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Revolutionizing Polyester Composites Using Synergistic Effects of Flax Fiber and Silicon Oxide Nanoparticles

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Abstract

In recent years, researchers have shifted their focus from traditional metals and alloys to composites in the search for lightweight, highly functional materials. Glass fibers are more durable, cost-effective, and fireproof than natural fibers. The effect of silicon oxide (SiO_2) on the mechanical and physical properties of woven polyester reinforced composite is investigated. I weight ratio of SiO_2 nanoparticle filler, II fiber content, and III fiber diameter were used in the manual construction of nanocomposites. Nine composite samples are manufactured and evaluated in accordance with the ASTM standard using the L9 (33) orthogonal design. Studies show that hybrid composites made from 6% SiO_2 powder and 20% flax fiber (with a diameter of 0.4 mm) have exceptional mechanical strength. The mechanical properties of virgin polyester are enhanced by the addition of fiber. More work was required to crack the matrix and resin bond as the percentages of fiber and filler increased. The material's tensile strength (TS) went up 14.76%, its flexural strength (FS) went up 14.07%, and its hardness went up 25.55%.

Keywords

Tensile strength, Flexural strength, Hardness, Flax fiber

Introduction

One of the most exciting fields of research nowadays is bio-composites. Germany is the most important European market for organic fiber composites [1]. Traditional materials have been largely phased out in favor of polymers due to their superior manufacturing efficiency, greater productivity, and substantial cost savings. Polymers can be modified to better meet the high strength/modulus requirement by adding fillers and fibers [2]. There are a wide variety of uses for composites reinforced with glass fiber. However, at the end of their life cycle, their inability to be recycled is a drawback [3]. Biodegradability, non-exhaustibility of raw materials, and reduced aggressive and dangerous behavior are only a few of the environmental benefits that result from using natural fibers in a composite [4]. Natural fibers have many desirable properties for usage as reinforcing agents in polymers, such as low cost, low power requirements, great biocompatibility, and lack of abrasion. Natural fibers, like synthetic ones, have a high specific property and a low density [5]. Natural fibers can be used as conventional reinforcement since they share the same mechanical characteristics [6]. Therefore, the inherent qualities of natural fibers can meet the demands of worldwide markets, especially in the weight-loss sector. Because of this, they could potentially replace synthetic materials that cannot be replenished [7]. Lightweight fabrics are typically made from natural fibers like wool, flax, jute, and silk due to these materials' high quality and quantity. Jute fiber has various benefits when used in composites. As a besets fiber, for instance, it shares some characteristics with wood [8].

Flax is one of the hardest and quickest-growing plants around. The area of land covered by flax woods is greater than 23 million hectares. China is the richest nation since it is home to one-third of the world's flax forest [9]. Flax has several uses because of its rapid growth, durability, stiffness, simplicity of processing, and low environmental impact [10]. Flax has been used and studied for at least the past eight thousand years. China's weavers, woodworkers, newspaper publishers, and composite fiber producers have relied on flax for decades because of the plant's abundance of high-quality cellulose fibers [11]. Common traditional necessities and handmade creations made from flax include hardwood, paper, fiber, ashes, acid, photography props, and leaf extracts [12]. Despite using flax in the production of a variety of goods (including handicrafts, chairs, hardwood, reed hardwood composite, and more), the flax industry as a whole isn't making the most of flax's ecological and economic potential [13]. The low comprehensive use of flax materials, low levels of automation, the production of few high-value commodities, and a lack of scalability are all problems plaguing the current flax sector [14]. However, natural fibers' hydrophilic nature is a major hindrance when used as fiber materials. Natural fibers have poor hydrophilicity and incompatibilities with hydrophobic polymers because of low moisture friction [15]. Polymeric matrices often have their bonding and adhesive affinities enhanced and their dimensions fine-tuned through chemical or physical modifications [16, 17]. Chemical surface modification using bonding agents is commonly used to improve adhesion and interface between the nonpolar cellulosic fibers and the polar matrix, and to optimize the hydration of the latter for durability in polymer matrices. [18]. Alkaline treatments, methylation, grafting copolymerization, and maleic-anhydride-polypropylene copolymer have all been shown to alleviate the incompatibility of the interface polarity between natural fiber and polymer matrices [19].

Many researchers have attempted to improve the mechanical properties of natural fibers by hybridizing them, with varying degrees of success [20]. Composites that combine different filler types into a single matrix are known as "hybrid composites". Hybridization improves natural fiber reinforced plastic composites' mechanical qualities by compensating for each component's weaknesses [21]. However, there is a limit to the degree to which mechanical characteristics can be enhanced by mixing fibers in matrices. To further enhance the fiber's properties, nanoparticles are used to fortify the link between the fiber and matrix [22]. Therefore, nanoparticles are being included into epoxy resins. This research looks into the possibility of using nano powder to control the behaviors of bio-composites. Due to their nanoscale dimensions, nanoparticles provide novel possibilities for product development and enhancement [23]. Nanoparticles have many uses, from cleaning water and powering generators to keeping tabs on environmental contamination. The potential of novel nanoparticles to solve pressing environmental problems is the primary focus of much of the study. SiO_2 occurs in nature both as an amorphous and crystalline metal [24]. Crystalline iron is tetrahedral, as is hematite, while anatase is extradural. Due to their nanoscale dimensions, nanoparticles exhibit unique characteristics [25, 26].

This is one of the first studies to apply grey-based Taguchi optimization to the evaluation of composites utilizing woven. Its originality stems from the use of flax as a reinforcing material and nanoscale SiO_2 as a filler in epoxy resin. This fresh concept was incorporated into the revised draught. The objective of this study is to develop, test, and optimize the mechanical characteristics of hybridized bio-composites by varying the proportion of SiO_2, the length, and the diameter of flax fibers. The SiO_2 filled composites were made using a straightforward hand lay-up method. Alkali treatment of natural fibers improved adhesion and decreased moisture absorption, while Taguchi techniques based on grey-level statistical analysis were used to examine and improve the fibers' mechanical properties. The results of this study should broaden the range of uses for composites made from organic fibers.

Experimentation

Materials

The flax fibers were provided by Go green Products of Chennai, Tamil Nadu, India. The flax fibers were rinsed in clean water and dried in the solar for two days to get rid of extra moisture. After that, a NaOH solution was left to soak with the fiber for four hours. The fiber was then washed in fresh water before being woven at a temperature of 75 °C. Epoxy was used as a matrix in this study parallel to SiO_2.

Fabrication

We started by honing a stainless-steel mold that measured 150 x 150 x 3 mm in depth. Together with the right amount of hardener and accelerator, the polyester matrix was completely mixed (10:1). The composite of SiO_2 powder and flax fiber was made using hand lay-up. The epoxy resin was mixed by hand with a glass rod to distribute the SiO_2 particles at varying weight percentages. The fiber layers in the mold were saturated with the matrix mixture. After 24 h of curing in the open air with the mold connected, the fiber mats were completely saturated with matrix mixes. A set of nine composite plates was manufactured for further examination, and the L9 orthogonal array was selected because it best meets Taguchi's method for 3 constraints, each of which comprises three stages. Desiccant treatments were applied to the hybrid composite samples to reduce their moisture absorption. The parameters, their intervals, and Taguchi's orthogonal array are displayed in table 1 and table 2.

Results and Discussion

Description of nanocomposite

For tensile testing, ASTM D 638-03 replicates were cut

Table 1: Constrains and their stages for hybrid composite.

S. No.	Constraints	Symbol	Stage 1	Stage 2	Stage 3
1	SiO_2 powder (wt.%)	X	3	6	9
2	Flax fiber length (mm)	Y	10	15	20
3	Flax fiber diameter (mm)	Z	0.4	0.6	0.8

Table 2: L9 orthogonal array of hybrid composites.

Trail No.	X	Y	Z
1	3	10	0.4
2	3	15	0.6
3	3	20	0.8
4	6	10	0.6
5	6	15	0.8
6	6	20	0.4
7	9	10	0.8
8	9	15	0.4
9	9	20	0.6

to dimensions of 150 mm x 15 mm x 3 mm; for flexural testing, ASTM D-790 replicas were cut to dimensions of 10 mm x 125 mm x 3 mm; and for hardness testing, ASTM E-10 replicas were cut to dimensions of 20 mm x 20 mm x 3 mm.

Experimental outcomes by GRG method

The various factors in a process can be explained, investigated, and optimized with the help of Taguchi's experimental process technique [26]. The experimental findings of the present study are presented in table 3. Finding the fundamental constraints requires transforming the research findings into a signal-to-noise (S/N) ratio. The definitive justification for enhancing the primary feature led to the segmentation of the S/N ratio characteristics into three groups: (i) larger is better, (ii) nominally better, and (iii) lowest is better.

Analysis of S/N ratio

The S/N ratio enhances with larger feature sizes across the board, regardless of the best performing feature group. Mechanical properties of flax/SiO_2/polyester composites are shown in figure 1 in terms of the S/N ratio. Therefore, the best S/N ratio occurs at the ideal setting of the parameter. Throughout the testing of composites, this overarching notion was applied to analyses of hardness, compressive, and impact strengths. Larger S/N ratios (better) are used to illustrate the significance of the most notable features.

Table 3: Results from the current research.

Exp. run	TS (MPa)	FS (MPa)	Hardness (BHN)
1	51.28	84.56	41.56
2	52.44	87.22	42.42
3	54.78	88.65	43.88
4	55.68	89.54	45.69
5	53.98	87.41	43.87
6	62.41	96.77	52.47
7	49.88	83.96	39.58
8	51.66	85.44	41.57
9	55.28	88.21	48.59

$$\frac{S}{N}Ratio = -10\log_{10^{\frac{1}{2}\sum_{a=i}^{e}\frac{1}{X_{ab}^{2}}}} \quad (1)$$

Normalized S/N ratio

The term "normalization" refers to a statistical input transformation that standardizes and quantifies the data into a meaningful set before further analysis. Zab is defined as K_{ij} ($0 \le K_{ij} \le 1$) by solving a system of equations that allows us to draw the correct conclusion about each component and eliminate any inconsistencies (Equation 2) [27]. The study's focus was on hardness, compressive strength, and impact toughness. The S/N ratio and the standardized S/N ratio (cS/N) are optimal for the subsequent conditions. Table 4 displays the obtained and normalized signal-to-noise ratios.

$$K_{ij} = \frac{Z_{ab} - \min\left(Z_{ab}a = 1,2,\ldots,e\right)}{\max\left(Z_{ab} = 1,2,\ldots,k\right) - \min\left(Z_{ab} = 1,2,\ldots,e\right)} \quad (2)$$

Grey relational grades (GRG)

Each Gray Relational Coefficients (GRC) solution is transformed into a GRG using equation 3. The optimal values for each variable are calculated using the grey relational grading. Table 4 displays the GRG results.

$$y_J = \frac{1}{k}\sum\nolimits_{i=1}^{m} y_{ij} \quad (3)$$

The sum of performance features is denoted by k, and the GRG for trial j is denoted by γ. The GRC and GRG were then carried out for all L9 (33) trials. By integrating Taguchi techniques with grey relational analysis, we were able to reduce the multi response optimization problem to a single-response optimal solution. The single-performance characteristic is the

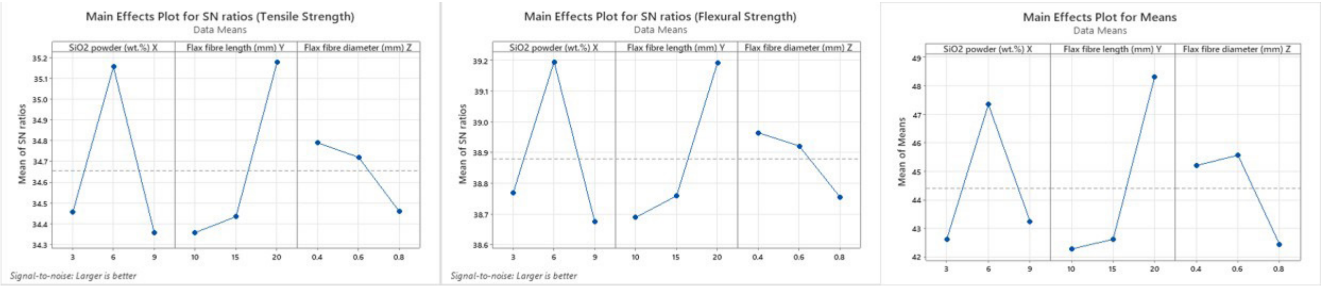

Figure 1: Flax/SiO_2/polyester composites' S/N ratio for their mechanical properties.

Table 4: S/N and normalized S/N ratio.

Exp. No.	S/N ratio			Normalized S/N ratio		
	TS (MPa)	FS (MPa)	Hardness (BHN)	TS (MPa)	FS (MPa)	Hardness (BHN)
1	34.199	38.543	32.374	34.199	38.543	32.374
2	34.393	38.812	32.551	34.393	38.812	32.551
3	34.772	38.954	32.845	34.772	38.954	32.845
4	34.914	39.040	33.196	34.914	39.040	33.196
5	34.645	38.831	32.843	34.645	38.831	32.843
6	35.905	39.715	34.398	35.905	39.715	34.398
7	33.959	38.481	31.950	33.959	38.481	31.950
8	34.263	38.633	32.376	34.263	38.633	32.376
9	34.851	38.910	33.731	34.851	38.910	33.731

complete GRG produced by the grey-based Taguchi method [28]. If tweak some parameters, might be able to improve your overall grey relationship rating. The GRC and GRG trial findings are tabulated in table 5.

The hybrid polyester composites' mechanical properties were optimized using the Taguchi method and a grey relation research. The most effective groups for constriction were determined using grey-based testing, and the most crucial property of natural composites was isolated using analysis of variance (ANOVA). Using the retort table from the Taguchi approach, the typical GRG across all levels of restriction was determined. SiO_2 powder's grey relation score was arrived by adding the results from the flat (level 1) GRC (i.e., Experiments 1, 2, and 3) and the level 2 trials in the same column.

In experiments 4 - 6, the level three relationship values from column X are averaged to get a final value for each experiment. Similarly, the diameter and length of flax fibers will be chosen for their uniformity of thickness. This is seen in table 6. The GRG's reaction facts at varying composite limitations are shown in figure 2. The best process constraint level is associated with the highest grey relation grade, according to the statistics.

Including nano silicon into the mix will greatly increase the composite's overall durability. The GRG value for SiO_2 powder mass, flax fiber length, and diameter is highest at levels X2, Y3, and Z1. Hybrid composites fared best when composed of 6% silicon powder and 20 mm flax fiber of 0.4 mm diameter. When additional filled SiO_2 was added to the polymer matrix, the decohesion link between the matrix and the fiber changed. Increases in the SiO_2 weight ratio reduce the strength of the bond between the matrix and the fibers. SiO_2 acclamations in the matrix may be to cause.

Table 6: The GRG response table.

Level	X	Y	Z
1	0.4035	0.3959	0.5775
2	0.6406	0.3995	0.4706
3	0.4082	0.6569	0.4042
Delta	0.2370	0.2610	0.1733
Rank	2	1	3

The mechanical characteristics of natural fiber polymer composites are affected by a wide variety of factors, including content, diffusion, direction, composition, wettability, binding, fiber-matrix bond strength, origin, complex formation, electrostatic interaction, physical interfacial, and fiber length. The length of the fibers used in reinforcing polymeric materials is a crucial factor in their production. When fibers are too lengthy, they get knotted and difficult to disperse. However, if the fiber length is inadequate, not enough stress will be passed from the matrix to the fiber. Fiber breaking in fiber-reinforced composites depends largely on the composite type and the initial aspect ratio of the fibers. The impact of fiber length on the characteristics of fiber-reinforced polymer composites has been the subject of a number of research efforts. The mechanical characteristics of nanocomposites were found to improve with an increase in fiber length from 10 mm to 15 mm and then 20 mm in this study. Mechanical properties are improved

Table 5: GRC and GRG of the composites.

Exp. No.	GRC			GRG	Rank
	TS (MPa)	FS (MPa)	Hardness (BHN)		
1	0.363	0.345	0.377	0.3616	8
2	0.392	0.406	0.399	0.3987	6
3	0.462	0.448	0.441	0.4502	4
4	0.495	0.478	0.505	0.4926	3
5	0.436	0.411	0.441	0.4291	5
6	1.000	1.000	1.000	1.0000	1
7	0.333	0.333	0.333	0.3333	9
8	0.372	0.363	0.377	0.3708	7
9	0.480	0.434	0.647	0.5204	2

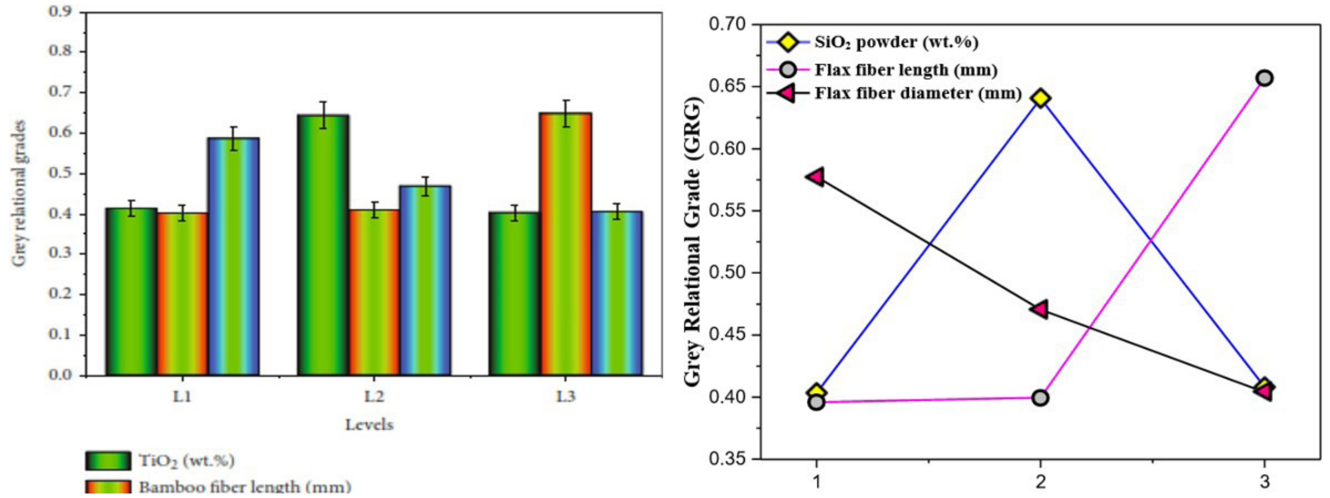

Figure 2: GRG values of flax/SiO_2/polyester-based nanocomposites.

in composites with longer fibers.

In most cases, the performance of natural fiber reinforced polymer composites can be enhanced by utilizing fibers with a smaller radius or of a finer grade. As can be seen in figure 3, the mechanical properties of the nanocomposite are greatly influenced by fiber length and fiber content in addition to fiber diameter. The composite improves in the following ways as fiber diameter is decreased or fineness is raised: raised contact area between fibers and polymer matrices as a result of (i) enhanced infrastructural facility and (ii) enhanced surface-to-volume ratios. Fiber sizes above a certain value result in nanocomposites with lesser strength, hence this property is also important. As a result, the performance of polymeric materials reinforced with fibers of greater sizes will suffer.

ANOVA analysis

Results from an analysis of variance are used to pinpoint which parameters affect which variables during production of hybrid composites made of SiO_2 and flax. The conventional GRG value can be used in the ANOVA. Changes in processing parameters' influence on performances can be estimated using the sum of squared deviations as a percentage of the total.

According to the results of the ANOVA, shown in table 7, the SiO_2 powder, flax fiber length, and flax fiber diameter each accounted for 33.44, 40.77, and 13.91% of the total variation, respectively. Inclusion of nanoparticles and the length of the fibers appear to be crucial in the current study.

Moisture absorption behavior

High moisture retention in polymer composites is typically induced by fiber reinforcement. Composites based on the initial parameters (X2, Y2, and Z3) had a high moisture content, while those based on the optimal parameters had a low relative humidity. Analyses of mechanically broken samples revealed that the optimum composite had strong fiber-to-matrix bonding. The most noticeable effect of this is improved resistance to water. The fiber is protected from the outside environment by the polymer matrix, which bonds extremely well to it. Water molecules may have easy access to the fiber surface

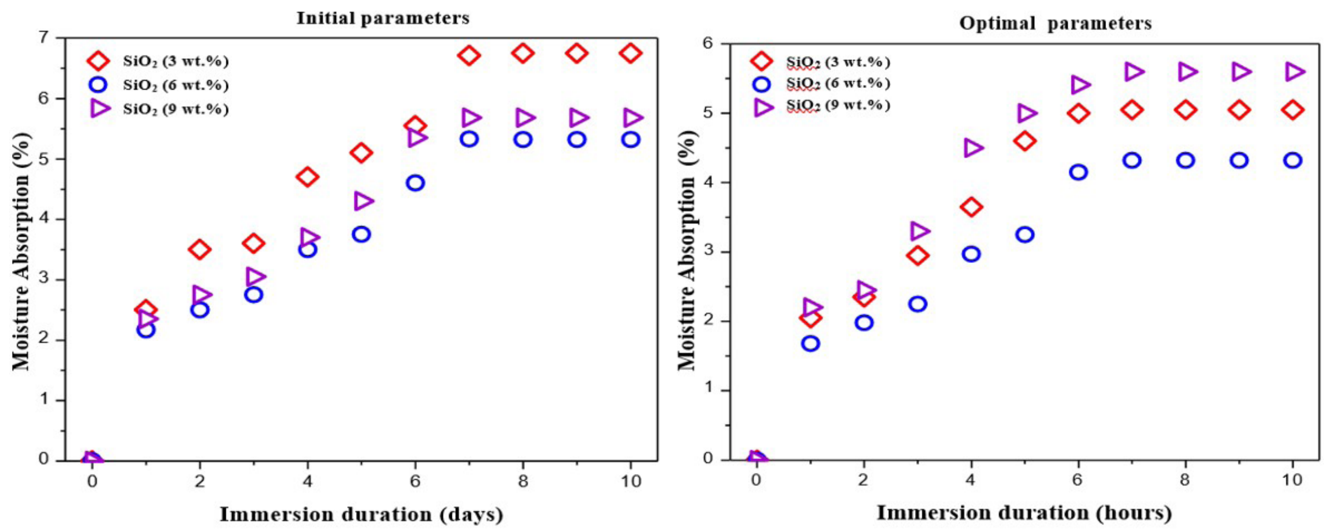

Figure 3: Moisture absorption behavior of **(a)** Initial and **(b)** Optimal parameter-based nanocomposites.

Table 7: ANOVA of GRG.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	p-value
SiO_2 powder (wt.%) X	2	0.11020	33.44%	0.11020	0.05510	2.82	0.262
Flax fiber length (mm)Y	2	0.13437	40.77%	0.13437	0.06718	3.43	0.226
Flax fiber diameter (mm) Z	2	0.04585	13.91%	0.04585	0.02293	1.17	0.461
Error	2	0.03915	11.88%	0.03915	0.01957		
Total	8	0.32957	100.00%				

in early parameter composites due to the poor interaction between the fiber and the matrix. This enhanced the composite's capacity to absorb water. The initial and optimal parameter composites reached saturation after the 6th day of incubation.

Conclusion

The Taguchi method and GRA were used to optimize the procedure's constraints while analyzing the mechanical properties of hybrid polyester composites containing SiO_2 and flax. These findings arrived at: For hybrid composites made of SiO_2 and flax, these are the proposed controlled process conditions. When various materials are combined, hybrid composites are created with superior mechanical properties. ANOVA revealed that the length of the flax fiber was the most influential factor, accounting for 40.77% of the total, followed by the nano SiO_2 concentration (33.44%) and the diameter of the fiber (13.91%). Thirdly, the interfacial adhesion between the matrix and reinforcement is enhanced by the longer flax fiber. This will increase the efficiency with which the matrix's stresses are transferred to the reinforcement. The high process value is confirmed by the grey relation analysis, which is significantly greater than the findings of the empirical tests. Tensile strength rose by 14.76%, flexural strength by 14.07%, and hardness by 25.55 %. In this paper, the mechanical properties of flax and nanoscale SiO_2 were optimized by extensive experimental research. It is true, however, that making natural composites using nanofillers presents a number of challenges and compromises material quality and properties. A high-quality product with improved specialized qualities can be achieved by carefully selecting and optimizing the processing parameters. Matrix materials made from natural fibers and nanofillers may be studied in terms of production and assessment. Matrix aggregation caused by the addition of fillers can be avoided with the right methods. The resulting composite's physical and mechanical properties will be drastically altered as a result.

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None.

Conflict of Interest

None.

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