MultiCraft

International Journal of Engineering, Science and Technology
Vol. 1, No. 1, 2009, pp. 123-135

INTERNATIONAL JOURNAL OF ENGINEERING, SCIENCE AND TECHNOLOGY

www.ijest-ng.com

Modelling and analysis of abrasive wear performance of composites using Taguchi approach

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Abstract

Short lignocellulosic fibres are extensively used these days as reinforcing materials in many thermoset and thermoplastic matrices due to their low cost, lower density than inorganic fibres, environmentally-friendliness, and the relative ease of obtaining them. Such fibres would not contribute to the wear and tear of polymer processing equipment and may not suffer from size reduction during processing, both of which occur when inorganic fibres or fillers are used. These fibres can also be easily moulded to wide variety of shapes during composite preparation. However, modelling and analysis of behaviour of composites reinforced with short fibre drawn from agricultural resources has been studied to a limited extent. Particularly, the optimum size of short fibre just capable of transferring the load and flexibility during preparation has not been studied through a simple systematic modelling approach due to the complexity involved in its modelling aspect. To this end, an attempt has been made in this work to study the abrasive behaviour of untreated sugarcane fibre reinforced composites in a simplified manner and develop empirical model. The effect of various test parameters and their interactions have been studied using Taguchi method to find out optimal parameter setting for minimum wear (weight loss). It has been observed that fibre length plays a major role in wear phenomenon. The length of the fibre has been optimized using a popular evolutionary technique known as particle swarm optimization (PSO) and neural network. The study recommends that fibre length should be 7-8 *mm* for minimum wear of the composites.

Keywords: sugarcane fibre; abrasive wear; Taguchi method; PSO; neural networks

1. Introduction

Although strength and stiffness reduce considerably with the use of discontinuous (or short-fibre) reinforcements for composite materials in comparison to continuous fibres, there is wide interest in the use of short-fibre. The major advantage obtained with the use of short-fibre reinforced materials is that it can be moulded to a much wider variety of shapes than their continuous-fibre counterparts. Recently, composites based on short-fibers obtained from agricultural resources are being developed. These fibres are usually of lower density than inorganic fibres, environmentally-friendly, and relatively easy to obtain (Satyanarayana *et al,* 1990a; Satyanarayana*. et al*., 1990b). It is likely that the fibres would not contribute to the wear and tear of polymer processing equipment and may not suffer from size reduction during processing, both of which occur when inorganic fibres or fillers are used. Lignocellulosic fibres such as jute, sisal, hemp, coir, and banana have been successfully used as reinforcing materials in many thermoset and thermoplastic matrices to study mechanical, thermal, electrical, and wear characterization (D'any' *et al*., 1996; Mohanty *et al*., 2006; Joseph *et al*., 1996; Joseph *et al*., 2002a; Varma *et al.*, 1989; Pothana *et al*., 2003; Tong *et al*., 1998; Tong *et al*., 2005). In organic fibre reinforced composites, the increase in the absolute property is not expected to be nearly as high as inorganic fibre reinforced composites but the specific properties increases with use of natural fibres due to the much lower density of the organic fibres. In short-fibre reinforced polymer composites, the integrity of the fibre/matrix interface needs to be high for efficient load transfer. Ideally, the molten polymer would spread over and adhere to the fibre; thus creating a strong adhesive bond. Inorganic fibers like glass and cellulosic fibers have hydrophilic surfaces that make them incompatible with hydrophobic polymers. Therefore, inorganic and cellulosic fibers usually require chemical modification to increase fibre/polymer interactions (Brahmakumar *et al.*, 2005; Arzondo *et al.*, 2005; Choudhury, 2005). In composites, overall aged fibre composite shows better mechanical properties than fresh fibre composites. The reason proposed is that mechanical properties of composites not only rely upon the fibre strength alone which is better in fresh fibre but also on the interfacial adhesion between the fibre and the matrix which assists stress transfer (Mukhopadhyay and Srikanta, 2008).

The adhesion between the fibre and matrix is superior with aged fibre due to the fact that the aged fibre has less moisture absorption. Reduced moisture content also resists degradation of fibres resulting in better strength (Pracella *et al.*, 2006). The mechanical properties of fibre reinforced composites strongly depend on several factors such as fibre size, fibre loading, fibre dispersion, fibre orientation and fibre matrix interfacial bond strength (Rana *et al*, 2003; Kumar *et al*., 2005). Despite the interest and environmental appeal of natural fibres, their use has been limited to non-tribological applications due to their lower strength and stiffness as compared to synthetic fibre reinforced polymer composite (Hepworth *et al*., 2000). However, the stiffness and strength shortcomings of bio-composites can be overcome by structural configurations and better arrangement in a sense of placing fibres in specific locations for highest strength performance. Sugarcane fibres are long plant fibres, like hemp, flax, and bamboo that have considerable potential in the manufacture of composite materials (Tong *et al*., 1998; Tong *et al*., 2005; Hepworth *et al*., 2000a;Hepworth *et al*., 2000b; Joseph *et al*., 2002b; Monteiro *et al*., 1998). Bagasse fibre is a by-product of the sugarcane industry. Sugarcane bagasse is the leftover after crushing of the stalk to extract the sugarcane juice from which sugar is obtained by evaporation and crystallization. The bagasse/stalk ratio by mass is around 30%. Bagasse can be used as an animal feed, in paper manufacture, or as fibres to replace asbestos in a cement matrix. In view of this, the potentiality of using sugarcane fibre reinforced polymer composite has been exploited as a promising reinforcement agent for polymer to substitute conventional synthetic glass fibre. Natural fibres need to be chemically treated first to make them more compatible with thermosets and thermoplastics to improve the mechanical properties of the composites. But, untreated sugarcane fibre has a large amount of gummy tissues and debris attached to its surface and this may help in strengthening the interfacial adhesion between fibre and matrix. Nevertheless, for treated sugarcane bagasse, it was reported that the treatments do not produce a complete clean surface of the fibre (Monteiro *et al*., 1998).

In view of this, the present work investigates the effect of using untreated sugarcane fibre on abrasive characteristics of sugarcane reinforced polymer composite. The study on tribology literature suggests that little attempt has been made to understand tribological behaviour of natural fibre reinforced polymers (El-Tayeb and Yousif, 2007; El-Tayeb, 2008a). Only few articles have focussed on the use of sugarcane bagasse to reinforce low cost composites and to reinforce cement composite (Monteiro *et al*., 1998; Aggarwal, 1995; El-Tayeb, 2008b). Furthermore, a series of articles have focused on the study of abrasive wear behaviour of bamboo fibres (Chand and Dwivedi, 2007; Chand *et al*., 2007). It has been reported that relatively soft, non-abrasive nature, ability to deform and bend well under sliding conditions of sugarcane fibre is well suited for tribological applications compared to glass fibre reinforced polymer composites (El-Tayeb, 2008a).

To this end, an attempt has been made in this study to characterise tensile strength, hardness and abrasive wear behaviour of chopped untreated sugarcane fibre reinforced (oriented randomly) composites. The effect of various process parameters and their interaction on abrasive behaviour of the composite has been studied using Taguchi method. Taguchi method being an inexpensive and efficient strategy for analysing complex process like abrasive wear needs less number of experimental runs as compared to traditional method. A predictive equation has been developed for weight loss relating to abrasive process parameters via regression analysis. The equation has been used to denote objective function to determine optimum size of the fibre in Particle Swarm Optimization (PSO). The rationale behind using PSO lies in the fact that it guarantees global solution with less computational effort. It also requires few parameters need to be adjusted in comparison to other soft computing techniques. Since abrasive wear is a complex and extremely nonlinear process which poses difficulty to understand, neural network has been implemented to predict the weight loss in this case. The results are compared to gain insight into the mechanism of wear of the composite.

2. Experimental details

2.1 Specimen preparation

The preparation of the sugarcane fibres begins after crushing the sugarcane stalk and extracting the sucrose. Then, the bagasse fibre was repeatedly washed with water and the sugarcane fibre are separated from undesirable foreign matter and shifted manually from fibre bundles. The average diameter of fibre is 0.268 *mm* having a tensile strength of 0.16-0.19 *GPa*. The linear density of fibre is found to be 0.035 *tex*. Unsaturated polyester resin supplied by Ciba-Geigy Private Limited (India) is used as matrix. The tensile strength of polyester is 0.0753 *GPa* and density of 1.025 g/cm^3. The composite specimens were prepared in a laboratory using hand-lay up and closed mould techniques. A stainless steel mould is used and internal surfaces of the mould are sprayed by a release agent (silicon) before using the mould to facilitate easy removal from mould. The polyester resin is poured on the chopped sugarcane fibre (1 to 10 mm in length) inside the mould and the mix of chopped fibres and polyester is stirred manually for sufficient time to disperse the fibres in the matrix. Care was taken to evenly distribute the fibre material in the mould to ensure a uniform sample since natural fibres have a tendency to clump and tangle together when mixed. The chopped sugarcane fibre reinforced polyester composite sample is cured for a 24*h* at room temperature and then taken out of the mould and post cured in the air for another 24 *h*. Specimens of chopped sugarcane fibre composite are then machined from moulded composite plate measuring 90*mm*×90*mm*×20*mm* into 10*mm*×10*mm*×20*mm* for abrasive wear test. The density of the sugarcane reinforced polyester composite was found to be 1.60 g/cm^3. The weight percent of the fibre in the composite was about 3.52-4.23. The surface roughness (*Ra*) of the test specimen ranges from 4-8 μm when tested using Surtronic 3+ roughness instrument (Taylor-Hobson, Leicester, England) using a diamond stylus with a radius of 5 μm.

2.2 Hardness shore D

The shore scleroscope measures hardness in terms of the elasticity of the material. A diamond-tipped hammer in a graduated glass tube is allowed to fall from a known height on the specimen to be tested, and the hardness number depends on the height to which the hammer rebounds; the harder the material, the higher the rebound. Shore hardness is a measure of the resistance of material to indentation by three spring-loaded indenter. Shore Hardness, using either the Shore *A* or Shore *D* scale, is the preferred method for rubbers/elastomers and is also commonly used for 'softer' plastics such as polyolefins, fluoropolymers, and vinyls. The Shore A scale is used for 'softer' rubbers while the Shore *D* scale is used for 'harder' ones. If the indenter completely penetrates the sample, a reading of 0 is obtained, and if no penetration occurs, a reading of 100 results. The reading is dimensionless. The Shore hardness is measured with an apparatus known as a Durometer and consequently is also known as 'Durometer hardness'. The hardness value is determined by the penetration of the Durometer indenter foot into the sample. Because of the resilience of rubbers and plastics, the hardness reading may change over time - so the indentation time is sometimes reported along with the hardness number. The ASTM test number is ASTM D2240 while the analogous ISO test method is ISO 868.

2.3 Tensile test

The tensile test is generally performed on flat specimens. The commonly used specimens for tensile test are the dog-bone type and the straight side type with end tabs. During the test, a uniaxial load is applied through both the ends of the specimen. The ASTM standard test method for tensile properties of fiber resin composites has the designation D 638 M91. The length of the test section should be 180 *mm*. The tensile test is performed in the universal testing machine (UTM) Instron 1195.

2.4 Abrasive wear test

Two-body abrasive wear tests are performed using pin-on-ring machine shown in Figure 1 (SUGA abrasion tester model-NUS1 Japan). The block specimen of 10*mm*×10*mm*×20*mm* with rubbing surface of 10*mm*×10*mm* is abraded against water proof silicon carbide (SiC) abrasive paper of 400 grit size. The abrasive paper was pasted on a rotating cylinder (stainless steel) of 60*mm* diameter using double-sided adhesive tape. The effects of load, sliding velocity and fibre length for test duration of 180 s are studied. The weight loss in the specimen is determined after each experiment using 0.001*g* balance (Contech Instruments Ltd.). The test was conducted at room temperature (temperature varies from 26^0C to 32^0C having average temperature of 28^0C) and average relative humidity of 82%. The experiments were conducted as per L_{27} OA as discussed later. Each run is conducted at specified factor level settings shown in Table 2 for 180 *s* and weight loss is determined. It has been observed that friction coefficients vary from 0.015 to 0.025 depending on load and velocity used for particular test.

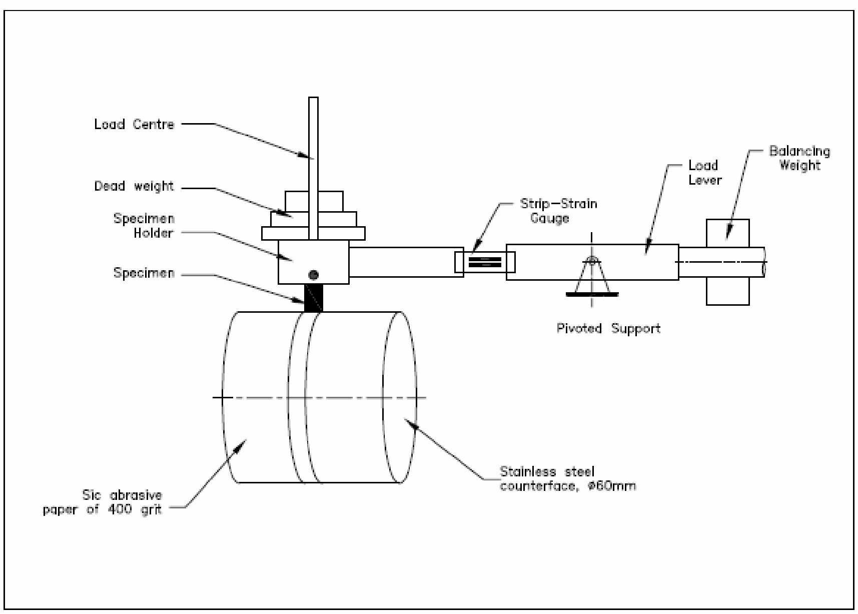

Figure 1. Schematic diagram of abrasive wear tester.

In this study, Taguchi method, a powerful tool for parameter design of the performance characteristics has been used to determine optimal parameters settings for minimization of abrasive wear. Based on Taguchi's Orthogonal Array design, the experimental data needs to be transformed into a signal-to-noise (S/N) ratio for analysis. The characteristic that lower value represents desired response, such as abrasive wear 'lower-the-better', LB is used. The loss function (L) for objective of LB is defined as follows:

$$L_{LB} = \frac{1}{n}\sum_{i=1}^{n} y_w^2 \qquad (1)$$

where y_w represent response abrasive wear and n denotes the number of experiments.

The S/N ratio can be calculated as a logarithmic transformation of the loss function as shown below.

$$\text{S/N ratio for wear} = -10\log_{10}(L_{LB}) \qquad (2)$$

In order to study the effect of various variables (factors) such as applied load, sliding velocity and fibre length and their interactions on abrasive wear, a L_{27} (3^{13}) orthogonal array is chosen. Table 1 indicates the factors to be studied and the corresponding levels of factors. Using linear graph shown in Figure 2, the factors are assigned to columns of the *OA* array. The first column is assigned to load (A), the second column assigned to sliding velocity (B) and fifth column assigned to the fibre length (D). The third and fourth column is assigned to the interaction of load and sliding velocity (AxB), the sixth and seventh column to the interaction of sliding velocity and fibre length (BxD) and the eight and eleven column assigned to the interaction of load and fibre length (AxD). The response (abrasive wear, weight loss in g) is transformed into signal to noise (S/N) ratio using lower is better condition. An analysis of means (ANOM) was performed to establish statistically significant parameters (Glen, 1993).

Table 1. Levels of the variable used in the experiment

	Level			
Control factors	I	II	III	Units
A: Load	10	15	20	*N*
B: Sliding Velocity	15	30	45	*cm/s*
D: Fibre length	1	5	10	*mm*

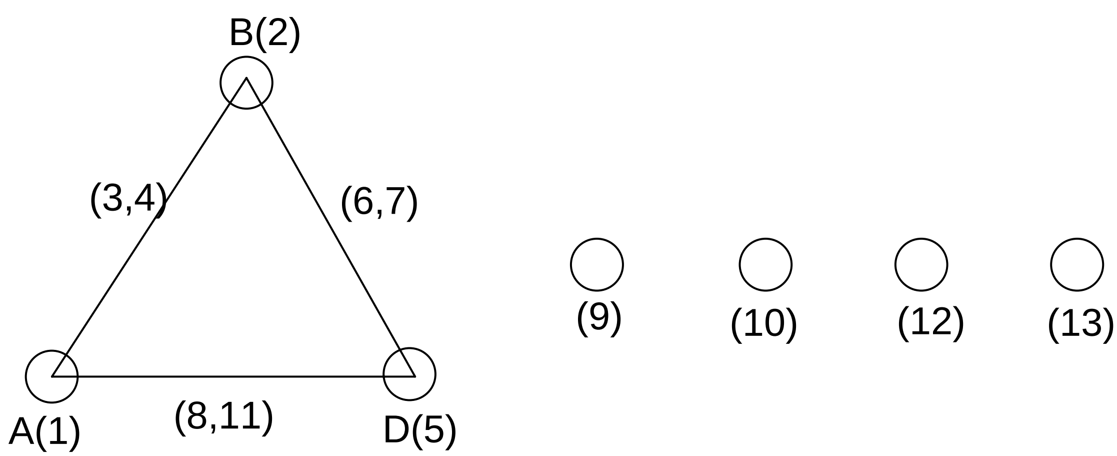

Figure 2. Linear graph for L_{27} orthogonal array

3. Particle swarm optimization

Particle Swarm Optimization (PSO) is one of the latest evolutionary optimization techniques based on the metaphor of the social interaction and communication of bird flocking and fish schooling (Kennedy *et al*., 2001). In PSO, the members of the entire population are maintained through the search procedure so that information is socially shared among individuals to direct the search towards the best position in the search space. PSO has been recognized as an evolutionary computation technique and has features of both genetic algorithms (GA) and evolution strategies (ES). It is similar to a GA in that the system is initialized with a population of random solutions. However, unlike a GA each population individual is also assigned a randomized velocity, in effect, flying them through the solution hyperspace. As is obvious, it is possible to simultaneously search for an optimum solution in multiple dimensions. Compared to GA, the information sharing mechanism in PSO is significantly different. In GAs, chromosomes share information with each other. So the whole population moves like a group toward an optimal area. In PSO, only global best gives out the information to others. It is a one-way information sharing mechanism. The evolution only looks for the best solution. Compared with GA, all the particles tend to converge to the best solution quickly even in the local version in most cases. The advantages of PSO are that PSO is easy to implement and there are few parameters to adjust. However, PSO initially converges fast and then becomes extremely slow. Moreover, there is a tendency of being trapped at local optimum point or premature convergence. In this work, these issues have been resolved using a mutation strategy. Extensive experimental results prove that PSO with mutation outperforms basic PSO and genetic algorithm (GA).

In PSO, each member is called particle, and each particle moves around in the multidimensional search space with a velocity which is constantly updated by the particle's own experience and the experience of the particle's neighbours or the experience of the whole swarm. Application of PSO algorithm requires that parameters be initialized and the initial population generated randomly.

After evaluation, the PSO algorithm repeats the following steps iteratively:

- Each particle with its position, velocity, and fitness value updates its personal best (best value of each individual so far) if an improved fitness value is found.
- The best particle in the whole swarm with its position and fitness value is, on the other hand, used to update the global best (best particle in the whole swarm).
- Then each particle updates its velocity based on the experiences of personal best and the global best in order to update the position of each particle with the velocity currently updated.

After finding the personal best and global best values, velocities and positions of each particle are updated using Equations (3) and (4) respectively.

$$v_{ij}^{t} = v_{ij}^{t-1} + c_1 r_1 (p_{ij}^{t-1} - x_{ij}^{t-1}) + c_2 r_2 (g_j^{t-1} - x_{ij}^{t-1}) \tag{3}$$

$$x_{ij}^{t} = x_{ij}^{t-1} + v_{ij}^{t} \tag{4}$$

where v_{ij}^{t} represents velocity of particle *i* at iteration *t* with respect to j^{th} dimension (j =1,2,……n). p_{ij}^{t} represents the position value of the i^{th} personal best with respect to the j^{th} dimension. x_{ij}^{t} is the position value of the i^{th} particle with respect to j^{th} dimension. c_1 and c_2 are positive acceleration parameters, called cognitive and social parameter, respectively and r_1 and r_2 are uniform random numbers between (0,1). w is known as intertia weight which is updated as $w^t = w^{t-1} \times \alpha$ where α is a decrement factor. The parameter '*w'* controls the impact of the previous velocities on the current velocity. Termination criterion might be a maximum number of iteration or maximum CPU time to terminate the search.

4. Results and discussions

The neat polyester has strength of 0.0753 *GPa* in tension. It is interesting to note that this value drops to 0.053 *GPa* when fibre length is 1 *mm*. As the fibre length increases, the tensile strength of the composite improves to 0.0746 *GPa* for fibre length of 5 *mm* and again this value drops to 0.0645 *GPa* for fibre length of 10 *mm* (Figure 3). The decline in strength may be attributed to weak chemical reaction at the interface between the fibre and the matrix unable to transfer the tensile stress. Chemical surface treatment might result in strong interface bond and tensile strength may improve. It is well known that sugarcane fibre contains a high percentage of lignin (21% on the average) which is considered to prevent a good surface wetabillity between polymer matrix and natural fibres (Monteiro *et al*., 1998). More efficient chemical cleaning to the fibre would increase the bond strength and consequently give different results. Another slightly possible reason could be due to experimental aspect related to the voids and pores which strongly affect the mechanical properties. The hardness of polyester matrix is 85.57. It is evident from Figure 4 that hardness values go on decreasing monotonically as the fibre length increases.

The data on responses viz., weight loss collected for 27 experimental runs as per combination of abrasive wear process parameters. The experimental data on weight loss are converted into S/N ratios using Equation 2. The data are shown in Table 2. Taguchi method is adopted to analyze the effect of various process parameters viz., *A*, *B*, and *D* on weight loss. The analyses are made using the popular software specifically used for design of experiment applications known as MINITAB 14. Figure 5 shows graphically the effect of the three control factors on weight loss.

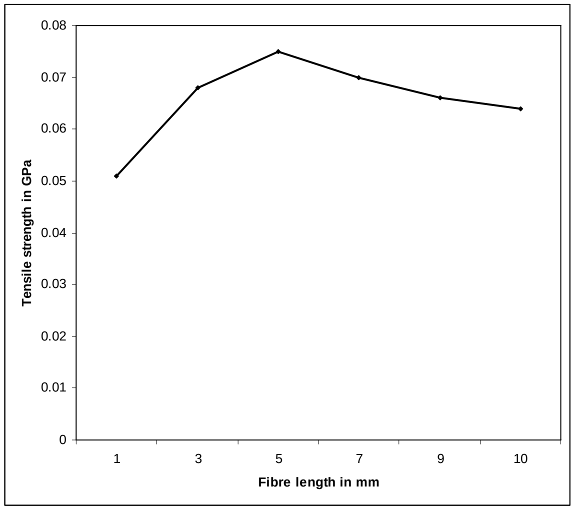

Figure 3. Variation of tensile strength with fibre length

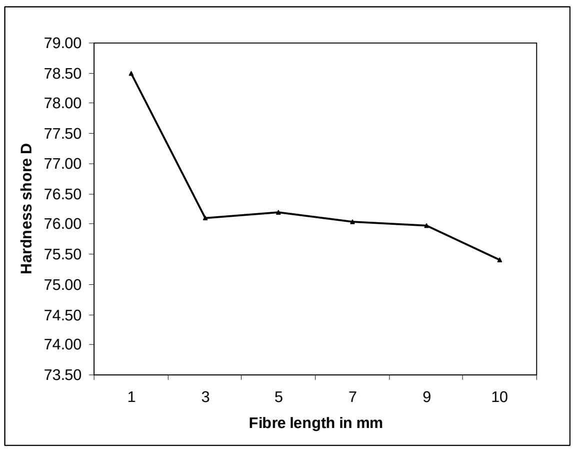

Figure 4. Variation of hardness with fibre length

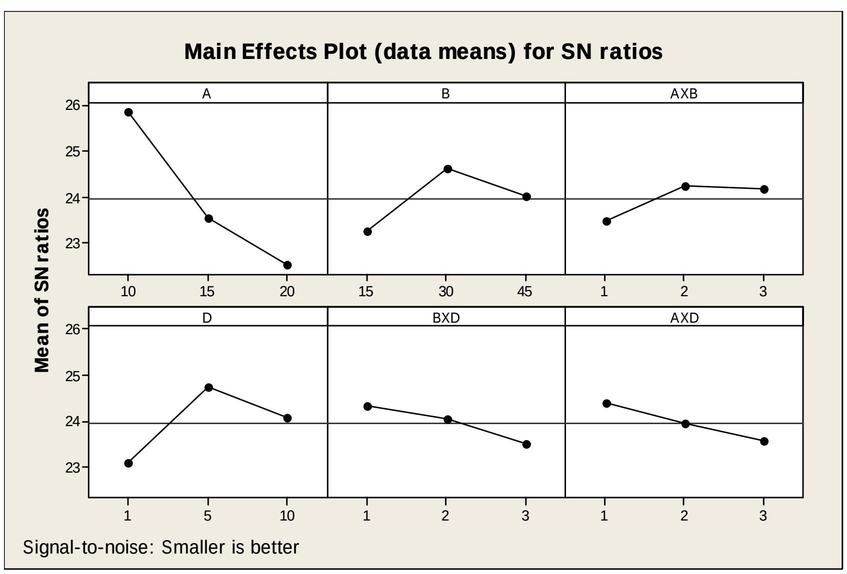

Figure 5. Effect of various factors on weight loss

Table 2. Experimental data

Expt. No.	Factor *A* Load in *N* (Column 1)	Factor *B* Sliding Velocity in *cm/s* (Column 2)	*AXB* (Column 3)	Factor *D* Fibre Length in *mm* (Column 5)	*BXD* (Column 6)	*AXD* (Column 8)	Response Abrasive wear in *g*	S/N Ratio
1	10	15	1	1	1	1	0.090	20.9151
2	10	15	2	5	2	2	0.040	27.9588
3	10	15	3	10	3	3	0.078	22.1581
4	10	30	1	5	3	3	0.057	24.8825
5	10	30	2	10	1	1	0.030	30.4576
6	10	30	3	1	2	2	0.044	27.1309
7	10	45	1	10	2	2	0.072	22.8534
8	10	45	2	1	3	3	0.048	26.3752
9	10	45	3	5	1	1	0.032	29.8970
10	15	15	3	1	2	3	0.096	20.3546
11	15	15	1	5	3	1	0.056	25.0362
12	15	15	2	10	1	2	0.073	22.7335
13	15	30	3	5	1	2	0.070	23.0980
14	15	30	1	10	2	3	0.049	26.1961
15	15	30	2	1	3	1	0.064	23.8764
16	15	45	3	10	3	1	0.082	21.7237
17	15	45	1	1	1	2	0.061	24.2934
18	15	45	2	5	2	3	0.060	24.4370
19	20	15	2	1	3	2	0.092	20.7242
20	20	15	3	5	1	3	0.055	25.1927
21	20	15	1	10	2	1	0.061	24.2934
22	20	30	2	5	2	1	0.098	20.1755
23	20	30	3	10	3	2	0.057	24.8825
24	20	30	1	1	1	3	0.090	20.9151
25	20	45	2	10	1	3	0.084	21.5144
26	20	45	3	1	2	1	0.070	23.0980
27	20	45	1	5	3	2	0.080	21.9382

Figure 5 clearly shows that weight loss is highly sensitive to load (factor *A*). Concrete visualization of impact of various factors and their interactions can be easily made with the help analysis of means as shown in the response table (Table 3). The last row indicates the order of significance of factors and their interactions. It can be observed that the load, factor *A* (Rank 1), fibre length, factor *D* (rank 2) and sliding velocity, factor *B* (rank 3) have great influence on weight loss. Before setting the optimal levels of factors for minimum weight loss, the interaction effects of factors need to be analyzed. As such, the interactions do not have much influence in comparison to factors as evident from the response table. The interaction graphs are shown in Figures 6-8. The interaction between load (factor *A*) and fibre length (factor *D*) ranks highest among all interactions. The interactions *BXD* and *AXB* are ranked next to *AXD* interaction in the order of significance. Analysis of factors and their interactions helps to set the optimal process parameters for minimum weight loss as $A_1B_2D_2$. The factor plots suggest that weight loss increases monotonically as the load (factor *A*) increases. As far as sliding velocity is concerned, the weight loss is more at low level and high level of velocity (15 *cm/s* and 45 *cm/s* respectively) but comparatively less weight loss is observed at medium level of velocity i.e. 30 *cm/s*. Similarly, weight loss first increases at low level of fibre length and then decreases at medium level of fibre length (5 *mm*) and again increases at high level of 10 *mm*.

Table 3. Response table for smaller is better characteristic

Level	*A*	*B*	*AXB*	*D*	*BXD*	*AXD*
1	25.85	23.26	23.48	23.08	24.34	24.39
2	23.53	24.62	24.25	24.74	24.06	23.96
3	22.53	24.01	24.17	24.09	23.51	23.56
Delta	3.32	1.36	0.77	1.66	0.82	0.83
Rank	1	3	6	2	5	4

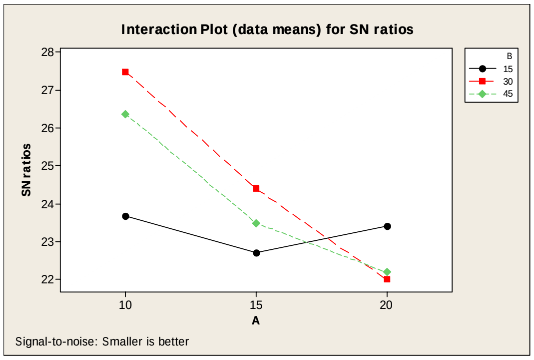

Figure 6. Interaction plot of *AXB*

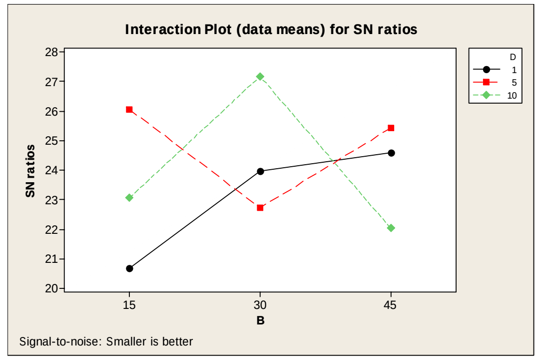

Figure 7. Interaction plot of *BXD*

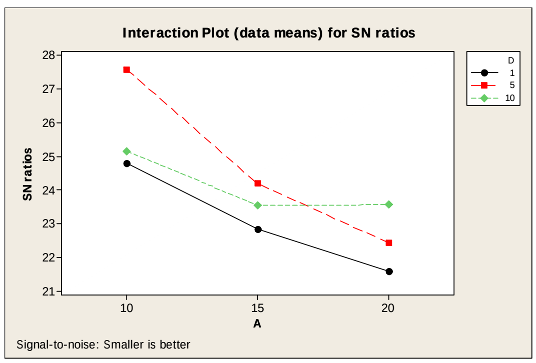

Figure 8. Interaction plot of *AXD*

After analyzing the factor and interaction effects and setting optimal process parameter levels, it is customary to develop a linear predictive equation for confirmation and verification tests. Therefore, the predictive equation for optimal factor settings, $A_1B_2D_2$ can be represented as follows:

$$\hat{\eta} = \overline{T} + (\overline{A}_1 - \overline{T}) + (\overline{B}_2 - \overline{T}) + [(\overline{A_1}\,\overline{B_2} - \overline{T}) - (\overline{A}_1 - \overline{T}) - (\overline{B}_2 - \overline{T})] + (\overline{D}_2 - \overline{T}) + [(\overline{A_1}\,\overline{D_2} - \overline{T}) - (\overline{A}_1 - \overline{T}) - (\overline{D}_2 - \overline{T})] + [(\overline{B_2}\,\overline{D_2} - \overline{T}) - (\overline{B}_2 - \overline{T}) - (\overline{D}_2 - \overline{T})] \quad (5)$$

$\hat{\eta}$ Predicted response

$\overline{T}$ Overall experimental mean

$\overline{A}_1, \overline{B}_2, \overline{A_1}\,\overline{B_2}, \overline{D}_2, \overline{A_1}\,\overline{D_2}, \overline{B_2}\,\overline{D_2}$ Mean values of factors and interactions at designated level

Similar equations can be developed for different levels of factor combination and prediction of weight loss can be made. Such a prediction is known as Taguchi prediction.

The predicted S/N Ratio for factor setting $A_3B_3D_2$ is found to be 21.4451 and the experimental result with this setting is 21.9382. Since the error between the predicted and experimental result is less than 1%, it is confirmed that Taguchi optimal setting is good enough to be used for setting parameters for minimum weight loss. In order to predict the weight loss correctly, artificial neural network (ANN) model based on back propagation algorithm has been implemented. The network architecture has three neurons at the input layer to feed the normalized data of process parameters such as load, sliding velocity and fibre length. The output layer contains only one node to predict the normalized weight loss. The number of neurons at the hidden layer, the momentum and learning parameters are varied until the network converges to minimum root mean square (RMS) error. Out of 27 experimental data, fifteen are used for training and twelve are tested. The momentum and learning parameters are set at 0.20 and 0.30 respectively. Number of neurons at the hidden layer is 4. The number of epochs needed for training is 25805 when root mean square (RMS) error is 0.01. The popular neural network software Neunet Pro 2.3 is used for neural network implementation. The neural network prediction is shown in Figure 9. It is evident that the maximum error between experimental data and neural network prediction is around 0.7%. Therefore, it can be concluded that neural network prediction has proceeded in correct manner.

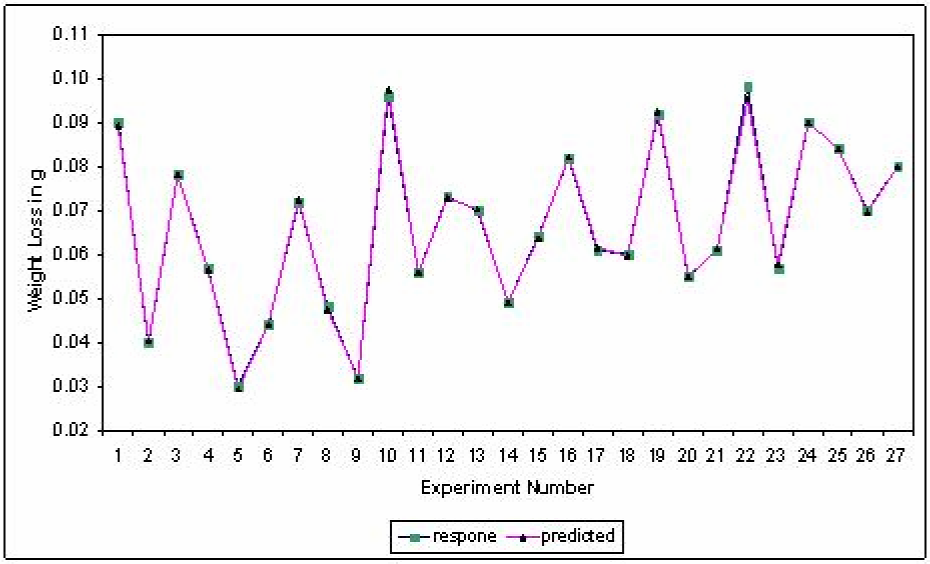

Figure 9. Neural network prediction of experimental data

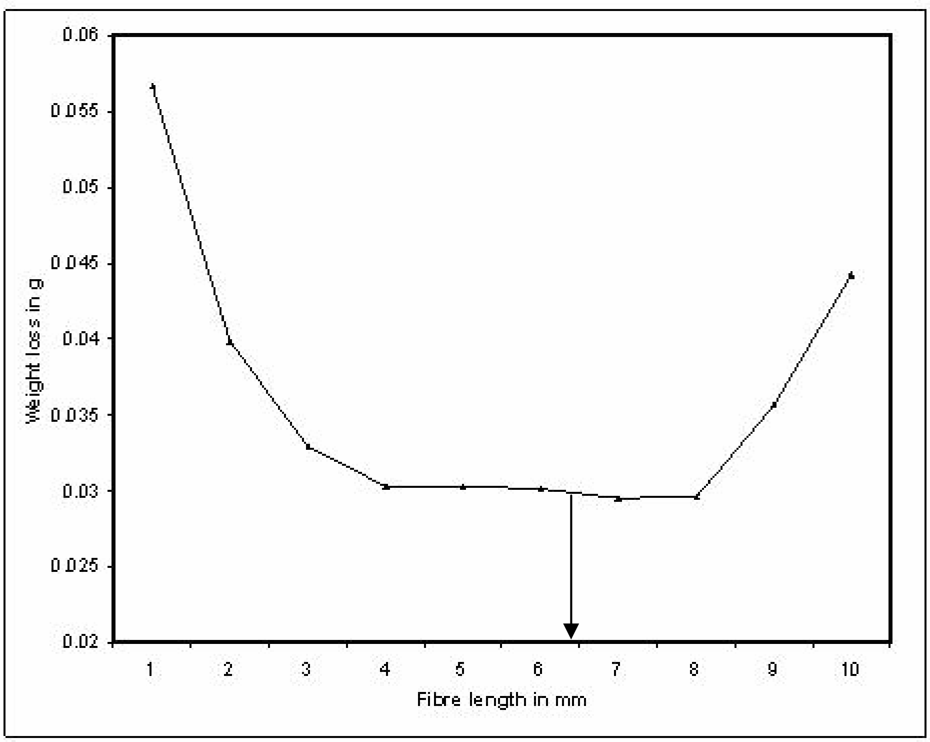

Figure 10. Estimation of optimal fibre length via neural network

The trained neural network is used to predict the optimal fibre length for minimum weight loss in abrasive wear. It has been demonstrated that weight loss depends on the factors viz., the load, fibre length, and sliding velocity in the order of importance. Among them, sliding velocity has least influence on weight loss. The factors such as load and sliding velocity are to be maintained at low and medium level i.e 10 *N* and 30 *cm/s* respectively. Therefore, neural network is tested with varying fibre length from 1 *mm* to 10 *mm* keeping the setting for load and sliding velocity at 10 N and 30 cm/s respectively. The predicted weight loss as the fibre length varies from 1 *mm* to 10 *mm* is shown in Figure 10. It is found that the fibre length must be maintained at 8 *mm* to obtain minimum weight loss in abrasion test.

A more rigorous optimization technique based on PSO is used to find out the optimal fibre length in abrasive wear. The experimental data is used to develop an equation relating to weight loss with process parameters such as load, sliding velocity and fibre length. Non-linear regression equation is developed using software known as Systat 7.0 as shown in Equation 6. The coefficient of determination (r^2) is found to be 0.994. The rationale behind using PSO to determine optimal fibre length lies on the fact that it is one of the popular soft-computing techniques that generate optimal values with less computational efforts and controlling few parameters.

$$\ln y = \ln 0.024 + 0.559 \ln A - 0.095 \ln B - 0.149 \ln D \quad (6)$$

where y is the response and A, B and D represents three process parameters.

The parameters of PSO are set as recommended by Kennedy *et al*. (2001). Both the cognitive (c_1) and social parameter (c_2) parameters are set at 2.0. Inertia weight (w) and decrement factor (α) are taken 0.8 and 0.9 respectively. The algorithm is coded in Turbo C^{++} and run on Pentium IV desktop PC. The program was run 50 iterations and the results are noted down. The mathematical formulation of the optimization problem is given as:

Maximize

$$Z = -f(x)$$

subjected to constraints:

$$A_{\min} \leq A \leq A_{\max} \quad (7)$$

$$B_{\min} \leq B \leq B_{\max} \quad (8)$$

$$D_{\min} \leq D \leq D_{\max} \quad (9)$$

Z represents objective function value evaluated using Equation (14). The min and max in Equations 7-9 shows the lowest and highest control factor settings used in this study (Table 1).

The optimal parameter settings are found to be load (A) equals 10.023 *N*, sliding velocity at 29.300 *cm/s* and fibre length 7.004 *mm*. It is to be noted that there is slight discrepancy in the order of 1 mm on optimum fibre length resulting from ANN prediction and PSO results. Therefore, it is suggested that optimum fibre length varies from 7 to 8 mm beyond which the wear performance of composites degrades. The convergence curve is shown in Figure 11.

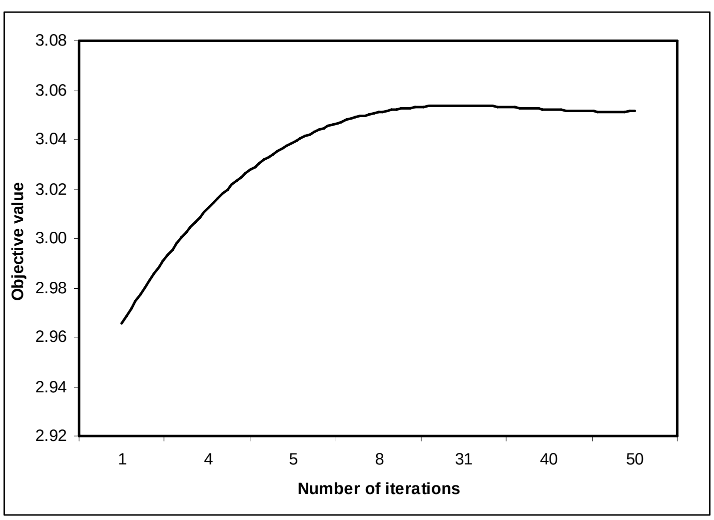

Figure 11. The convergence curve

4 Conclusions

Abrasive wear performance and mechanical property characterization of sugarcane fibre reinforced composites were determined experimentally and the following conclusions were drawn:

- Composites using chopped sugarcane fibre as reinforcement in polyester resin matrix have been successfully developed.

- Results of composites under consideration revealed that abrasive wear (weight loss) increases with increasing load because high temperature is generated at higher load causing degradation of the composite surface. The factor, sliding velocity, does not have significant contribution on weight loss. However, the size of the chopped sugarcane fibre plays an important role on surface damage by abrasive wear.
- Minimum resistance to wear is observed at lowest size of the fibre i.e 1mm. Again, at highest length of fibre i.e 10 *mm*, the wear (weight loss) increases. The minimum wear is observed at fibre length of 5 *mm*. The reasons for such behaviour may be explained as that the fibres do not get support from the matrix at lower length because of poor interface adhesion. Therefore, the fibre has been pulled out easily from the matrix by the rubbing surface. As the fibre length becomes too large, anisotropy of the composite might increase due to random orientation of the fibre causing increase in weight loss. If the long fibre would have been used, the composite might have been behaved differently. In this study, untreated fibre has been used but chemical treatment of the fibre may give rise to different result.
- Taguchi's experimental design is a simple and systematic way of analyzing a complex process with less experimental runs. The optimum abrasive process parameters as suggested by Taguchi analysis is estimated as $A_1B_2D_2$.
- Although fibre length of 5*mm* gives rise to minimum weight loss, it may not be a global optimum point because Taguchi method tests only few discrete points in the landscape of optimal surface. Therefore, a global optimum strategy known as particle swarm optimization (PSO), a search procedure, has been implemented after developing a predictive equation relating weight loss with the process parameters using non-linear regression method. The validity of the equation is tested using coefficient of determination. The optimal parameter settings as found by PSO are given as: load equals 10.023 *N*, sliding velocity at 29.300 *cm/s* and fibre length 7.004 *mm*.
- A neural network has been implemented to predict the correct optimum fibre size and it is found to be 8 *mm*. The discrepancy between the results of PSO and neural network may be attributed to difference in principle of prediction method by two techniques rather than implementation aspects. Therefore, it is suggested that best size of fibre length for minimum abrasive wear should be 7 to 8 *mm*.
- The hardness of the composite monotonically decreases as the fibre length increases but tensile strength first increases and then decreases as length of the fibre is increased. In contrary to common belief that hardness and tensile strength improve wear resistance, it has been observed that parameters encountered in wear process strongly influence wear resistance.
- In future, the study can be extended to other natural fibres to find out the optimum fibre length. The abrasive wear behaviour of chemically treated sugarcane fibre and aging effects of the fibre on abrasive behaviour of the composite can be studied.

Notations

L_{LB}	Loss function for 'lower-the-better' quality characteristic
y_w	Abrasive wear response
n	Number of experiments
A	Load in N
B	Sliding velocity in cm/s
D	Fibre length in mm
v_{ij}^t	Velocity of particle i at iteration t with respect to jth dimension
p_{ij}^t	Personal best position value of the ith particle with respect to the jth dimension
x_{ij}^t	Position value of the ith particle with respect to jth dimension at iteration t
g_j^t	Global best position value of the swarm with respect to jth dimension at iteration t
c_1	Cognitive parameter
c_2	Social parameter
r_1 and r_2	Uniform random numbers between (0,1)
w	Intertia weight
α	Decrement factor
$\hat{\eta}$	Predicted response
$\overline{T}$	Overall experimental mean
$\overline{A}_1, \overline{B}_2, \overline{A_1B_2}, \overline{D}_2, \overline{A_1D_2}, \overline{B_2D_2}$	Mean values of factors and interactions at designated level
Z	Objective function value

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Received September 2009
Accepted November 2009
Final acceptance in revised form November 2009