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Erosion Wear Response of Pineapple Leaf Fiber (PALF) Reinforced Vinylester Composites Filled with Silicon Carbide (SiC)

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Abstract: Natural fiber-based composites are under intensive study due to their eco-friendly nature and peculiar properties. The advantage of natural fibers is their continuous supply, easy and safe handling, and biodegradable nature. Natural fibers exhibit admirable physical and mechanical properties. Pineapple leave fiber (PALF) is one of the natural fibers abundantly available wastes materials in India and has not been studied yet. This research work is carried out a possibility that the incorporation of both particulate filler and fibers in polymer could provide a synergism in terms of improved properties. In view of this, the present research work is undertaken the fabrication of a set of Pineapple leaf fiber (PALF) reinforced Vinylester composites filled with Silicon Carbide (SiC) as the particulate filler. These results are compared with those of a similar set of Glass fiber reinforced Vinylester composites filled with same particulate filler. It also attempts to study the solid particle erosion wear response of these composites under multiple impact condition. The methodology based on Taguchi's experimental design approach is employed to make a parametric analysis of erosion wear process. This systematic experimentation has led to determination of significant process parameters and material variables that predominantly influence the wear rate of the particulate filled composites reinforced with pineapple leaf fiber. The significant control factors predominantly influencing the wear rate are identified. The filler content in the composites, the impingement angle and erodent temperature are found to have substantial influence in determining the rate of material loss from the composite surface due to erosion.

Keyword: - Natural fiber, Pineapple leaf fiber, particulate filler, Taguchi experimental design, erosion wear

I. INTRODUCTION

Over the past few decades, it is found that polymers have replaced many of the conventional metals/materials in various applications. This is possible because of the advantages such as ease of processing, productivity, cost reduction etc. offered by polymers over conventional materials. In most of these applications, the properties of polymers are modified by using fibers to suit the high strength/high modulus requirements. All synthetic polymers (Thermoplastics, Thermoset and Elastomers) can be used as matrices in PMCs. As far as the reinforcement is concerned, extensive use has been made of inorganic man-made fibers such as glass and organic fibers such as carbon and aramid. As all these reinforcing fibers are expensive, various fibers like cellulose, wool, silk etc. abundantly available in natures are also used in composites. Cellulosic fibers like henequen, sisal, coconut fiber (coir), jute, palm, bamboo, Pineapple leaves fiber (PALF) and wood, in their natural conditions and several wastes cellulosic products such as shell flour, wood flour and pulp have also been used as reinforcing agents of different Thermosetting and thermoplastic resins. It is well known that natural fibers impart high specific stiffness, strength and biodegradability to polymer matrix composites. Also, cellulosic fibers are readily available from natural sources and most importantly, they have low cost per unit volume.

There are many natural resources available which has potential to be applied in industries as raw materials such as pineapple, kenaf, coir, abaca, sisal, cotton, jute, bamboo, banana, Palmyra, talipot, hemp, and flex [1,2]. Among them Pineapple leaf fiber (PALF) is one of the waste materials in agriculture sector, which is widely grown in India as well as Asia. After banana and Citrus, Pineapple (Ananas comosus) is one of the most essential tropical fruits in the world [3]. Commercially pineapple leaves are considered as waste materials of fruit which is being used for producing natural fibers. The chemical composition of PALF constitute holocellulose (70– 82%), lignin (5–12%), and ash (1.1%).

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Major constituents in a natural fiber reinforced composite are the reinforcing fibers and a matrix, which acts as a binder for the fibers. In addition, particulate fillers can also be used with some polymeric matrices primarily to reduce cost and improve their dimensional stability. So, although a judicious selection of matrix and the reinforcing phase can lead to a composite with a combination of strength and modulus comparable to or even better than those of conventional metallic materials [4], the physical and mechanical characteristics can further be modified by adding a solid filler phase to the matrix body during the composite preparation. The fillers play a major role in determining the properties and behavior of particulate reinforced composites. The term ‘filler’ is very broad and encompasses a very wide range of materials. It is arbitrarily defined as a variety of natural or synthetic solid particulates (inorganic, organic) that may be irregular, circular, fibrous or flakey. The improved performance of polymers and their composites in industrial and structural applications by the addition of particulate fillers has shown a great promise and so has lately been a subject of considerable interest.

Another possibility that the incorporation of both particulates and fibers in polymer could provide a synergism in terms of improved properties and wear performance has not been adequately explored so far. However, some recent reports suggest that by incorporating filler particles into the matrix of fiber reinforced composites, synergistic effects may be achieved in the form of higher modulus and reduced material cost, yet accompanied with decreased strength and impact toughness. Such multi-component composites consisting of a matrix phase reinforced with a fiber and filled with particulates are termed as hybrid composites.

Nowadays much attention is devoted towards the study of solid particle erosion behavior of polymer composites due to the high potential use of these materials in many mechanical and structural applications. Hence, erosion resistance of polymer composites has become an important material property, particularly in selection of alternative materials and therefore the study of solid particle erosion characteristics of the polymeric composites has become highly relevant. Differences in the erosion behaviour of various types of composite materials are caused by the Amount, Type, Orientation and Properties of the reinforcement on one hand and by the type and properties of the matrix and its adhesion to the fibers/fillers on the other hand. A full understanding of the effects of all system variables on the wear rate is necessary in order to undertake appropriate steps in the design of machine or structural component and in the choice of materials to reduce/control wear [5].

II. METHODOLOGY OF THE PRESENT RESEARCH WORK

1. Fabrication of Vinylester based hybrid Composites.
2. Planning of Taguchi Experimental Design (Control parameter: - Erodent size, impact velocity, Erodent Temperature, Filler Content, Stand-off Distance, Impingement edge)
3. Erosion Test Experimentation utilizing Erosion test rig device.
4. Investigate the samples surfaces specifically by using Scanning Electron Microscope (SEM).
5. Comparison of rate of erosion of Pineapple Leaves fiber (PALF) - Vinylester composites with E-glass-Vinylester composites in various experiment conditions.

III. EXPERIMENTAL DETAILS

In this present research work Vinylester is chosen as the matrix material, i.e., grade of FB-701, Density 1.35 gm/cc, Elastic modulus 3.25 Gpa, (Supplied by Zenith Industrial supplies, Bangalore) and the Raw natural Pineapple leaf fiber (PALF) mat is unidirectional horizontal. The width is 17 inch and thickness are 2.8 mm, Density 1.56 gm/cc, Elastic Modulus 62.1 Gpa, (supplied by Go-green products, Chennai) are used as the reinforcing phase in the composites.

Though the present research work is focused mainly on the pineapple leaf fiber reinforced composites, their relative evaluation can only be made on comparing them with a similar set of composites with some conventional synthetic fiber. In the present work, E-glass fibers chopped strand mat density 2.54 gm/cc; modulus 72.4 Gpa, (supplied by Zenith Industrial supplies, Bangalore) has been used as the reinforcing material in the composites. The major constituents of E-glass are silicon oxide (54 wt. %), aluminum oxide (15 wt. %), calcium oxide (17 wt. %), boron oxide (8 wt. %) and magnesium oxide (4.5 wt. %).

A variety of natural or synthetic solid particulates, both organic and inorganic is already being commercially used as reinforcing fillers in polymeric composites. While ceramic powders such as Alumina (Al_2O_3), Silicon Carbide (SiC), silica (SiO_2), titanium (TiO_2) etc. are widely used as conventional fillers. In view of this, in the present work a conventional filler such as Silicon Carbide (SiC) are chosen as particulate fillers to be used in the composites.

Silicon Carbide (SiC), which has an incredible potential to be utilized in different polymeric matrices. It is the only chemical compound of carbon and silicon. It was originally produced by a higher temperature electro-chemical response of sand and carbon. Nowadays the material has been developed into a high-quality technical grade ceramic with excellent mechanical properties. It is used in abrasives, refractories, and ceramics in many high-performance structural and wear applications. This can likewise be made an electrical conductor and has applications in resistance heating, flame igniters and electronic components. SiC is composed of tetrahedral of carbon and silicon atoms with strong bonds in the crystal lattice. This produces a very hard and strong material. SiC is not attacked by any acids, alkalis

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or molten salts up to 800°C. It has low density of about 2.6 gm/cc, high strength, high thermal conductivity, high hardness, low thermal expansion, high elastic modulus, outstanding thermal shock resistance and superior chemical inertness.

The chemical compositions and density of Silicon Carbide (SiC) particulate filler materials for this study are mentioned in the Table 1.

Table 1. Chemical compositions and density of Silicon Carbide (SiC) filler

Filler	Composition/Chemical formula	Density (gm/cc)
Silicon Carbide	SiC	2.6

A. *Composite Fabrication*

The resin used in this research work is Vinylester FB-701 resin (density 1.35 gm/cc, Elastic modulus 3.25Gpa) and reinforcing phase a unidirectional Pineapple Leaves Fiber (PALF) and E-glass fibers are reinforced separately in Vinylester resin to prepare the fiber reinforced composites P_1 and G_1 in which no particulate filler Material is used. The other composite samples $P_2 – P_3$ and $G_2 – G_3$ Silicon Carbide (SiC) particulate fillers of varied amount but with fixed fiber loading (30 wt %) are fabricated. The composition and designation of the composites prepare for this study are listed in Table 2.

The Cobalt Naphthenate 2% is mixed thoroughly in Vinylester resin and then 2% methyl ethyl ketone peroxide (MEKP), 2% N- dimethylaniline is mixed in the resins prior to reinforcement. The fiber loading weight fraction of unidirectional Pineapple Leaves Fiber (PALF) or E-glass fiber chopped strand mat in the composite is kept 30 wt% for all the samples. The stacking procedure consists of placing the fabric one above the other with the resin mix well spread between the fabrics on a mould release sheet.

A porous Teflon film was again used to complete the stack. To ensure uniform thickness of the sample, a 4mm spacer was used. The mould plates were coated with release agent in order to aid the ease of separation on curing. A metal roller was used so that uniform thickness and compactness could obtain the whole assembly is placed in the light compression molding machine at a pressure of 40Kgf/cm2 and allowed to cure at room temperature for 24hrs. The laminate sheets of sizes 210 x 210 x 4mm were prepared. Specimens of suitable dimensions were cut using a diamond cutter for physical and mechanical characterization as per ASTM standard.

Table 2. Designations and detailed compositions of the composites

Designation	Composition
P_1	Vinylester (70 wt %) + PALF (30 wt %)
P_2	Vinylester (60 wt %) + PALF (30 wt %) + Silicon Carbide (10 wt %)
P_3	Vinylester (50 wt %) + PALF (30 wt %) + Silicon Carbide (20 wt %)
G_1	Vinylester (70 wt %) + Glass Fiber (30wt %)
G_2	Vinylester (60 wt %) + Glass Fiber (30wt %) + Silicon Carbide (10 wt %)
G_3	Vinylester (50 wt %) + Glass Fiber (30wt %) + Silicon Carbide (20 wt %)

B. *Erosion Wear test*

The set up for the solid particle erosion wear test used in this study is capable of creating reproducible erosive situations for assessing erosion wear resistance of the prepared composite samples.

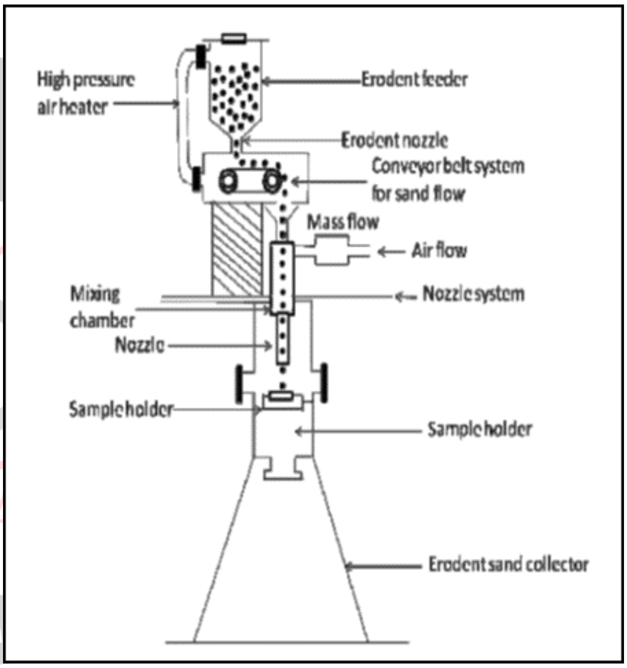

Figure 1. A Schematic diagram of the erosion test rig

The pictorial view and the schematic diagram of the erosion test rig are given in Figure 1. The test rig consists of an air compressor, an air-drying unit, a conveyor belt-type particle feeder and an air particle mixing and accelerating chamber. In the present study, dry silica sand (assumed to be square pyramidal shaped) of different particle sizes (300µm, 450µm and 600µm) are used as the erodent. The dried and compressed air is mixed with the erodent which is fed constantly by a conveyor belt feeder into the mixing chamber and then is accelerated by passing the mixture through a convergent brass nozzle of 3 mm internal diameter. The erodent particles impact the specimen which can be held at different angles with respect to the direction of erodent flow using a swivel and an adjustable sample clip. The velocity of the eroding particles is determined using the standard double disc method. The apparatus is equipped with a heater which

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can regulate and maintain the erodent temperature at any pre-determined fixed value during an erosion trial. The samples are cleaned in acetone, dried and weighed before and after the erosion trials using a precision electronic balance to an accuracy of ± 0.1 mg. The weight loss is recorded for subsequent calculation of erosion rate. The process is repeated till the erosion rate attains a constant value called steady state erosion rate. The erosion rate is defined as the ratio of this weight loss to the weight of the eroding particles causing the loss.

C. Taguchi Method

In any experimental research, since test procedures are generally expensive and time consuming, the need to satisfy the design objectives with the least number of tests is clearly an important requirement. In this context, Taguchi method provides the designer with a systematic and efficient approach for experimentation to determine near optimum settings of design parameters for performance and cost. This method involves laying out the experimental conditions using specially constructed tables known as 'orthogonal arrays. Use of orthogonal arrays significantly reduces the number of experimental configurations to be studied. The conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their settings. The most important stage in the design of experiment lies in the selection of the control factors.

Therefore, initially a large number of factors are included so that non-significant variables can be excluded at the earliest opportunity. Exhaustive literature review reveals that parameters i.e., impact velocity, impingement angle; fiber loading, filler content, erodent size, stand-off distance etc. largely influences the erosion rate of polymer composites [6, 7].

However, the author has not come across any report on the influence of a factor like erodent temperature on wear performance of polymer composites. Therefore, the present work, to explore the possible effect of erodent temperature, it is also considered as a control factor in addition to impact velocity, impingement angle, filler content, erodent size and stand-off-distance. Thus, the impact of six parameters is studied using L_{27} (3^{13}) orthogonal design. The control factors and the parameter settings for erosion test are given in Table 3. and Table 4. Presents the selected levels for various control factors.

The standard linear graph as shown in Figure 2 is used to assign the factors and interactions to various columns of the orthogonal array [9,10.14]. The selected parameters viz., impact velocity, filler content, erodent temperature, stand-off distance, impingement angle and erodent size, each at three levels, are considered in this study. These six parameters each at three levels would require 3^6 = 729 runs in a full factorial experiment whereas Taguchi's experimental approach reduces it to 27 runs only offering a great advantage.

Table 3. Parameter settings for erosion test

Control Factors	**Symbols**	**Fixed parameters**	
Impact velocity	Factor A	Erodent	Silica sand
Filler content	Factor B	Erodent feed rate (g/min)	10.0 +1.0
Erodent Temperature	Factor C	Nozzle diameter (mm)	3
Impingement angle	Factor D	Length of nozzle (mm)	80
Standoff distance	Factor E		
Erodent size	Factor F		

The plan of the experiments as shown in Table 5. is as follows: the first, second, fifth, ninth, tenth and twelfth columns are assigned to impact velocity (A), filler content (B), erodent temperature (C), impingement angle (D), stand-off distance (E) and erodent size (F) respectively. The third and fourth column are assigned to $(A\times B)_1$ and $(A\times B)_2$ respectively to estimate interaction between impact velocity (A) and filler content (B), the sixth and seventh column are assigned to $(B\times C)_1$ and $(B\times C)_2$ respectively to estimate interaction between filler content (B) and erodent temperature (C), the eighth and eleventh column are assigned to $(A\times C)_1$ and $(A\times C)_2$ respectively to estimate interaction between the impact velocity (A) and erodent temperature (C) and the remaining columns are used to estimate experimental errors.

The experimental observations are transformed into signal-to-noise (S/N) ratios. There are several S/N ratios available depending on the type of characteristics such as:

$$'\text{Smaller} - \text{the} - \text{better}'\ \text{characterstic}:$$

$$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \tag{1}$$

Table 4. Levels for various control factors

Control factor	**LEVEL I**	**LEVEL II**	**LEVEL III**	**Unit**
A: Impact velocity	45	55	65	m/sec
B: Filler content	0	10	20	%
C: Erodent Temperature	40	50	60	°C
D: Impingement angle	30	60	90	degree
E: Stand-off distance	65	75	85	mm
F: Erodent size	300	450	600	µm

Where **n** is the number of observations, **y** is the observed data, **Y** the mean and **S** the variance. The S/N ratio for minimum erosion rate comes under 'smaller-the-better' characteristic, which can be calculated as logarithmic transformation of the loss function by using Eq. (1).

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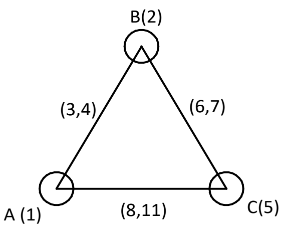


Figure 2. Linear graphs for L_{27} orthogonal array

Table 5. Orthogonal array for L_{27} (3^{13}) Taguchi Design

L_{27} (3^{13})	1	2	3 $(AxB)_1$	4 $(AxB)_2$	5	6 $(BxC)_1$	7 $(BxC)_2$	8 $(AxC)_1$	9	10	11 $(AxC)_2$	12 F	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	3	2
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

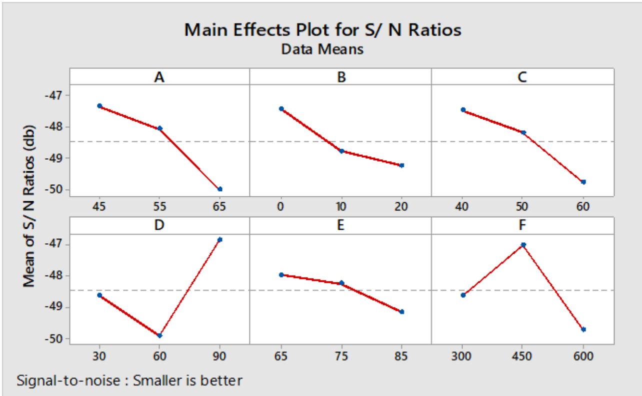
IV. RESULT AND DISCUSSION

A. Erosion Wear Characteristics

This part presents the analysis and comparison of erosion response of PALF-Vinylester and Glass-Vinylester composites filled with Silicon Carbide (SiC). The experiments have been carried out using Taguchi experimental design (L_{27} Orthogonal array) given in Table 5. and the subsequent analysis of the test results is made using the popular software specifically used for design of experiment applications known as MINITAB 18. Finally, the micro-structural features of the composite samples eroded under different operating conditions are described based on SEM micrographs.

B. Taguchi Experimental Analysis

The results of erosion experiments carried out according to Taguchi experimental design on SiC filled PALF-Vinylester and glass-Vinylester composites. The overall mean for the S/N ratio of the erosion rate is found to be -48.4701 db for PALF based composites and -48.5753 db for the glass-based ones. PALF-Vinylester composites exhibit much lower wear rates than those by Glass-Vinylester composites.

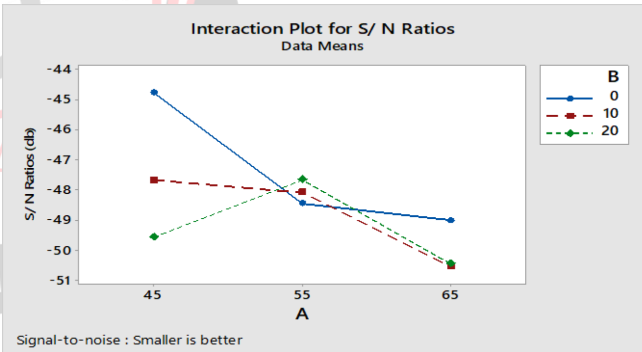


*A= Impact Velocity, B=Filler content, C= Erodent Temperature, D=Impingement angle, E= Stand –off-distance, F=Erodent Size

Figure 3. Effect of control factors on erosion rate (For SiC filled PALF-Vinylester composites)

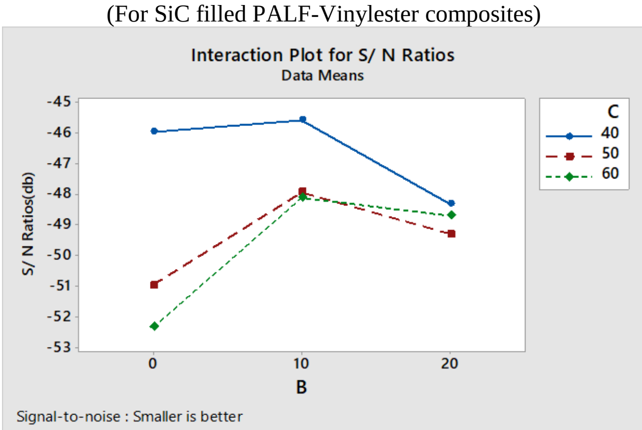
*A= Impact Velocity, B=Filler content, C= Erodent Temperature, D=Impingement angle, E= Stand –off-distance, F=Erodent Size

Figure 4. Effect of control factors on erosion rate (For SiC filled Glass-Vinylester composites)



*A= Impact Velocity, B=Filler content

Figure 5. Interaction graph between impact velocity and filler content (A X B) for erosion rate (For SiC filled PALF-Vinylester composites)



*B= Filler content, C=Erodent Temperature

Figure 6. Interaction graph between filler content and erodent temperature (B X C) for erosion rate

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(For SiC filled Glass- Vinylester composites)

Figures 3. and Figure 4. Illustrate the effect of control factors on erosion rate of PALF-Vinylester and Glass-Vinylester composites respectively. Analysis of the results leads to the conclusion that factor combination A_1(Impact velocity: 45 m/sec), B_2(Filler content: 10wt%), C_2 (Erodent temperature: 50^0C), D_3 (Impingement angle: 90^0) E_3 (Stand-off distance: 85mm), and F_1 (Erodent size: 300µm) gives minimum erosion rate as seen in Figure 3. for PALF-Vinylester composites and the factor combination A_1(Impact velocity: 45 m/sec), B_2(Filler content: 10wt%), C_1(Erodent temperature: 40^0C), D_3(Impingement angle: 90^0), E_1 (Stand-off distance: 65mm) and F_1 (Erodent size: 300µm) gives minimum erosion rate as seen in Figure 4. for glass-Vinylester composites. The respective interaction graphs are shown in the Figures 5. for PALF-Vinylester composites and Figures 6. for Glass-Vinylester composites.

C. ANOVA and the Effects of Factors

In order to find out statistical significance of different factors like impact velocity (A), SiC content (B), erodent temperature (C), impingement angle (D), stand-off distance (E) and erodent size (F) on erosion rate, analysis of variance (ANOVA) is carried out on experimental data. Table 6. and Table 7. demonstrate the results of the ANOVA with the erosion rate of PALF-Vinylester and Glass-Vinylester based composites taken in this study. The last column of the table shows percentage contribution of the control factors and their interactions on the performance output i.e., erosion rate [9]. From Table 6. it can be observed for the SiC filled PALF-Vinylester composites that impingement angle (p=0.416), impact velocity (p = 0.469), erodent size (p=0.476) and erodent temperature (p = 0.550) have significant influence on erosion rate. The interaction of impact velocity and SiC content (p=0.800) as well as SiC content and erodent temperature (p=0.879) show considerable contribution on the erosion rate. The remaining factors and interactions have moderately less considerable contribution.

Table 6. ANOVA table for erosion rate (For SiC filled PALF-Vinylester composites)

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
A	2	34.147	34.147	17.073	1.13	0.469
B	2	16.116	16.116	8.058	0.53	0.652
C	2	24.681	24.681	12.341	0.82	0.550
D	2	42.466	42.466	21.233	1.41	0.416
E	2	6.897	6.897	3.448	0.23	0.814
F	2	33.294	33.294	16.647	1.10	0.476
A X B	4	24.466	24.466	6.116	0.40	0.800
A X C	4	6.085	6.085	1.521	0.10	0.972
B X C	4	16.131	16.131	4.033	0.27	0.879
Error	2	30.208	30.208	15.104		
Total	26	234.491				

Similarly, from Table 7, it can be observed that erodent temperature (p = 0.053), SiC content (p=0.091), impact velocity (p = 0.184), impingement angle (p = 0.545) and erodent size (p = 0.606) have significant influence on erosion rate. The interaction of SiC content and erodent temperature (p = 0.177) as well as impact velocity and SiC content (p = 0.375) show considerable contribution on the erosion rate whereas the remaining factor and interactions have moderately less considerable contribution.

Table 7. ANOVA table for erosion rate (For SiC filled Glass-Vinylester composites)

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
A	2	13.202	13.202	6.6011	4.44	0.184
B	2	29.805	29.805	14.9024	10.03	0.091
C	2	52.707	52.707	26.3535	17.74	0.053
D	2	2.483	2.483	1.2416	0.84	0.545
E	2	0.531	0.531	0.2656	0.18	0.848
F	2	1.933	1.933	0.9665	0.65	0.606
A X B	4	11.220	11.220	2.8051	1.89	0.375
A X C	4	10.756	10.756	2.6890	1.81	0.386
B X C	4	29.033	29.033	7.2582	4.89	0.177
Error	2	2.971	2.971	1.4857		
Total	26	154.642				

D. Justification Experiment

The Justification experiments are the final test during the design of experiment process. The motivations behind the Justification experiments are to be approving the conclusions drawn at the time of the analysis stage. But, last proceed in any design of experiment approach is to anticipate and check upgrades in experimental values using the optimal combination level of control factors. The Justification experiment is carried out for PALF-Vinylester composites by taking an arbitrary set of factor combination $A_3B_3C_1D_2F_2$. Here, factor E has been omitted because it has the least effect on performance characteristic as manifest from Table 6. Also, for the Glass-Vinylester composites, the confirmation experiment is carried out by taking another arbitrary set of factor combination $A_2B_3C_2D_3F_2$. Here besides, factor E has been omitted for being the least considerable as seen in Table 7.

Table 8. Results of the confirmation experiments for erosion rate

	Optimal control parameters (For PALF-Vinylester composites)		Optimal control parameters (For Glass-Vinylester composites)	
	Prediction	Experimental	Prediction	Experimental
Level	$A_3B_3C_1D_2F_2$	$A_3B_3C_1D_2F_2$	$A_2B_3C_2D_3F_2$	$A_2B_3C_2D_3F_2$
S/N ratio for Erosion rate (db)	- 50.9800	-52.1974	-50.3306	-50.8935

The estimated S/N ratio for the composites with Silicon Carbide (SiC) filler, the erosion rate can be calculated with the help of following prediction equations:

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$$\bar{\eta}_{PALF-SiC} = \bar{T} + (\bar{A}_3 - \bar{T}) + (\bar{B}_3 - \bar{T}) + [(\bar{A}_3\bar{B}_3 - \bar{T}) - (\bar{A}_3 - \bar{T}) - (\bar{B}_3 - \bar{T})] + (\bar{C}_1 - \bar{T}) + [(\bar{B}_3\bar{C}_1 - \bar{T}) - (\bar{B}_3 - \bar{T}) - (\bar{C}_1 - \bar{T})] + (\bar{D}_2 - \bar{T}) + (\bar{F}_2 - \bar{T}) \quad (3.1)$$

$$\bar{\eta}_{GF-SiC} = \bar{T} + (\bar{A}_2 - \bar{T}) + (\bar{B}_3 - \bar{T}) + [(\bar{A}_2\bar{B}_3 - \bar{T}) - (\bar{A}_2 - \bar{T}) - (\bar{B}_3 - \bar{T})] + (\bar{C}_2 - \bar{T}) + [(\bar{B}_3\bar{C}_2 - \bar{T}) - (\bar{B}_3 - \bar{T}) - (\bar{C}_2 - \bar{T})] + (\bar{D}_3 - \bar{T}) + (\bar{F}_2 - \bar{T}) \quad (3.2)$$

$\bar{\eta}_{PALF-SiC}$ and $\bar{\eta}_{GF-SiC}$: Predictive averages for Silica filled PALF fibers based as well as Glass fiber-based composite correspondingly.
$\bar{T}$ = Overall average of experimented.

$\bar{A}_2, \bar{A}_3, \bar{B}_3, \bar{C}_1, \bar{C}_2, \bar{D}_2, \bar{D}_3$, and $\bar{F}_2$: Average reaction factors as well as relations on designated levels.

With adding terms, the equation (3.1) as well as equation (3.2) converted into,

$$\bar{\eta}_{PALF-SiC} = \bar{A}_3\bar{B}_3 + \bar{B}_3\bar{C}_1 - \bar{B}_3 + \bar{D}_2 + \bar{F}_2 - 2\bar{T} \quad (3.3)$$

$$\bar{\eta}_{GF-SiC} = \bar{A}_2\bar{B}_3 + \bar{B}_3\bar{C}_2 - \bar{B}_2 + \bar{D}_3 + \bar{F}_2 - 2\bar{T} \quad (3.4)$$

A new combination of factor levels A_2, A_3, B_3, C_1, C_2, D_3 and F_2 is used to predict erosion rate through prediction equation and it is found to be $\bar{\eta}_{PALF-SiC}$ = - 50.9800 dB and $\bar{\eta}_{GF-SiC}$= - 50.3306 dB respectively.

For each performance measure, experimentation is conducted for the same set of factor combinations and the obtained S/N ratio value is compared with that obtained from the predictive equation as shown in Table 8. The resulting model seems to be capable of predicting erosion rate to a reasonable accuracy. An error of 2.33% and 1.10 % for the S/N ratio of erosion rate is observed for PALF-Vinylester composites and Glass-Vinylester composites respectively. But the error can be further reduced if the number of measurements is increased. This validates the mathematical model for predicting the measures of performance based on knowledge of the input parameters.

E. Effect of Impingement Angle and Erodent Temperature on Erosion

Generally, the erosion behavior of materials is broadly classified as either ductile or brittle depending on the variation of erosion rate with impingement angle. The erosion wear rates of SiC filled PALF-Vinylester and Glass-Vinylester composites as a task of impingement angle are revealed in Figure 7 at constant impact velocity (55m/sec), erodent temperature (50^0C), stand-off distance (75mm) and erodent size (450µm). It can be seen that the presence of SiC reduces the wear rate of the composites moderately considerable. In additional, whereas the maximum erosion is noticed to be occurring at impingement angle of 60^0 for the unfilled PALF-Vinylester composite and it take place at impingement angle of 75^0 for composites filled with SiC. This change in the erosion behavior is a sign of loss of ductility and is obviously attributed to the brittle nature of PALF fibers and SiC particulates embedded in the matrix body. Similar behaviour is also shown by Glass fiber reinforced Vinylester composites filled with SiC particles. It is also significant to note that the composites with high filler content show better erosion resistance.

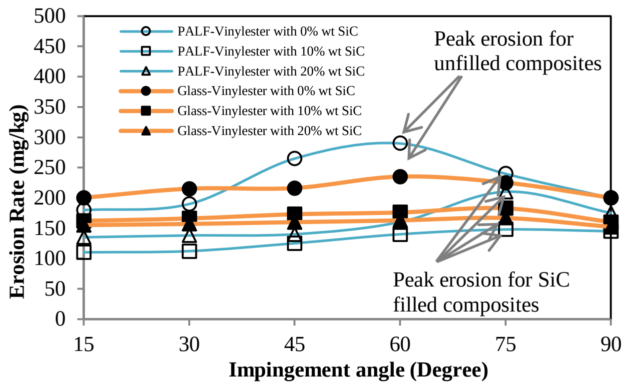

Figure 7. Effect of impingement angle on the erosion wear rate of SiC filled composites

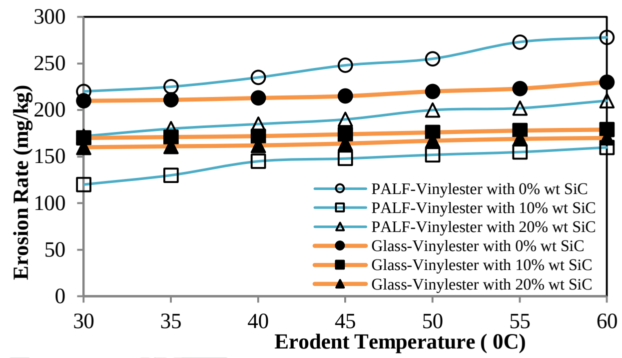

Figure 8. Effect of erodent temperature on the erosion wear rate of SiC filled composites

Also, the difference of erosion rate of unfilled and SiC filled composites with erodent temperature at constant impact velocity (55m/sec), impingement angle (90^0), stand-off distance (75mm) and erodent size (450µm) are shown in Figure 8. Erosion test are conducted for seven different erodent temperatures under normal impact condition. From this figure, it can be observed that for all the composite samples, the erosion rates remain almost unaffected by the change in erodent temperature from ambient to 40^0C. The effect of erodent temperature on erosion is significant above 40^0C and the rate of increase in erosion rate is greater at high temperatures.

F. Discussion on Surface Morphology

Figure 9. illustrate scanning electron micrographs of SiC filled PALF-Vinylester composite surface eroded at impact velocity of 55 m/sec. It is manifest from the micrographs from the Figures 9a. and 9b. that the material removal in PALF-Vinylester composite with 10wt% SiC is subjected by plastic deformation. Formation of micro-cracks and embedment of fragments of sand particles is manifest from the micrograph in Figure 9c. show the erosion at 60^0 impingement angles.

Though, during the normal impact the major part of the initial energy of the erodent is changed into heat and

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therefore the matrix is become softer which resulted in embedment of sand particles as seen in Figure 9d. These particles control further erosion of the target surface. Figures 9e. and 9f. illustrate micrographs of eroded surfaces of composites with 20 wt% SiC. At normal impingement angle, removal of matrix along the length of the fiber and consequent exposure of fibers can be seen from the micrograph in Figure 6.40e at an impact velocity of 55m/sec. At high impact velocity (65m/sec), the erodent particles possess high kinetic energy that results in increased plastic deformation and removal of matrix leading to protrusion of fibers out from the matrix as seen in Figure 6.40f. Scanning electron micrographs of the worn-out surfaces of both unfilled and SiC filled Glass-Vinylester composites are shown in Figure 10. The SEM image of the composite without filler eroded at an impingement angle of 30^0 and an impact velocity of 45 m/sec is shown in Figure 10a. When impacting at low angles, the hard erodent particles enter the surface of the samples and cause material removal by micro-cutting and micro-ploughing as seen in Figures 10a. and 10b. With it is possible to investigate the particle flow direction easily from the wear trace of the particles, which are specifying by black arrows in the micrographs. Figures 10c. and 10d. show the worn-out surfaces of SiC filled composites subjected to high erodent impact velocity of 55 m/sec. These micrographs illustrate the distribution of filler particles in the matrix and features like surface roughening. Figure 10e. illustrate a portion of the eroded surface where matrix covering the fiber seems to be chipped off and the crater thus formed shows an array of almost intact fibers.

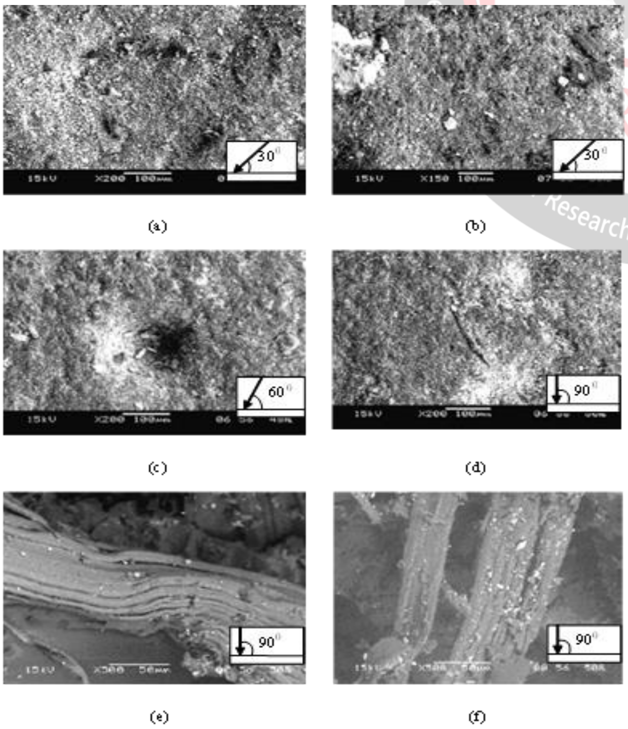

Figure 9. SEM images of eroded surfaces of Alumina filled PALF-Vinylester composites

Also, in Figure 10f. there is confined removal of matrix material from the impacted surface resulting in exposure of fibers to the erosive environment. Figures 10g. and 10h. illustrate the exposed fibers getting fragmented and dislodged from the matrix body leading to a superior degree of surface damage.

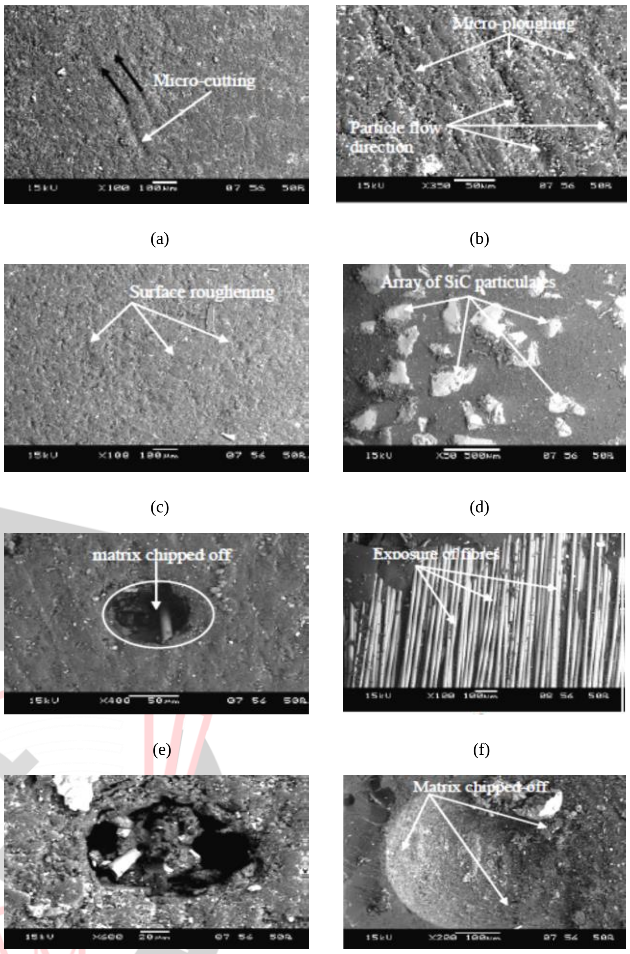

Figure 10. SEM micrographs of the eroded Glass-Vinylester composites filled with SiC.

This is a case of the erodent particles striking forcefully the composite surface at higher impingement angle with higher impact velocity. Due to frequent impact of the erodent carrying high energy, the fibers under the matrix layer break and the SiC particles in the matrix body and along the matrix fiber interface also undergo fragmentation resulting in loose debris. The matrix exhibits multiple fractures and material removal. The exposed fibers are broken down into fragments and hence can be easily removed from the worn-out surfaces.

V. CONCLUSION

1. This study reveals the semi-ductile response for most of these particulates filled PALF/Glass Vinylester composites with respect to erosion wear. The peak erosion rate is found to be occurring at 60^0 impingement angles for the unfilled composites as well as for Silicon Carbide filled composites with both PALF as well as glass reinforcement.

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2. The presence of particulate fillers in PALF- Vinylester composites improves their erosion wear resistance and this improvement depends on the type and content of the fillers. It is interesting to note that Silicon Carbide as the particulate filler, show lower erosion rates. Further, the filler materials considered in this study, Silicon Carbide (SiC) emerges as the best filler material to be used in Vinylester based composites, irrespective of fiber type, as far as the resistance to solid particle erosion is concerned.

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