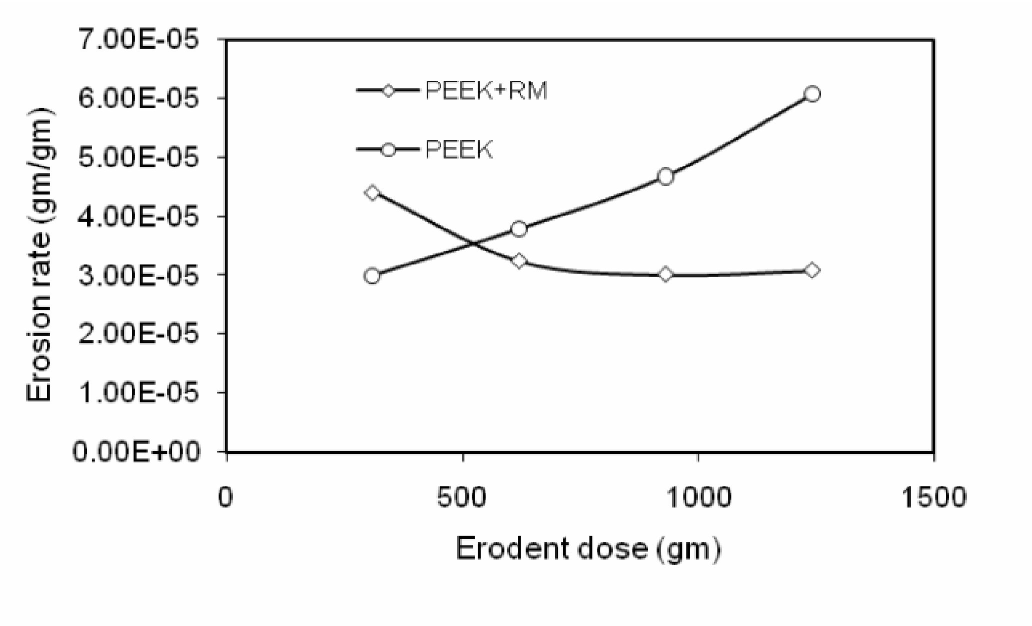


**Fig.5.1** Variation of erosion rate with cumulative weight of impinging particles at impingement angle $30^0$ and velocity 58 m/s

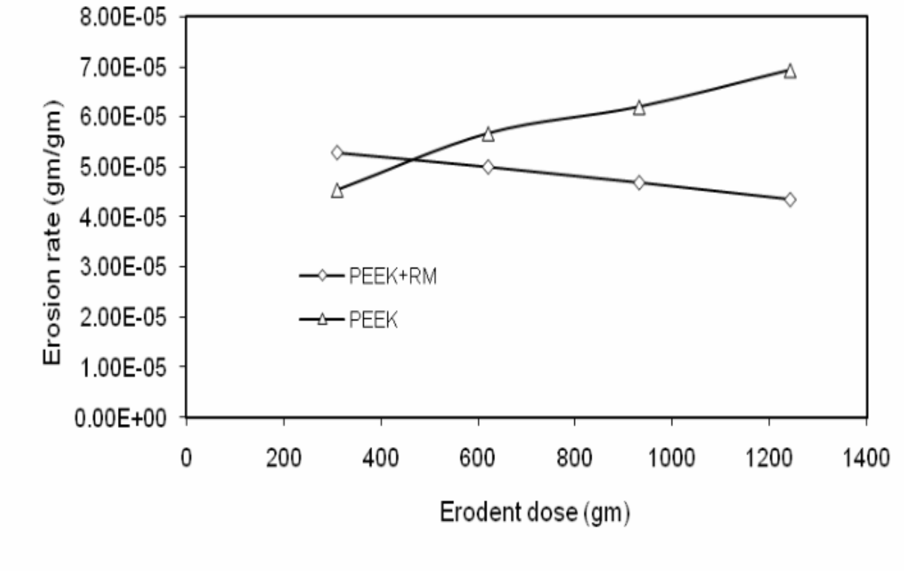


**Fig.5.2** Variation of erosion rate with cumulative weight of impinging particles at impingement angle $45^0$ and velocity 32 m/s

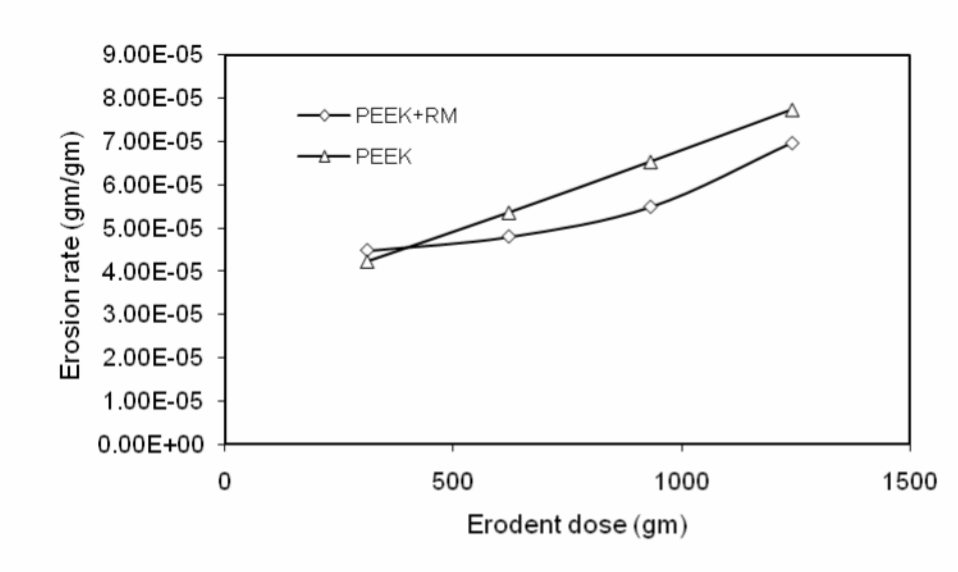


**Fig.5.3** Variation of erosion rate with cumulative weight of impinging particles at impingement angle $60^0$ and velocity 58 m/s

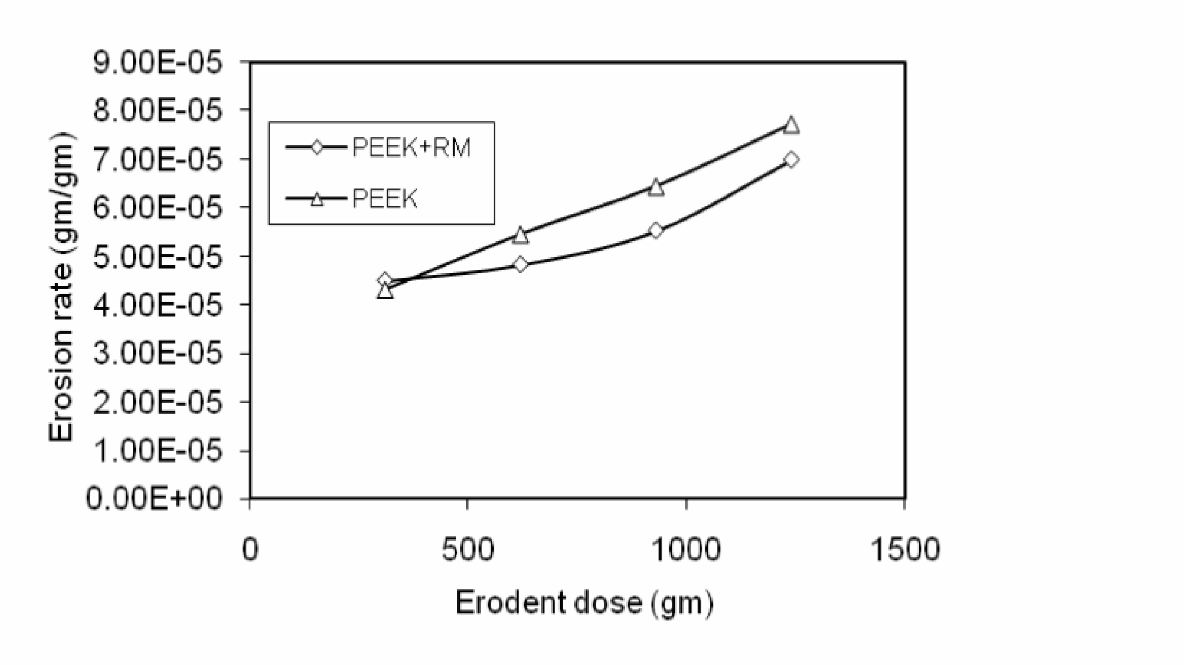


**Fig.5.4** Variation of erosion rate with cumulative weight of impinging particles at impingement angle $75^0$ and velocity 58 m/s

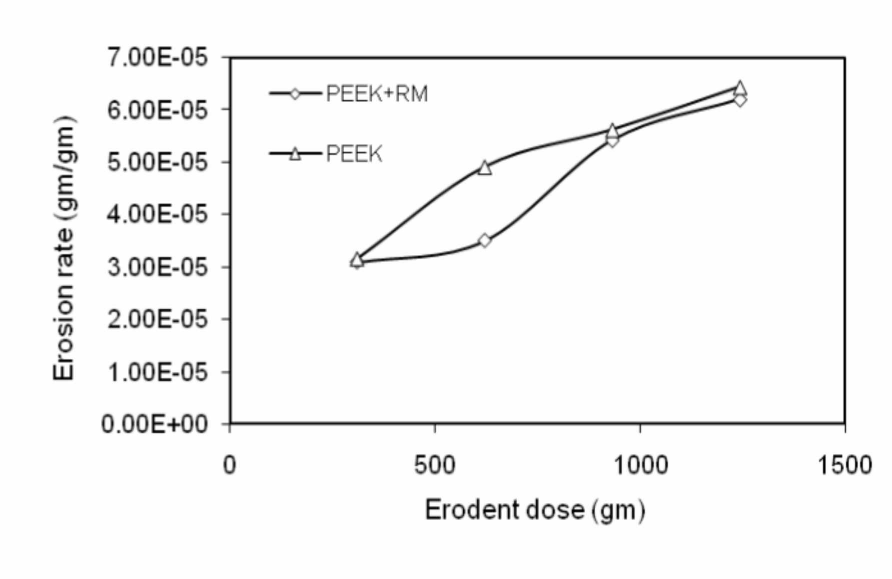


**Fig.5.5** Variation of erosion rate with cumulative weight of impinging particles at impingement angle $90^0$ and velocity 58 m/s

### 5.3 Influence of impingement angle on wear behaviour

It is known that impingement angle is one of the most important parameters for the erosion behaviour of materials. In the erosion literature, materials are broadly classified as ductile or brittle based on the dependence of their erosion rate on impingement angle. The behaviour of ductile materials is characterized by maximum erosion rate at low impingement angles ($15^0$ to $30^0$). Brittle materials on the other hand show maximum erosion under normal impact angle ($90^0$).

It is seen in **Fig 5.6** that the PEEK glass fiber reinforced composites under this investigation in this work are exhibiting a somewhat semi-ductile behaviour with the peak erosion occurring at $60^0$. For all the three composites the variation of erosion rate with impact angle is showing similar trend. Initially with increase in the impingement angle the rate of erosion increases, reaches a peak value and with further increase in angle the wear rate decreases. In all the cases the minimum erosion was recorded at normal impact ($90^0$). This may be attributed to its ductile nature.

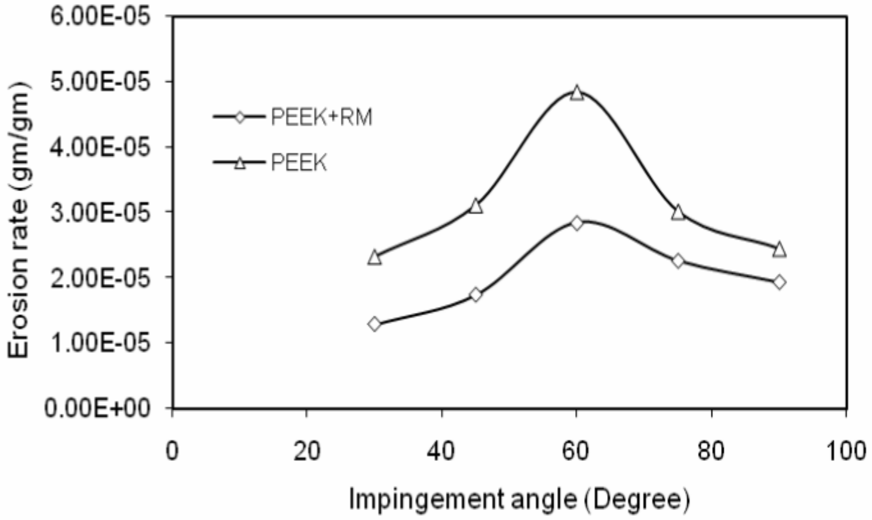


**Fig.5.6** Variation of erosion rate with impingement angle at velocity 58 m/s.

### 5.4 Effect of velocity

The velocity of the erosive particles has a very strong effect on erosion rate. In order to study the effect of particle velocity on erosion rate, erosion tests were performed by varying the particle velocity from 32 to 58m/s at impingement angles of $30^0$ - $90^0$. **Fig 5.1 – Fig 5.5** represents the erosion dependence on impact velocity at $30^0$ - $90^0$ impingement angles for PEEKs and its composites. The least-squares fits to the data points were obtained by using a power law ($E = kv^{n,}$ where $E$ is the steady-state erosion rate, $v$ the impact velocity of particles, $n$ a velocity exponent and $k$ a constant). The velocity exponents were in the range of 1.5–1.70 for the various materials at 30 and 90◦ impingement angles, respectively. **Fig 5.7** shows that the erosion rate increases with rise in particle velocity but erosion rate of PEEK-GF Composite is reduced with the increase of weight percentage of filler. However, erosion rate is strongly affected by the variation of impingement angle of the particles and it is observed that the PEEK-GF composite gives higher value than the Red mud filled PEEK-GF composites. The velocity of the erosive particles has a very strong effect on erosion rate.

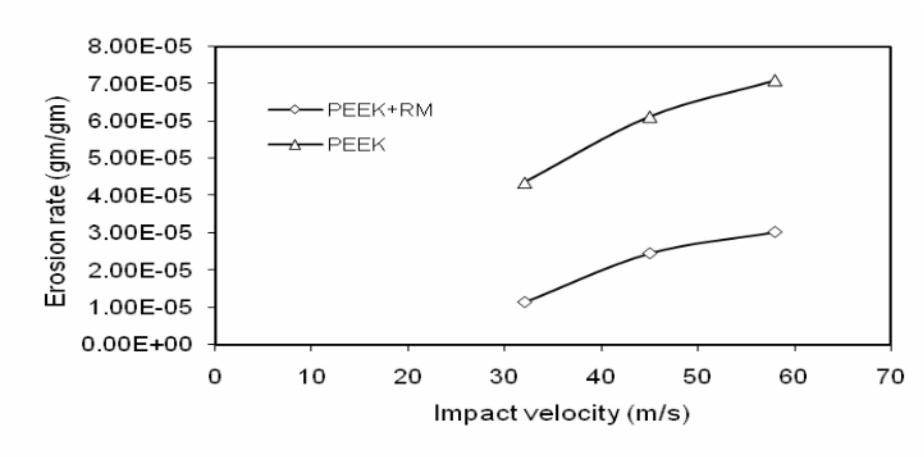


**Fig.5.7** Variation of erosion rate with velocity of particle at impingement angle $60^0$

## 5.5 Comparison

The comparison between considered composites shows that erosive wear of PEEK-GF composites without any filler material is much higher than that of Red mud and SIC filled PEEK-GF composites. This may be due to the interface between matrix material and glass fibre that would be mechanically weak. Also, from the results of erosion tests it is clear that the erosion of PEEK-GF composite is more than that of Red mud and SIC filled PEEK-GF composites. The larger is fraction of crater volume that is removed. It is clear from **Fig 5.8** that 20% Red mud and SIC filled PEEK-GF composite shows the lowest erosion rate at particle velocity of 32m/s. This may be due to the restriction of debonding between matrix and fibres.

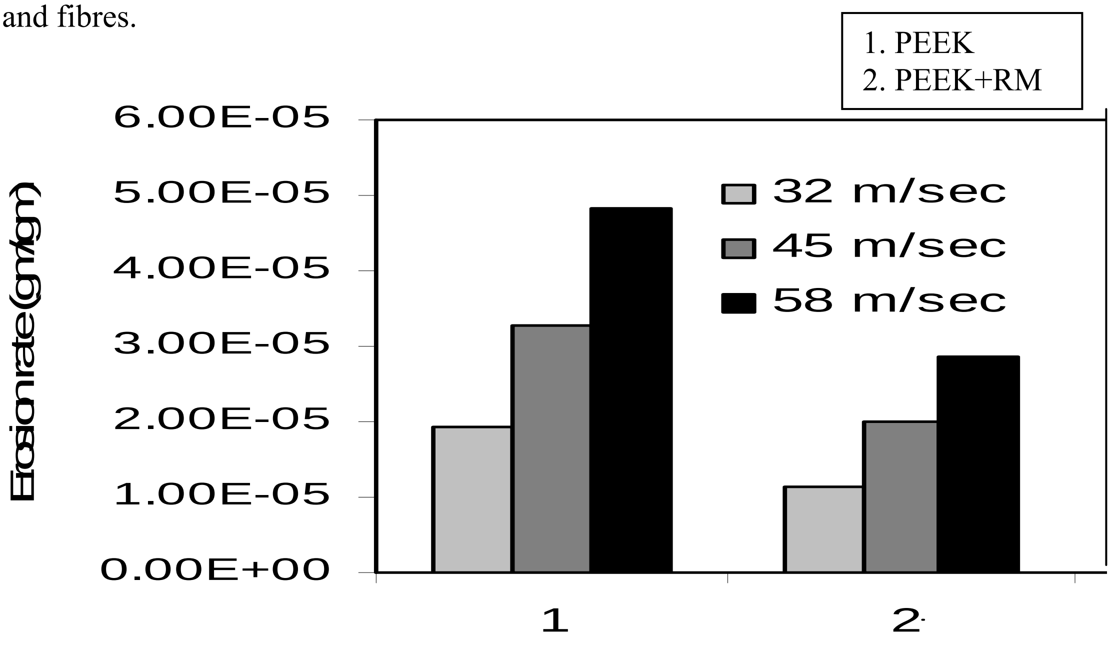


**Fig.5.8** Bar diagram showing the steady state erosion rate of all samples at impingement angle $60^0$ with different particle velocities.

## 5.6 Study of Surface Morphology

In general, thermoplastic matrix composites exhibit a ductile erosive wear (plastic deformation, ploughing, and ductile tearing) while thermosetting matrix composites erode in a brittle manner (generation and propagation of surface lateral cracks). However, this failure classification is not definitive because the erosion behaviour of composites depends strongly on the experimental conditions and the composition of the target material. It is well known that impingement angle is one of the most important parameters in erosion behaviour.

**Fig 5.9** shows the worn surface of neat PEEK eroded at an impingement angle of $60^0$ and an impact velocity of 58 m/s. It can be seen from the micrograph that, when impacting at angles, the hard erodent particles can penetrate the surfaces of the samples and cause material removal by microcutting and microploughing indicates plastic deformation and micro cracking as the dominant wear mechanisms.

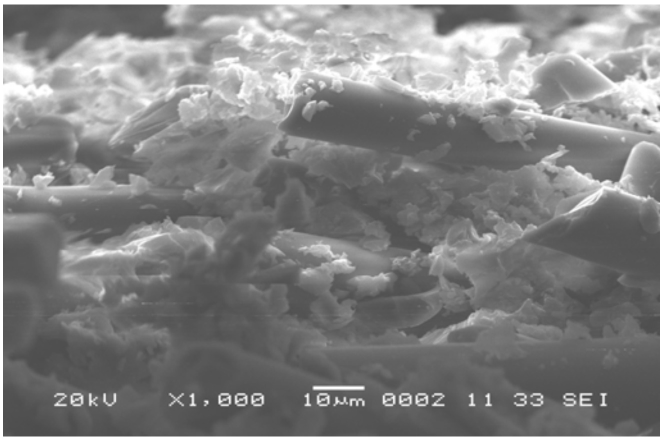
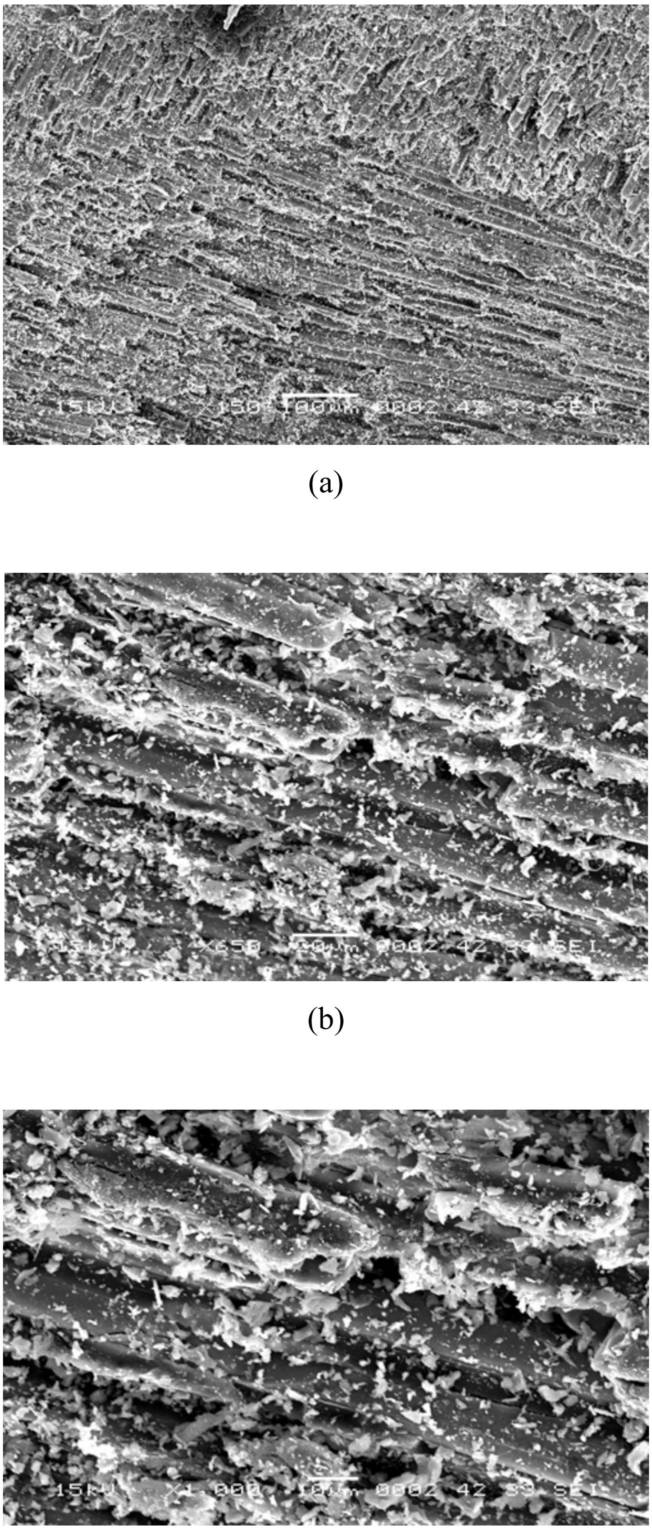


**Fig.5.9** Scanning electron micrograph of neat PEEK surfaces eroded at impingement angle of $60^0$ and impact velocity of 58 m/s.



(a)

(b)

(c)

**Fig.5.10 A B C**. Scanning electron micrograph of (PEEK+20%RM) surfaces eroded at impingement angle of $60^0$ and impact velocity of 58 m/s.

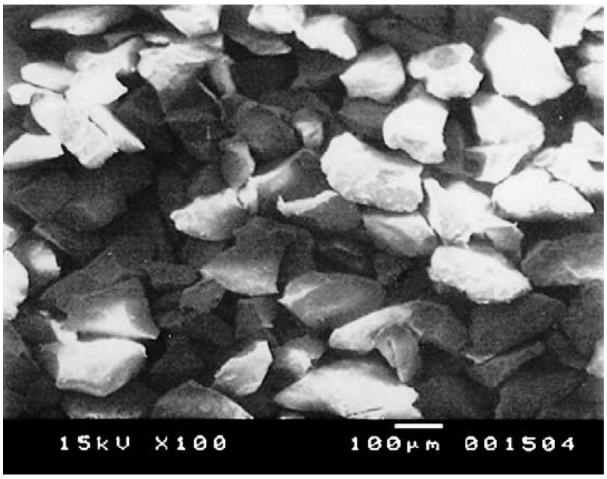


**Fig.5.11** Scanning electron micrograph of silica sand (500 micron)

**Fig 5.10 A, B ,C** shows micrographs of surfaces eroded at an impingement angle of $60^0$ and an impact velocity of 58 m/s Micrographs a–c are for material (PEEK + 20% RM). Repeated impact of the erodent caused roughening of the surface of the material. Characteristic features of more cutting with chip formation is reflected (**Fig. 5.9**). Erosion along the fibres and clean removal of the matrix to expose glass fibres is also seen (**Fig. 5.10 A, B**). The matrix shows multiple fractures and material removal. The exposed fibres are broken into fragments and thus can be easily removed from the worn surfaces (**Fig. 5.10 C**).

PEEK is a ductile polymer. However, the failure mechanism does not reflect any ductility; instead a brittle failure appearance is reflected in the micrographs Penetration of silica sand particles in the matrix is also visible in a micrograph (**Fig. 5.11**). It is obvious, that during normal erosion all available energy is dissipated by impact. Hence angular sand particles penetrate very easily in to the soft polymer matrix. The continuous impact of sand particles on the composite surface resulted in local removal of matrix and hence fibres protruded out of the matrix phase

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# CHAPTER 6

## DISCUSSION & CONCLUSIONS

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### DISCUSSION

The important factors influencing the erosion rate of materials are the impact velocity, impact angle of erodent particles, the size, shape and hardness of eroding particles. This has been reported by a number of researchers for a wide range of materials and erodents. Many investigators have used angular silica sand, alumina, corundum particles or irregular silicon carbide abrasives. In the present study dry silica sand is used as erodent. Hence it is difficult to compare present erosion data precisely with literature data. The results of investigation by Tilly and Saga on the influence of velocity, impingement angle, particle size etc. for nylon, carbon fiber reinforced nylon and epoxy and epoxy resin, polypropylene ,polyetherether-ketone (PEEK) and glass fiber reinforced plastic show that, for certain materials, the composites generally behaved in an ideally brittle fashion (i.e maximum erosion rate occurred at normal impact). Miyazaki and Hamao reported that un-reinforced polyetherether-ketone (PEEK) shows maximum erosion rate at impingement angle of $60^0$. Manish Roy et al conducted a series of experiments on various polymer composites and concluded that composites with a thermoset matrix (Epoxy and Phenolic) behave in a brittle manner while the composites with a thermoplastic matrix (PEEK) respond in a ductile fashion. Erosion wear behaviour can thus be grouped in ductile and brittle categories, although this grouping is not definitive. Thermoplastic matrix composites show generally ductile erosion while the thermosetting ones erode in a brittle manner. However, there has been a dispute about this failure classification, as the erosive wear behaviour depends strongly on the experimental conditions and also equally on the art and relative content of the constituent materials of the composites.

In the present study, it was observed that for un-reinforced PEEK matrix, the peak erosion rate is at $60^0$ impact angle. This is typical for ductile materials. A ductile material has a relatively high resistance to impact due to its good capability to accommodate plastic deformation. It is known that the fracture is generally caused by tensile or shear stress.

When impinging by solid particles is at $90^0$ (normal impact), the lateral tensile stress may not effectively result in fracture. As a result the ductile material should have less damage when impacted at $90^0$. It was further observed in the present study that the PEEK matrices reinforced with glass fiber of different weight fraction show the maximum erosion rate at impingement angle $60^0$. A possible reason for this kind of erosion behaviour may be that the glass fiber used as reinforcement is a typical brittle material and erosion therefore is mainly caused by damage mechanism as micro cracking/plastic deformation due to the impact of erodent particles. Such damage is supposed to increase with increase of kinetic energy loss. According to Hutchings et al, kinetic energy loss is maximum at an impingement angle $60^0$, where the erosion rates are maximum for brittle materials. In this study, the peak erosion rate shifts to a larger value of impingement angle ($30^0$ - $90^0$ of PEEK GF Composites) due to the brittle nature of glass fiber. The composites under this study, thus exhibit a semi ductile behaviour in response to solid particle impact. This is not surprising as many previous investigators have reported similar observation for reinforced composites exhibiting maximum erosion in the range $30^0$ to $60^0$ .

The angle of impact is a major operational parameter influencing the erosion rate of the target material. This angle determines the relative magnitude of the two velocity component; one normal to the surface and the other, parallel to the surface. The normal component will determine how long the impact will last (i.e contact time) and the load. The product of contact time ($t_c$) and the tangential velocity component determines the amount of sliding that takes place. The tangential velocity component also provides a shear loading to the surface, which is in addition to the normal load that the normal velocity component causes. Hence as this angle changes the amount of sliding that takes place also changes as does the nature and magnitude of the stress system. Both of these aspects influence the way a material wears. These changes imply that different types of material would exhibit different angular dependency.

Another important finding in the present work is the reduction in erosion rate with increase in fiber content in the PEEK matrix. This observation is understandable. The relatively soft matrix is strengthening by the embedded reinforcing fibers; the reinforcing phase makes it difficult to remove the material from surface. On the other hand the relatively brittle reinforcing phase is protected by the ductile matrix that absorbs impact energy and accommodates deformation. All these factors affect the erosion behaviour of the composite. However, when too much reinforcing fibers is introduced the composite may become brittle and the loss of ductility may lead to an increase in the erosion loss.

## CONCLUSIONS

Based on the experimental results and findings the following conclusions can be drawn:

1. Reinforcement of glass fiber into the PEEK matrix improves the flexural strength quite significantly, thus making them potential materials for structural applications.
2. Addition of Red mud to glass fiber reinforced composites also enhances the flexural strength, flexural modulus and tensile strength of the material.
3. PEEK with glass fiber reinforcement exhibits better resistance to solid particle erosion in comparison to the un-reinforced PEEK resin.
4. The rate of wear of the composite material is also greatly influenced by operational variables like impact angle and the velocity of impact. Further, material variables like erodent and type of composite also affect the erosion rate.
5. The neat PEEK and 20% Red mud filling of glass fibre reinforced PEEK composite exhibited maximum erosion rate at an impingement angle of $60^0$ under the present experimental conditions studied
6. In PEEK-GF composites the steady-state erosion rate ($E$) is related to particle velocity ($v$) as $E = kv^{n.}$ The effect of fibres on the value of the exponent '$n$' is relatively small.

Tribiological evaluation of polyester composite is a less studied area although these materials are degradation prone in actual operational environment. There is a very wide scope for future scholars therefore to explore this area of research. Many other aspects of this problem like effect of fiber orientation, loading pattern, ceramic filling on erosion response of such composites require further investigation.

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