Assessment of mechanical and three-body abrasive wear peculiarity of TiO₂- and ZnO-filled bi-directional E-glass fibre-based polyester composites

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Abstract. This paper is about the development of bi-directional E-glass fibre-based polyester composites filled with zinc oxide (ZnO) and titanium dioxide (TiO₂) fillers, respectively. The mechanical characterization of these composites is performed. The three-body abrasive wear characteristic of fabricated composites has been assessed under different operating conditions. For this, the three-body abrasion test is done on dry abrasion test rig (TR-50) and analysed using Taguchi's experimental design scheme and analysis of variance. The results obtained from these experiments are also validated against existing microscopic models of Ratner–Lancaster and Wang. A good linear relationship is obtained between specific wear rate and the reciprocal of ultimate strength and strain at tensile fracture of these composites. It indicates that the experimentally obtained results are in good agreement with these existing models. It is found that the tensile strength decreases with filler loading, while hardness, flexural strength, inter-laminar shear strength and impact strength are increased. TiO₂-filled composites were observed to perform better than ZnO-filled composites under abrasive wear situations. The wear mechanism is studied in correlation with the SEM micrograph of the worn-out surface of composites. Performance optimization of composites is done by using VIKOR method.

Keywords. Mechanical property; three-body abrasive wear; Taguchi methodology; surface morphology; VIKOR method.

1. Introduction

The word 'composite' means 'constituting of two or more distinct parts.' Thus, a material having two or more distinct constituent materials or phases may be considered a composite material. It is only when the constituent phases have significantly different physical properties and thus the composite properties are noticeably different from the constituent properties that we recognize these materials as composites [1]. In past years, because of fairly good strength, low density and high performance/cost ratios with rapid clean processing, tremendous growth in the development and applications of fibre and filler-reinforced thermo-setting polymer composites such as epoxy, polyester and vinyl ester have been observed. Polymer and their composites are used in a variety of industrial applications such as bearing material, rollers, seals, gears, cams, wheels, clutches and transmission belts [2–5]. Therefore, the mechanical and tribological behaviours of these materials should be studied systematically. Carbon, glass, aramide and graphite fibres are most common fibres used as reinforcing material in polymer matrix composites [6,7]. It is evident from the literature that in general, the short fibre reinforcement led to the deterioration in the abrasive wear resistance of the matrix [8], while on the

other hand, reinforcement of the fabric improved the abrasion resistance of the polymers [9]. That is why the bi-directional fabric reinforcement offers a unique solution for the advanced materials in terms of better performance and ease of processing [10].

Fillers as reinforcing material have been used by various researchers. Kumaresan *et al* [11] have done the dynamic mechanical analysis (DMA) and three-body wear of carbon–epoxy composite filled with SiC particles and found that the abrasive wear and DMA investigations on SiC-filled samples exhibit the better wear resistance, higher T_g and improved storage modulus than neat C–E materials proposed for bearing applications. Suresha *et al* [12] investigated the abrasive wear behaviour of filled epoxy composite systems and concluded that low wt% of boron carbide filler in epoxy showed good performance to the three-body abrasive wear. Higher wt% of BC filler (>10%) was observed to be non-beneficial to abrasive wear performance. Under the two-body abrasive wear, some differentiation in wear behaviour between the neat LDPE- and nano-clay-filled LDPE/EVA (low-density polyethylene/ethylene vinyl acetate) composite was seen. Nano-clay filled LDPE/EVA composite with compatibilizer exhibited superior abrasion resistance [13]. The silane-treated graphite filler addition to C–E samples has exceptionally improved the abrasive wear and the physical and mechanical properties like density, tensile strength, tensile modulus and hardness properties. Hence, higher graphite

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Table 1. Designations and detailed compositions of the composites.

Composite designation	Composite composition
C _U	Polyester + 40 wt% glass fibre
C _{T10}	Polyester + 40 wt% glass fibre + 10 wt% TiO ₂ composites
C _{T20}	Polyester + 40 wt% glass fibre + 20 wt% TiO ₂ composites
C _{Z10}	Polyester + 40 wt% glass fibre + 10 wt% ZnO composites
C _{Z20}	Polyester + 40 wt% glass fibre + 20 wt% ZnO composites

addition is the preferred choice for the application involving abrasive wear situations [14].

Many researchers have been investigated the three-body abrasive wear behaviour of polymer composites [15–18]. Sanjeev *et al* [19] studied the influence of amount and size on the abrasive wear performance of SiC-UHMWPE (ultrahigh-molecular-weight polyethylene) nano-composites and concluded that inclusion of SiC proved beneficial to enhance the abrasive wear resistance of UHMWPE, the extent of which depended on applied load, amount and size of particles. The increase in hardness of composites due to the inclusion of SiC filler reduced the severity of an abrasion process, which was supported by SEM (scanning electron microscope) studies (reduced micro-cutting).

The present work is undertaken for assessing the wear behaviour of bi-directional E-glass fibre-based polyester composites filled with ZnO and TiO₂, respectively, under abrasive situations. The mechanical characterization of these composites is also performed so as to have an insight into this aspect. An economical and viable experimental strategy based on Taguchi's parameter design has been used to analyse the effect of various parameters and their interactions. This experimental procedure has been successfully applied earlier for solid particle erosion behaviour and dry sliding characteristics of polymer–matrix composites [20–22].

2. Experimental

2.1 Composite fabrication

Bi-directional E-glass fibre is reinforced in polyester resin filled with TiO₂ and ZnO fillers, respectively. In the present study, five types of composites are fabricated and designated as C_U, C_{T10}, C_{T20}, C_{Z10} and C_{Z20}. The composition of the prepared composites is listed in table 1. The fabrication of the composite is done by conventional hand-layup technique followed by light compression moulding technique. The following operations are involved in a typical hand lay-up process:

2.1a Mould preparation: This is an important function in the moulding cycle. If it is done well, the prepared samples appear good and separate easily from the mould. In the present work, wood is used to prepare the mould. A silicon rubber sheet is used at the base of the mould as a releasing

Table 2. Properties of polyester resin.

Density (g cm ⁻³)	1.1–1.4
Tensile strength (MPa)	34.5–103.5
Tensile modulus (GPa)	2–4.4
Thermal expansion (10 ⁻⁶ °C ⁻¹)	55–100
Water absorption (% in 24 h)	0.15–0.6

agent. The choice of releasing agent depends on the type of surface to be moulded and the degree of luster desired on the finished product.

2.1b Hand lay-up: After preparing the mould properly, the filler material is mixed with the matrix material (polyester resin) as per required wt% in a glass jar. Mixture of filler and polyester resin is thoroughly stirred with the help of a glass stirrer for 2 min. Hardener is mixed into the resin mixture for curing the composite material. Resin mixture and hardener (methyl-ethyl-ketone-peroxide) are mixed in a ratio of 10 : 1 by weight as recommended. After preparing the resin mixture in a glass jar, a layer of resin mixture is put on the silicon rubber sheet of the prepared mould by the hand brush. A single ply of bi-directional E-glass fibre is placed on the layer of the resin mixture. A serrated roller is used to compact the glass fibre against the mould to remove any entrapped air. After rolling, another layer of resin mixture is placed on the glass fibre and again a single ply of bi-directional E-glass fibre placed on it. This process is continued until the desired thickness of the composite is obtained. After obtaining the required thickness of the composite material, another silicon rubber sheet is put on the last layer of the glass fibre, and mould is closed with the wooden block. The weight of 5 kg is placed on the mould and it is left for 24 h for curing.

Polyester resin, bi-directional E-glass fibre and the hardener are supplied by Shakshi dyes and chemicals, New Delhi, India. Properties of polyester resin and glass fibre are shown in tables 2 and 3, respectively. TiO₂ and ZnO fillers are supplied by the Pioneer Chemical Company, Delhi, India. Properties of TiO₂ and ZnO fillers are shown in table 4. The ply of fibres of dimension 300 × 300 mm² and 200 × 200 mm² are used for fabrication of wear test samples and mechanical properties samples, respectively. Silicon sheets with dimensions of 310 × 310 × 80 mm³ and 210 × 210 × 40 mm³ are used for fabrication of composites. A releasing agent (silicon spray) is used to facilitate easy removal of the

Table 3. Properties of bi-directional E-glass fibre.

Density (g cm^{-3})	2.55–2.6
Bulk modulus (GPa)	43–50
Elastic modulus (MPa)	2750–2875
Hardness (MPa)	3000–6000
Shear modulus (GPa)	30–36
Tensile strength (MPa)	1950–2050
Young's modulus (GPa)	72–85
Endurance limit (MPa)	2970–3110
Thermal expansion ($10^{-6} \text{ }^{\circ}\text{C}^{-1}$)	4.9–5.1
Thermal conductivity (W mK^{-1})	1.2–1.35
Poisson's ratio	0.21–0.23

Table 4. Properties of TiO_2 and ZnO filler.

	TiO_2	ZnO
Density (g cm^{-3})	4.01	5.61
Melting point ($^{\circ}\text{C}$)	1840	1975
Thermal conductivity (W mK^{-1})	11.8	60
Heat of fusion (J g^{-1})	875	642
Dielectric constant	10	8.5

Figure 1. Typical appearance of wear scars on specimens.

composite from the mould after curing. The cast of each composite is cured under a load of about 50 kg for 24 h before it is removed from the mould. After this, the cast posts cured in the air for another 24 h. Wear out samples are shown in figure 1.

2.2 Abrasive wear test

To evaluate the performance of composites under three-body abrasion conditions, wear tests are carried out as per ASTM G 65 using the dry abrasion test rig (TR-50) supplied by DUCOM Ltd, Bangalore, India, as shown in figure 2 [23]. The

Figure 2. Abrasive wear test setup.

dry sand/rubber wheel ($\varnothing$ 228.6 mm, hardness durometer A-60) abrasion test involves the abrading of the test specimen with a grit of controlled size and composition. The abrasive is introduced between the test specimen and a rotating wheel with a chlorobutyl rubber tire. The test specimen is pressed against a rotating wheel at a specified force using a lever arm, while a controlled flow of grit abrades the test surface. The test duration and force applied by the lever arm are varied. Schematic diagram of dry abrasion test rig is shown in figure 3. The specimens are weighed before and after the test and loss in mass are recorded but due to the wide difference in material density abrasion are reported on volume loss basis as [24–26].

$$W_s = \frac{\Delta m}{\rho L F_n}, \quad (1)$$

where Δm is the mass loss in the test duration in grams (g), ρ the density of the composite (g cm^{-3}), L the sliding distance (m) and F_n is the normal load (N). The specific wear rate is defined as the volume loss of the specimen per unit sliding distance per unit applied normal load.

3. Mechanical characterization

The experimental density of the composites is obtained by Archimedes principle by weighing small pieces cut from the large composite panel first in the air and then in water. The theoretical density of the composite is calculated and compared with experimental density to calculate the void fraction of the composites. The hardness measurement is done using a Rockwell-hardness tester equipped with a steel ball ($1/16''$) indenter by applying a load of 100 kgf. The tensile

Figure 3. Schematic diagram of dry abrasion tester (TR-50).

test is performed on flat dog-bone shaped composite specimens as per ASTM D 3039-76 test standards on the universal testing machine (UTM) Hounsfield H50KS [27]. The flexural and inter-laminar shear strength test is conducted as per ASTM standard D2344-84 using the same UTM [28]. The low velocity instrumented impact tests are carried out on composite specimens. The tests are done as per ASTM D 256 using an impact tester [29]. Finally, the worn surfaces of some selected samples are examined by scanning electron microscope Carl Zeiss NTS GmbH, SUPRA 40 VP.

4. Experimental design

In the present investigation, five factors and three levels were selected for Taguchi design of experiment as shown in table 5. The impact of five parameters is investigated using L_{27} orthogonal design (figure 4). The L_{27} (3^{13}) is a more conventional 3^n series orthogonal array and contains three levels in each of its 13 columns. A maximum of 13 three-level factors can be incorporated into the L_{27} (3^{13}). As many as three interactions can be assigned within the array. But as more interactions are included, fewer factors (main effects) can be considered. The L_{27} array required only 27 experiments, while the conventional full-factorial experiment design would have required $3^4 = 81$ runs. In the L_{27} array,

Table 5. Levels for various control factors.

Control factor	Levels		
	I	II	III
Sliding speed (A), m s^{-1}	0.5	1	1.5
Filler loading (B), wt%	0	10	20
Normal load (C), N	4	8	12
Sliding distance (D), m	40	120	200
Abrasive size (E), μm	300	450	600

interaction takes place between the factors and there are 13 columns as shown in table 6.

The plan of the experiments is: the first column is assigned to sliding velocity (A), filler content (B) is assigned second column, the fifth and ninth columns are assigned to normal load (C) and sliding distance (D), respectively. The third and fourth columns are assigned to estimate interaction between sliding velocity (A) and filler content (B) as $(A \times B)_1$ and $(A \times B)_2$, respectively, the sixth and seventh columns are assigned to $(B \times C)_1$ and $(B \times C)_2$, respectively, to estimate the interaction between filler content (B) and normal load (C), the eighth and eleventh columns are assigned to $(A \times C)_1$ and $(A \times C)_2$, respectively, to estimate interaction between the sliding velocity (A) and normal load (C) and the remaining columns are used to estimate experimental errors.

Figure 4. Linear graph for L_{27} orthogonal array.

Table 6. Orthogonal array for L_{27} (3^{13}) Taguchi design.

L_{27} (3^{13})	1 A	2 B	3 ($A \times B$) ₁	4 ($A \times B$) ₂	5 C	6 ($B \times C$) ₁	7 ($B \times C$) ₂	8 ($A \times C$) ₁	9 D	10 E	11 ($A \times C$) ₂	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

There are three categories of quality characteristics, i.e., lower-the-better, higher-the-better and nominal the-better. To obtain optimal performance, lower-the-better characteristic for wear rate must be taken. The mean-square deviation (M.S.D.) for the lower-the-better characteristic can be expressed as [30]:

$$\text{'Smaller-the-better' characteristic: } \frac{S}{N} = -10 \log \frac{1}{N} \left(\sum y^2 \right), \quad (2)$$

where N is the number of observations and y the observed data.

5. Performance optimization of composites using VIKOR method

VIKOR method is introduced as one applicable technique to be implemented within multi-attribute decision making (MCDM) problem and it is developed as an MCDM method to solve a discrete decisionmaking problem with non-commensurable (different units) and conflicting criteria [31,32]. This method focusses on ranking and selecting from a set of alternatives and determines compromise solution for a problem with conflicting criteria, which can help the decision makers to reach a final solution. The compromise

ranking algorithm of the VIKOR method has the following steps [33]:

Step 1: Determine the best f_j^* and the worst f_j^- values of all criterion functions $j = 1, 2, \dots, n$. If the j th function represents a benefit then:

$$f_j^* = \max_i f_{ij}, \quad f_j^- = \min_i f_{ij}. \quad (3)$$

If the j th function represents a cost then:

$$f_j^* = \min_i f_{ij}, \quad f_j^- = \max_i f_{ij}. \quad (4)$$

Step 2: Compute the values S_i and R_i ; $i = 1, 2, \dots, m$, by these relations:

$$S_i = \sum_{j=1}^n (f_j^* - f_{ij}) / (f_j^* - f_j^-), \quad (5)$$

$$R_i = \max_j (f_j^* - f_{ij}) / (f_j^* - f_j^-). \quad (6)$$

Step 3: Compute the values Q_i ; $i = 1, 2, \dots, m$, by the following relation:

$$Q_i = v(S_i - S^*) / (S^- - S^*) + (1 - v)(R_i - R^*) / (R^- - R^*), \quad (7)$$

where

$$S^* = \min_i S_i, \quad S^- = \max_i S_i, \quad (8)$$

$$R^* = \min_i R_i, \quad R^- = \max_i R_i, \quad (9)$$

v is introduced as weight of the strategy of 'the majority of criteria' (or 'the maximum group utility'), here suppose that $v = 0.5$.

Step 4: Rank the alternatives, sorting by the values of Q_i in decreasing order.

6. Results and discussion

6.1 Mechanical properties

In the present research work, the theoretical density of composite materials in terms of weight fraction is calculated by using the equation proposed by Agarwal and Broutman [1].

$$\rho_{ct} = \frac{1}{(W_m / \rho_m) + (W_f / \rho_f)}, \quad (10)$$

where W and ρ represent the weight fraction and density, respectively. The suffix m, f and ct stand for the matrix, particulate filler and the composite materials, respectively.

The actual density (ρ_{ca}) of the composite, however, can be determined experimentally by Archimedes principle (ASTM: D792). The volume fraction of voids (V_v) in the composites is calculated using the equation:

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}}. \quad (11)$$

Theoretical and measured densities of composites, along with the corresponding volume fraction of voids are shown in table 7. It is found that the composite density values calculated theoretically from weight fractions are not equal to the experimentally measured values, as expected. It is evident from table 7 that the density of TiO₂- and ZnO-filled composites increase with the filler content.

Hardness values of the TiO₂-filled E-glass fibre-based polyester composites have been obtained and are compared with those of a similar wt% of ZnO-E-glass fibre-based polyester composites. The test results (figure 5) show that the hardness of polyester composites is improved, and this improvement is a function of the filler loading. The hardness of TiO₂-filled composites are more as compared to ZnO-filled composites.

The variation of the tensile strength of both the TiO₂-filled and ZnO-filled E-glass fibre-based polyester composites are presented in figure 6. The figure shows a decrement in tensile strength for TiO₂-filled composites when wt% of TiO₂ increased. The same pattern is observed in the case of ZnO-filled composite. Whereas in unfilled composites, the tensile

Figure 5. Variation of hardness of the composites with fibre loading.

Table 7. Composite designations and their experimental and theoretical densities.

Composite designation	Composite composition	Experimental density (δ_e) g cm ⁻³	Theoretical density (δ_t) g cm ⁻³	Void fraction (%) $V_f = (\delta_t - \delta_e) / \delta_t$
C _U	Polyester + 40 wt% glass fibre	1.593021	1.668103	4.5010
C _{T10}	Polyester + 40 wt% glass fibre + 10 wt% TiO ₂ composites	1.686673	1.821328	7.3932
C _{T20}	Polyester + 40 wt% glass fibre + 20 wt% TiO ₂ composites	1.732313	2.005549	13.6240
C _{Z10}	Polyester + 40 wt% glass fibre + 10 wt% ZnO composites	1.667932	1.840782	9.3900
C _{Z20}	Polyester + 40 wt% glass fibre + 20 wt% ZnO composites	1.686534	2.053341	17.8639

Figure 6. Variation of tensile strength of composites with filler loading.

Figure 8. Variation of inter-laminar shear strength with filler loading.

Figure 7. Variation of flexural strength of composites with filler loading.

Figure 9. Variation of impact strength of the composites with filler loading.

strength is comparatively higher than the filled composites. TiO₂-filled composites had higher tensile strength than ZnO-filled composite for the same filler loading conditions. There can be two reasons for the decline in the tensile strength; one possibility is that the interface bonding between the filler particles and the matrix may be too weak to transfer the tensile stress. It is due to reduced wt% of the matrix material. The second possibility is that the decrement with filler loading in tensile strength may be because of insufficient wetting of polyester into the fibre and poor fibre–matrix adhesion [18]. In higher volume fraction, many fibres end in unit volume that leads to higher stress concentration that in turn results in crack propagation at the finite localized region. The region is not able to sustain the applied tensile stress [34]. ZnO composite filled with 20 wt% have the minimum tensile strength of all the fabricated composites. It may happen due to the high void fraction as shown in table 7.

The variation of the flexural strength of both the TiO₂-filled and ZnO-filled E-glass fibre-based polyester composites with different filler loading is shown in figure 7. A gradual improvement in flexural strength with the filler weight fraction is noticed in both the TiO₂-filled and ZnO-filled E-glass fibre-based polyester composites. In the present work, short beam shear test is carried out on the composites with different filler loading to determine the inter-laminar shear strength (ILSS). The variation of ILSS of E-glass

fibre-based polyester composites filled with TiO₂ and ZnO, respectively, are presented in figure 8. A gradual improvement in ILSS with the filler weight fraction is noticed in E-glass fibre-based polyester composites. TiO₂-filled composites had higher ILSS as compared to ZnO-filled composites at 10 wt% as well as at 20 wt% of filler loading.

Figure 9 presents the measured impact energy values of the various composites under this investigation. It is seen from this figure that the impact energies of glass fibre–polyester composites increase gradually with an increase in filler wt%. Here also, TiO₂-filled composites have better impact energy than the ZnO-filled composites. TiO₂-filled composite with 20 wt% has maximum impact strength.

7. Steady-state specific wear

7.1 Variation of specific wear rate with normal load under steady-state condition

Figure 10 shows the variation of specific wear rate with normal load under steady-state conditions for TiO₂- and ZnO-filled E-glass fibre–polyester composites at sliding speed of 0.5 m s⁻¹ and figure 11 shows same at sliding speed 1.0 m s⁻¹. It is observed that specific wear rate increases with increase in the load [35]. The unfilled composite exhibits highest wear rate for all load conditions for each sliding

Figure 10. Variation of specific wear rate with normal load under steady-state condition (sliding speed = 0.5 m s^{-1} , sliding distance = 120 m, abrasive size = 425 μm).

Figure 12. Variation of specific wear rate with sliding distance under steady-state condition (normal load = 4 N, sliding speed = 0.5 m s^{-1} , abrasive size = 425 μm).

Figure 11. Variation of specific wear rate with normal load under steady-state condition (sliding speed = 1 m s^{-1} , sliding distance = 120 m, abrasive size = 425 μm).

Figure 13. Variation of specific wear rate with sliding distance under steady-state condition (normal load = 12 N, sliding speed = 0.5 m s^{-1} , abrasive size = 425 μm).

speed, i.e., 0.5 and 1.0 m s^{-1} . At extreme loading conditions of 12 N, it is found that unfilled E-glass fibre-reinforced composites exhibit higher wear rate, while again 20 wt% TiO₂-filled E-glass fibre-reinforced composites exhibit lowest wear rate. The reason is that TiO₂-filled composites have excellent mechanical properties as compared to ZnO-filled composites. There is comparatively good adhesion between the fibre and matrix. The wt% of filler is also affected the wear response of composites. TiO₂-filled composites performed better as compared to ZnO-filled composites as observed from figures 10 and 11.

7.2 Variation of specific wear rate with sliding distance under steady-state condition

Figure 12 shows the variation of specific wear rate with sliding distance under steady-state conditions for TiO₂- and ZnO-filled E-glass fibre-polyester composites at normal load of 4 N. Figure 13 shows same at normal load of 12 N. It is found that at small sliding distance, unfilled E-glass fibre-reinforced composites exhibit highest specific wear rate and

the same phenomenon is shown among all the sliding distances. Specific wear rate of composites is decreased with increase in the sliding distance [11,36]. The lowest wear rate is shown by 20 wt% TiO₂-filled composites at a sliding speed of 200 m. For both loading conditions, there is significant variation in the trend of specific wear rate. For all sliding distance of 20 wt%, TiO₂-filled E-glass fibre-reinforced composites exhibit the lowest wear, but 10 wt% TiO₂-filled composite have higher wear rate than 20 wt% ZnO-filled composite. It is found that for same wt% of filler loading, TiO₂ effects wear rate more than ZnO filler. TiO₂-filled composites performed better at low as well as at high load conditions. Therefore, it is suggested that during abrasive wear condition of 40 wt% fibre loading, filler TiO₂ is better than ZnO.

8. Taguchi experimental analysis

This part presents the analysis and comparison of abrasive wear response of bi-directional E-glass fibre-based polyester composites filled with TiO₂ and ZnO, respectively. The experiments have been carried out using Taguchi experimental design L₂₇. The subsequent analysis of the test results

is made using the popular software specifically used for the design of experiment applications known as MINITAB 16.

The results of abrasive wear experiments carried out according to the predetermined design on bi-directional E-glass fibre-based polyester composites filled TiO_2 and ZnO are presented in tables 8 and 9, respectively. The eighth column in tables represents S/N ratio of the wear rate of TiO_2 -filled bi-directional E-glass fibre–polyester composites, and ZnO-filled bi-directional E-glass fibre–polyester composites, respectively. The overall mean for the S/N ratio of the wear rate is found to be -18.6721 db for TiO_2 -filled bi-directional E-glass fibre–polyester composite and -19.6254 db ZnO-filled bi-directional E-glass fibre–polyester composites. Before any attempt is made to use this simple model as a predictor for the measure of performance, the possible interactions between the control factors must be considered and in this particular case $A \times B$, $A \times C$ and $A \times E$ interactions among the control factors are done. Analysis of the result leads to the conclusion that factor combination of A_1 (sliding speed, 0.5 m s^{-1}), B_2 (filler loading, 10%), C_1 (normal load, 4 N), D_1 (sliding distance, 40 m) and E_1 (abrasive size, $300 \mu\text{m}$) gives minimum wear rate (figure 14) for TiO_2 -filled bi-directional E-glass fibre–polyester composites. For ZnO-filled bi-directional E-glass fibre–polyester composites,

the factor combination of A_1 (sliding speed, 0.5 m s^{-1}), B_2 (filler loading, 10%), C_1 (normal load, 4 N), D_1 (sliding distance, 40 m) and E_1 (abrasive size, $300 \mu\text{m}$) gives minimum wear rate (figure 15). Figures 16 and 17 present the interaction graph for specific wear rate of TiO_2 -filled and ZnO-filled composites, respectively.

9. Surface morphology

To characterize the morphology and to find out predominant wear mechanisms, worn surfaces of materials were examined by SEM. Abrasive wear occurs by three different mechanisms, viz. microploughing, microcutting and microcracking (brittle fracture) [37]. Using SEM images, it is possible to identify qualitatively the dominant mechanism that operates and thus, gain insight into the influence that the reinforcement has on the abrasive wear process. The examination of the wear scars indicated that the damage morphologies for all samples were similar, consisting of three zones, a short entrance, exit area and the main central wear zone. A typical wear scar obtained at different loading conditions is shown in figure 1. Figures 18–20 present the SEM micrographs of TiO_2 -filled bi-directional E-glass fibre-reinforced composites. Figure 18 shows the SEM micrograph of unfilled

Table 8. Experimental design using an L_{27} orthogonal array for TiO_2 -filled bi-directional E-glass fibre-based polyester composites.

Runs	Sliding speed (A) (m s^{-1})	Filler loading (B) (%)	Normal load (C) (kgf)	Sliding distance (D) (m)	Abrasive size (E) (μm)	$W_{\text{ST}} (10^{-2} \times \text{mm}^3 \text{Nm}^{-1})$	S/N ratio (db)
1	0.5	0	4	40	300	8.24318	-18.3219
2	0.5	0	8	120	425	10.71233	-20.5977
3	0.5	0	12	200	600	9.11589	-19.196
4	0.5	10	4	120	600	6.02183	-15.5946
5	0.5	10	8	200	300	4.1319	-12.323
6	0.5	10	12	40	425	1.2949	-2.24472
7	0.5	20	4	200	425	5.9901	-15.5487
8	0.5	20	8	40	600	12.3585	-21.8393
9	0.5	20	12	120	300	5.6102	-14.9796
10	1	0	4	40	300	9.899	-19.9118
11	1	0	8	120	425	11.4235	-21.156
12	1	0	12	200	600	15.5462	-23.8325
13	1	10	4	120	600	6.8748	-16.7452
14	1	10	8	200	300	4.2019	-12.4689
15	1	10	12	40	425	12.9152	-22.222
16	1	20	4	200	425	6.1871	-15.8297
17	1	20	8	40	600	19.9867	-26.0148
18	1	20	12	120	300	5.6062	-14.9734
19	1.5	0	4	40	300	10.9423	-20.7822
20	1.5	0	8	120	425	12.522	-21.9535
21	1.5	0	12	200	600	17.8156	-25.016
22	1.5	10	4	120	600	9.0316	-19.1153
23	1.5	10	8	200	300	5.0389	-14.0467
24	1.5	10	12	40	425	25.6144	-28.1697
25	1.5	20	4	200	425	7.1941	-17.1395
26	1.5	20	8	40	600	22.3259	-26.9762
27	1.5	20	12	120	300	7.2017	-17.1487

Table 9. Experimental design using an L_{27} orthogonal array for ZnO-filled bi-directional E-glass fibre-based polyester composites.

Runs	Sliding speed (A) (m s^{-1})	Filler loading (B) (%)	Normal load (C) (kgf)	Sliding distance (D) (m)	Abrasive size (E) (μm)	W_{SZ} ($10^{-2} \times \text{mm}^3 \text{Nm}^{-1}$)	S/N ratio (db)
1	0.5	0	4	40	300	8.24318	-18.3219
2	0.5	0	8	120	425	10.71233	-20.5977
3	0.5	0	12	200	600	9.11589	-19.196
4	0.5	10	4	120	600	10.4397	-20.3738
5	0.5	10	8	200	300	4.1127	-12.2825
6	0.5	10	12	40	425	13.6544	-22.7055
7	0.5	20	4	200	425	5.8298	-15.3131
8	0.5	20	8	40	600	17.7559	-24.9869
9	0.5	20	12	120	300	4.2496	-12.567
10	1	0	4	40	300	9.899	-19.9118
11	1	0	8	120	425	11.4235	-21.156
12	1	0	12	200	600	15.5462	-23.8325
13	1	10	4	120	600	8.6987	-18.7891
14	1	10	8	200	300	3.4903	-10.8573
15	1	10	12	40	425	15.1209	-23.5916
16	1	20	4	200	425	5.9386	-15.4737
17	1	20	8	40	600	19.7479	-25.9104
18	1	20	12	120	300	6.4989	-16.2568
19	1.5	0	4	40	300	10.9423	-20.7822
20	1.5	0	8	120	425	12.522	-21.9535
21	1.5	0	12	200	600	17.8156	-25.016
22	1.5	10	4	120	600	10.8887	-20.7395
23	1.5	10	8	200	300	3.5862	-11.0927
24	1.5	10	12	40	425	20.3836	-26.1856
25	1.5	20	4	200	425	7.5834	-17.5973
26	1.5	20	8	40	600	22.9319	-27.2088
27	1.5	20	12	120	300	7.2344	-17.1881

Main effects plot for S/N ratios

Data means

Signal-to-noise: smaller is better

Figure 14. Effect of control factors on wear rate (TiO₂-filled E-glass fibre polyester composites).

Figure 15. Effect of control factors on wear rate (ZnO-filled E-glass fibre polyester composites).

Figure 16. Interaction graph for specific wear rate (TiO₂-filled E-glass fibre polyester composites).

composite for normal load of 12 N. Figure 12 shows that unfilled composite exhibits higher abrasion wear rate. This is due to ploughing and large depth grooves cutting mode

abrasive wear that results in the bulk removal of the material. This is also shown in figure 18. The unfilled composite shows higher wear rate for both 4 and 12 N loads.

Figure 17. Interaction graph for specific wear rate (ZnO-filled E-glass fibre polyester composites).

Figure 18. SEM micrographs of the abraded unfilled composites for normal load 12 N.

Figure 19 shows SEM micrographs of TiO₂-filled composites. From figures 12 and 13, it is clear that TiO₂-filled composite shows moderate wear rate. This is due to wedge formation in 10 wt% TiO₂-filled composite (figure 19a). For high filler loading and normal low load, wear is less because of filler makes a mask on the fibres, and hard TiO₂ particle prevents from abrasion. In case of normal load of 12 N, wear rate is comparatively high as shown in figure 13. This is due to the breakage of fibre by ploughing. This wear behaviour is also shown by ZnO filler.

Figure 20 shows micrographs of the abraded ZnO-filled composite. TiO₂-filled composites showed better wear resistance than ZnO-filled composites. It is clear from figures 19 and 20 that wear debris and breakage of fibres high in ZnO-filled composites as compared to TiO₂-filled composites cause high abrasive wear.

10. ANOVA and effects of factors

To find out statistical significance of various factors like sliding speed (A), filler loading (B), normal load (C), sliding distance (D) and abrasive size (E) on specific wear rate, analysis of variance (ANOVA) is performed on experimental data. Tables 10 and 11 show the results of ANOVA for the specific wear rate of TiO₂-filled E-glass fibre–polyester composites and ZnO-filled E-glass fibre–polyester composites, respectively. The last column of the table indicates percentage contribution of the control factors on the performance output i.e., specific wear rate.

From table 10, it is observed that sliding speed (A) ($P = 18.56\%$), abrasive size (E) ($P = 17.97\%$) and filler loading (B) ($P = 16.79\%$) have considerable influence on specific wear rate of TiO₂-filled E-glass fibre–polyester composites, but the factor normal load (C) ($P = 2.46\%$) and sliding distance (D) ($P = 6.24\%$) have less significant contribution to wear rate of bi-directional E-glass fibre composites. The interactions sliding speed/filler loading ($P = 7.48\%$) and sliding speed/abrasive size ($P = 6.57\%$) have less significant effect

Figure 19. SEM micrographs of the abraded TiO₂-filled E-glass fibre composites: (a) filler loading 10 wt% and normal load 4 N; (b) filler loading 10 wt% and normal load 12 N; (c) filler loading 20 wt% and normal load 4 N and (d) filler loading 20 wt% and normal load 12 N.

Figure 20. SEM micrographs of the abraded ZnO-filled E-glass fibre composites: (a) filler loading 10 wt% and normal load 4 N; (b) filler loading 10 wt% and normal load 12 N; (c) filler loading 20 wt% and normal load 4 N and (d) filler loading 20 wt% and normal load 12 N.

Table 10. ANOVA table for abrasive wear rate (TiO₂-filled composites).

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P (%)
A	2	141.58	141.58	70.792	2.88	18.56
B	2	128.09	128.09	64.047	2.61	16.79
C	2	18.79	18.79	9.397	0.38	2.46
D	2	47.61	47.61	23.804	0.97	6.24
E	2	137.12	137.12	68.562	2.79	17.97
A × B	4	57.06	57.06	14.265	0.58	7.48
A × C	4	84.19	84.19	21.047	0.86	11.04
A × E	4	50.17	50.17	12.542	0.51	6.57
Residual error	4	98.24	98.24	24.561	—	12.87
Total	26	762.86	762.86	—	—	100

DF: degree of freedom, Seq. SS: sequential sum of squares, Adj. SS: extra sum of squares, Adj. MS: extra mean squares, F: F-test, P: percent contribution.

Table 11. ANOVA table for abrasive wear rate (ZnO-filled composites).

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P (%)
A	2	25.609	25.609	12.804	0.25	4.52
B	2	35.240	35.240	17.620	0.35	6.22
C	2	20.615	20.615	10.307	0.20	3.64
D	2	0.262	0.262	0.131	0.00	0.04
E	2	258.368	258.368	129.184	2.57	45.65
A × B	4	8.444	8.444	2.111	0.04	1.49
A × C	4	14.677	14.677	3.669	0.07	2.59
A × E	4	1.452	1.452	0.363	0.01	0.25
Residual error	4	201.273	201.273	50.318	—	35.56
Total	26	565.940	—	—	—	100

DF: degree of freedom, Seq. SS: sequential sum of squares, Adj. SS: extra sum of squares, Adj. MS: extra mean squares, F: F-test, P: percent contribution.

on specific wear rate, but the interaction sliding speed/normal load ($P = 11.04\%$) has great influence of specific wear rate.

Similarly, in case of ZnO-filled E-glass fibre-polyester composites (table 11), the abrasive size (E) ($P = 45.65\%$) has significant contribution to wear rate but sliding speed (A) ($P = 4.52\%$), filler loading (B) ($P = 6.22\%$), normal load (C) ($P = 3.64\%$) and sliding distance (D) ($P = 0.04\%$) have less contribution to specific wear rate. Whereas, the interactions sliding speed/filler loading ($P = 1.49\%$) and sliding speed/normal load ($P = 2.59\%$) have great significant effect on specific wear rate while interaction sliding speed/abrasive size ($P = 0.25\%$) has less significant effect on specific wear rate.

11. Confirmation experiment

The optimal combination of control factors has been explored in the previous section. However, the final step in

any design of experiment approach is to predict and verify improvements in observed values through the use of optimal combination level of control factors. The confirmation experiment is accomplished by taking an arbitrary set of factor combination $A_1B_2C_1D_1E_1$ for TiO₂-filled E-glass fibre-based polyester composite. Factors B and E with factor A interaction $\{(A \times B) \text{ and } (A \times E)\}$ have a lesser effect on specific wear rate. Therefore, interaction $(A \times B)$ and $(A \times E)$ can be omitted for further prediction. In similar fashion, for ZnO-filled E-glass fibre-based polyester composite, the arbitrary set of factor combination is taken i.e., $A_1B_2C_1D_1E_1$ but factor E with factor A interaction $(A \times E)$ has lesser effect on minimum wear rate as evident from table 11; therefore, interaction $(A \times E)$ can be omitted for further prediction for composites. The estimated S/N ratio for wear rate can be calculated with the help of following predictive equation [30]:

$$\begin{aligned}\bar{\eta}_{\text{TiO}_2} = & \bar{T} + (\bar{A}_1 - \bar{T}) + (\bar{B}_2 - \bar{T}) + (\bar{C}_1 - \bar{T}) \\ & + (\bar{D}_1 - \bar{T}) + (\bar{E}_1 - \bar{T}) + [(\bar{A}_1\bar{C}_1 - \bar{T}) \\ & - (\bar{A}_1 - \bar{T}) - (\bar{C}_1 - \bar{T})],\end{aligned}\quad (12)$$

$$\begin{aligned}\bar{\eta}_{\text{ZnO}} = & \bar{T} + (\bar{A}_1 - \bar{T}) + (\bar{B}_2 - \bar{T}) + (\bar{C}_1 - \bar{T}) \\ & + (\bar{D}_1 - \bar{T}) + (\bar{E}_1 - \bar{T}) + [(\bar{A}_1\bar{B}_1 - \bar{T}) \\ & - (\bar{A}_1 - \bar{T}) - (\bar{B}_2 - \bar{T})] + [(\bar{A}_1\bar{C}_1 - \bar{T}) \\ & - (\bar{A}_1 - \bar{T}) - (\bar{C}_1 - \bar{T})],\end{aligned}\quad (13)$$

$\bar{\eta}_{\text{TiO}_2}$ and $\bar{\eta}_{\text{ZnO}}$ = predicted average for bi-directional E-glass TiO₂- and ZnO-filled composites.

$\bar{T}$ = Overall experimental average,

$\bar{A}_1, \bar{B}_2, \bar{C}_1, \bar{D}_1, \bar{E}_1$ = Mean response for factors at designated levels.

The equation reduces to

$$\bar{\eta}_{\text{TiO}_2} = \bar{B}_2 + \bar{D}_1 + \bar{E}_1 + \bar{A}_1\bar{C}_1 - 3\bar{T},\quad (14)$$

$$\bar{\eta}_{\text{ZnO}} = \bar{D}_1 + \bar{E}_1 + \bar{A}_1\bar{B}_2 + \bar{A}_1\bar{C}_1 - 2\bar{T} - \bar{A}_1.\quad (15)$$

A new combination of factor levels is used to predict deposition rate through prediction equation, and it is found to be $\bar{\eta}_{\text{TiO}_2} = -9.2911$ db and $\bar{\eta}_{\text{ZnO}} = -13.7444$ db. For each performance measure, an experiment is conducted for different factors combination and compared with the result obtained from the predictive equation as shown in table 12. Actual runs were performed to verify if the results obtained by above equations are acceptable.

It is found that when actual runs have been performed on above factor settings, an error of 5.97% (TiO₂-filled E-glass fibre-based polyester composite) and 7.13% (ZnO-filled E-glass fibre-based polyester composite) has occurred which is well within the reasonable limits. The error can be reduced if the number of runs is enhanced. This verifies that the predicted values are reliable and testifies the validity of this predictive model for predicting the performance output on the basis of input characteristics.

12. Theoretical prediction of specific wear rate

Mechanical properties of polymers and polymer composites are much dependent on temperature, wear rates, hardness and elastic moduli. Bijwe *et al* [38] considered that in abrasive wear situations, the Ratner–Lancaster plots showed good linearity indicating that ultimate tensile strength and elongation to break were the prominent factors controlling the abrasive wear behaviour of the composites. Ratner *et al* [39] considered that in abrasive wear situations, the wear rates are very much dependent on the magnitude of elongation to break. As the product of $\sigma_u \varepsilon_u$ represents the work required for detaching a particle from the wearing surface by tensile failure, this relationship emphasizes the role of plastic deformation in the wear process. Wang *et al* [40] considered that in abrasive wear, the scale of plastic deformation is limited to the sites of intimate micro-asperity contacts and the wear rate is defined by a critical strain criterion. Siddhartha and Gupta [18] extensively investigated the results obtained from these experiments and validated against existing microscopic models of Ratner–Lancaster and Wang. They also observed that good linear relationships are held between specific wear rate and ultimate strength and strain rate of these composites and results were in good agreement with these existing models.

In case of Wang model [40]

$$K_0 \alpha (\sigma_u)^{-3/2} (\varepsilon_u)^{-1}. \quad (16)$$

Moreover, by Ratner–Lancaster correlation [39]

$$K_0 \alpha (\sigma_u \varepsilon_u)^{-1}, \quad (17)$$

where K_0 is specific wear rate ($\text{mm}^3 \text{Nm}^{-1}$), σ_u the ultimate tensile strength (MPa) and ε_u the elongation at tensile fracture of the test sample. In case of experimental variables to calculate specific wear rate, the Wang's model and Ratner's correlation both insist on the importance of ultimate strength and strain at tensile fracture. In this research work the test results are validated against these existing models. It is observed from figures 21–23 that specific wear rate and the reciprocal of toughness show excellent linear relationship that supports the fact the experimental results are in harmony

with the microscopic wear models proposed by researchers [39,40].

13. Performance ranking of composites using VIKOR method

In this research work, eleven performance defining criterias (PDCs) are selected as shown in table 13. PDCs are based on the mechanical and abrasive wear peculiarity of unfilled, TiO₂- and ZnO-filled glass–polyester composites.

Figure 21. Variation of specific wear rate of unfilled and bi-directional E-glass fibre-reinforced polyester composites filled with ZnO and TiO₂, respectively, with $(\sigma_u)^{-3/2} (\varepsilon_u)^{-1}$.

Figure 22. Variation of specific wear rate of unfilled and bi-directional E-glass fibre-reinforced polyester composites filled with ZnO and TiO₂, respectively, with $(\sigma_u \varepsilon_u)^{-1}$.

Table 12. Results of the confirmation experiments for wear rate of TiO₂- and ZnO-filled E-glass fibre-based polyester composite.

	Optimal control parameters		
	Prediction	Experimental	Error
Level	A ₁ B ₂ C ₁ D ₁ E ₁	A ₁ B ₂ C ₁ D ₁ E ₁	(%)
S/N ratio for wear rate (db) (TiO ₂ -filled E-glass fibre-based polyester composite)	−9.2911	−8.7364	5.97
S/N ratio for wear rate (db) (ZnO-filled E-glass fibre-based polyester composite)	−13.7444	−12.7644	7.13

Figure 23. Variation of specific wear rate of unfilled and bi-directional E-glass fibre-reinforced polyester composites filled with ZnO and TiO₂, respectively, with $(\epsilon_u)^{-1}$.

Experimental data of the composites for 11 PDCs are given in table 14. Group utility (S_i) and individual regret (R_i) are calculated by using equations (5) and (6), respectively. It is shown in table 15. Aggregating index (Q_i) is calculated from equation (7) and shown in table 15. Finally, the calculation of ranking order by using VIKOR method for the analysis of mechanical and abrasive wear behaviour of unfilled and filler-filled glass–polyester composites are done. The ranking order of composites is shown in table 15. The analysis shows that 20 wt% of TiO₂-filled glass–polyester composite shows the best performance, while unfilled glass–polyester composite shows inferior result in terms of mechanical and abrasive wear behavior. ZnO-filled glass–polyester composites performance is better than unfilled glass–polyester composite.

Table 13. Description of different performance defining criteria (PDC).

PDC	Description of individual PDC	Performance implications of different PDC
PDC-1	Hardness as a measure of resistance to indentation under loads was measured on a Rockwell hardness tester	Larger the better
PDC-2	Tensile strength of the composite is the maximum stress that a material can withstand while being stretched or pulled before necking and is determined by using Universal Testing Machine	Larger the better
PDC-3	Flexural strength of the composite is defined as a material's ability to resist deformation under load and is determined by using Universal Testing Machine	Larger the better
PDC-4	Inter-laminar shear strength of the composite is the maximum shear stress existing between layers of laminated composite materials and is determined by using Universal Testing Machine	Larger the better
PDC-5	Experimental impact strength of the composite is defined as the amount of energy absorbed before fracture and is determined by using Impact Testing Machine	Larger the better
PDC-6	Specific wear rate is determined at minimum normal load 4 N, sliding speed = 1 m s ⁻¹ , sliding distance = 120 m and abrasive size = 425 μm	Smaller the better
PDC-7	Specific wear rate is determined at maximum normal load 12 N, sliding speed = 1 m s ⁻¹ , sliding distance = 120 m and abrasive size = 425 μm	Smaller the better
PDC-8	Specific wear rate is determined at minimum sliding speed = 0.5 m s ⁻¹ , normal load = 8 N, sliding distance = 120 m and abrasive size = 425 μm	Smaller the better
PDC-9	Specific wear rate is determined at maximum sliding speed = 1 m s ⁻¹ , normal load = 8 N, sliding distance = 120 m and abrasive size = 425 μm	Smaller the better
PDC-10	Specific wear rate is determined at minimum sliding distance 40 m, normal load = 12 N, sliding speed = 0.5 m s ⁻¹ and abrasive size = 425 μm	Smaller the better
PDC-11	Specific wear rate is determined at maximum sliding distance 120 m, normal load = 12 N, sliding speed = 0.5 m s ⁻¹ and abrasive size = 425 μm	Smaller the better

Table 14. Experimental data of the PDCs.

Composites designation	PDC-1	PDC-2	PDC-3	PDC-4	PDC-5	PDC-6	PDC-7	PDC-8	PDC-9	PDC-10	PDC-11
C _U	63	330	201	427	1.6	10.1974	15.9812	13.4125	13.4125	20.7801	13.1236
C _{T10}	75	312	291	618	1.9	9.2226	12.3584	10.5441	11.5441	16.4449	9.0802
C _{T20}	78	290	343	728	2.1	6.4371	11.4386	8.1395	8.1395	14.2543	6.5925
C _{Z10}	72	295	253	538	1.7	9.7923	14.1902	11.9282	12.9282	17.8898	11.8002
C _{Z20}	76	240	301	640	1.8	8.3814	11.9993	9.9572	10.9572	15.1521	8.3691

Table 15. Ranking order of alternatives.

Composites designation (alternatives)	S_i	R_i	Q_i	Ranking
C _U	5.0437	1.0873	1.0000	5
C _{T10}	2.1780	0.8055	0.4837	2
C _{T20}	0.2222	0.4444	0.0000	1
C _{Z10}	3.7055	0.9702	0.7702	4
C _{Z20}	2.1479	1.0000	0.6318	3

Preference ranking of composites: C_{T20} > C_{T10} > C_{Z20} > C_{Z10} > C_U.

14. Conclusion

From abrasive wear studies of bi-directional E-glass fibre-reinforced polyester composites filled with TiO₂ and ZnO filler, respectively, the following conclusions are drawn:

1. Bi-directional E-glass fibre-reinforced polyester composite filled with 20 wt% of TiO₂ exhibits most superior hardness of 78 HRB, while 20 wt% of ZnO-filled composite shows highest hardness of 76 HRB.
2. On the increase of filler weight fraction, the tensile strength of bi-directional E-glass fibre-reinforced polyester composites decreases because of increase in the void fraction of composites. Unfilled glass–polyester composite shows the highest tensile strength.
3. Under flexural loading and interlaminar shear loading situations, TiO₂-filled glass–polyester composites performed better than ZnO-filled glass–polyester composites. Bi-directional E-glass fibre-reinforced polyester composite filled with 20 wt% of TiO₂ has maximum ILSS and flexural strength among all the fabricated composites. The same pattern is also found for impact strength.
4. Abrasive wear rate is higher in unfilled bi-directional E-glass fibre-reinforced polyester composites as compared to filled composites.
5. Abrasive wear characteristics of these composites are successfully analysed using Taguchi experimental design scheme, ANOVA and effect of each control factor on abrasive wear characteristics are investigated. TiO₂-filled glass–polyester composites perform better than ZnO-filled glass–polyester composites under abrasive wear situations.
6. SEM feature shows matrix and fibre debris, the extent of which depends on the system, load and abrading distance involved. The abrasive action of sand on neat vinyl ester gets augmented when glass fibres are involved in the system. However, an additional presence of particulate fillers seems to reverse this pattern.
7. VIKOR method is a competent tool for the ranking or selection of composites and is helpful in the optimal composition selection. The 20 wt% of TiO₂-filled glass–polyester composite proved best as it exhibits the optimal properties.

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