Materials Research Express

TOPICAL REVIEW

A critical review on erosion wear characteristics of polymer matrix composites

Vasavi Boggarapu ©, Raghavendra Gujjala © and Shakuntla Ojha ©
Department of Mechanical Engineering, National Institute of Technology, Warangal, India
E-mail: shaku30@gmail.com

Keywords: erosion, polymer composite, impact angle, erodent characteristics, Filler particles, solid particle erosion review

Abstract

Polymer matrix composites (PMCs) are extensively known for their higher strength and stiffness at lower weight compared to traditional materials. They are extensively used in numerous engineering applications. Utilization of these materials had been extended to novel areas where it is essential to study their tribological performance. Several research works reported the tribological performance of polymer composites. The aim of the review is to provide broad information on erosion behaviour of polymeric composites. Attention is paid towards the effect of test parameters i.e. impact velocity, erodent characteristics, impingement angle on the erosion wear rate and their failure mechanisms were discussed. Inclusion of various fillers in to polymeric composites enriched the erosion resistance property that attracted the researchers to find out their application. However limited literature were available on the erosion behaviour of particle filled composites. Hence, another objective is to review available literature on the erosion response of filled composites.

1. Introduction

Polymer composites have been an interesting research area due to their superior engineering properties. These materials offer high strength and durability, toughness, are easy to fabricate, corrosion resistant and are known for cost-effectiveness. Composites constitute the most important class of materials next to steels in industrial applications [1]. Other applications include aerospace [2], automotive industry [3], sporting goods [4, 5], marine structures [6, 7], food packaging [8], home appliances, medical applications [9] and construction industry [10]. In such applications it is required to know the mechanical and tribological properties of polymer composites. Polymer composites are employed in particular components like air craft wings, turbine blades etc. where the surface is impacted by solid particles. Hence it is extremely important to know the erosion resistance behaviour of polymeric composites. Presently a wide range of research is targeted towards erosion characteristics of PMCs owing to their potential use in many engineering applications. Composites are subjected to different tests for predicting their erosion endurance.

Wear is unwanted damage to the surface of a solid that involves gradual loss of material from the contacting surfaces due to their relative motion. It is an external response of a material which can be either mechanical or chemical. Research towards wear in industrial countries started in early sixties. There are mainly five modes of wear, namely, abrasive, adhesive, fretting, erosion and fatigue wear. Among them, abrasive and erosion wear are most important as they contribute 75% of total wear cost [11].

One of the typical mode of wear is Solid particle erosion (SPE) which is defined as the material loss due to repetitive impact of hard and angular particles. The solid particles move at distinct velocities and impact angles and strike the surface of material. The exposed surface undergoes degradation. SPE identified as a serious problem in various machinery parts that include hydraulic systems, steam and jet turbines, pipelines and valves, airplane parts, liquid impellers etc. [12]. In such applications, erosion characteristic is very important as they are operated in dusty environment [13]. But in certain situations of solid particle erosion, such as sand-blasting, the erosion is a useful phenomenon as it improves surface finish to final manufactured components [14]. In defense applications, the resistance to rain and soil particle erosion were key issues for non-metallic materials [15].
SPE is a tribological phenomenon which is a combination of mechanical load that is associated with secondary thermal, physical or chemical reaction between the counter surfaces [16]. In comparison with metals, composites have complicated failure mechanisms that influence their working conditions as well as material properties. Erosion affects solid materials in highly erosive environment. That’s the reason why from past decades, the erosion characteristics of polymer composites has been an interesting subject to many researchers. This paper presents an extensive review on the influence of erosion test parameters on fiber-filler reinforced polymer composites.

2. Factors affecting the SPE of polymer composites

In fiber reinforced polymer matrix composites, the erosion process takes place in three modes [17] as follows:

(i) Removal of matrix resin locally from the surface by the impact of erodent which results in fiber exposure to the erosive environment.

(ii) Impact of erodents on the fibers causes breakage due to crack formation perpendicular to length.

(iii) Final damage occurs due to the breakage of interface between resin and broken fibers which are removed by continuous impact.

The erosion resistance behaviour of PMCs are influenced by many parameters such as impact angle, impact velocity, shape and size of erodent particles, erodent flux rate, pressure, standoff distance, temperature, fiber length, fiber orientation, fiber and filler content. For polymer composites, the factors affecting the erosion wear rate is mainly influenced (a) Type of polymer matrix i.e. whether Thermoplastic or Thermoset, (b) Brittleness of fiber reinforcements, (c) Fiber and matrix interface bonding [18]. The popular method in improving the erosion resistance of PMCs is by incorporating the fibers and filler particles as reinforcements based on application need.

2.1. Effect of impact velocity on SPE

Erosion wear rate is due to increased velocity of erodent particles and their impact energy. The velocity with which erosive particle (erodent) strikes the target material is termed Impact or Impingement velocity which has a strong influence on erosion. As the velocity increases, the eroded surface undergoes plastic deformation and subsurface cracking is observed due to the impact of particles. Even melting at impacted surface may happen at high particle velocities. On the other hand, at low velocity, the stress due to impact is insufficient for plastic deformation and wear occurs by surface fatigue. Low impact velocity events can be treated as quasi-static. Impact velocities are classified based on severity of damage. Low impact velocity is characterized by delamination and matrix cracking whereas high velocity is characterized by penetration that induces fiber breakage [19]. It is very essential to identify the type of failure mode as it gives information about structural residual strength [20].

A review paper by Ritesh Kaundal [21] mentioned the relation between wear rate and variation of impact velocity from medium to high which is given by power law $-\frac{dn}{dt} = Kn^q$. Where $m$ is the worn-out specimen mass, $t$ is the process time duration, $n$ is a velocity exponent, $K$ is empirical constant. The value of exponent $n$ is determined by erodent and target material characteristics. For polymer materials having ductile nature, the value of $n$ varies from 2 to 3 whereas for brittle nature it varies from 3–5. In general, for most of the PMCs the velocity exponent is found to vary from 1.5 to 2.9. Pani et al. [22] gave another relationship between variation of velocity ($V$) with respect to Erosion value ($E_r$) as shown in equation (1). Where $p$ is material constant and one of the testing variables that includes particle characteristics. And $q$ is material independent, which is influenced by erosion test apparatus. An extensive study on the influence of impingement velocity on erosion behavior of glass fiber epoxy composites with the addition of ceramic particles (red mud) was carried out by Biswas and Satapathy [23]. They had reported that influence of impingement velocity on erosion wear rate is less when compared to all other testing parameters. Similar results were also concluded by Patnaik et al. [24, 25] for glass fiber/polyester composites with the addition of SiC, Alumina ceramic particles respectively.

$$E_r = p \times V^q$$ (1)

2.2. Effect of impingement angle on SPE

Along the longitudinal fiber direction, the erodent may strike at any angle. But the literature available is restricted to $0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $90^\circ$ fiber orientation to the erodent flow. This can be further extended to other angles for detail study on material behavior. To study the erosion behavior, the target material is assumed to be perfectly plastic neglecting elastic rebound effect and the impact particle to be rigid. Thus this theory is often
referred to as ‘rigid-plastic’. Based on the impact angle ($\alpha$) the erosion is classified into two types [26]: (i) For $\alpha \approx 90^\circ$ erosion occurs at normal impact angles (ii) For $0^\circ < \alpha < 90^\circ$ the erosion occurs at oblique impact angles. For lower impact angles the wear process of materials is due to the abrasion whereas for high impact angle, the wear process is of SPE.

The erosion wear of PMCs is categorized as brittle and ductile subjected to variation in erosion rate with regard to impingement angles. Ductile nature is identified for maximum erosion rate which occurs at lower impact angles i.e. $15^\circ < \alpha < 30^\circ$. In this stage the target material experiences weight gain as erodent particles are embedded into the surface. In contrast, if the maximum erosion wear occurs at normal impact angle ($\alpha = 90^\circ$) then the material is considered to be brittle. In this case, there is an increase of weight loss with respect to exposure time of target material. It was found that FRPs exhibit semi-ductile nature with maximum erosion observed at impact angle between $45^\circ$ and $60^\circ$ [27].

### 2.3. Effect of erodent characteristics

The physical characteristics like size and shape of eroding material play a major role in SPE of PMCs. Transitions in wear mechanism is often affected by changes in the shape and hardness of erodent particles. For harder or brittle materials, erosion wear increases with increase in erodent size and hardness until the saturation level is reached. In case of ductile polymers, there is no such noticeable effect with the variation of erodent hardness [28]. It was also observed that under 100 $\mu$m diametrical size erodent particles only produce considerable erosion effect for ductile materials [29]. Erosion rate is independent of particle size beyond the critical value of 100–200 $\mu$m [30]. Up to the critical value, the erosion rate increases with erodent size but beyond the critical value, the erosion rate gets decreased due to increased particle collisions. One more reason can be the fewer number of particles that reach per unit weight of sample as erodent size increases which often results in lower erosion wear rate [29, 31, 32].

The shape of erodent particles influences the erosion rate of PMCs. Spherical shape of eroding particle leads to plastic deformation whereas sharp particles cause brittle fragmentation [30]. The impingement of spherical particles on ductile materials causes ploughing action which forms the lips around the crater that break in succeeding impact [33]. A study by Hutchings & Winter [34] found that the angular shaped erodents remove the material by ploughing and micro-cutting. Levy et al [35] studied the erosion of AISI 1020 steel target material by angular and spherical shaped steel shots. They observed that four times more erosion rate is caused due to angular grits when compared with spherically eroding particle. Erosion rate is dependent on exposure conditions. Similar results were also reported by Liebhard et al [36] on 1018 steel material by erodents of spherical glass beads and angular SiC. Erosion tests on polymer composites are generally conducted at room temperature (RT). The erosion trend is higher for the polymers with glass transition temperature ($T_g$) beyond RT [28]. In contrast the erosion wear decreases for the polymers of $T_g < RT$ [37].

Z Feng and A Ball [38] studied the effect of erosion rate for seven different erodent particles on the different target materials i.e. Glass, alumina, tungsten carbide and Stainless steel. From their studies they have concluded that the erosion rate for brittle materials is affected by erodent size and kinetic energy. For ductile materials erodent shape and kinetic energy influence the erosion behavior. There is no substantial effect of toughness and hardness of eroding particles on erosion rate. Sinnmazzelik and Sari [39] extensively studied the effect of erodent size and impact angle on erosion resistance of glass fiber-polyphenylene sulfide composite. Alumina with different sizes were used as erodent particles. It was found that the maximum erosion rate occurs by smaller size eroding particles at impact angle of $30^\circ$. And the erosion due to larger size particles occurs between $45^\circ$ to $60^\circ$ impact angle.

The erodent hardness influences erosion wear which depends on erosion wear mode i.e. ductile or brittle. The eroding particle hardness in brittle mode is more significant than in ductile mode. The harder particles causes high wear rate than softer ones. It is difficult to differentiate the particle hardness from other features like its geometry. If the particle is hard and blunt, then erosion is higher [30]. The erosion wear rate increases with higher hardness and larger size of erodent particles until saturation level is reached. In case of ductile polymers, due to their low hardness no significant change in the hardness of much harder erodent particles is noticed [28].

The erodent fracture toughness is one of the controlling parameters of erosion wear when the fragmentation of erodent particles is observed after their impact. During the fragmentation of particle, the stresses are distributed over the surface. During this process the energy getting into target material reduces, which further decreases the wear. However, fragments having sharp edges than the original eroding particles may increase the wear [40]. Erodent flux or feed rate has a significant influence on the erosion wear rate. It can be defined as the mass of impacting particles per unit area and unit time. The flux rate of eroding particles can be maintained by controlling the distance between particle feeding hopper and the belt drive that carries the particles to mixing chamber. With the variation in pressure of compressed air, the impingement velocity of eroding particles can be varied. The velocity of eroding particles can be determined by rotating disc method [41]. Theoretically, erodent...
flux rate doesn’t influence erosion rate because all the particles hit the target with identical impact velocity and angle. But practically the flux rate affects measured erosion rate. Erosion rate is proportion to threshold feed rate limit of 100 kg/m²s for elastomers to 10,000 kg m⁻²s⁻¹ in case of erosion on metals by large erodents. It was observed that wear rate slightly decreases when the limiting feed rate exceeds a certain level. J C Arnold and Hutchings [42] studied the feed rate of silica erodent on the erosion wear of elastomers and found that erosion rate increases at low particle flux. Conversely, Anand et al [43] analyzed the erosion of 1018 steel and witnessed a significant decrease in erosion wear with increase of erodent flux rate. Sundar rajan and Roy [44] mentioned that there is no effect of particle feed rate on the erosion wear of metals but then observed an exponential decrease in erosion rate with increase of flux rate.

Erosion tests are usually conducted at room temperature conditions. If the solid particles are heated to higher temperature, then the target material dissipates thermal energy along with kinetic energy. Due to large energy dissipation, great damage occurs on the surface of target material. Shimizu et al [45] extensively reported the influence of erodent temperature on the erosion behavior of stainless steel eroded by alumina particles at constant impact velocity. Their study revealed that erosion rate tended to increase with testing temperature. Similar erosion trend was observed for epoxy polymer composites, as reported by Biswas et al [46, 47].

2.4. Influence of fiber material on SPE

The strength and stiffness of polymers increase when they are reinforced with fibers. Such composites are often referred to as Fiber reinforced composites (FRPs). So far fibers such as carbon [48, 49], Kevlar [50, 51], banana [52, 53], jute [54, 55], sisal [56], bamboo [57, 58], glass [59–61], hemp [62, 63], Aramid [64, 65], coir [66, 67] etc. had been studied. At present more than 90% of FRPs are reinforced with either glass or carbon fibers due to their vast applications. Very few studies are available for other fibers. Polymer matrix composite materials with continuous fibers possess very attractive mechanical properties like high elastic modulus and strength per unit weight, impact resistance, durability and good chemical and environmental resistance as that of traditional materials. Most research has been carried out on FRPs in comparison with un-reinforced matrices. As the nature of fibers is brittle, their inclusion in composites leads to the weakening of erosion resistance of matrix. Ductile fiber reinforced polymers are called self-healing polymers which are employed in advanced high performance composite materials. In a comparison between glass fiber (GF) and carbon fiber (CF) epoxy composites, the glass fiber reinforced composites (GFRP) show higher erosion wear for all fiber orientations. The reason may be weak interfacial bonding between matrix and glass fibers [68].

From recent years, short fiber reinforced polymer matrix composites (SFRP) have rapidly grown in numerous engineering applications due to high erosion resistance compared to long fiber reinforced composites. SFRP possess easy process ability with low manufacturing cost [69]. Miyazaki et al [70] evaluated the erosion performance of short glass fiber and carbon fiber in thermoplastic resin matrices. They observed that erosion rate for short fibers added FRPs depend on the type of matrix and the volume content of fibers.

Zhang et al [71] performed the test to investigate the wear on SFRP. Composites were fabricated with carbon fiber of 400 mm and 90 mm lengths. Their studies revealed that short carbon fiber of 400 mm shows greater wear resistivity than others because of its bond strength with the matrix.

2.5. Effect of fiber orientation during erosion

Most of the studies reported on erosion are confined to fiber orientations of 0°, 30°, 45°, 60° and 90°. Limited studies [72, 73] were available for 15° fiber orientation angle. But the investigations can be extended further on other fiber orientation angles to study the erosion rate in detail. The erosion studies were reported for both uni and bi-directional fiber reinforcement composites. Different orientation angles for a bi-directional fibers is shown in figure 1. The orientation of reinforcement fibers can be in any direction with respect to impacting erodent. Unless otherwise stated, the erodent stream can strike the fibers at any angle with respect to longitudinal direction of fibers. The results from the literature showed various trends in erosion rate that depends on parameters like impingement angle, nature of fiber, adhesion of fiber and matrix, fiber content etc. It was noticed that the removal of fiber was because of unsupported fiber bending, which occurs due to the removal of surrounding matrix. The bending resistance of fiber depends on matrix-fiber adhesion bonding.

The shape of fibers which are exposed changes with fiber orientation angle. This exposure shape is mostly influenced by the impact angle [26]. Hence the role of fiber orientation is essential in understanding the erosion wear behaviour of polymer composites along with all other parameters. Researches [72, 74] showed that fiber laminate orientation strongly effects the erosion rate for unidirectional composites. It was also noticed that 90° uni-directional composites are more prone to erode than other uni-directional angles.

Naidu et al [60] examined the erosive characteristics of bi and multi-directional glass fiber epoxy composites. For both the composites, maximum erosion occurred between 30 to 45 degree impact angles proving their nature as semi-ductile. Their studies concluded that fiber orientation has least influence on erosion wear. On the
contrary M K Reddy et al\cite{72} performed erosion tests for carbon fiber reinforced epoxy composites for different fiber orientations. Their studies revealed that irrespective of fiber volume, erosion rate increase with fiber orientation. It was concluded that erosion wear is strongly dependent on fiber orientation. Similarly A Kim et al\cite{75} reported the wear rate for CFRP composites with uni and multi directional fiber orientations. It was observed that erosion resistance for multi-directional composites is high compared to uni-directional. It is because the cross fibers present in multi-directional composites held tightly with the matrix and therefore resists erosion strongly. Brandt et al\cite{76} suggested that fiber orientation needs to be considered in choosing the required reinforcement type for structural load carrying applications. Generally parallel longitudinal strands (0° or 90°) offer compression and impact strength whereas helical strands (33° or 45°) are able to hold torsional stresses.

2.6. Effect of fiber treatment
Fibers are divided into two categories, namely synthetic (engineering fibers) and natural based on their origin as shown in figure 2. The choice of fiber depends on the desired properties. From the past decades, there has been a lot of research on natural fibers as a replacement for synthetic fibers which has opened up further industrial possibilities\cite{77}. The components in natural fibers are cellulose, hemicellulose, lignin, pectin, waxes and water soluble elements. Natural fiber reinforced composites can be used in packaging and automobile industries to reduce material costs.

Natural fibers have the benefits of low cost, low density, renewability, biodegradability and are abundantly available. However, they have some limitations of high moisture absorption, low thermal stability and are highly flammable. Important drawback with natural fibers is their poor adhesion compatibility between matrix and reinforcing fiber. In order to overcome the drawback chemical treatments have been adopted to modify fiber surface properties. Additionally, chemical treatments also provide fiber strength and reduce the moisture absorption that improve mechanical strength and erosion resistance of composites. The added chemicals activate hydroxyl groups than can interlock the matrix effectively. Typical chemical treatments of fiber include acetylation, silane, alkali, benzyolation, acylation, isocyanates, maleated coupling agents, permanganate, peroxide and etc\cite{79}.

Gupta et al\cite{80} analyzed the erosion behaviour of alkali treated bi-directional bamboo fiber reinforced Cement By-pass dust filled (CBPD) epoxy composites. The chemical treatment involved the immersion of fibers in alkali solution followed by neutralization with sulfuric acid solution. The erosion rate for chemically treated composites was found to be low compared to un-treated samples. They have concluded that the impingement angle, stand-off distance, filler content and impact velocity have pronounced influence on erosion rate of chemical treated samples. The erosion wear of un-treated composites are influenced only by filler content and impact angle. Similarly Vigneshwaran et al\cite{81} performed erosion test on alkali and silane treated jute-polyester composites. They have found that fiber treatment enhances erosion resistance and treated samples exhibited semi-ductile nature. In addition the increase in hardness and decrease in void content of fiber treated composites were also reported. Husnil et al\cite{82} mentioned that alkali and bleaching treatment of sorghum fiber reinforced polypropylene could increase the crystallinity of composites. It was found that some of the regions on fiber got eroded due to the chemical treatment.

Research by Sahu and Gupta\cite{83} explores the erosion characteristics of eco-friendly treated sisal fiber composites. The fibers are subjected to sodium bicarbonate treatment. The results revealed that erosion resistance of treated samples is 20%–30% lower than untreated samples for 60° impact angle. Chemical treatment of natural fibers intended to improve the adhesion with polymer matrices were reported by numerous researchers\cite{78,79,81,84}. However they had used different chemicals in their studies.

2.7. Influence of filler particles on SPE
Polymer matrix composites consisting of fillers generally endow them with superior performance than pure polymers which might not be achieved alone by the reinforcement and matrix materials. Matrix act as a binder
to interlock the fibers in uni-directional position. Its role is to transfer the load between the fibers. Addition of fillers leads to adequate interface bonding with polymer matrices. It is necessary to maximize the properties of fillers where they can be used for advance applications. The properties of composites are dominated by fillers. Inclusion of fillers in the composites reduces the cost as they are least expensive than major ingredients.

Fillers can enhance mechanical properties such as flexural modulus, ultimate tensile strength and etc. In addition they also improve fire properties by reducing organic matter in composite laminates. The shrinkage of filled matrix resins is less than that of unfilled resins. Therefore improvement in dimensional stability of molded parts is obtained. With the proper use of fillers, essential properties such as water resistance, surface smoothness, temperature resistance etc. can be enhanced. Fillers are often termed as extenders [89]. Based on their size they are classified as macro, micro, and nano. Nano filler reinforced composites are comparatively better than micro and macro for identical loading conditions due to their improved high degree of contact with the matrix which is termed as ‘nano-effect’ [90]. Inclusion of high amount of nano-fillers like carbon nanotubes, graphene etc, invest the polymer matrices with novel properties like high electrical conductivity, dielectric and mechanical properties, responses to certain stimuli like pH, thermal and magnetic fields [91].

Fillers are inorganic, organic and hard particulates (metals or ceramics) [92]. Many studies have reported improvement in properties of composite materials with the addition of organic or inorganic fillers. Generally, fillers are chosen based on their availability, rigidity and cost effectiveness. In the past, fillers were used mainly to reduce the cost of the raw material system but as time progressed, fillers improved the performance of composite in terms of mechanical and tribological strength. Filled polymer composites are attractive because of their superior strength. Such composites can be a better replacement for conventional materials that pose severe environmental hurdles. Great demand for these materials and their potential utilization use encourage

---

**Figure 2.** Classification of fibers [78].
researchers to design such materials. Some of the recent research on various particulate filled hybrid composites and their tribological behaviour are discussed.

Egg shells are inorganic material which are composed of 94–96 wt % calcium carbonate which has been a main constituent of various manufacturing industries. On average, eggshell comprises 0.3% phosphorous, 0.3% magnesium, and traces of sodium, potassium, iron, copper, zinc and manganese. If calcium is removed from egg shells, an organic material remains as a residue [93]. Manoj et al [94] extensively studied the erosion properties of egg shell particulate epoxy composites. They observed that erosion resistance is more for un-boiled egg shell particulate in comparison with boiled eggshell particulate composites as seen in figure 3. The composites exhibited semi-brittle nature. As reported by Zaman et al [95] natural sources of carbonates as particulate fillers have been implemented in polymer materials for enhancing their thermal stability, rigidity and density. Eggshells could be valuable raw material for making glass-ceramic products due to their brittle property.

Addition of egg shell particles in glass fiber/epoxy hybrid composites was studied by khan et al [96]. They have proved that filler percentage and erodent flow rate have promising significance on erosion rate. They have observed that egg shell particles have resistance towards erosion. Therefore when these particles are added to glass fibers, composite erosion wear gets decreased.

Girimurugan et al [97] prepared epoxy composite with the inclusion of egg shell and coconut shell particles at different weight percentages. They have proposed that such composites can have a potential application in interior parts of an aircraft and automobile where low hydrophilic characteristic is necessary.

Researchers YiLi et al [98], Anil et al [99], Bootklad and Kaewtatip [100] have also reported the egg shell particulate PMCs.

Marble dust is one among the fillers incorporated in polymer composites, which has been studied by some of the researchers. It comprise about 66% calcite. Marble stone industry generates stone slurry as waste material during cutting that causes environmental pollution. Hence waste material reuse has been emphasized. Marble slurry could be raw material in the production of ceramic tiles [101]. Choudary et al [102] reported erosion studies on marble dust filled aramid fiber epoxy composites. It had been revealed that incorporation of filler shifted the impingement angle from 45° to 60° which indicated the semi- brittleness nature of composites. Similar erosion behaviour of marble dust with jute fiber/epoxy composites was observed by Sharma et al [103].

The inclusion of marble dust in glass/epoxy composites were studied by Subrajith et al [104]. Artificial neural network method was adopted to find out the optimal process parameters for achieving minimal erosion rate. From the reported results, it was evident that filler content has an appreciable effect than other factors. The majority of composite wear with marble dust contributed to the presence of hard and non-uniform fragmented particles [105].

A new class of polymer composites with Granite dust as a filler was reported. It is a by-product produced through cutting and grinding process of granite stone. As per the reports, nearly 65% of total production from the granite industry remains waste which leads to soil pollution. Primarily the granite dust is angular and porous with rough crystalline surface texture. It is composed of silica (72%), potassium, alumina and traces of magnesium and calcium. [106]. Ray et al [107] observed the tribological behavior of glass/epoxy composites filled with granite dust. The experiments were conducted according to Taguchi experimental design for various control factors like filler content (0%, 5%, 10% and 15 wt %), different impact velocities varying between
attaining lower erosion rate. The results indicated that 10 wt% of resistance of fabricated composites. Mathavan et al. prepared the aramid fiber reinforced granite dust filled polyester composites. The hardness (120 Rockwell hardness) of composites was high due to the presence of more silica content due to which the researchers proposed that such composite could be an alternative for alloys in hydraulic turbine blade application. Slurry jet erosion tests performed on composites revealed that 10 wt% of granite is an optimum value to achieve lower erosion wear. Incorporation of granite dust particles into the glass fiber/epoxy composites were studied by Rout et al. and Pawar. The filled composites were semi-brittle in nature. The erosion rate showed a positive effect on the composites. However, both the studies proposed different results. The erosion rate is lower at an optimum filler content of 20 wt% as evident from figure 4 and the other with filler content of 14 wt%.

The use of traditional PMCs appears to be insufficient for present day necessities. Nano composites are probably an alternative to achieve superior properties. Inorganic or organic fillers of a few nanometer size are considered nano particles whereas those with a size of few meters to tens of meters are termed micro particles. Erosion wear rate is also influenced by the size of the filler particles.

Pun et al. developed glass-fiber/vinyl ester composites with the addition of micro and nano silica (SiO₂) particles. Maximum erosion of all composites showed at 60° impingement angle indicating semi-ductile nature of particles. It was observed that erosion resistance is high in nano filler than micro filler filled composites for different weight filler percentages at all testing conditions. From surface morphology, the crater formation is more in micron particulate composites compared to nano filler composite. The combination of micro and nano ceramic particles filled epoxy hybrid composites reinforced with fixed weight percentage of glass fiber was reported by Kuruvilla et al. The utilization of such hybrid combination progressively helps to accomplish better performance of composites. These composites were proposed for high voltage outdoor insulation applications. The blend of micro and nano particulates filled polymer composites were also reported by Rudresh et al. Ceramic filled polymer composite have been broadly explored in recent decades, and these are expensive because the cost of ceramic fillers is high. Investigation into the capability of modest resources like industrial wastes turned out to be significant.

Red mud is a by-product from bauxite used in aluminum production through Bayer’s process. It comprises 50% iron oxide (Fe₂O₃). It is highly corrosive in nature. The fine particles are toxic and dangerous to the surroundings. Such industrial wastes have no proper disposal methods and are dumped into the environment where they affect the atmosphere. Due to the presence of heavy metal oxide in red mud it is having potential in improving the hardness of composites which makes it suitable for erosion applications. Researchers reported that the addition of red mud waste in fiber reinforced polymer matrix composites resulted in improved erosion resistance. A comparison study on erosion behaviour of red mud filled bamboo fiber and glass fiber reinforced composites were carried out by Biswas and Satapathy. All the composites showed maximum erosion at 60° impact angle proving the semi-ductile nature. It was noticed that for similar testing conditions, erosion wear is high for glass fiber reinforced composites than bamboo fiber composites. This shows a good bonding between bamboo fibers and red mud filler.

Copper slag is another industrial waste obtained during the extraction of copper by smelting process. Erosion characteristics of jute fiber reinforced with copper slag particulate polyester composites were investigated by Kalusuraman et al. Their results shows that copper particles up to 10 wt% improved matrix-fiber interfacial bonding which results in the prevention of erosion of composites. Beyond 10 wt% the
bonding gets degraded. The fabricated composites showed brittle nature. The reported results were in agreement with Biswas et al [120]. Inclusion of copper slag in bamboo fiber/epoxy composites were studied by Sandhyarani Biswas [121]. Lower erosion rate was observed with 15 wt% of filler content. It was recommended that such composites have potential in wear applications such as industrial fans, inexpensive housing, helicopter fan blades, pipes carrying coal dust etc.

Keeping in view the environmental concerns, bio waste or eco-friendly materials have been successfully introduced in composites in the form of fillers for various industrial applications. Some of the recent research on bio-filler filled polymer composites and their tribological performance are reported. Prakash et al [122] researched the erosion behavior of arhar fiber particles filled epoxy composites. Fabricated composites are exposed to distinct environmental conditions like saline & mineral water, kerosene and subzero temperatures. Erosion tests were performed for different impingement angles and impact velocities. All the composites showed semi-brittle nature. The investigators concluded that erosion resistance is least for samples subjected to sub-zero environment, as seen from figure 5. From SEM images it was revealed that arhar fiber have porous structure due to which matrix-reinforcement interfacial bonding is improved. Therefore, regardless of environmental conditions, the erosion resistance was enhanced for all the composites. In a study by Prakash et al [123] addition of rubber wood particulate from 10 to 40 wt% in epoxy revealed the semi ductile nature for maximum erosion wear occurring at 45° impact angle. They have concluded that micro-cutting and ploughing mechanisms are responsible for the erosion of composites. The results were in agreement with the research work carried out by Acharya and Vasunaik [124]. Another bio-filler, rice husk, which is an agricultural waste, contains high amounts (nearly 23%) of silica. There are huge amounts of un-used rice husk wastage all over the world. The residual ash produced due to the thermal treatment of rice husk at 900° causes environmental pollution. Therefore finding alternative eco-efficient use for rice-husk are essential [125].

Numerous researchers [126–128] have reported the applications of carbon extracted from rice husks for high strength and temperature resistant materials. Rout and Satapathy [129] examined the erosion characteristics of unfilled and rice husk particulate filled glass fiber epoxy hybrid composites. Addition of particulate in pure epoxy composites led to a shift from brittle to semi-brittle nature. At 15 wt% of filler the erosion resistance was maximum. Addition of rice husk particles in polymer matrices acts as a hurdle against erosion loss by decreasing erodent kinetic energy. The particulates absorb the part of impacting energy which delays the fiber exposure and leads to reduction of erosion wear.

An overview of other types of filler particles and their erosion performance are tabulated in the table 1. From the observations and reported results it was apparent that erosion rate of PMCs depend strongly on impingement angle, impact velocity and erodent properties. In most of the PMCs, peak erosion is observed between 30 and 90 impact angles which depend on the matrix and reinforcement combinations along with the experimental conditions. The nature of the composite can be determined based on impingement angle where maximum erosion is seen. Inclusion of different types of fillers in polymer matrices has enhanced erosion resistance whereas in other investigations erosion rate increased [130]. Hence it is necessary to choose the type and filler content in the polymer matrices for particular applications.

![Figure 5. Effect of impingement angle on erosion rate of Arhar particulate composites exposed to different environmental conditions [122].](image-url)
An overview of the erosion studies on polymer matrix composites after the year 2015.

| Year of publication | Matrix      | Reinforcement fiber/filler | Process parameters                                                                 | Key issues                                                                                                                      | Reference |
|---------------------|-------------|----------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|-----------|
| 2019                | Epoxy       | Alumina particles          | Three dimensionless Parameters r₁, r₂, r₃                                            | Dominant erosion mechanism depends on the range of process parameters                                                        | [131]     |
| 2019                | Epoxy       | Cenosphere                 | Impact angle (deg) Impact velocity(m/s)                                              | Effect of erosion rate on silane treated surface modification of Cenosphere particles                                          | [85]      |
| 2019                | Vinyl Ester | Sanseveria cylindrica/Bio-char | Impact angle Impact velocity                                                         | Effect of filler content on erosion resistance                                                                             | [132]     |
| 2019                | Epoxy       | Sugarcane Bagasse          | Fiber content 10–30 wt% Impact velocity (m/s) Impact angles (deg) Standoff distance (mm) Erodent size (μm) | Relationship between Process parameters is Established by Taguchi technique                                                      | [133]     |
| 2019                | Epoxy       | Red brick Dust powder      | Filler content 0–30 wt% Impact velocity (m/s) Impact angles (deg) Erodent temp (°C) Erodent size (μm) | Ant lion optimizer Algorithm is proposed to achieve minimal erosion wear                                                  | [134]     |
| 2019                | Epoxy       | Polyester fiber            | Fiber content 10–30 wt% Impact velocity (m/s) Impact angles (deg) Erodent size (μm) | A set of process parameters is proposed to achieve least erosion wear                                                        | [135]     |
| 2019                | Epoxy       | Carbon black particulate   | Filler content 1–5 wt% Impact velocity (m/s) Impact angles (deg)                      | Influence of process Parameters on the Erosion characteristics                                                              | [136]     |
| 2019                | Polyurethane| Carbon Nano tubes          | Impact velocity (m/s) Impact angles (deg) Erodent size (μm)                          | Effect of testing conditions on erosion Rate of thermoplastic composites                                                     | [137]     |
| 2019                | Epoxy       | Glass fiber/Alumina        | Impact angles (deg) Working fluid – Water & Sand Erodent size (μm)                   | Comparative study on effect of erosion rate for micron and nano sized Alumina particulate composites                        | [138]     |
| 2019                | Epoxy       | Glass                     | Erodent-Alumina Impact velocity (m/s) Impact angles (deg) Erodent feed rate          | Erosion rate prediction Model was developed Using Response Surface methodology                                                | [13]      |
| 2019                | Epoxy       | E-Glass/WC/TaNbc           | Impingement angle (deg) Erodent-Alumina                                             | Wear behavior of Composites at ambient & elevated temperature conditions                                                     | [139]     |
| 2019                | Epoxy       | Glass fiber/Iron mud       | Impact velocity (m/s) Filler content - 50 wt% Filler content - 0–20 wt% Impact velocity (m/s) Impact angles (deg) Erodent discharge rate | Potential usage of Industrial waste for Composite preparation.Erosion rate predicted by ANN algorithm                          | [22]      |
| 2019                | Epoxy       | Carbon fiber/Silicon Nitride | Fiber content – 10 layers Filler content - 0–20 wt% Impact velocity (m/s) Impact angles (deg) | Significant parameters Which effect erosion rate is determined by Taguchi analysis                                             | [140]     |
| 2019                | Epoxy       | Glass fiber/Micro silica & Zinc oxide | Impact velocity (m/s) Impact angles (deg) Erodent size (μm) | Comparison of two Fillers on the erosion performance                                                                       | [61]      |
| 2018                | Epoxy       | Glass –Jute Fiber/Cenosphere | Filler content - 5 to 10 wt% Impact velocity (m/s) Impact angles (deg)              | Effect of filler on erosion rate of hybrid composites is studied.                                                            | [141]     |
| 2018                | Epoxy       | Bamboo -Glass fiber/Zirconia and Titania | Impact velocity (m/s) Impact angles (deg)                                           | A comparison on Erosion rate of two Ceramic fillers in Hybrid composites                                                    | [142]     |
| 2018                | Epoxy       | Glass-Jute fibers          | Loading conditions                                                                  | Improvement of wear Resistance for varying combinations of fiber combinations                                               | [143]     |
| Year of publication | Matrix | Reinforcement fiber/filler | Process parameters | Key issues | Reference |
|---------------------|--------|-----------------------------|-------------------|------------|-----------|
| 2018                | Vinyl ester | sansevieria cylindrical fiber | Fiber length 30 & 40 mm, Fiber content 30–50 wt% Exposure time (min), Erodent feed rate (g/min) | Effect of fiber treatment on the erosion wear | [144] |
| 2018                | Polyester | Glass fiber/Flyash | Fiber content -50 wt% Filler content -10 & 20 wt% | Investigation of mechanical and erosion properties | [145] |
| 2018                | Epoxy    | Hemp-kevlar/palm and cocoonut powders | Fiber content 60-40 wt% Filler content 0–5 wt% Erodent flow rate | Erosion time and erosion flow rate have significant effect on erosion rate | [146] |
| 2018                | Epoxy    | Glass fiber/Iron-mud | Filler content 0–20 wt% Alumina erodent Erodent velocity (m/s), Impact angles (deg), Erodent flux rate | Response surface methodology is adopted for erosion analysis | [147] |
| 2018                | Epikote  | Carbon fiber/Metal wire | Impact angles (deg) | Influence of impingement angle on erosion rate | [148] |
| 2018                | Polyurethane | Carbon black | Impact angles (deg) | Effect of nano particle on the erosion wear | [149] |
| 2018                | Epoxy    | Glass fiber – Carbon nano Paper layer | CNF paper thickness 0.15 and 0.30 mm | Improvement of mechanical and tribological performance due to addition of CNF layer | [150] |
| 2017                | Polyvinyl pyrrolidone | Date palm Leaf fiber | Impact velocity (m/s), Impact angles (deg) | Effect of process Parameters on erosion rate. Erosion efficiency was evaluated to understand wear mechanisms | [151] |
| 2017                | Epoxy    | Coir fiber/Alumina particles | Fiber length -3 to 15 mm, Filler content – 10 wt% | Influence of fiber length & filler content on the erosion wear | [152] |
| 2017                | Poly- propylene | Coconut shell fiber particles | Fiber content - 5 to 15 wt% | Effect of chemical treatment on the erosion rate | [153] |
| 2017                | Epoxy    | Poly-propylene Non-woven fabric mat | Fabric mat content - 20, 30, 40 wt% Impact angles (deg), Impact velocity (m/s) | Effect of experimental parameters on the wear behavior | [154] |
| 2017                | Ebonite  | Carbon fiber/Alumina | Erodent shape - irregular Erodent size (μm), Impact angles (deg), Impact velocity (m/s) | Effect of erosion rate on multi-directional carbon fiber | [155] |
| 2016                | Epoxy    | Glass fiber/Borax particles | Impact velocity (m/s), Impact angle (deg), Fiber orientation -90°,45° | Effect of fiber orientation on the erosion rate | [156] |
| 2016                | Epoxy    | Glass fiber/Alumina and Silica particle | Filler content- 15% each Impact velocity (m/s), Impact angles (deg), Fiber orientation 90°,45° | Optimal process parameters for achieving minimum wear rate is established by Taguchi method | [157] |
| 2016                | Epoxy    | Glass-Bamboo fiber | Impingement angle (deg) | Effect of stacking sequence on the erosion wear rate | [158] |
| 2016                | Epoxy    | Multi wall carbon nano tubes/Alumina | Fillers content 0.5 to 2.5 wt Impingement angle (deg) | Improvement of erosion performance with the addition of nano fillers | [159] |
| 2016                | Epoxy    | Carbon fiber/Carbon nano tubes(CNT) | Fiber orientation (deg), Impingement angle (deg) | Erosion mechanism with the addition of CNT’s | [160] |
| 2016                | Polyester | Unidirection-al Carbon & Dynema fiber | Impingement angle (deg) | Effect of fiber orientation on erosion rate | [161] |
| 2016                | Polyetherimide & polyethylene terephthalate | Plain-weave polybenzoazole fiber | Fiber orientation 0°–45° Impingement angle (deg) | Mathematical model was proposed to predict erosion rate of ductile materials | [73] |
et al. Incorporation of both fiber and filler particles in matrices which is often referred to as Hybrid composites provides synergism in terms of improved erosion resistance. The effect of fillers in modifying the matrices for improved erosion characteristics has received great research attention. As reported in literature, erosion performance depends on matrix and fiber/filler reinforcement bonding. Improved bonding strength increase the hardness of composites that offers the high erosion resistance. Therefore interface plays a key role in affecting erosion wear rate is been concluded. From the literature there is no proper understanding of constituent’s interfacial effect on the erosion mechanism of PMCs. In addition, particle size is also important in determining the performance of composites. Nature of filler particles and their wt% can vary composite erosion performance. It appears that literature on the wear phenomenon of hybrid composites is inadequate. A further study can be performed on hybrid composites with the inclusion of solid lubricants for improvement in erosion wear resistance.

The fibers as reinforcement in polymer matrix improves erosion wear characteristics of composites. Along with that, fiber orientation, fiber weight and fiber treatment are considered as crucial factors in examining the tribological performance of polymer composites. Chemically treated fiber evades moisture content present in it.

### Table 2. Erosion mechanism and its nature with regard to erosion efficiency [164].

| Erosion efficiency $\eta$ | Nature of erosion | Erosion mechanism |
|---------------------------|-------------------|-------------------|
| $\eta = 0$                | No erosion        | Micro-ploughing   |
| $\eta = 100\%$            | —                 | Ideal micro-cutting |
| $\eta < 100\%$            | Ductile           | Platelet formation |
| $\eta > 100\%$            | Brittle           | Spalling           |
| $\eta < 10\%$             | Ductile           | High impact velocity |
| $\eta = 10\%–100\%$      | Semi-brittle      | Low impact velocity |

### 3. Erosion efficiency $\eta$

Erosion efficiency is accomplished for recognizing the dominant mechanism that leads to SPE [161]. It is defined as the ratio of actual volume of material removed as erosion fragments to the displaced volume and is given by equation (2)

$$\eta = \frac{2EH}{\rho v^2}$$

where $H$ (in Pa) and $v$ (in m/s) are the hardness and velocity of erodent particles respectively, $\rho$ (in kg/m$^3$) is the density of target material and $E$ (in kg/s) is the erosion rate (ER). Here ER is the fraction of mass loss of erodent material to erodent mass. ER strongly depends on impact velocity according to power law $E \alpha v^n$ applicable for all the materials. In other words erosion efficiency is defined as the volume lost per unit mass of erodent and given by equation (3). Erosion efficiency depends on the hardness of eroding material.

$$\eta = \frac{2E \rho H}{v^2}$$

The value of $\eta$ indicates the nature of erosion mechanism. If the value of $\eta = 0$ then ideal ploughing had taken place where only the displacement of material from the crater is involved without fracture. In contrast if $\eta = 1$ or 100%, then material removal is due to micro-cutting. The value of $\eta$ is greater than 1 for brittle materials where erosion mechanism is due to spalling and interlinking of cracks. For ductile materials, the value of $\eta$ is much lower than 100% in which fracture occurs due to repetitive impact of erodents. Elastomers have $\eta < 0.1\%$ which show that they are more resistive towards erosion. Table 2 gives the type of erosion with respect to erosion efficiency. The erosion efficiency of different types of PMCs were reported by Sundararajan et al [162] and Suresh et al [163].

Erosion efficiency for glass fiber/epoxy hybrid composites with varying wt% of iron mud as particulate filler increase with the increase of erodent particle velocity. Lower values of $\eta$ indicate exceptional erosion resistance whereas higher values indicate poor resistance [22]. On the contrary, Srivastava et al [165] evaluated erosion efficiency of fly ash filled glass fiber/epoxy composites. A decrement in erosion efficiency with increase of erodent velocity was observed. It can concluded from both the studies [22, 165] that erosion efficiency strongly depends on the type of filler particles.

### 4. Conclusion of literature review

A meticulous review of literature revealed that much work has been reported on the erosion characteristics of PMCs. Incorporation of both fiber and filler particles in matrices which is often referred to as Hybrid composites provides synergism in terms of improved erosion resistance. The effect of fillers in modifying the matrices for improved erosion characteristics has received great research attention. As reported in literature, erosion performance depends on matrix and fiber/filler reinforcement bonding. Improved bonding strength increase the hardness of composites that offers the high erosion resistance. Therefore interface plays a key role in affecting erosion wear rate is been concluded. From the literature there is no proper understanding of constituent’s interfacial effect on the erosion mechanism of PMCs. In addition, particle size is also important in determining the performance of composites. Nature of filler particles and their wt% can vary composite erosion performance. It appears that literature on the wear phenomenon of hybrid composites is inadequate. A further study can be performed on hybrid composites with the inclusion of solid lubricants for improvement in erosion wear resistance.

The fibers as reinforcement in polymer matrix improves erosion wear characteristics of composites. Along with that, fiber orientation, fiber weight and fiber treatment are considered as crucial factors in examining the tribological performance of polymer composites. Chemically treated fiber evades moisture content present in it.
which is essential in improving the adhesive bonding strength at fiber and matrix interface. From the literature it
is observed that there is a lack of basic understanding on the interfacial interaction between the chemically
treated fibers and polymer matrices. Therefore, a thorough investigation on interfacial interactions is needed
and this could be a new area for the researchers to work on it.

The studies on SPE have been mostly experimental. The studies reported the usage of statistical tools in
analyzing the wear phenomenon. The present review focused on the process parameters and their trend on
erosion response of various PMCs. The extensive literature presented in this review discloses the emerging
analyzing the wear phenomenon. The present review focused on the process parameters and their trend on
and this could be a new area for the researchers to work on it.

References

[1] Clyne T W and Hall D 2019 An Introduction to Composite Materials. (University of Cambridge: Cambridge university press) (https://
doi.org/10.1017/9781139050586)
[2] Souts C 2005 Fibre reinforced composites in aircraft construction Prog. Aerosp. Sci. 41 143–51
[3] Friedrich K and Almajid A A 2013 Manufacturing aspects of advanced polymer composites for automotive applications Appl. Compos.
Mater. 20 107–28
[4] Ullah H, Harland A R and Silberschmidt V V 2015 Dynamic bending behaviour of woven composites for sports products: experiments and damage analysis Mater. Des. 88 149–36
[5] Grant A 2005 Sporting composites Reinf. Plast. 49 16–9
[6] Davies P and Arhart M 2019 Fatigue behaviour of acrylic matrix composites: influence of seawater Appl. Compos. Mater. 26 507–18
[7] Mouritz A P, Gellert E, Burchill F and Challis K 2001 Review of advanced composite structures for naval ships and submarines Compos. Struct. 53 21–42
[8] Youssif A M and El-Sayed S M 2018 Bio nano composites materials for food packaging applications: concepts and future outlook Carbohydrate Polym. 193 19–27
[9] Ramakrishna S, Mayer J, Winterrmantel E and Leong KW 2001 Biomedical applications of polymer–composite materials: a review Compos. Sci. Technol. 61 1189–224
[10] Bakis C E, Bank L C, Brown V, Cosenza E, Davalos J F, Lesko J J, Machida A, Rizzalla S H and Triantafillou T C 2002 Fiber–reinforced polymer composites for construction—State-of-the-art review J. Compos. Constr. 6 73–87
[11] Harsha A P 2018 Solid particle erosion behavior of polymers and their composites Handbook of Particle Tribology 361–99
[12] Tewari U S, Harsha A P, Hüger A M and Friedrich K 2002 Solid particle erosion of unidirectional carbon fibre reinforced polyetheretherketone composites Wear 252 992–1000
[13] Padmraj N H, Vijaya K M and Dayananda P 2019 Experimental investigation on solid particle erosion behaviour of glass/epoxy Quasi–isotopic laminates Mater. Res. Express 6 085339
[14] Pola A, Battini D, Tocci M, Avanzini A, Girelli L, Petrogalli C and Gelof C 2019 Evaluation on the fatigue behavior of sand-blasted AlSi10Mg obtained by DMLS Frattura ed Integrità Strutturale 13 775–90
[15] Triantafillou T C 1986 Survey of sand and rain erosion of composite materials Journal of Composites, Technology and Research 8 154–8
[16] Mathew M T, Sinivasai Pau P, Pourzal R, Fischer A and Wimmer M A 2009 Significance of tribocorrosion in biomedical applications: overview and current status Advances in tribology 2009 12
[17] Pool K V, Dharan C K H and Finnie l 1986 Erosive wear of composite materials Wear 107 1–12
[18] Patnaik A, Satapathy A, Chand N, Barkoula N M and Biswas S 2010 Solid particle erosion characteristics of fiber and particulate filled polymer composites: a review Wear 268 249–63
[19] Liu D and Malvern L E 1987 Matrix cracking in impacted glass/epoxy plates J. Compos. Mater. 21 594–609
[20] Richardson M O W and Wisheart M J 1996 Review of low-velocity impact properties of composite materials Composites Part A: Applied Science and Manufacturing 27 1123–31
[21] Kaundal R 2014 Role of process variables on the solid particle glass erosion of polymer composites: a critical review Silicon 6 5–20
[22] Pani B, Chandrasekhar P and Singh S 2019 Investigation of erosion behaviour of an iron–mud filled glass-fibre epoxy hybrid composite Bull. Mater. Sci. 42 217
[23] Biswas S and Satapathy A 2009 Tribio–performance analysis of red mud filled glass epoxy composites using Taguchi experimental design Mater. Des. 30 2841–53
[24] Patnaik A, Satapathy A, Mahapatra S S and Dash R R 2008 Implementation of Taguchi design for erosion of fiber-reinforced polyester composite systems with SiC filler J. Reinf. Plast. Compos. 27 1093–111
[25] Patnaik A, Satapathy A, Mahapatra S S and Dash R R 2008 Parametric optimization erosion wear of polyester–GF–alumina hybrid composites using the Taguchi method I. Reinf. Plast. Compos. 27 1039–58
[26] Barkoula N M and Karger–Kocsis J 2002 Review processes and influencing factors of the solid particle erosion of polymers and their composites J. Mater. Sci. 37 3807–20
[27] Mohan N, Mahesh C R and Rajaprabhakar B 2013 Erosive wear behaviour of WC filled glass epoxy composites Procedia Engineering 68 694–702
[28] Friedrich K 1986 Erosive wear of polymer surfaces by steel ball blasting J. Mater. Sci. 21 3317–32
[29] Tilly G P and Sage W 1970 The interaction of particle and material behaviour in erosion processes Wear 16 647–65
[30] Stachowiak G W and Batchelor A W 1993 ‘Engineering Tribology Series 24’ (Amsterdam: Elsevier) 586978–0 12–397047–3

ORCID iDs

Vasavi Boggarapu @ https://orcid.org/0000-0003-2130-1163
Raghavendra Gujalia @ https://orcid.org/0000-0003-0199-9576
Shakuntla Ojha @ https://orcid.org/0000-0002-1303-8134
[31] Hutchings I M 1992 Ductile-brittle transitions and wear maps for the erosion and abrasion of brittle materials J. Phys. D: Appl. Phys. 25 A212
[32] Stack M M and Pungwivat N 1999 Slurry erosion of metallics, polymers, and ceramics: particle size effects Mater. Sci. Technol. 15 337–44
[33] Hutchings I M and Winter R E 1974 Particle erosion of ductile metals: a mechanism of material removal Wear 27 121–8
[34] Winter R E and Hutchings I M 1974 Solid particle erosion studies using single angular particles Wear 29 181–94
[35] Levy A V and Chik P 1983 The effects of erodent composition and shape on the erosion of steel Wear 89 151–62
[36] Liebhaf M and Levy A 1991 The effect of erodent particle characteristics on the erosion of metals Wear 151 381–90
[37] Marei A and Izvozhikov P V 1967 Abrasion of Rubber Ed I James (London: MacMyn) pp 274
[38] Feng Z and Ball A 1999 The erosion of four materials using seven erodents—towards an understanding Wear 233 674–84
[39] Simmazzelcki T and Sari N Y 2010 Erosion type effect on the erosion of polystyrene sulfide composite Polym. Compos. 31 985–94
[40] Gross K J 1988 Dissertation University at Stuttgart
[41] Ruff A W and Ives L K 1975 Measurement of solid particle velocity in erosive wear Wear 35 195–9
[42] Arnold J C and Hutchings I M 1989 Flux rate effects in the erosive wear of elastomers J. Mater. Sci. 24 833–9
[43] Anand K S K H, Hovis S K, Conrad H and Scattergood R O 1987 Flux effects in solid particle erosion Wear 118 243–57
[44] Sundararajan G and Roy M 1997 Solid particle erosion behaviour of metallic materials at room and elevated temperatures Tribol. Int. 30 359–59
[45] Shimizu K, Xinba Y and Araya S 2011 Solid particle erosion and mechanical properties of stainless steels at elevated temperature Wear 271 1357–64
[46] Biswas S and Satapathy A 2010 A comparative study on erosion characteristics of red mud filled bamboo–epoxy and glass–epoxy composites Mater. Des. 31 1752–67
[47] Biswas S 2010 Processing, Wear and Wear Response of Particulate Filled Epoxy Based Hybrid Composites (Doctoral dissertation)
[48] Song B et al 2011 Interfacially reinforced carbon fiber/epoxy composite laminates via in-situ synthesized graphitic carbon nitride (g-CN)4 Composites Part B: Engineering 158 239–69
[49] Das T K, Ghosh P and Das N C 2019 Preparation, development, outcomes, and application versatility of carbon–fiber–based polymer composites: a review Advanced Composites and Hybrid Materials 2 214–33
[50] Park S J, Seo M K, Ma T J and Lee D R 2002 Effect of chemical treatment of Kevlar fiber-reinforced epoxy composite Polym. Compos. 23 2387–96
[51] Hossain M M, Keya K N, Kona N A, Islam M N, Koly F A, Khan M A, Siddiquee M A B, Mahmud J and Khan R A 2019 Mechanical, thermal and interfacial properties of Carbon–Kevlar reinforced epoxy composite Materials Engineering Research 1 56–63
[52] Venkateshwaran N and Elayarajumal A 2010 Banana fiber reinforced polymer composites—a review J. Reinf. Plast. Compos. 29 387–96
[53] Boopalan M, Niranjana M and Umapathy M J 2013 Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites Composites Part B: Engineering 51 54–7
[54] RagHAVendra G, Ojha S, Acharya S K and Pal S K 2014 Jute fiber reinforced epoxy composites and comparison with the glass and neat epoxy composites J. Compos. Mater. 48 2337–47
[55] Gujala R, Ojha S, Acharya S K and Pal S K 2014 Mechanical properties of woven jute–glass hybrid–reinforced epoxy composite J. Compos. Mater. 48 945–53
[56] Khanam P N, Khalil H A, Reddy G R and Naidu S V 2011 Tensile, flexural and chemical resistance properties of sisal fiber reinforced polymer composites: Effect of fibre surface treatment J. Polym. Environ. 19 113–9
[57] Giridharan R, Raatan V S and Janarthanan M P 2019 Experimental study on effect of fibre length and fibre content on tensile and flexural properties of bamboo fiber/epoxy composite Multidiscipline Modeling in Materials and Structures 15 947–57
[58] Latha P S, Rao M V, Kumar V K, RagHAVendra G, Ojha S and Inala R 2016 Evaluation of mechanical and tribological properties of bamboo–glass hybrid fiber reinforced polymer composite J. Ind. Text. 46 3–18
[59] Batalay A, Nayak R K and Tripathy S 2018 Evaluation of mechanical properties of glass fibre and carbon fibre reinforced polymer composite Journal of Communication Engineering & Systems 8 66–74
[60] Naidu P P, RagHAVendra G and Ojha S 2019 Comparison of erosion wear of bidirectional and multidirectional oriented glass fiber epoxy composites In Materials Science Forum 969 (Switzerland: Trans Tech Publications Ltd) pp 157–62
[61] Ozturk B, Gedikli H and Kilicsarslan Y 2020 Erosive wear characteristics of E-glass fiber reinforced silica fume and zinc oxide-filled epoxy resin composites Polym. Compos. 41 326–37
[62] Song Y, Liu J, Chen S, Zheng Y, Ruan S and Bin Y 2013 Mechanical properties of poly (lactic acid)/hemp fiber composites prepared with a novel method J. Polym. Environ. 21 1117–27
[63] Bhooopathi R and Ramesh M 2019 Mechanical properties’ evaluation of hemp fibres–reinforced polymer composites In Advances in Materials and Metallurgy (Singapore: Springer) pp 343–51
[64] Nasser J, Liu J, Steinke K and Sodano H A 2019 Enhanced interfacial strength of aramid fiber reinforced composites through adsorbed aramid nanofiber coatings Comps. Sci. Technol. 174 125–33
[65] Sharma C and Kumar S R 2019 Erosion analysis of aramid fiber–epoxy composite In Advances in Engineering Design (Singapore: Springer) pp 469–74
[66] Zhang Z F, Xu Z H and Kong Z N 2014 Mechanical and thermal properties of short-coir–fiber–reinforced natural rubber / polyethylene composites Mech. Compos. Mater. 50 543–543
[67] Suresha B 2019 Influence of coir fiber loading on mechanical properties vinyl ester composites International Journal of Engineering Sciences and Management (In Materials Science Forum 969 (Switzerland: Trans Tech Publications Ltd) pp 157–62
[68] Liew S H, Harasha A P, Hugar A M and Friedrich K 2003 Solid particle erosion of carbon fibre– and glass fibre–epoxy composites Comps. Sci. Technol. 63 549–57
[69] Kaundal R, Patnaik A and Satapathy A 2012 Solid particle erosion of short glass fiber reinforced polyester composite American Journal of Materials Science 2 22–7
[70] MIYAZAKI N and HAMAZO T 1994 Solid particle erosion of thermoplastic resins reinforced by short fibers J. Compos. Mater. 28 871–83
[71] Zhang H, Zhang Z and Friedrich K 2007 Effect of fibre length on the wear resistance of short carbon fiber reinforced epoxy composites Comps. Sci. Technol. 67 222–30
[72] Reddy M K, Babu V S and Srinadh K V 2019 Investigation on effect of fibre volume and fiber orientation on erosive wear behavior of carbon fiber reinforced epoxy (CFRP) composites In Materials Science Forum 969 (Switzerland: Trans Tech Publications Ltd) pp 134–9
Singh M, Srivastava A and Bhunia D 2016 Potential applications of marble dust in industrial use by characterization techniques

Choudhary M, Sharma A, Purohit A, Nagar R and Patnaik A 2019 Analysis of erosion properties of polymer composite structures, properties, and applications

Subhrajit R A Y, Rout A K and Sahoo A K 2018 A Study on Erosion Performance Analysis of Glass-Epoxy Composites Filled with Marble Dust as Replacement for River Sand

Mochane MJ, Mokheta TC, Mokhotru TH, Mithe A, Sadiku E R, Ray S S, Ibrahim I D and Daramola O O 2019 Recent Progress on Natural Fiber Hybrid Composites for Advanced Applications: A Review. 13 159–98

Saha N, Tahir P M and Jawaid M 2014 A review on potentiality of nano filler/natural fiber filled polymer hybrid composites Polymers 6 2247–73

Li X, Tabil L G and Panigrahi S 2007 Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review Mater. Res. Express 4 100

Tewari U S, Harsha A P, Häger A M and Friedrich K 2003 Solid particle erosion of carbon fibre– and glass fibre–epoxy composites Compos. Sci. Technol. 63 549–57

Kim A and Kim I 2009 Solid particle erosion of CFRP composite with different laminate orientations Wear 267 1922–6

Brandt W and Goldsworthy S 2004 Encyclopedia of Polymer Science and Technology 2 (New York: Wiley) pp 56–67

Handbook/Reference Book 10: 0–471–27507–7

Mojangi M J, Mokheta T C, Mokhotru T H. Mithe A, Sadiku E R, Ray S S, Ibrahim I D and Daramola O O 2019 Recent Progress on Natural Fiber Hybrid Composites for Advanced Applications: A Review. 13 159–98

Saha N, Tahir P M and Jawaid M 2014 A review on potentiality of nano filler/natural fiber filled polymer hybrid composites Polymers 6 2247–73

Li X, Tabil L G and Panigrahi S 2007 Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review Mater. Res. Express 4 100

Tewari U S, Harsha A P, Häger A M and Friedrich K 2003 Solid particle erosion of carbon fibre– and glass fibre–epoxy composites Compos. Sci. Technol. 63 549–57

Kim A and Kim I 2009 Solid particle erosion of CFRP composite with different laminate orientations Wear 267 1922–6

Brandt W and Goldsworthy S 2004 Encyclopedia of Polymer Science and Technology 2 (New York: Wiley) pp 56–67

Handbook/Reference Book 10: 0–471–27507–7

Mojangi M J, Mokheta T C, Mokhotru T H. Mithe A, Sadiku E R, Ray S S, Ibrahim I D and Daramola O O 2019 Recent Progress on Natural Fiber Hybrid Composites for Advanced Applications: A Review. 13 159–98

Saha N, Tahir P M and Jawaid M 2014 A review on potentiality of nano filler/natural fiber filled polymer hybrid composites Polymers 6 2247–73

Li X, Tabil L G and Panigrahi S 2007 Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review Mater. Res. Express 4 100
[110] Pawar M J, Pattnaik A and Nagar T 2018 Tribo-performance of Granite Powder Filled Glass-epoxy Composites Available at SSRN 3328465
[111] Pun A K and Singh A K 2019 Thermo-mechanical and erosion wear peculiarity of hybrid composites filled with micro and nano silicon dioxide fillers—a comparative Study Silicon 11 1885–901
[112] Kuruvilla S P, Renukappa N M and Rajan J S 2019 Development of epoxy with nano and micro fillers for core insulation of composite insulators In 2019 Int. Conf. on High Voltage Engineering and Technology (ICHVET) (Disaateway, NI) (IEEE) pp 1–5
[113] Rudresh B M, Kumar B R and Madhu D 2019 Combined effect of micro-and nano-fillers on mechanical, thermal, and morphological behavior of glass–carbon P666/PTFE hybrid nano-composites. Advanced Composites and Hybrid Materials 2 176–88
[114] Agrawal S, Rayapudi V and Dhwani N 2018 Extraction of Iron values from Red mud Materials Today: Proceedings 5 17064–72
[115] Rachchhi N V, Misra R K and Roychowdhary D G 2015 Effect of red mud filler on mechanical and buckling characteristics of coir fibre-reinforced polymer composite Iran. Polym. J. 24 253–65
[116] Vigneshwaran S, Uthayakumar M and Arumugappuru V 2019 Solid particle erosion study on redmud-an industrial waste reinforced sisal/polyester hybrid composite Mater. Res. Express 6 065307
[117] Sutar H, Mishra S C, Sahoo S K, Satapathy A and Kumar V 2012 Morphology and Solid Particle Erosion Wear Behavior of Red Mud Composite Coatings 4 1–7
[118] Saradava B J, Rachchhi N V, Misra R K and Roychowdhary D G 2013 Mechanical characterization of coir fiber reinforced polymer epoxy composites filled red mud as filler J Inf Knowl Res Mech Eng 2 472–6
[119] Kalusuraman G, Kumaran S T, Aslan M, Küçükömerölü T and Siva I 2019 Use of waste copper slag filled jute fiber reinforced composites for effective erosion prevention Measurement 148 106950
[120] Biswas S and Satapathy A 2010 Use of copper slag in glass-epoxy composites for improved wear resistance Waste Manage. Res. 28 615–25
[121] Biswas S 2013 Erosion Wear Behaviour of Copper Slag Filled Short Bamboo Fiber Reinforced Epoxy Composites 6 91–4 (http://ijetch.org/papers/672-W0001.pdf
[122] Om Prakash M, Raghavendra G, Panchal M, Olja S and Anji Reddy B 2018 Effects of environmental exposure on tribological properties of Achar particulate/epoxy composites Polym. Compos., 39 3102–9
[123] Prakash V, Bera T and Acharya S K 2019 Mechanical and erosive wear behavior of rubber wood particulate reinforced epoxy composite Materials Today: Proceedings. (https://doi.org/10.1016/j.mtpr.2019.06.708)
[124] Acharya S K and Vasunaik D 2017 Solid Particle Erosion behavior of Rubber wood particulate Reinforced Epoxy Composite (Kolkata, India, December 6–9, 2017) Presented at the 9th International Conference on Industrial Tribology (ICT-2017)
[125] Antunes A, Faria P, Silva V and Brás A 2019 Rice husk–earth based composites: A novel bio-based panel for buildings refurbishment Constr. Build. Mater. 221 99–108
[126] Olja S, Anjali A and Gujiala R 2019 Extraction and Characterization of Carbon from Bio Waste Silicon 11 1–9
[127] Liu Y, Guo Y, Gao W, Wang Z, Ma Y and Wang F 2012 Simultaneous preparation of silica and activated carbon from rice husk ash J. Clean. Prod. 32 204–9
[128] Teo E Y L, Muniandy L, Ng E P, Adam F, Mohamed A R, Jose R and Chong K F 2016 High surface area activated carbon from rice husk as a high performance supercapacitor electrode Electrochim. Acta 192 110–9
[129] Rout A K and Satapathy A 2012 Study on mechanical and tribo-performance of rice-husk filled glass–epoxy hybrid composites Mater. Des. 41 131–41
[130] Harsha A P, Tewari U S and Venkatraman B 2003 Solid particle erosion behaviour of various polyaryletherketone composites Wear 254 693–712
[131] Arani NH, Rabwa W and Papini M 2019 Solid particle erosion of epoxy matrix composites reinforced by Al2O3 spheres Tribol. Int. 136 432–45
[132] Johnson R D J, Arumugappuru V, Kumar M P and Dheeraj K 2019 Solid particle erosion on the biochar filled hybrid vinyl ester composite AIP Conf. Proc. 2057 (AIP Publishing) pp 020664
[133] Singh T, Tejyan S, Patnaik A, Singh V, Zsollo L and Fekete G 2019 Fabrication of waste bagasse fiber-reinforced epoxy composites: study of physical, mechanical, and erosion properties Polym. Compos. (https://doi.org/10.1002/pc.25239)
[134] Pati P R and Satapathy M P 2019 Investigation on red brick dust filled epoxy composites using ant lion optimization approach Polym. Compos. (https://doi.org/10.1002/pc.25246)
[135] Tejyan S, Singh T, Patnaik A, Fekete G and Gangi B 2019 Physico-mechanical and erosive wear analysis of polyester fibre-based nonwoven-fabric-reinforced polymer composites J. Ind. Text. 49 447–64
[136] Deep N and Mishra P 2019 Study and optimization of erosive behavior of carbon black–epoxy polymer composites using taguchi method In Innovation in Materials Science and Engineering (Singapore: Springer) pp 209–17
[137] Dong M, Wang C, Liu H, Liu C, Shen C, Zhang J, Jia C, Ding T and Guo Z 2019 Enhanced solid particle erosion properties of thermoplastic polyurethane–carbon nanotube nanocomposites Macromol. Mater. Eng. 304 1–11
[138] Ahmedizat S R, Al-Zubaidi A B, Al-Tabbakh A A, Achour A and Hamed A A 2019 Comparative study of erosion wear of glass fiber/ epoxy composite reinforced with Al2O3 nano and micro particles Materials Today: Proceedings. 20 420–7
[139] Rani P U, Rajapakrash B M, Mohan N and Prasad M A 2019 Study on thermal and erosive wear behaviour of hard powders filled glass-epoxy composite Materials Today: Proceedings
[140] Kukshal V, Sharma A, Kiragi V R, Patnaik A and Pattnaik T K 2019 Erosive wear behaviour of carbon fiber/silicon nitride polymer composite for automotive application In Automotive Tribology (Singapore: Springer) 117–29
[141] Dalbehera S and Acharya S K 2018 Impact of cenosphere on the erosion wear response of woven hybrid jute–glass epoxy composites Adv. Polym. Tech. 37 240–6
[142] Latha P S and Rao M V 2018 Investigation into effect of ceramic fillers on mechanical and tribological properties of bamboo-glass hybrid fiber reinforced composites Silicon 10 1543–50
[143] Jha K, Samantaray B B and Tamrakar P 2018 A study on erosion and mechanical behavior of jute/e-glass hybrid composite Materials Today: Proceedings 5 5601–72
[144] Johnson R D J, Arumugappuru V, Uthayakumar M, Vigneshwaran S, Manikandan V and Bennet C 2018 Erosion performance studies on sansevieria cylindrica reinforced vinylester composite Mater. Res. Express 5 035309
[145] Kaundal R 2018 Utilization of flyash as filler material in hybrid polyester composites for improved thermo-mechanical and erosion wear behavior Silicon 10 2439–52
[146] Chellagnesan D, Khan M A, Ashif A M, Selvan T R, Nachiappan S and Jappes J W 2018 Composite material and solid particle erosion studies IOP Conf. Series: Materials Science and Engineering 346 (Bristol) (IOP Publishing) 012014
[147] Pani B, Chandrasekhar P and Singh S 2018 A study on erosion wear behavior of iron–mud/glass fiber reinforced epoxy composite IOP Conf. Series: Materials Science and Engineering 455 (Bristol) (IOP Publishing) 012068
Arslan G, Fidan S and Sinmazcelik T 2018 Solid particle erosion behavior of carbon fiber-metal wire hybrid reinforced polymer composites Journal of Science and Engineering 5 182–90

Dong M, Li Q, Liu H, Liu C, Wujcik E K, Shao Q, Ding T, Mai X, Shen C and Guo Z 2018 Thermoplastic polyurethane-carbon black nanocomposite coating: fabrication and solid particle erosion resistance Polymer 158 381–90

Zhang D, Cabrera E, Zhao Y, Zhao Z, Castro J M and Lee L J 2018 Improved sand erosion resistance and mechanical properties of multifunctional carbon nanofiber nanopaper-enhanced fiber reinforced epoxy composites Adv. Polym. Tech. 37 1878–85

Mohanty J R 2017 Investigation on solid particle erosion behavior of date palm leaf fiber-reinforced polyvinyl pyrrolidone composites J. Thermoplast. Compos. Mater. 30 1003–16

Das G and Biswas S 2017 Erosion wear behavior of coir fiber-reinforced epoxy composites filled with Al2O3 filler J. Ind. Text. 47 472–88

Sarkar N, Sahoo G, Khuntia T, Priyadarsini P, Mohanty J R and Swain S K 2017 Fabrication of acrylic modified coconut fiber reinforced polypropylene biocomposites: study of mechanical, thermal, and erosion properties Polym. Compos. 38 2852–62

Tejyan S and Patnaik A 2017 Erosive wear behavior and dynamic mechanical analysis of textile material reinforced polymer composites Polym. Compos. 38 2201–11

Debnath U K, Chowdhury M A, Kowser M A and Mia M S 2017 Study of erosion characterization of carbon fiber reinforced composite material AIP Conf. Proc. 1851 (AIP Publishing) 020098

Bagci M and Imrek H 2016 Erosion wear performance of borax filled novel hybrid composites by using the Taguchi experimental design Industrial Lubrication and Tribology 68 134–40

Bagci M 2016 Determination of solid particle erosion with Taguchi optimization approach of hybrid composite systems Tribol. Int. 94 336–45

Babu B G, Karthikeyan P N, Siva K and Sabarinathan C 2016 Study of erosion characteristics of MWCNT’s-alumina hybrid epoxy nanocomposites under the influence of solid particles Digest Journal of Nanomaterials and Biostructures 11 1367–73

Papadopoulos A, Giikas G, Paipetis A S and Barkoula N M 2016 Effect of CNTs addition on the erosive wear response of epoxy resin and carbon fibre composites Composites Part A: Applied Science and Manufacturing 84 299–307

Bao L, Kameel H and Kermochochi K 2016 Effects of fiber orientation angles of fiber-reinforced plastic on sand solid particle erosion behaviors Adv. Compos. Mater. 25 81–93

Roy M, Vishwanathan B and Sundararajan G 1994 The solid particle erosion of polymer matrix composites Wear 171 149–61

Sundararajan G, Roy M and Venkataraman B 1990 Erosion efficiency-a new parameter to characterize the dominant erosion micromechanism Wear 140 369–81

Arjula S and Harsha A P 2006 Study of erosion efficiency of polymers and polymer composites Polym. Test. 25 188–96

Chowdhury M A, Debnath U K, Nuruzzaman D M and Islam M 2015 Experimental evaluation of erosion of gunmetal under asymmetrical shaped sand particle Advances in Tribology 2015 31

Srivastava V K and Pawar A G 2006 Solid particle erosion of glass fibre reinforced flyash filled epoxy resin composites Compos. Sci. Technol. 66 3021–8