JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Application of Multi Response Performance Index for Optimization of Kevlar/Epoxy Composites strengthened with Hybrid SiC-ZnO Nanofillers

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Abstract: Fibre Reinforced Polymer Composites (FRPCs) have been described as the materials of the future due to their limitless applications. They have been found to exhibit enhanced mechanical properties on addition of nanofillers. Recent research has also used hybrid nanofillers to synergistically enhance their mechanical properties. In this present research, an attempt has been made to study the effect of hybrid Silicon Carbide (SiC) – Zinc Oxide (ZnO) nanofillers on the mechanical properties of Kevlar/Epoxy composite specimens. Multi Response Performance Index (MRPI) technique has been employed in this current research for optimisation of influencing important process parameters for enhanced tensile strength, flexural strength, inter laminar shear strength and energy absorbed. Confirmatory tests have also been performed for repeatability and validity.

***Keywords* -** Fibre Reinforced Polymer Composites, Hybrid Nanofillers, Vacuum Bag Moulding, MRPI.

I. INTRODUCTION

Fibre Reinforced Polymer Composites (FRPCs) are materials that combine reinforcing fibres with a continuous matrix to achieve properties far superior to those of the individual components. The fibres serve as the reinforcement phase, imparting strength, stiffness, and resistance to fatigue, while the matrix, often a polymer, acts as the binding phase that holds the fibres together and transfers loads between them. This combination results in lightweight yet durable materials that outperform metals and conventional plastics in many applications. Their versatility allows tailoring of mechanical properties for specific needs, making them indispensable in aerospace, automotive, marine, and civil engineering industries [1].

Researchers have found that the addition of nanofillers have been shown to significantly enhance the performance of fibre reinforced polymer composites by improving fibre–matrix adhesion, increasing tensile strength, stiffness, and fatigue resistance while also enhancing thermal stability and reducing moisture uptake.

Chang, Xin, et. al., investigated the enhancement of mechanical behaviour of FRPCs modified by silica nanoparticles. Three types of composites were fabricated: Epoxy-Basalt, Epoxy-Carbon and Vinyl Ester- Basalt. Multiple specimens with various weight percentages of silica nanopowder were prepared. Various mechanical tests were carried out on all the specimens. Scanning electron microscopy was employed to study the structure of the specimens after testing. Results concluded that the addition of silica nanoparticles had significantly improved the properties of the composites and it was most significant for the epoxy based composites. Scanning electron microscopy revealed a rough surface which implied an increase in fracture toughness [2].

Sujesh and Ganesan studied the effect of inclusion of nano silica particle in the Glass Fibre Reinforced Plastic (GFRP) manufactured by vacuum bagging technique. They also studied the behaviour of Nano filled bidirectional fibre reinforced polymer under uniaxial loading at different strain rates. The results show that nanofilled GFRP have better tensile strength compared to plane GFRP. Result shows that addition of nanoparticle increased the mechanical properties such as tensile strength, tensile modulus and Ultimate tensile load without considerable weight increment [3].

Thiagarajan, Melvin, et. al., investigated the tensile strength of silicon carbide epoxy polymer nanocomposite. The materials used were epoxy resin, glass fibre of Woven Roving Mat (WRM) and Chopped Strand Mat (CSM) and silicon carbide nanoparticle. The Nanocomposite laminates were prepared by hand layup method by varying the Silicon carbide nanoparticles at 0, 1, 2 and 3 Wt. %. The fabricated nanocomposites were then subject to tensile test. It was observed that by increasing the weight percentage of silicon carbide nanoparticles, the tensile strength also increased [4].

Setayesh Zaer-Miri and Hamed Khosravi, assessed the wear behaviour and inter laminar shear properties of modified nano-TiO_2/jute fibre/epoxy multiscale composites. The authors functionalized TiO_2 nanoparticles by using a amin-terminated silane-coupling agent. The multiscale composites were fabricated using hand layup technique by dispersing various amounts of the functionalized TiO_2 nanoparticles (0.5, 1, 3, and 5 wt.%) in the matrix and by using jute fibre as reinforcement. The wear behaviour and inter laminar shear properties of the fabricated multiscale nano-TiO_2/jute fibre/epoxy composites were investigated. It was observed that the addition of 3 wt.% TiO_2 increased the inter laminar shear strength of the composite and decreased the wear rate and coefficient of friction of the jute fibre/epoxy composite [5].

Vipin Kumar Tripathi and Shailesh Ambekar investigated the wear behaviour of Carbon Fibre Reinforced Polymer (CFRP) hybrid nano composite with nanoclay and nano ZnO as fillers. The CFRP nanocomposite laminates were manufactured by a hand layup method followed by vacuum bagging. The clay and Zinc Oxide nanoparticles were used as filler. The wt.% of nanoparticle used was in the range of 1 to 5 % with the epoxy resin and hardener mixture. The wear properties of CFRP hybrid nanocomposites were tested by using a pin-on-disc machine under various loads. ANOVA results shows that the nanoclay and nano ZnO had an improved effect on wear properties with the 2–3% of the each nanoclay and nano ZnO particles [6].

Çağrı Uzay and Safa Kamer, investigated the effect of Silane-Coated SiO_2 Nanoparticles on the Hardness Values of Glass FRP Composites. The SiO_2 Nanoparticles were coated with two different types of silane coating (KH550 and KH570). The nanoparticles were dispersed within the polymer epoxy at 1.5 and 3 wt.% ratios. The vacuum bag method was applied to produce silane-coated nano SiO_2 filled glass FRP composites. The fabricated nanocomposites were subjected to various mechanical testing. It was found that the addition of silane-coated SiO_2 nanoparticles into the polymer matrix considerably improved the hardness of the developed composite structures [7].

In recent years, researchers have also found that hybrid nanofillers, which combine two or more nanofillers, have shown synergistic effects in enhancing the properties of FRPCs. Studies demonstrate that hybrid systems improve fibre–matrix interfacial bonding more effectively than single nanofillers, resulting in superior mechanical strength, toughness, and fatigue resistance, making hybrid nanofillers a promising route for next-generation aerospace, automotive, and structural composites.

Megahed, Tobbala, et. al., combined silica and cobalt ferrite nanoparticles. Glass/epoxy hybrid composite laminates with hybrid nanofillers were fabricated using hand lay-up technique. The resultant hybrid nanocomposites showed good mechanical properties as compared to hybrid nanocomposites fabricated by individually loading nanoparticles [8].

Azhagarsamy and Pannirselvam developed Basalt Fibre Reinforced Polymer (BFRP) composites using Isophthalic Polyester (IP) resin modified with Graphene Oxide (GO) and Nano Silica (NS) hybrid nanofillers. BFRP laminates were produced via hand lay-up and compression moulding. They observed that the addition of hybrid nanofillers exhibited further enhancements with tensile strength, flexural strength, impact strength and hardness. They concluded that GO–NS hybrid nanofillers were an efficient reinforcement strategy for IP resin–based BFRP composites [9].

Sathish, Boobalan, et. al., evaluated tensile performance of basalt/glass fibre-reinforced polymer composites enhanced with hybrid nanofillers, comprising equal proportions of multi-walled carbon nanotubes and silicon dioxide. They found that the hybrid nanofillers synergistically enhance the tensile properties, load transfer efficiency and interfacial bonding [10].

Esranur, Osman, et. al., mixed hybrid multiwalled carbon nanotubes and graphene nanoparticles to epoxy matrices for carbon fibre laminates for various weight percentages. They evaluated the specimens for various mechanical properties and observed that the use of hybrid nanofillers led to synergistic gains in stiffness and fracture resistance. They concluded that the hybrid nanofillers produce best results at specific nanofiller ratios [11].

In this study, an attempt has been made to evaluate the mechanical properties of Kevlar/Epoxy composites strengthened with hybrid SiC-ZnO nanofillers and to optimize them using MRPI technique.

II. MATERIALS AND EXPERIMENTATION

2.1 Materials

The materials used in this research were: Kevlar Fibre Fabric Mat as the reinforcement material, Epoxy resin with hardener as the matrix material and Silicon Carbide (SiC) nanoparticles and Zinc Oxide (ZnO) nanoparticles as the hybrid nanofillers. The Kevlar Fibre Fabric Mat was sourced by GoGreen Products, Chennai, Tamil Nadu, India. The specifications of the Kevlar Fibre Fabric Mat used for the current research is shown in Table 1.

Table 1 Specifications of Kevlar Fibre Mat

Area Weight (g/m^2)	220
Dry Fabric Thickness (mm)	0.32
Density (g/cm^3)	1.44
Filament Diameter (µm)	12
Elongation (%)	2.8

The epoxy resin LY556 with hardening agent HY951 was sourced by Zenith Industrial Supplies, Bangalore, Karnataka, India. The specifications of the epoxy resin and hardener are shown in Table 2 and Table 3 respectively.

Table 2 Specifications of Epoxy Resin LY556

Chemical Name	Phenol 4,4-(-1-Methyleneethylienedene) bipolymer with (Chloromethyl) oxirane
State	Liquid
Colour	Light yellow
Density	1.2 g/cm^2
Viscosity	1800-2200 MPa/sec

Table 3 Specifications of Hardener HY951

Chemical Name	Triethyleneteramine (TETA)
State	Liquid
Colour	Clear pale yellow
Density	0.937 g/cm^2
Viscosity	10-20 MPa/sec

The SiC nanopowder was supplied by Ultrananotech Private Limited, Bangalore, Karnataka, India. The ZnO nanopowder was supplied by Adnano Technologies, Shimoga, Karnataka, India. Table 4 details the specifications of the nanofillers.

Table 4 Specifications of The Nanofillers

Nanofiller	Form	Purity	Colour	Size	CAS No.
Silicon Carbide (SiC)	Powder	99.9%	Greenish Grey	30 - 50 nm	409-21-2
Zinc Oxide (ZnO)	Powder	99%	White	30 - 50 nm	1314-13-2

2.2 Selection of Process, Process Parameters and their Levels

The fabrication of the FRPC specimens was to be done by vacuum bag moulding process. The process parameters which were selected for optimisation were: Weight percentage of SiC nanofiller, Weight % of ZnO nanofiller, Curing temperature and Curing time. The parameters and their levels which were selected are shown in Table 5. The number of Kevlar layers was kept constant at eight layers. The values of levels of process parameters are derived based on the trial experiments for feasibility study.

Table 5 Process Parameters and their Levels

Parameter	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Wt. % of SiC	0.5	0.75	1	1.25
Wt. % of ZnO	1	1.25	1.5	1.75
Curing Temperature (ºC)	95	100	105	110
Curing Time (mins)	55	60	65	70

2.3 Design of Experiments

Since there are four parameters and four levels, Taguchi L16 array was employed and as a result of which 16 specimens are fabricated. Table 6 shows the list of specimens to be fabricated as per Taguchi L16 array.

Table 6 Experimental Design Using Taguchi L16 Array

Experiment No.	**Wt. % of SiC**	**Wt. % of ZnO**	**Temperature (ºC)**	**Time (mins)**
1.	0.5	1	95	55
2.	0.5	1.25	100	60
3.	0.5	1.5	105	65
4.	0.5	1.75	110	70
5.	0.75	1	100	65
6.	0.75	1.25	95	70
7.	0.75	1.5	110	55
8.	0.75	1.75	105	60
9.	1	1	105	70
10.	1	1.25	110	65
11.	1	1.5	95	60
12.	1	1.75	100	55
13.	1.25	1	110	60
14.	1.25	1.25	105	55
15.	1.25	1.5	100	70
16.	1.25	1.75	95	65

2.4 Fabrication of specimens by Vacuum Bag Moulding

The Kevlar/Epoxy composite specimens were fabricated by using hand layup method followed by vacuum bag moulding. The Kevlar Fibre Mat was cut into 30 x 30 centimetre squares. The resin mixture comprising of epoxy resin and hardener were prepared in the ratio of 10:1. The ZnO and SiC nanoparticles with weight percentages as per the experimental plan were then stirred into the epoxy-hardener mixture for 10 minutes. The mixture was then spread on the mould and a kevlar fibre mat was placed on this layer. The epoxy-hardener-nanoparticle resin mixture was then poured onto the kevlar fibre mat and evenly spread using a roller. This process was repeated until eight layers of mat were obtained. Fig. 1 shows the specimen after hand layup.

Fig. 1 The specimen after hand layup process

The specimen was then covered with a layer of peel ply sheet (Fig. 2 (a)) followed by a layer of vacuum bag film (Fig. 2 (b)) and breather fabric (Fig. 2 (c)). The whole mould was then sealed with a plastic bag and a pipe connected to a vacuum pump was introduced inside the mould, subjecting it to vacuum conditions (Fig. 2 (d)). The mould was under vacuum for three hours after which the vacuum pump was turned off. The specimens were then left to cure in the mould for 24 hours following which they were removed. Fig 2. shows the various stages of the vacuum moulding process.

Vacuum bag moulding process was selected because it enhances both quality and performance of FRPCs. The uniform pressure from the vacuum pump ensures better fibre consolidation, minimizes voids, and improves resin distribution, which directly translates to higher mechanical strength and durability of the composite. Additionally, vacuum bagging reduces porosity and enhances surface finish, making the final FRPCs more reliable for structural applications.

(a) (b) (c) (d)

Fig. 2 Various stages of the vacuum bag moulding process

The specimens were then cured as per the predetermined curing temperature and curing time in a hot air oven at the Micropaleontology Lab, Department of Geology, Bangalore University, Bangalore. Fig. 3 shows the specimens fabricated as per experimental plan.

Fig 3. Specimens fabricated as per experimental plan

2.5 Cutting of specimens by Abrasive Waterjet Cutting

The fabricated fibre reinforced polymer composite specimens were then cut according to dimensions mentioned in ASTM standards for mechanical characterization. The specimens were cut by an abrasive waterjet cutting machine at BMS College of Engineering, Bangalore, Karnataka, India. Fig. 4 shows the specimen cut for various mechanical tests.

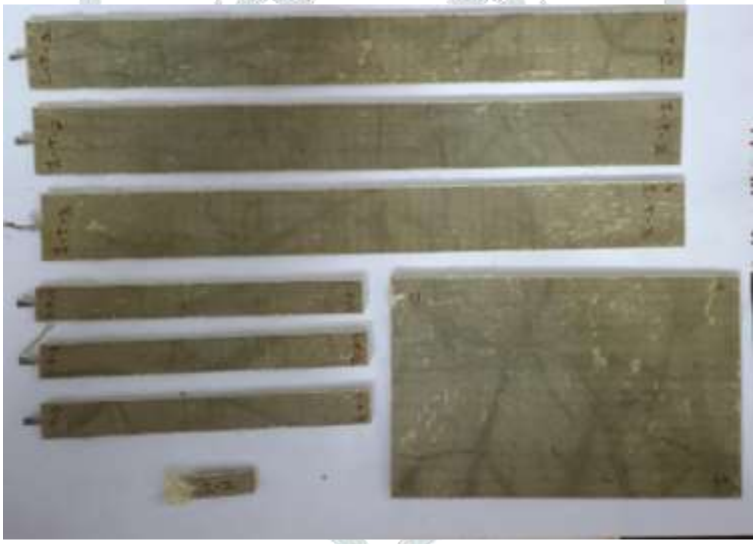

Fig. 4 A fabricated specimen cut for various tests

2.6 Mechanical Characterization

The characterization of the fabricated specimens involved conducting four tests, namely, Tensile Test (ASTM D3039), Flexural Test (ASTM D790), Inter Laminar Shear Strength Test (ASTM D2344) and Energy Absorption Test. The tensile test, flexural test and inter laminar shear strength tests were conducted using a Universal Testing Machine at SLN Testing Laboratory Private Limited, Bangalore, Karnataka, India. The energy absorption test was conducted using the drop weight test facility at Vemana Institute of Technology, Bangalore, Karnataka, India. Fig. 5 shows the drop weight impact test facility.

Fig 5. Drop weight impact test facility

III. RESULTS AND DISCUSSIONS

3.1 Results of Mechanical Characterization

The results of mechanical characterization tests conducted: tensile test, flexural test, inter laminar shear strength (ILSS) test and energy absorption test are shown in Table 7.

Table 7 Results of Mechanical Characterization of Specimens

Specimen	Wt.% of SiC	Wt.% of ZnO	Temperature (^{0}C)	Time (Minutes)	Tensile Strength (MPa)	Flexural Strength (MPa)	ILSS (MPa)	Energy Absorbed (J)
1	0.5	1	95	55	461.23	160.8	431.32	44
2	0.5	1.25	100	60	338.57	197.07	387.54	60
3	0.5	1.5	105	65	215.84	114.84	212.65	60
4	0.5	1.75	110	70	261.16	139.36	260.25	43
5	0.75	1	100	65	276.98	131.17	290.65	45
6	0.75	1.25	95	70	392.42	174.55	290.65	44
7	0.75	1.5	110	55	279.16	139.87	330.57	55
8	0.75	1.75	105	60	440.41	167.52	417.32	60
9	1	1	105	70	335.73	145.7	301.58	60
10	1	1.25	110	65	349.63	155.51	360.58	58
11	1	1.5	95	60	385.03	168.14	426.32	54
12	1	1.75	100	55	251.83	114.03	287.32	53
13	1.25	1	110	60	289.6	145.12	287.32	31
14	1.25	1.25	105	55	310.7	143.21	312.35	38
15	1.25	1.5	100	70	356.16	122.94	403.32	36
16	1.25	1.75	95	65	354.77	142.65	360.58	51

3.2 Multi Response Performance Index (MRPI)

Multi Response Performance Index (MRPI) studies were conducted to determine the performance index of fabricated specimen which had the highest performance index and also to determine the parametric conditions for the best possible optimized specimen which could be fabricated. Table 8 shows the weights of all the properties and the MRPI values of all the specimens. It can be observed from Table 8 that Specimen 1 has the highest MRPI value, with the highest performance which indicates that it has the best overall mechanical performance, ensuring reliability and efficiency.

Table 8 MRPI Table

Specimen	**TS**	**W_{TS}**	**FS**	**W_{FS}**	**ILSS**	**W_{ILSS}**	**EA**	**W_{EA}**	**MRPI**
1	461.23	0.087	160.8	0.068	431.32	0.080	44	0.055	**87.987**
2	338.57	0.063	197.07	0.083	387.54	0.072	60	0.075	70.089
3	215.84	0.040	114.84	0.048	212.65	0.039	60	0.075	26.939
4	261.16	0.049	139.36	0.058	260.25	0.048	43	0.054	35.69
5	276.98	0.052	131.17	0.055	290.65	0.054	45	0.056	39.832
6	392.42	0.074	174.55	0.073	290.65	0.054	44	0.055	59.896
7	279.16	0.052	139.87	0.059	330.57	0.061	55	0.069	46.572
8	440.41	0.083	167.52	0.070	417.32	0.077	60	0.075	84.891
9	335.73	0.063	145.7	0.061	301.58	0.058	60	0.075	52.03
10	349.63	0.065	155.51	0.065	360.58	0.067	58	0.073	61.226
11	385.03	0.072	168.14	0.071	426.32	0.079	54	0.068	77.011
12	251.83	0.047	114.03	0.048	287.32	0.053	53	0.066	36.035
13	289.6	0.054	145.12	0.061	287.32	0.053	31	0.039	40.927
14	310.7	0.058	143.21	0.060	312.35	0.058	38	0.047	46.515
15	356.16	0.067	122.94	0.052	403.32	0.075	36	0.045	62.124
16	354.77	0.066	142.65	0.060	360.58	0.067	51	0.064	59.396

Table 9 shows the level totals of the MRPI values. It can be observed from Table 9 that the optimum process parameter for the specimen for maximum MRPI is A2B2C1D2.

Table 9 Level Totals of the MRPI Values

Level	**Wt. % of SiC**	**Wt. % of ZnO**	**Temperature (^{0}C)**	**Time (Minutes)**
1	220.705	220.776	**284.29**	217.109
2	**231.291**	**237.726**	208.08	**272.918**
3	226.302	212.646	210.375	187.393
4	208.962	216.012	184.415	209.74

The combinations for optimized mechanical properties along with their predicted value is given in Table 10.

Table 10 Predicted Optimized MRPI Table

Output Parameter	**Optimized MRPI Process Parameter**	**Predicted Value**
Maximum Tensile Strength	**A2B2C1D2**	**512.1 MPa**
Maximum Flexural Strength		**232.45 MPa**
Maximum ILSS		**421.86 MPa**
Maximum Energy Absorption		**52**

3.3 Confirmatory Test

A specimen was fabricated as per the parametric levels derived from the MRPI optimization studies. The specimen for the confirmatory tests was fabricated by vacuum bag moulding process. The specimen fabricated was to test for confirming the maximum tensile strength, flexural strength, inter laminar shear strength and energy absorption with the process parameter A2B2C1D2 derived from the MRPI optimization technique.

Table 11 MRPI Confirmatory Tests Table

Output Parameter	Optimized MRPI Process Parameter	Predicted Value	Experimental Value	Error %
Maximum Tensile Strength	**A2B2C1D2**	**512.1 MPa**	**468.31 MPa**	**8.5**
Maximum Flexural Strength		**232.45 MPa**	**211.62 MPa**	**8.9**
Maximum ILSS		**421.86 MPa**	**387.32 MPa**	**8.1**
Maximum Energy Absorption		**52 J**	**48 J**	**7.6**

Table 11 shows the results of the confirmatory tests conducted. The predicted value, experimental value and the error percentage can also be observed from the table.

IV. CONCLUSIONS AND SCOPE

The specimens were fabricated as per the Taguchi L16 experimental plan and were evaluated for mechanical properties such as tensile strength, flexural strength, inter laminar shear strength and energy absorption. MRPI optimization studies were conducted to predict the optimal conditions for specimens. Finally, confirmatory tests were carried out for repeatability and validity of the experimental design.

MRPI optimization studies predicted that for optimal mechanical properties, the parametric condition was A2B2C1D2 (0.75 weight percent of SiC, 1.25 weight percent of ZnO, curing temperature of 95^0C and curing time of 60 minutes).

Confirmatory tests were conducted for repeatability and validation of the MRPI optimization and it was observed that the predicted value and experimental values were in good agreement with each other.

V. ACKNOWLEDGMENT

The authors would like to acknowledge and thank: The Department of Geology, Bangalore University, Bangalore; The Department of Mechanical Engineering, BMS College of Engineering, Bangalore and The Department of Mechanical Engineering, Vemana Institute of Technology, Bangalore, for extending their facilities for fabrication and testing of specimens during this research.

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