

Erosion Wear Response of Pineapple Leaf Fiber (PALF) Reinforced Vinylester Composites Filled with Alumina (Al₂O₃)

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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 leaf 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 Alumina (Al₂O₃) 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

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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 nature 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%).

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 is 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 (Al₂O₃), silicon carbide (SiC), silica (SiO₂), titanium (TiO₂) etc. are widely used as conventional fillers. In view of this, in

the present work a conventional filler such as Alumina (Al₂O₃) are chosen as particulate fillers to be used in the composites.

Alumina is an inorganic material that can possibly be utilized as filler in different polymer matrices. Aluminium oxide (Al₂O₃) generally referred to as alumina, can exist in several crystalline phases which all revert to the most stable hexagonal alpha phase at high temperatures. This is the phase of particular interest for structural applications. Alumina is the mainly cost effective and extensively used material in the family of engineering ceramics. It is wear-resistant, hard, has tremendous dielectric properties, resistance to strong acid and alkali attack at high temperatures, high stiffness and strength. With a tremendous mixture of properties and a reasonable price, it is no surprise that fine grain technical grade alumina has a very extensive range of applications.

The chemical compositions and density of Alumina (Al₂O₃) particulate filler materials for this study are mentioned in the Table 1.

Table 1. Chemical compositions and density of Alumina (Al₂O₃) filler

Filler	Composition/Chemical formula	Density (gm/cc)
Alumina	Al ₂ O ₃	2.1

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 P1 and G1 in which no particulate filler Material is used. The other composite samples P2 – P3 and G2 – G3 Alumina 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 %) + Alumina (10 wt %)
P ₃	Vinylester (50 wt %) + PALF (30 wt %) + Alumina (20 wt %)
G ₁	Vinylester (70 wt %) + Glass Fiber (30wt %)
G ₂	Vinylester (60 wt %) + Glass Fiber (30wt %) + Alumina (10 wt %)
G ₃	Vinylester (50 wt %) + Glass Fiber (30wt %) + Alumina (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.

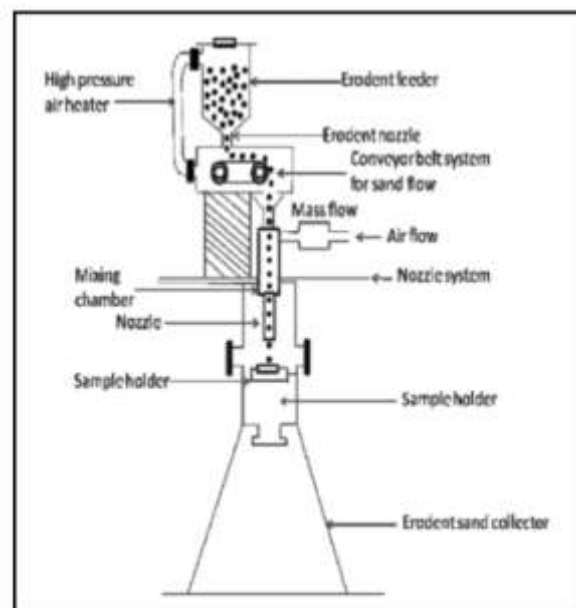


Figure 1. A Schematic diagram of the erosion test rig

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 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 L27 (313) 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 36 = 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 (AXB)1 and (AXB)2 respectively to estimate interaction between impact velocity (A) and filler content (B), the sixth and seventh column are assigned to (BXC)1 and (BXC)2 respectively to estimate interaction between filler content (B) and erodent temperature (C), the eighth and eleventh column are assigned to (AXC)1 and (AXC)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:

'Smaller - the - better' characteristic:

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

Table 4. Levels for various control factors

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

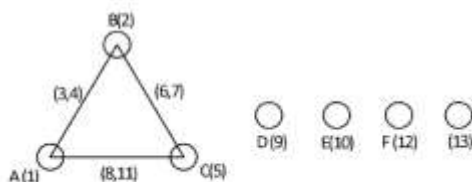


Figure 2. Linear graphs for L₂₇ orthogonal array

Table 5. Orthogonal array for L₂₇ (3¹³) Taguchi Design

L ₂₇ (3 ¹³)	A	B	3 (AxB)	4 (AxB)	C	6 (BxC)	7 (BxC)	8 (AxC)	D	E	11 (AxC)	12 _a	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2	2	2	2	2	2	2
3	1	1	1	3	3	3	3	3	3	3	3	3	3
4	1	2	2	1	1	1	2	2	2	3	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	3	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	3	3	3	2	2	2	2
8	1	3	3	3	2	2	2	1	1	3	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

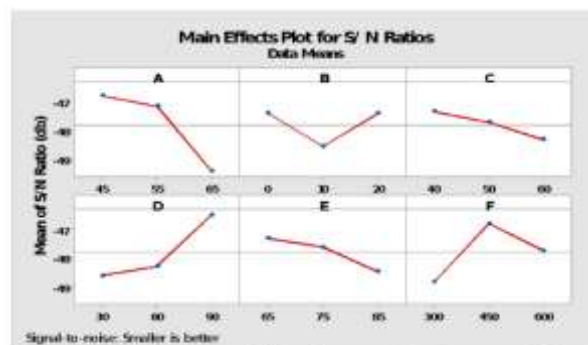
A. Erosion Wear Characteristics

This part presents the analysis and comparison of erosion response of PALF-Vinylester and Glass-Vinylester composites filled with Alumina. The experiments have been carried out using Taguchi experimental design (L₂₇ 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.

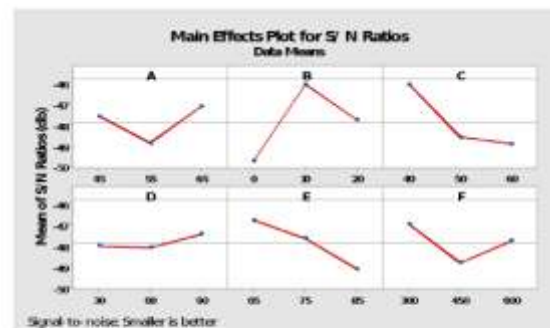
B. Taguchi Experimental Analysis

The results of erosion experiments carried out according to Taguchi experimental design on Alumina filled PALF-Vinylester and Glass-Vinylester composites, the overall mean of the S/N ratios is found to be -47.8076 db for PALF based composites and -47.8648 db for the Glass based ones. For similar test conditions, PALF-Vinylester composites exhibit much lower wear rates than those by Glass-Vinylester composites.



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

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



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

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

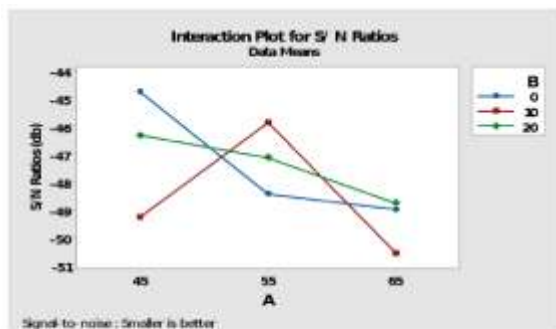


Figure 5. Interaction graph between impact velocity and filler content (A X B) for erosion rate (For Alumina filled PALF-Vinylester composites)

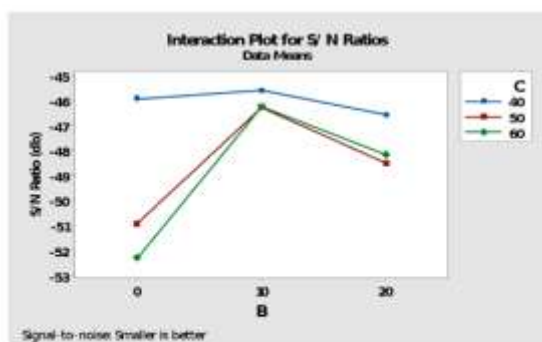


Figure 6. Interaction graph between filler content and erodent temperature (B X C) for erosion rate (For Alumina filled Glass- Vinylester composites)

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 of A1(Impact velocity: 45 m/sec), B2 (Filler content: 10wt%), C1(Erodent temperature: 400C), D3 (Impingement angle: 900), E2 (Stand-off distance: 75mm) and F2 (Erodent size: 450µm) gives minimum erosion rate (Figure 3) for PALF-Vinylester composites and the factor combination of A2 (Impact velocity: 55 m/sec), B2 (Filler content: 10wt%), C1(Erodent temperature: 400C), D1 (Impingement angle: 300), E2 (Stand-off distance: 75mm) and F3 (Erodent size: 600µm) gives minimum erosion rate (Figure 4) for Glass-Vinylester composites. The respective interaction graphs are shown in the Figures 5. and Figure 6. For PALF-Vinylester and Glass-Vinylester composites respectively.

C. ANOVA and the Effects of Factors

In order to find out statistical significance of various factors like impact velocity (A), Alumina content (B), erodent temperature (C), impingement angle (D), stand-off distance (E) and erodent size (F) on erosion rate, analysis of variance (ANOVA) is performed on experimental data. Table 6. and Table

7. show the results of the ANOVA for the erosion rate of PALF-Vinylester composites and Glass-Vinylester composites respectively. The last column of the table indicates 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 alumina filled PALF-Vinylester composites that impact velocity ($p = 0.366$), erodent temperature ($p = 0.481$), erodent size ($p = 0.537$) and alumina content ($p = 0.725$) have significant influence on erosion rate. The interaction of impact velocity and alumina content ($p = 0.586$) as well as alumina content and erodent temperature ($p = 0.656$) show considerable contribution on the erosion rate. The remaining factor and interactions have relatively less considerable contribution.

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

Source	D.F	Seq SS	Adj SS	Adj MS	F-Value	P-Value
A	2	37.564	37.564	18.782	1.73	0.366
B	2	8.196	8.196	4.098	0.38	0.725
C	2	4.558	4.558	2.279	0.21	0.826
D	2	23.397	23.397	11.699	1.08	0.481
E	2	6.577	6.577	3.288	0.30	0.767
F	2	18.675	18.675	9.337	0.86	0.537
A X B	4	39.059	39.059	9.765	0.90	0.586
A X C	4	17.890	17.890	4.473	0.41	0.795
B X C	4	30.669	30.669	7.667	0.71	0.656
Error	2	21.657	21.657	10.828		
Total	26	208.242				

Similarly, from Table 7. it can be observed for the alumina filled glass-Vinylester composites that alumina content ($p = 0.044$), erodent temperature ($p = 0.059$), stand-off distance ($p = 0.101$), erodent size ($p = 0.152$) and impact velocity ($p = 0.158$) have significant influence on erosion rate. The interaction of alumina content and erodent temperature ($p = 0.161$) as well as impact velocity and erodent temperature ($p = 0.204$) show considerable contribution on the erosion rate. The remaining factor and interactions have quite less considerable contribution on erosion rate.

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

Source	D.F	Seq SS	Adj SS	Adj MS	F-Value	P-Value
A	2	14.966	14.966	7.483	5.32	0.158
B	2	61.430	61.430	30.715	21.83	0.044
C	2	44.723	44.723	22.362	15.90	0.059
D	2	2.181	2.181	1.091	0.78	0.563
E	2	25.120	25.120	12.560	8.93	0.101
F	2	15.756	15.756	7.878	5.60	0.152
A × B	4	7.414	7.414	1.853	1.32	0.475
A × C	4	23.221	23.221	5.805	4.13	0.204
B × C	4	30.639	30.639	7.660	5.44	0.161
Error	2	2.814	2.814	1.407		
Total	26	228.263				

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 by taking an arbitrary set of factor combination A3B2C2E3F1 for PALF-Vinylester composites and A2B3C2E3F2 for Glass-Vinylester composites, however the factor D has been omitted in both PALF and Glass fiber reinforced Vinylester composites as it has the least effect on performance characteristics.

Table 8. Results of the confirmation experiments for erosion rate

Level	Optimal control parameters (For PALF-Vinylester composites)		Optimal control parameters (For Glass-Vinylester composites)	
	Prediction	Experimental	Prediction	Experimental
S/N ratio for Erosion rate (db)	-53.7068	-50.7914	-53.8623	-50.3639

The estimated S/N ratio for the composites with alumina filler, the erosion rate can be calculated with the help of following prediction equations:

$$\bar{\eta}_{PALF-Alumina} = \bar{T} + (\bar{A}_3 - \bar{T}) + (\bar{B}_2 - \bar{T}) + [(\bar{A}_3\bar{B}_2 - \bar{T}) - \bar{T}] \quad (3.1)$$

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

$\bar{\eta}_{PALF-Alumina}$ and $\bar{\eta}_{GF-Alumina}$: Predictive averages for Alumina filled PALF fibers based as well as Glass fiber-based composite correspondingly.

\bar{T} = Overall average of experimented.

$\bar{A}_3, \bar{A}_2, \bar{B}_2, \bar{B}_3, \bar{C}_2, \bar{E}_3, \bar{F}_1$, 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,

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

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

A new combination of factor levels $A_3, A_2, B_2, B_3, C_2, E_3, F_1$, and F_2 is used to predict erosion rate through prediction equation and it is found to be $\bar{\eta}_{PALF-Alumina} = -53.7068$ dB and $\bar{\eta}_{GF-Alumina} = -53.8623$ dB respectively.

For each performance measure, an experiment 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 realistic accuracy. An error of 5.42 % and 6.49 % 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 Eroder 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 alumina filled PALF-Vinylester and Glass-Vinylester composites as a task of impingement angle are revealed and compared in Figure 7. The figure illustrates the peak erosion taking place at an impingement angle of 600 for the unfilled as well as the alumina filled PALF-Vinylester and Glass-Vinylester composites. This evident show that these composites respond to solid particle impact neither in a purely ductile nor in a purely brittle manner. This behaviour can be termed as semi-ductile in nature which may be credited to the incorporation of PALF/Glass fibers and alumina particles within the

Vinylester body. Also, the difference of erosion rate of unfilled and alumina filled composites with erodent temperature is shown in Figure 8. This figure also presents a comparison between the erosion of composites with PALF fiber reinforcement against Glass fiber reinforcement for various erodent temperatures. Erosion test are conducted at seven various temperatures under normal impact condition. It is seen that for all the composite samples, the erosion rates remain unaffected or very slightly affected by the change in erodent temperature from ambient to 400C. The effect of erodent temperature on erosion is considerable above 400C and the rate of increase in erosion rate is larger at high temperatures. It also becomes manifest from this figure that the alumina filled Vinylester composites with PALF fiber reinforcement show enhanced erosion wear resistance as compared to Glass reinforced composites under similar operating environment.

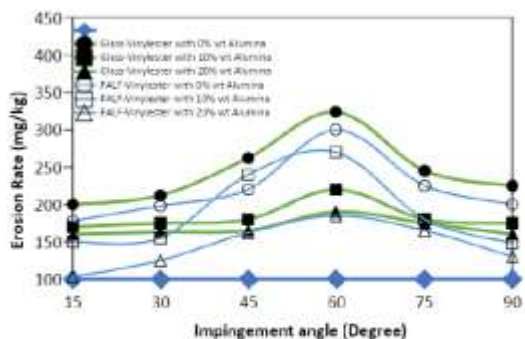


Figure 7. Effect of impingement angle on the erosion wear rate of Alumina filled composites

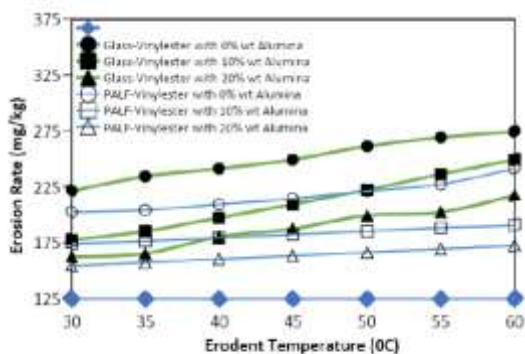


Figure 8. Effect of erodent temperature on the erosion wear rate of Alumina filled composites

F. Discussion on Surface Morphology

The SEM image as seen in Figure.9 a of the un-eroded surface of alumina filled PALF-Vinylester composite illustrate sprinkled alumina particles on the upper surface. Figure.9 b, show the worn-out surface of the composite eroded at 900 reveal mainly the matrix fracture. The eroded surfaces show sign of

plastic deformation in the matrix rule at an impact velocity of 55 m/sec and erodent temperature

of 600C which signify the beginning of surface damage as seen in Figure. 9 c. Also, the most visible leading features as noticed in Figure.9 d are the fracture and cutting of fibers. Many fibers have cracked into small fragments and they are removed from their places fairly with the surrounding matrix like spalled fragments. Consequently, under similar situation as mentioned above there is removal of matrix material from the surface resulting in exposure of broken fibers to erosive environment as seen in Figure.9 e. In this micrograph, the fibers are still held tightly in place by the matrix surrounding them. Frequent impacts progressively cause fiber-matrix de-bonding, brittle fracture of matrix and pulverization of fibers. The fibers are broken by means of shearing action that can be seen from the micrograph due to impingement of particles at high impact velocity as seen in Figure.9 f.

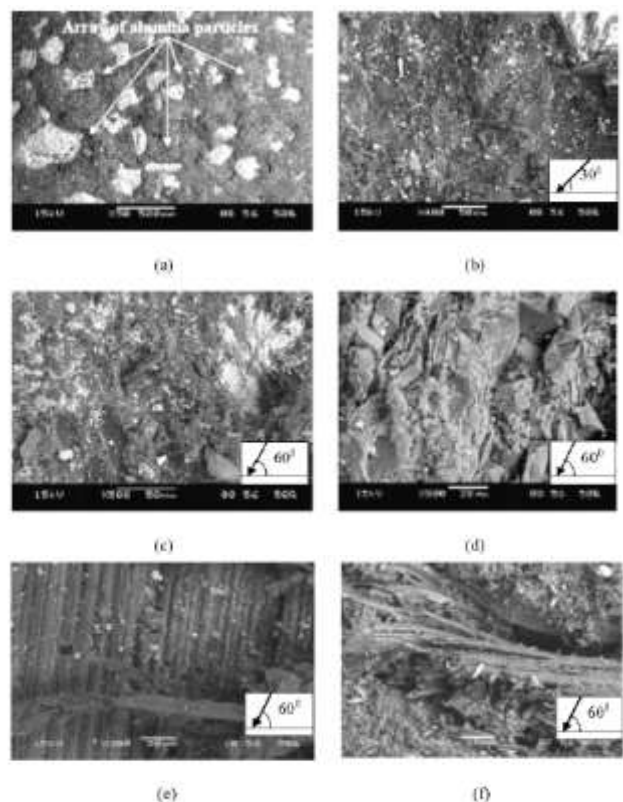


Figure 9. SEM images of eroded surfaces of Alumina filled PALF-Vinylester composites

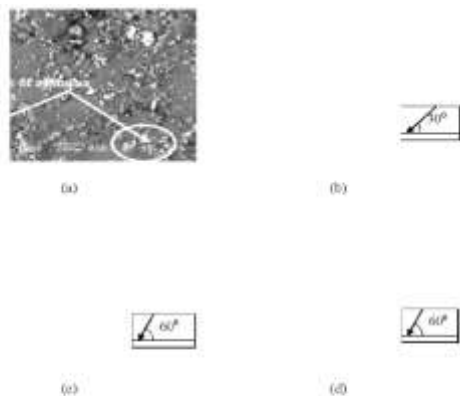


Figure 10. Scanning electron micrograph of Alumina filled Glass-Vinylester matrix composite surfaces eroded at impact velocity 45m/sec, impingement angle 30°, filler content 10wt%, erodent temperature 60°C, erodent size 450 µm and S.O.D 65mm.

Figure.10 a illustrates a portion of the alumina filled Glass-Vinylester composite surface before the erosion has taken place. Small and big clusters of alumina particles are observed on the upper surface of the composite. At impingement angle of 30°, the SEM image of the eroded surface of the composite is seen in Figure.10 b. At this point, the erodent particles are at a high temperature of 600°C impacting the composite surface with a speed of 45 m/s. Because of the smaller normal component of the erodent impact velocity at this low impingement angle, the fibers resist to cracking and as expected not much fiber cracking is seen to have occurred. At high impingement angle of 60° as seen in Figures.10 c and Figure.10 d, though, large craters are noticed in the matrix indicating surface damage due to erosion.

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° impingement angles for the unfilled composites as well as for Alumina filled composites with both PALF as well as glass reinforcement.
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 Alumina as the particulate filler, show lower erosion rates. Further, the filler materials considered in this study, Alumina 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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