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Thermo-mechanical and Wear Properties of Natural Fiber-reinforced Epoxy Composites for Structural Applications.

KEYWORDS

Natural fiber;
Mechanical;
DMA analysis;
Taguchi analysis.

ABSTRACT

Grewia Optiva fiber-based polymer composites were prepared with the addition of Marble dust (MD) in varying percentages by hand-layup technique. To understand the behavior of the material, a detailed physical, mechanical, and thermo-mechanical analysis of the samples was conducted. The findings reveal that the addition of MD to 10 wt. % helps in enhancing the interfacial bonding between the fiber and epoxy. Due to the high void fraction and poor surface interaction, further addition of MD restricts beneficial changes in the composite. The thermo-mechanical analysis (DMA) illustrates that adding marble dust powder results in a decrease in chain mobility, hence enhancing the storage modulus of all samples. Due to its maximum elastic and low viscous regions, the GM-2 (MD 10 wt. %) specimen exhibits the lowest level of energy dissipation. The research also focuses on the sliding wear behavior of the material, and a Taguchi design approach is also used for parametric analysis of wear response. In conclusion, the Grewia Optiva fiber polymer composite with (GM-2) 10 wt.% marble dust shows the best mechanical, thermo-mechanical, and sliding wear results due to its superior interfacial bonding and can be found suitable for fabrication of portable cabins.

1. Introduction

The growing global environmental issues and new environmental regulations legislation have prompted the hunt for new composites that are environmentally friendly [1]. Bio-based composites are promising materials for future automotive industry applications. The market potential for **biocomposite**s may, however, increase with appropriate development [2]. The performance of composite materials usually depends on their mechanical properties such as tensile strength, flexural strength, hardness, etc. Still, apart from this, cost-effectiveness and environmental concern are also the most important criteria. In this regard, many research works were inclined towards natural fiber/ industrial waste-reinforced composites [3,4]. The development of natural fiber composites has led to a substantial drop in material costs and opened up a wide range of applications in automotive fields [5]. Commonly used plant fibers are jute, bamboo, Grewia optiva ramie, banana, kenaf, hemp, coconut, flax, etc.[6] Among these natural fibers, one of the natural fibers is Grewia Optiva, which is found in the Himalayan region and locally known as Bhimal. Due to its remarkable mechanical properties, this fiber is popular among researchers. Grewia optiva is a bast fiber that contains 58-75% of cellulose [7, 8,9]. As per the increasing demand for green movement, studies in the field of Grewia Optiva are gaining interest. The tensile strength of 0.03 mm diameter Grewia Optiva was measured by Verma et al.[10]. The tensile strength and elongation results obtained were 15.35 MPa and 10.28. But, the study of Bhanu et al.[11] reported a very low value (1.8 MPa) of tensile strength. The value obtained in this research did not mention the diameter taken for the study. Upreti et al. investigated the mechanical properties of fiber-reinforced polymer composites made from Grewia optiva fibers. [12]. The study reveals that mechanical properties were found to be maximum at 5wt.%. Gupta et al. [13] studied the effects of different fibers on mechanical properties of composites. In their study, they used Grewia Optiva, flax, and Palmyra-reinforced composites. The results obtained were proportionally better for Grewia Optiva in comparison to others. Being a porous fiber material, it possesses good sound absorption characteristics as well [14]. Kumar et al.[5] selected two fibers namely G. Optiva fiber and Bauhinia vahlii fiber to fabricate hybrid polymer composites. The results revealed that 6 wt.% G. optiva gives the best mechanical properties. A.K. Rana et al.[15] concluded that based on mechanical properties, Grewia optiva

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fiber can be a potential natural fiber in comparison to other natural fibers, which can stir the composite material market in a revolutionary manner. However, the properties obtained from natural fiber composites are inferior to those obtained from synthetic fibers due to their high moisture absorption capability. Furthermore, there is always room for improvement in terms of physical, mechanical, tribological, and water absorption properties. As a result, natural fiber composites will be able to find their suitability for practical applications such as portacabins. These constraints can be reduced to some extent by the use of the hybridization method. Basappa Hulugappa et al.[16] added graphite and SiC filler in woven glass **fiber** reinforced epoxy to check their influence on mechanical properties. The tensile, flexural, and fracture toughness of the manufactured composites substantially improve with the addition of fillers. In the way of development, the rapid exploitation of natural resources and ineffective waste management are leading to adverse environmental and social consequences. Due to this, the human race is moving towards sustainable technology, waste management, and industrial waste disposal [17, 18]. Sanjay Mavinkere Rangappa et al. [19] utilized one of the unattended wastes, chicken feather, and Ceiba Pentandra bark **fiber** as a reinforcement in the Biopoxy matrix. The study reveals that thermal and mechanical properties were improved by their addition. Another type of unattended waste is Marble dust, which is separated from the processing and polishing of marble. Major constituents found in marble dust are CaO, Fe_2O_3, Al_2O_3, SiO_2, etc. This sediment dust is neither suitable for human health nor agricultural land. Utilization of such filler in the fabrication of composite materials not only helps in reducing the cost but also improves mechanical and thermomechanical characteristics of composite. Glass fiber-epoxy composites with a 20 wt. % marble dust waste shows good mechanical characteristics. However, it was found that the addition of marble content above it deteriorates the mechanical properties. The results show that the addition of 15 wt.% marble dust in 7.5 wt.% bagasse fiber improves the physico-mechanical behavior of fabricated samples. Apart from these properties, the addition of marble dust improves wear and thermal characteristics as well [20]. The impact of marble dust on basalt fiber-reinforced polymer composite was examined for mechanical and tribological behavior by Abhinay Singh Rajawat et al. [21]. Marble dust was varied up to 10 wt.% (0, 2.5, 5, 7.5, and 10 wt. %.) and Basalt fiber was put constant at 20 wt.%. The research reveals that favorable mechanical properties were achievable up to 7.5 wt% Marble dust only. The DMA analysis is useful for finding the viscoelastic behavior of polymeric materials. The material undergoes sinusoidal mechanical stress, and the sample strain is measured. DMA enables the identification of thermal effects from diverse modulus variations. From the DMA analysis, one can determine the glass transition (Tg), cross-linking density, and dynamic fragility of the composites. The natural fiber is composed of lignin, hemicellulose, cellulose, and pectin, and has microstructure defects as compared to synthetic fibers [9]. Therefore, thermomechanical properties like DMA, TGA, etc, of natural fiber/filler-based hybrid polymer composites need to be explored more. The current work centers around the conceivable utilization of marble dust particles with the natural Grewia Optiva fiber-reinforced epoxy-based hybrid composites. The exploitation of natural fiber and industrial waste into the polymeric matrices can assist in improving various properties of the fabricated composites, while the cost of the material can be reduced as well. Some of the studies are reported on the sliding wear behavior of natural fiber composites. S. S. Vinay et al. [22] in their research added Al_2O_3 nanoparticles in the basalt epoxy matrix and found that the addition of nanoparticles significantly drops wear loss. An investigation by Kumar et al. [9] found that optimum wear properties were obtained when B. vahlii and sisal were added to epoxy at 4 wt. %. Tej Singh et al. [23] studied silica nanoparticle incorporated hybrid natural fiber composite. Researchers used an L16 orthogonal array in their study to determine which control factor resulted in greater wear resistance. The study reported that silica nanoparticles had the greatest influence on wear resistance. From the past literature it is found that no work has been reported yet on G. optiva fiber/ MD reinforced polymer composite. Thus, the objective of the study is to create an innovative, low-cost composite material and to investigate its mechanical and tribological behavior in order to harness natural resources and recyclable waste materials for structural uses such as portacabin creation.

2. Materials and Method

2.1. Materials

For the fabrication of composite material, the ingredients used were epoxy (LY 556), hardener (HY 951), Grewia Optiva fiber, Marble Dust, and NaOH for treatment. Epoxy, hardener, and NaOH were purchased from Geetanjali Enterprises in Roorkee, India. While, Grewia optiva fiber was purchased from the local weavers in Srinagar Garhwal, and Marble dust was obtained from Rajasthan, India. The mats were treated in 5 wt.% NaOH and water solution for sufficient time and afterward washed properly. These fibers were cured in an oven for 24 hours at 60°C and then placed in sunlight for a week. The fibers after treatment were weaved bi-directionally.

2.2. Composite Processing

Marble dust-filled and Grewia Optiva fiber-reinforced hybrid composite is fabricated by hand lay-up technique. Hand lay-up is a versatile and cost-effective method for manufacturing polymer composites. It offers flexibility in complex shapes and designs, requires a minimal initial investment in specialized equipment, and is suitable for small-batch production. It allows for adjustable fiber orientation, making it suitable for thick sections and complex geometries. Hand lay-up also allows for skill-based quality control, resulting in higher-quality parts with fewer defects. It is more cost-effective for small to medium production runs than automated processes and allows for easy material integration. Hand lay-up is also environmentally friendly, generating less waste and energy compared to automated processes. Despite its limitations, hand lay-up remains a valuable technique in polymer composite production.

Here, epoxy resin was used as a polymer matrix, and a mold made of wood of size 300mm×300mm×25mm was used in the fabrication process. The mold was pre-treated with mold-releasing spray to assist easy removal of fabricated composite from mold. A mixture of epoxy and hardener in 10:1 with the required amount of marble dust was prepared in a pot and stirred to get a homogeneous paste. This mixture was placed as a layer on the mold surface, afterwards, a 2-D mat of Grewia optiva was placed, followed by another layer of mixed paste. These layers were stacked properly as alternate layers up to a certain limit. In order to reduce the porosity mold was then cured iso-statically under a load of 15 kg for 24 hours [24].

High-pressure hardened materials show reduced porosity and lower levels of inter-laminar matrix. After a curing time of 24 hrs, samples were taken out from the mold and then left for the 3cut into desired shapes based on ASTM standards for characterization. A schematic diagram and designation of the fabricated samples are shown in Figure 1 and Table 1 respectively.

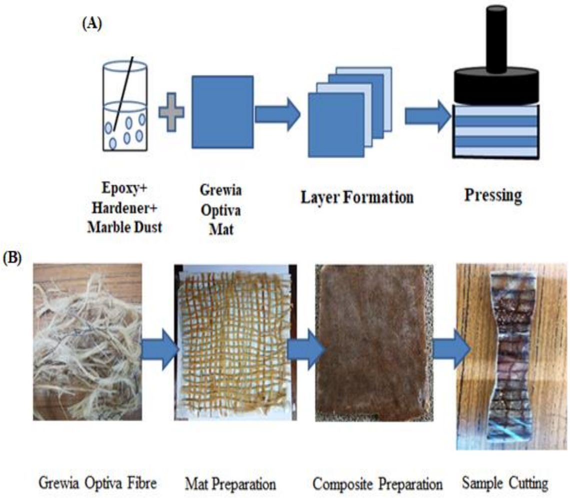

Fig 1 (A)Schematic diagram for composite fabrication (B) Sample Preparation

Table 1 Designation and Composition of Samples

S.N	Designation	Epoxy (wt. %)	Grewia Optiva (wt. %)	Marble Dust (wt. %)
1	GM-0	80	20	0
2	GM-1	75	20	5
3	GM-2	70	20	10
4	GM-3	65	20	15

2.3. Characterization

2.3.1. Physical Characterization

The samples were characterized physically on the basis of their density and porosity (void) content. Archimedes's principle was used for finding the density of neat specimens and ASTM D2734 was used for finding the void content.

2.3.2. Tensile and Flexural Test

Both tests on the specimens were conducted using the Heico universal testing machine HL590. For the study of specimens, cross-head speed was fixed at 5mm/min and the standards used were ASTM D3039 M and ASTM D790 [25] for tensile and flexural tests respectively.

2.3.3. Interlaminar Shear (ILSS)

The test was conducted in UTM (EMIC DI-3000) following ASTM D2344-06[25]. Thin samples of 30x10x2 mm^3 were cut for performing the test.

2.3.4. Hardness Test

Rockwell hardness test was conducted on the specimens based on ASTM E18[26] standard. The tests were conducted under a low load of 1 kg and a 15-second dwell time.

2.3.5. Impact Test

The impact tests were conducted on an AIT 300 D digital machine based on the ASTM: D256-10 [27] standard. For accuracy of results, the test was repeated 3 times on each composition.

2.3.6. DMA

The test was performed on 3-point bending deformation mode using DMA Q800 Dynamic Mechanical Analyzer. The dimension of the specimens was taken as 15mmx8mmx5mm.

2.3.7. Experimental design

The sliding wear behavior of the fabricated samples was identified through a pin-on-disc apparatus using ASTM G99 [28] standard. The specimens were cut 30x7 mm^2 and rotated over a steel disc. The value of the specific wear rate (SWR) was calculated by the given formula

$$SWR = \frac{(Mass_i - mass_f)}{\rho l f_n}$$

The mass is calculated in grams (*i*- initial and *f*-final), ρ represents density (gm/cm^3), l represents sliding distance (m), and f_n in the equation represents normal load in Newton.

The purpose of the experimental design is to use the Taguchi approach to identify the most important factors that will enable the fabricated composites to achieve the maximum increment of wear resistance and to achieve superior conditions in a minimum number of test runs. In the present research, the selected parameters and their levels are as follows; sliding velocity (2, 3, 4, 5 m/s); type of composites (GM-0, GM-1, GM-2, and GM-3); and normal load (20, 25, 30 and 35N). The L_{16} (orthogonal array) based on the Taguchi method has been used to evaluate the best combination of control parameters for minimal wear rate as depicted in Table 2. Further, the output response (SWR) is converted into S (signal) to N (noise) ratio. There are three types of S/N ratios namely smaller-is-better, larger-is-better, and nominal-is-better, respectively. In the present study, as the focus is on the sliding wear rate of composites, hence the smaller-is-better characteristic is taken and computed with the help of following Equation 2.

S/N ratio = $-10\times\log 1/k\,(\sum\beta^2)$ (2)

Where, S/N is used for the signal-to-noise ratio, k for a number of observations, and β for observed data.

Additionally, the Taguchi approach performs an ANOVA to determine the impact of every chosen input parameter and to compute each input variable's contribution to a certain wear rate of manufactured composites.

Table 2 Control parameters and levels used in measurement

Control parameters	Levels			
	I	II	III	IV
Sliding velocity (m/s)	2	3	4	5
Type of composite	GM-0	GM-1	GM-2	GM-3
Normal load (N)	20	25	30	35

3. Result and discussion:

3.1. Physico-Mechanical Properties

The physico-mechanical properties of all the samples are depicted in Table 3. The density of the sample and void fraction increases with an increase in the percentage of MD. The possible reason behind the void content is the increase in the viscosity of homogeneous paste. Due to an increase in viscosity, the flowability of paste reduces, hence some of the remote portions remain unfilled. Some other reasons might be the fiber–matrix interaction, the existence of lumens in natural fiber [5], and the clustering of fibers [29].

3.2. Tensile Strength

The value of tensile strength varies from 55.01 to 68.19 MPa. The results are found in increasing patterns up to 10 wt. % MD addition; nevertheless, the addition of MD above this percentage does not yield positive outcomes. Even though the void fraction increases with the percentage of MD, the tensile strength remained within good agreement up to 10 weight percent. The tensile strength of the GM-2 sample is found to be 23% higher than the composite without MD. The possible reason may be due to enhanced stress transfer behavior and robust surface bonding between the fiber and matrix [30, 31].

Generally, the fibrous structure is responsible for the formation of bigger grains and accumulation during composite preparation; however in the study addition of MD above a a certain percentage is causing adverse effects on porosity and improper surface interaction [32, 33].

3.3. Flexural Strength

Flexural strength represented in Figure 3 shows the same trend as observed for tensile strength. The flexural strength is found maximum for GM-2. The Flexural strength of the MD-loaded Grewia Optiva fiber composites depicted a gradual increase of up to 10 wt.%. Strong interfacial bonding between fibers and epoxy and transferring force effect improves the flexural strength of the samples, which in turn improves load transfer [34]. Moreover, an increase in the percentage of more than 10 wt.% of MD negatively impacts the flexural characteristics of the material. Previous studies suggest that the aggregation of particles on the surface of the fiber degrades the flexural property by increasing the stress concentration [25,30].

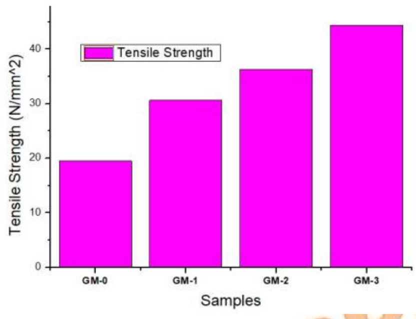

Fig. 2 Tensile strength of samples

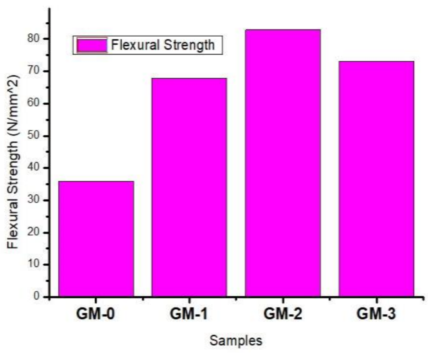

Fig. 3 Flexural Strength of samples

3.4. Inter Laminar Shear Strength (ILSS)

The study of Interlaminar Shear Strength focuses on pure interlaminar shear failure in order to derive interlaminar shear strength values [35,36]. The interlaminar shear strength of the sample increases up to 10 wt.% MD, and then decreases for GM-3 (Figure 4). The value of the void fraction is maximum for GM-3, which seems to be a possible reason behind the declining strength. The interlaminar shear strength of fiber matrix composites depends more on the matrix strength and interfacial bonds than on the fiber properties [37]. Moreover, other studies have found that along with the mentioned properties, fiber orientation, fiber volume proportion, and void content can also impact the ILSS [38].

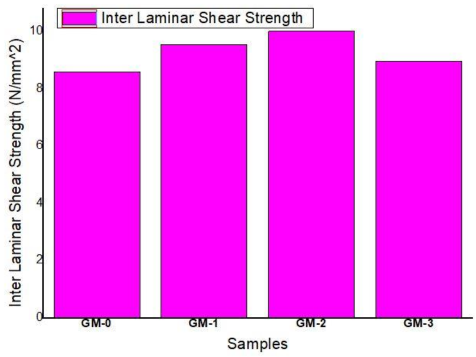

Fig. 4 ILSS of samples

3.5. Hardness

The Hardness of the samples increases with the increase in the percentage of MD as shown in Figure 5. A significant increase in hardness is observed up to 10 wt.% MD, but the value of hardness for the GM-3 sample is almost the same as GM-2. So after 10 wt. % MD addition, the effect of hybridization seems to be negligible.

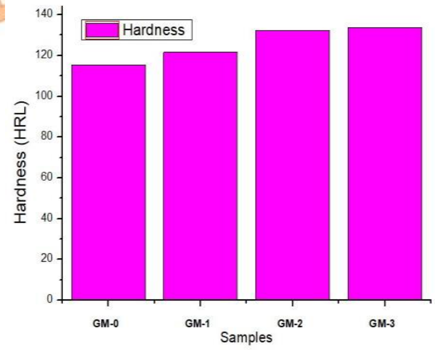

Fig. 5 Hardness of Samples

3.6. Impact Strength

The impact energy of the composites becomes better with the increase in MD percentage (Figure 6). The addition of MD increases the resistance and varies from 2.2 J to 3.4 J. Impact resistance refers to a material's ability to resist breaking (fracture) under a shock load and impact energy measures toughness. The toughness of polymeric materials depends on the properties of the fiber, the matrix material, and the interfacial adhesion [39-40]. Since the fiber loading is fixed and MD is being varied in the experiment, the crucial aspect for improvement might be the interfacial bonding, which is improving with the addition of MD. Due to greater adhesion, MD in the matrix offers resistance to crack propagation during impact and hence raises impact energy.

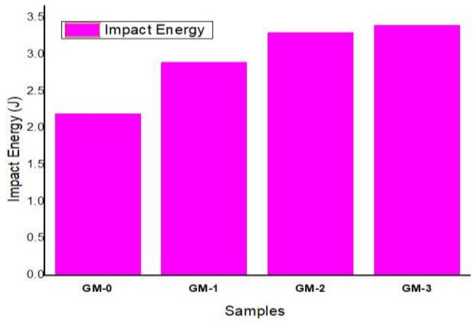

Fig. 6 Impact Energy of Samples in Joule.

3.7. DMA

The prepared samples underwent a DMA examination to determine the stiffness and damping values, which were expressed as modulus and tan delta, respectively. Figure (7, 8,9) shows storage modulus, loss modulus, and tan delta curves. Storage modulus is used to measure elastic behavior, Loss modulus gives the viscous responses, and tan delta represents energy dissipation of material under cyclic load [41]. It was observed that GM-3 shows the maximum storage modulus among the others. With the increase in percentage of Marble dust the value of stiffness increases. This shows the impetus of the addition of Marble dust. The decrease in mobility and the addition of reinforcement can be the possible reason for an increase in stiffness [34]. It is also worth noticing that the value of storage modulus falls rapidly in the elevated temperature range of 55-65 ^{0}C.

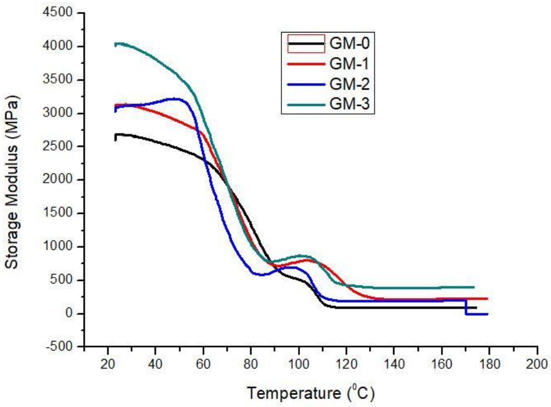

Fig. 7 Storage Modulus of samples

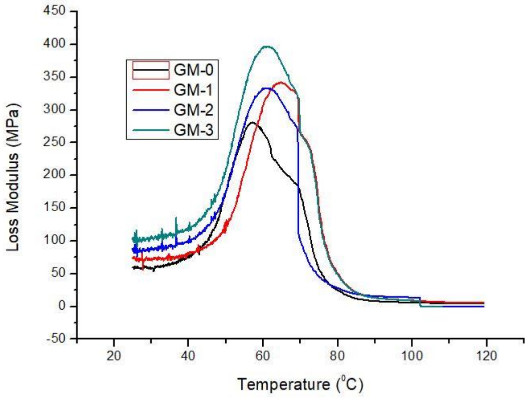

Fig. 8 Loss Modulus of samples

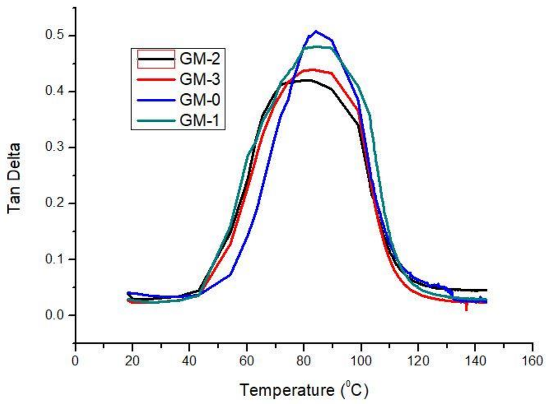

Fig. 9 Tan Delta

The loss modulus of the fabricated specimens is depicted in Figure. The Glass transition temperature (Tg) is represented by the peak of the loss modulus curves. It can be seen from the curve that the peaks are shifting toward the right. The increase in the value of T_g indicates the lower mobility of the specimens, which is achieved due to the strong covalent bonding of the reinforcements [42, 43]. The marble dust powder is affecting the bonding of the Grewia Optiva fiber and epoxy. So the use of marble dust plays a vital role in enhancing the adhesive behavior between fibers and matrix.

The next factor is Tan Delta which is the ratio of loss modulus to storage modulus. In a polymeric structure, damping properties maintain a balance between elastic and viscous phases. The elastic portion of the material assists in absorbing energy, while the viscous phase is responsible for energy dissipation. Tan Delta curve represents the energy dissipation. Tan Delta Curve represented in Figure 9 shows the lowest energy dissipation for GM-2. The GM-2 specimen shows the highest elastic and lowest viscous region. The addition of Marble dust up to 10 wt. % improves the bonding between the fiber and matrix. GM-3 specimen has the maximum storage modulus but it also has a comprehensive value of loss modulus, which increases the value of Tan Delta. A composite with weak interfacial bonding is likely to lose more energy than a material with a highly connected interface [44]. By adding MD up to 10 wt. %, the interfacial relationship between the fiber and matrix is therefore strengthened.

3.8. Taguchi analysis (L_{16}) of experimental results and statistical analysis of variance (ANOVA)

The optimization of the modifier's content to attain a minimal specific wear rate. Three factors, sliding velocity, type of composites, and normal load with four different levels were selected for experimental design. The overall mean for the S-N ratio of the specific wear rate is found to be -15.2dB. MINITAB 16, a popular software is used for generating the design of experiments. The quality characteristics conflicted with the desired values as indicated by the S-N ratio and depicted in Table 4. The results indicated that the wear response of GM-0 composites is improved significantly with the incorporation of marble dust. This may be due to the fact that the composite starts getting softened during sliding because of heat transfer generated due to sliding friction and is detached as a film. The softening process is delayed due to the inclusions of filler and mass loss of material is restricted due to fiber/filler reinforcement which acts as a barrier against sliding conditions [45]. This may be due to better adhesion between the fiber/filler and the matrix due to which a lesser mass loss rate is encountered [46, 47]. The specific wear rate increases from 2 m/s to 5 m/s and then it is amplified at higher SWR achieved at a sliding velocity of 5m/s (9.05×10^{-7} mm^3/N-m at 25N) for GM-0 composites. The optimum value of specific wear rate is achieved for GM-2 composites at 30 N load and 2 m/s sliding velocity having a value of 3.17×10^{-7} mm^3/N-m which is 51.67% lower than GM-0 composites.

The superior value of output response (SWR) is achieved by the highest value of the S-N ratio and the figure shows graphically the influence of the four control parameters on specific wear rate. The analysis of output response gives the most noteworthy combination of input parameters resulting in superior wear resistance (3.17 WGM× $10^{-7}mm^3$/N-m) of composites and revealed that factor combination; (sliding velocity=2m/s); (type of composite=GM-2); and normal load = 30 N) give a minimum specific wear rate of fabricated composites.

Table 4 Specific wear rate and corresponding S/N ratio.

S.No	Sliding velocity (m/s)	Type of composite	Normal load (N)	$W_{GM} \times 10^{-7}$ (mm^3/N-m)	S-N ratio (dB)
1	2	GM-0	20	6.56	-16.3
2	2	GM-1	25	5.83	-15.3
3	2	GM-2	30	3.17	-10.0
4	2	GM-3	35	3.42	-10.6
5	3	GM-0	25	7.21	-17.1
6	3	GM-1	20	5.21	-14.3
7	3	GM-2	35	4.44	-12.9
8	3	GM-3	30	6.84	-16.7
9	4	GM-0	30	8.03	-18.0
10	4	GM-1	35	7.88	-17.9
11	4	GM-2	20	5.49	-14.7
12	4	GM-3	25	4.99	-13.9
13	5	GM-0	35	9.05	-19.1
14	5	GM-1	30	5.43	-14.6
15	5	GM-2	25	6.21	-15.8
16	5	GM-3	20	6.78	-16.6

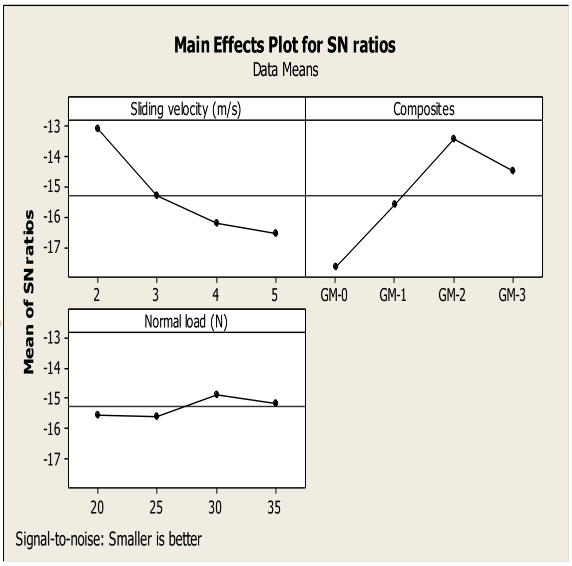

Fig. 8 Variation of S/N ratio of specific wear rate of composites versus controllable parameters.

To find out the percentage of contribution of various selected parameters; sliding velocity, type of composites, and normal load on the specific wear rate as presented in Figure 9. The result shows that the type of composite (56.7%) is the most noteworthy parameter affecting the wear resistance of the composites. The second rank is achieved by sliding velocity (41.49%) and the third rank is attained by normal load (1.81%). The present analysis indicated that the ranking of selected parameters according to ANOVA may be written as follows; type of composites>sliding velocity>normal load.

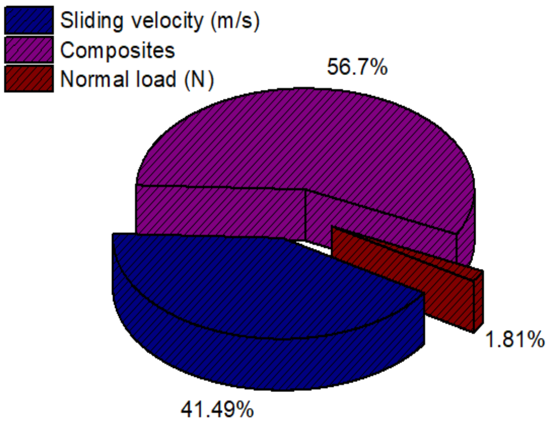

Fig. 9 The contribution of the control factors on the specific wear rate of composites.

4. Conclusion

In the current study, Grewia Optiva fiber (20 wt.%) based polymer composites with the addition of Marble dust (0,5,10,15 wt.%) were prepared. The results of the study show that the addition of Marble's dust up to 10 wt.% improves the interfacial bonding between the fiber and epoxy. Further addition of MD in the matrix does not give favorable results due to a higher void fraction and improper surface interaction.

The mechanical properties of the samples increase up to 10 wt.% addition of Marble dust. Results in the current study support previous research indicating that matrix strength and interfacial bonds play a more important role in interlaminar shear strength than fiber properties.

The thermo mechanical study shows that the storage modulus of all the samples increases due to a reduction in chain mobility obtained by the addition of marble dust powder. There is the lowest level of energy dissipation in the GM-2 specimen due to the highest elastic and lowest viscous regions.

The superior value of specific wear rate is achieved as 3.17 WGM× 10-7mm^3/N-m for GM-2 composite under 30N load, 2 m/s sliding velocity. The mean S-N ratio analysis imparts the rank of the parameters significantly affecting the dry sliding wear properties as follows; type of composites> sliding velocity> normal load for the optimal condition for minimization of SWR for composites. The analysis of variance results indicated that the most noteworthy variables affecting sliding wear rate are; type of composites (56.7%), sliding velocity (41.49%), and normal load (1.81%), for fabricated composites.

The thermo-mechanical and sliding wear analysis has shown that a material with a strongly bonded interface will likely dissipate less energy than a composite with weak interfacial bonding. Finally, it can be concluded that the Grewia Optiva fiber polymer composite (GM-2) with 10 wt.% Marble dust shows the most impressive mechanical and thermo-mechanical results due to better interfacial bonding.

By comprehensively studying these aspects, one can gain insights into the potential of natural fiber and marble dust-reinforced epoxy composites as sustainable and high-performance materials with applications in diverse fields.

Table 3 Properties of the fabricated composites

S.N.	Designation	T.S (MPa)	F.S (MPa)	HARDNESS(HRL)	IMPACT ENERGY (J)	DENSITY (g/cm³)	VOID FRACTION	ILSS (N/mm^2)
1	GM-0	55.01	65.44	115.45	2.2	0.922	1.2	8.60
2	GM-1	62.33	73.35	121.61	2.9	0.926	2.3	9.55
3	GM-2	68.19	76.87	132.33	3.3	0.931	3.3	10.01
4	GM-3	59.77	69.11	133.55	3.4	0.935	4.6	8.97

References

[1] Dhakal, H. N., Sarasini, F., Santulli, C., Tirillò, J., Zhang, Z., & Arumugam, V. (2015). Effect of basalt fiber hybridization on the post-impact mechanical behavior of hemp fiber reinforced composites. Composites Part A: Applied Science and Manufacturing, 75, 54-67.

[2] Boopalan, M., Niranjanaa, M. and Umapathy, M.J., 2013. Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites. *Composites Part B: Engineering*, *51*, pp.54-57.

[3] Hanan, F., Jawaid, M. and Tahir, P.M., 2018. Mechanical performance of oil palm/kenaf fiber-reinforced epoxy-based bilayer hybrid composites. *Journal of natural fibers*.

[4] Kumar, N., Singh, T., Grewal, J.S., Patnaik, A. and Fekete, G., 2019. A novel hybrid AHP-SAW approach for optimal selection of natural fiber reinforced non-asbestos organic brake friction composites. *Materials Research Express*, *6*(6), p.065701.

[5] Kumar, S., Patel, V.K., Mer, K.K.S., Fekete, G., Gangil, B. and Singh, T., 2018. Influence of woven bast-leaf hybrid fiber on the physico-mechanical and sliding wear performance of epoxy-based polymer composites. *Materials Research Express*, *5*(10), p.105705.

[6] Sanjay, M. R., & Yogesha, B. (2017). Studies on natural/glass fiber reinforced polymer hybrid composites: An evolution. *Materials today: proceedings*, *4*(2), 2739-2747.

[7] Kumar, S., Patel, V. K., Mer, K. K. S., Gangil, B., Singh, T., & Fekete, G. (2019). Himalayan natural fiber-reinforced epoxy composites: effect of Grewia optiva/Bauhinia Vahlii fibers on physico-mechanical and dry sliding wear behavior. Journal of Natural Fibers.

[8] Zahoor, M., Bari, W. U., Zeb, A., & Khan, I. (2020). Toxicological, anticholinesterase, antilipidemic, antidiabetic and antioxidant potentials of Grewia optiva Drummond ex Burret extracts. *Journal of Basic and Clinical Physiology and Pharmacology*, *31*(2), 20190220.

[9] Kumar, S., Gangil, B., Mer, K. K. S., Gupta, M. K., & Patel, V. K. (2020). Bast Fiber-Based Polymer Composites. Hybrid Fiber Composites: Materials, Manufacturing, Process Engineering, 147-167.

[10] Verma, A., Singh, N. B., Saresh, N. V., Choudhary, P., Sankanur, M., Aggarwal, G., & Sharma, J. P. (2015). RAPD and ISSR markers for molecular characterization of Grewia optiva: an important fodder tree of north western Himalayas. Range Management and Agroforestry, 36(1), 26-32.

[11] Singha, A. S., Priya, B., & Pathania, D. (2015). Cornstarch/poly (vinyl alcohol) biocomposite blend films: Mechanical properties, thermal behavior, fire retardancy, and antibacterial activity. International Journal of Polymer Analysis and Characterization, 20(4), 357-366.

[12] Upreti, B., & Chaudhary, A. K. (2017). Experimental study of mechanical properties of bhimal fiber reinforced epoxy bio-composite. International Journal of Innovative Research in Science, Engineering and Technology, 6(8), 16926-16931.

[13] Gupta, K. M., & Kalauni, K. (2015). Fabrication and characterization of biocomposite using grewia optiva fiber (ie Bhimal) reinforced polyvinyl alcohol (PVA). Advanced Materials Research, 1105, 51-55.

[14] Kalauni, K., & Pawar, S. J. (2023). Estimation of the Physical Parameters of Grewia Optiva Fibers and Prediction of Sound Absorption Coefficient with Theoretical Models. Journal of Natural Fibers, 20(1), 2162189.

[15] Rana, A. K., Potluri, P., & Thakur, V. K. (2021). Cellulosic grewia optiva fibers: towards chemistry, surface engineering and sustainable materials. Journal of Environmental Chemical Engineering, 9(5), 106059.

[16] Hulugappa, B., Achutha, M. V., & Suresha, B. (2016). Effect of fillers on mechanical properties and fracture toughness of glass fabric reinforced epoxy composites. Journal of

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Minerals and Materials Characterization and Engineering, 4(1), 1-14.

[17] Tejyan, S., & Patnaik, A. (2017). Erosive wear behavior and dynamic mechanical analysis of textile material reinforced polymer composites. Polymer Composites, 38(10), 2201-2211.

[18] Tejyan, S., Sharma, D., Gangil, B., Patnaik, A., & Singh, T. (2020). Materials Today: Proceedings.

[19] Rangappa, S. M., Parameswaranpillai, J., Siengchin, S., Jawaid, M., & Ozbakkaloglu, T. (2022). Bioepoxy based hybrid composites from nano-fillers of chicken feather and lignocellulose Ceiba Pentandra. *Scientific reports*, *12*(1), 397.

[20] Rajput, V., Somani, S. K., Agrawal, A., & Pagey, V. S. (2021). Mechanical properties of epoxy composites filled with micro-sized kota stone dust. Materials Today: Proceedings, 47, 2673-2676.

[21] Rajawat, A. S., Singh, S., Gangil, B., Ranakoti, L., Sharma, S., Asyraf, M. R. M., & Razman, M. R. (2022). Effect of marble dust on the mechanical, morphological, and wear performance of basalt fiber-reinforced epoxy composites for structural applications. Polymers, 14(7), 1325.

[22] Vinay, S. S., Sanjay, M. R., Siengchin, S., & Venkatesh, C. V. (2021). Effect of Al2O3 nanofillers in basalt/epoxy composites: Mechanical and tribological properties. *Polymer Composites*, *42*(4), 1727-1740.

[23] Singh, T., Gangil, B., Ranakoti, L., & Joshi, A. (2021). Effect of silica nanoparticles on physical, mechanical, and wear properties of natural fiber reinforced polymer composites. *Polymer Composites*, *42*(5), 2396-2407.

[24] Savage, S. J., Larsson, F., & Svensson, L. (2003). Isostatic pressing carbon fiber composites.

[25] Dilfi KF, A., Che, Z., & Xian, G. (2019). Grafting ramie fiber with carbon nanotube and its effect on the mechanical and interfacial properties of ramie/epoxy composites. *Journal of Natural Fibers*, *16*(3), 388-403.

[26] Seth, S. A., Tokan, A., & Aji, I. S. (2019). Investigation of the impact, hardness, density and water absorption of polypropylene filled Doum palm shell particles composite. *J Inf Eng Appl*, *8*, 28-37.

[27] Romanzini, D., Lavoratti, A., Ornaghi Jr, H. L., Amico, S. C., & Zattera, A. J. (2013). Influence of fiber content on the mechanical and dynamic mechanical properties of glass/ramie polymer composites. *Materials & Design*, *47*, 9-15.

[28] Bisht, A., Gangil, B., Patel, V. K., & Kumar, S. (2023). Effect of zinc addition on the tribological behavior of aluminum-based close-cell metal foams. *Metallic Materials/Kovové Materiály*, *61*(1).

[29] Gokdai, D., Borazan, A. A., & Acikbas, G. (2017). Effect of marble: pine cone waste ratios on mechanical properties of polyester matrix composites. Waste and Biomass Valorization, 8, 1855-1862.

[30] Gopinath, A., Kumar, M. S., & Elayaperumal, A. J. P. E. (2014). Experimental investigations on mechanical properties of jute fiber reinforced composites with polyester and epoxy resin matrices. *Procedia Engineering*, *97*, 2052-2063.

[31] Singh, T., Puri, M., Tejyan, S., & Ravi, R. K. (2021). Abrasive wear and dynamic–mechanical behavior of marble dust filled bagasse fiber reinforced hybrid polymer composites. Polymer Composites, 42(6), 2817-2828.

[32] Dong, C., & Davies, I. J. (2012). Flexural properties of macadamia nutshell particle reinforced polyester composites. *Composites Part B: Engineering*, *43*(7), 2751-2756.

[33] Santos, A. S., Farina, M. Z., Pezzin, P. T., & Silva, D. A. (2008). The application of peach palm fibers as an alternative to fiber reinforced polyester composites. *Journal of reinforced plastics and composites*, *27*(16-17), 1805-1816.

[34]Chen, D., Pi, C., Chen, M., He, L., Xia, F., & Peng, S. (2019). Amplitude-dependent damping properties of ramie fiber-reinforced thermoplastic composites with varying fiber content. *Polymer Composites*, *40*(7), 2681-2689.

[35] Dilfi KF, A., Balan, A., Bin, H., Xian, G., & Thomas, S. (2018). Effect of surface modification of jute fiber on the mechanical properties and durability of jute fiber-reinforced epoxy composites. Polymer Composites, 39(S4), E2519-E2528.

[36] Fan, Z., Santare, M. H., & Advani, S. G. (2008). Interlaminar shear strength of glass fiber reinforced epoxy composites enhanced with multi-walled carbon nanotubes. Composites Part A: Applied science and manufacturing, 39(3), 540-554.

[37] Selmy, A. I., Elsesi, A. R., Azab, N. A., & Abd El-baky, M. A. (2012). Interlaminar shear behavior of unidirectional glass fiber (U)/random glass fiber (R)/epoxy hybrid and non-hybrid composite laminates. Composites Part B: Engineering, 43(4), 1714-1719.

[38] Ahmed, K. S., & Vijayarangan, S. (2008). Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites. Journal of materials processing technology, 207(1-3), 330-335.

[39] Selmy, A. I., Elsesi, A. R., Azab, N. A., & Abd El-baky, M. A. (2012). In-plane shear properties of unidirectional glass fiber (U)/random glass fiber (R)/epoxy hybrid and

non-hybrid composites. Composites Part B: Engineering, 43(2), 431-438.

[40] Huda, M. S., Drzal, L. T., Misra, M., Mohanty, A. K., Williams, K., & Mielewski, D. F. (2005). A study on biocomposites from recycled newspaper fiber and poly (lactic acid). Industrial & engineering chemistry research, 44(15), 5593-5601.

[41] Mohanty, S., Verma, S. K., & Nayak, S. K. (2006). Dynamic mechanical and thermal properties of MAPE treated jute/HDPE composites. *Composites Science and Technology*, *66*(3-4), 538-547.

[42] Ajayan, P. M., Suhr, J., & Koratkar, N. (2006). Utilizing interfaces in carbon nanotube reinforced polymer composites for structural damping. *Journal of Materials Science*, *41*, 7824-7829.

[43] Andrews, R., & Weisenberger, M. C. (2004). Carbon nanotube polymer composites. *Current opinion in solid state and Materials Science*, *8*(1), 31-37.

[44] Gairola, S. P., Tyagi, Y. K., Gangil, B., & Kumar, S. (2023). Synergy of wood ash on mechanical and sliding wear properties of banana/walnut-based epoxy composites and optimisation with grey relational analysis. *International* Journal of Materials and Product Technology, 66(1), 70-86.

[45] Yu, T., Ren, J., Li, S., Yuan, H., & Li, Y. (2010). Effect of fiber surface-treatments on the properties of poly (lactic acid)/ramie composites. Composites part a: applied science and manufacturing, 41(4), 499-505.

[46] Bajpai, P. K., Singh, I., & Madaan, J. (2013). Frictional and adhesive wear performance of natural fiber reinforced polypropylene composites. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 227(4), 385-392.

[47] Kumar, S., Mer, K. K. S., Gangil, B., & Patel, V. K. (2019). Synergy of rice-husk filler on physico-mechanical and tribological properties of hybrid Bauhinia-vahlii/sisal fiber reinforced epoxy composites. Journal of Materials Research and technology, 8(2), 2070-2082.