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Properties and prototype applications of polyester composites reinforced with woven fabric of *Agave vera-cruz* fiber

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Abstract

This study focused on the mechanical and thermal properties of polyester composites reinforced with woven fabric of *Agave vera-cruz* fibers. The woven fabrics were fabricated in various forms of randomly oriented *Agave vera-cruz* fiber, intentionally twisted *Agave vera-cruz* fiber rope, and *Agave vera-cruz* fiber rope. Polyester composites reinforced with woven fabrics were prepared by hand lay-up and tested in both longitudinal and transverse directions. The fiber-matrix interaction was investigated using scanning electron microscopy. The results showed that the fabrics prepared from *Agave vera-cruz* fibers as reinforcement in polyester gave better results in a less expensive material with superior quality and thermal resistance. For example, polyester composites reinforced with *Agave vera-cruz* fiber rope (vertical fabric) on the vertical direction had higher tensile strength (54.7 MPa), flexural strength (316.6 MPa), impact strength (109.6 kJ/m²), and barcol hardness (40) than the other three forms of the fibers (fiber random, fiber rope random, and horizontal direction fabric). In addition, *Agave vera-cruz* fiber rope vertical fabric had the lowest thermal conductivity (0.138 Wm⁻¹ K⁻¹) and the highest heat deflection temperature (77 °C) compared to the other three forms of the polyester composite. Prototypes of table tennis rackets and bicycle seats were successfully manufactured using polyester composites reinforced with woven *Agave vera-cruz* fiber fabric.

Keywords Natural fiber, Mechanical properties, Thermal properties, Polyester resin

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Introduction

The search for bio-based substitutes has been spurred by concerns about the environmental impact of polymer composites, despite their widespread use. One possibility is natural fiber/filler reinforcement, which is inexpensive, renewable, biodegradable and available in large quantities. [1, 2]. Interest in the benefits of natural fibers as reinforcements in polymer composites has been growing for some time. This is because natural fibers are superior to synthetic fibers in many ways, including lower density, higher specific strength, superior thermal properties, affordability, biodegradability and renewability [3, 4]. For a number of domestic and commercial applications, natural fibers are preferred due to the above advantages.

Applications for natural fiber reinforced polymer composites include food packaging, transportation, sports, low-cost housing and consumer goods [5]. Joseph et al. [6] investigated the mechanical properties of banana fiber and glass fiber reinforced phenol formaldehyde composites with varying fiber length and fiber loading. The result showed that both banana fiber and glass fiber composites exhibited an increase in properties with increasing fiber loading. Scanning electron microscope (SEM) analysis was used to evaluate fiber/matrix interactions [6]. Dabade et al. [7] developed short hybrid fiber reinforced polyester composites using different fiber lengths and weight ratios and investigated the effect of fiber length and weight ratio on the tensile properties of the composites. They found that 30 mm fiber length shows optimum tensile strength and further increase in fiber length above 30 mm decreases the tensile strength with increasing fiber length [7]. Udaya Kiran et al. [8] studied the properties of sun hemp, banana and sisal fiber reinforced polymer composites by varying the fiber length and fiber weight and the results showed that optimum value of tensile strength was obtained at 55% fiber weight ratio 55% and 30 mm fiber length. The short randomly oriented polyester composites reinforced with banana and sisal hybrid fibers at different fiber loadings (20% to 50% by volume) were investigated by Idicula et al. [9]. The results indicated that the mechanical properties of the composites improved by increasing the fiber loading. A volume percent of 0.40 also improved the performance of the composites. An SEM study was carried out to evaluate the fiber/matrix interactions [9]. Ramanaiah et al. [10] investigated the mechanical and thermal properties of *Typha angustifolia* fiber reinforced polymer composites. The results showed that the mechanical properties of the material improved as the amount of fibers in the composites increased. In addition, the density and thermal conductivity of the composites are lower [10]. Yousif et al. [11] analysed the flexural properties of unidirectional long kenaf fiber reinforced epoxy composites, both

treated and untreated. The results showed that while the untreated fibers improved the flexural strength of the composite by 20%, the epoxy reinforced kenaf fibers increased it by approximately 36%. This was due to the epoxy significantly improving the interfacial adhesion of the fibers [11].

Thermal conductivity, specific heat capacity and thermal diffusivity of waste grass broom fiber composites as a function of fiber content and temperature was investigated by Ramanaiah et al. [12]. Sawpan et al. [13] determined the mechanical properties of unsaturated polyester composites reinforced with chemically treated hemp fibers at fiber contents ranging from 0 to 60 wt%. At a fiber content of 40 wt%, the composites reinforced with a combination of alkali and silane outperformed the unsaturated polyester matrix in terms of the tensile strength. The treated fiber composites outperformed the untreated fiber composites in terms of impact strength across all fiber contents, and the orientation of the long fibers further improved the mechanical properties of the composites [13]. Sathishkumar et al. [14] investigated the mechanical properties and water absorption of isophthalic polyester composites reinforced with snake grass longitudinal fibers at different fiber weight percentages. Both longitudinal and transverse directions were investigated for mechanical parameters such as modulus, flexural strength and tensile strength as per the requirements. According to the results of the experiments, composites with high fiber weight composition significantly improve the mechanical properties and water absorption capacities [14]. Srinivasababu et al. [15] studied *Thysanolaena maxima* (broom grass) long fiber reinforced polyester composites, both untreated and chemically treated, for their mechanical and dielectric properties. Chemically treated broom grass fiber reinforced polymer (FRP) composites achieved a maximum fiber volume fraction tensile strength of 82.39 MPa. Compared to the other composites investigated, the FRP composites achieved a maximum flexural strength of 78.51 MPa. At a fiber volume fraction of 39.55%, broom grass FRP composites achieved an impact strength of 91.11 kJ/m² and SEM analysis of fiber shape was performed [15]. Pickering et al. [16] studied the mechanical performance of natural fiber composites and their recent advances. They talked about the different aspects that influence the mechanical performance of natural fiber composites. Interfacial strength, fiber dispersion, fiber orientation, fiber selection, matrix selection and porosity are the main factors they considered [16]. Fragassa et al. [17] analysed the mechanical properties of flax and basalt fiber reinforced vinyl ester composites and their hybrids. In particular, they focused on the types of damage observed as a result of impact energy absorption. The results showed

that hybridization significantly improved the impact properties of flax fiber composites with a non-excessive increase in weight [17].

The effect of integration on the mechanical properties of compression molded polyester composites reinforced with sisal fibers was investigated by Biswas et al. [18]. The mechanical properties were evaluated using Izod, flexure, tensile and hardness tests. To improve the mechanical properties, a filler was added to the unsaturated polyester matrix at a weight percentage of 35% [18]. Flax and glass vinyl ester reinforced composites were prepared by Naga Kumar et al. [19]. According to the study, the hybrid composites outperformed pure woven glass fibers in terms of tensile strength. The results showed high impact strength of 0.145 J/mm² and flexural strength up to 305.46 MPa [19]. Hanan et al. [20] investigated the physical, mechanical and morphological properties of epoxy composites reinforced with oil palm empty fruit bunch (EFB) mats and woven kenaf fabrics. A hand lay-up method was used to fabricate the composites. Increasing the percentage of kenaf fibers resulted in improvement in the tensile and flexural properties. However, the impact strength of the hybrid composites decreased with increasing kenaf fiber content, indicating the opposite trend. This was supported by the results of the physical property analysis which showed that the pure oil palm EFB composites had higher void content, water absorption and thickness swelling than the other samples. The mechanical, water absorption, and wear properties of the polymer composites were investigated by Sumesh et al. [21]. These composites were prepared by compressing pineapple/flax fibers with peanut oil cake (PCF) filler. The mechanical, water absorption and wear properties of the composites were investigated as a function of the weight percentage of the PF fibers, which ranged from 20 to 40 wt%, and the PCF filler, which ranged from 1 to 3 wt%. The mechanical test results showed that the properties were significantly improved by the use of the PCE. The composites with 20% PF and 2% PCF showed the best results with tensile strength of 37.89 MPa, flexural strength of 70.28 MPa and impact strength of 96.99 J/m [21].

Hybrid polymer composites have attracted the attention of researchers due to their physical, mechanical and thermal properties. Kumar et al. [22] investigated the mechanical and thermal properties of alumina oxide (AO), titanium oxide (TiO₂), and silicon carbide (SC) reinforced nylon 6 (N6) composites. The composites were prepared by injection molding with adjusted weight percentages. Preliminary results showed that the tensile properties and thermal stability of N6 polymer matrix composites were improved by the addition of TiO₂ (at 5 wt%), AO (at 10 wt%) and SC (at 5 wt%). The composite gears with N6, SC (10 wt%), TiO₂ (5 wt%) and AO (5

wt%) have been developed for automotive and industrial applications due to their improved hardness and impact resistance [22]. Mohit et al. [23] investigated the incorporation of plant cellulose fillers into polymeric laminates by using four additional eight-layer laminates containing titanium carbide nano-particles and biofillers (coir, sisal and hemp) and by using the wet lay-up technique to vary the stacking order of synthetic fabrics. According to the experimental results, the 3F8LTSE composite (sisal, hemp, coir fillers, 2 layers of carbon, kevlar, basalt, innegra fabrics, and titanium carbide reinforced synthetic epoxy) showed superior mechanical properties. Lightweight constructions could benefit from its reduced water absorption capacity [23]. Babu et al. [24] investigated the mechanical properties of several novel green fillers, including tamarind seed powder and rice husk. They prepared hybrid vinyl ester composites with fillers in the range of 0 to 30 wt% by compression molding. The mechanical properties of the green filler vinyl ester composites were evaluated by water absorption tests and flexure, impact and tensile tests. The test results showed that the hybrid filler reinforcement can change the properties and improve the specific capabilities of the vinyl ester composites.

Natural fibers have also been shown to agglomerate and lose their mechanical properties when added above a certain weight threshold, which was 15% [24]. Manikandan et al. [25] investigated the use of a hybrid powder as a reinforcing agent in vinyl ester composites made from solid biomass waste. The composites with filler concentrations of 0 to 15% and 0 to 9% graphite were prepared using the hand lay-up technique. The tensile modulus of the hybrid composite was 1.66 GPa and the ultimate tensile strength was 48.4 MPa. A hybrid filler with 15 wt% PLSF and 6 wt% graphite is the strongest, with a flexural strength of about 148 MPa. After the addition of 6 wt% hybrid filler, final values for impact strength (41.3 kJ/m²) and hardness (44.5 kJ/m²) were achieved [25].

Natural fiber-based composites can be made stronger by combining them with synthetic fibers or by subjecting them to various chemical treatments. Although these composites are stronger than other synthetic composites, they still can't hold a candle to their synthetic fiber counterparts. However, when natural fibers are woven into the composites, the strength increases dramatically. Reinforced polyester composites with natural or man-made fibers are rarely discussed, unlike those with randomly oriented.

Agave vera-cruz plant, which grows to a height of 4.9–6.6 m and has sword-shaped leaves, is a member of *Agave Sisalana* family. *Agave vera-cruz* plant typically produces 200–250 economically useful leaves during its 7–10 year life. On average, each leaf contains about 1000 fibers [26,



Fig. 1 *Agave vera-cruz* fiber rope bundle and fiber rope mat

27]. By weight, the fibers make up only 4% of the plant. The cellulose, hemicellulose, and lignin contents of the *Agave vera-cruz* fibers are 78%, 19%, and 8%, respectively [28]. *Agave vera-cruz* is easy to grow and requires little planting time. The plant grows organically along railway lines and in hedgerows. In this study, composite plates were produced by woven mats of fabrics produced by weaving *Agave vera-cruz* fibers and polyester resin in a hand lay-up process. The mechanical, thermal and morphological properties of the composites were investigated. Two different prototype products, a bicycle seat and a tennis racket, were successfully produced from the formulation that gave optimum performance.

Materials and methods

Materials

The method used to extract the fibers is decortication by means of a decortivating machine. A roller equipped with blunt blades crushes and brushes the leaves to extract the pure fiber. The mean moisture content of the fibers was 10–22% based on the oven-dry weight of the fiber. The diameter of the *Agave vera-cruz* fiber is 50–100 μm . Five separate lengths of *Agave vera-cruz* fiber were twisted using rope making equipment to produce the *Agave vera-cruz* fiber rope shown in Fig. 1, *Agave vera-cruz* fiber rope was converted into an *Agave vera-cruz* fiber rope mat using a weaving machine (Fig. 1). The properties of polyester resin are given in Table 1.

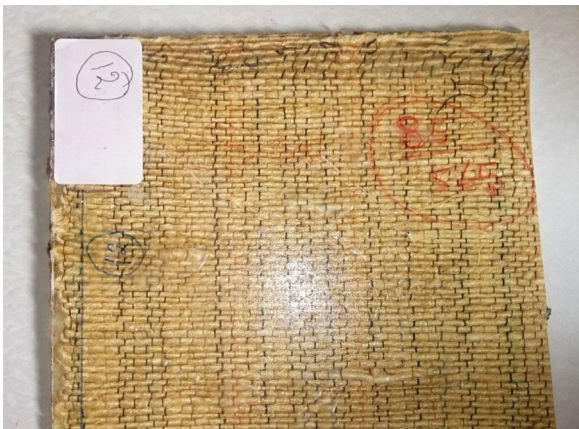


Fig. 2 *Agave vera-cruz* fiber rope mat reinforced polyester composites plate

Table 2 The woven fabrics fabricated from *A. vera-cruz* fibres and their codes

The woven fabric type	Code
Woven fabric from <i>Agave vera-cruz</i> fibre random	AVFR
Woven fabric from <i>Agave vera-cruz</i> fibre rope random	AVFRR
Woven fabric from <i>Agave vera-cruz</i> fiber rope horizontal direction	AVFRHM
Woven fabric from <i>Agave vera-cruz</i> fiber rope vertical direction	AVFRVM

Preparation of composites

In this work, 30 mm long chopped *Agave vera-cruz* fiber was used to make the composites, with the weight of the rope mat serving as the basis for maintaining a consistent weight percentage of chopped *Agave vera-cruz* fiber. A hand lay-up process was used to prepare the composite. A 300 mm $\times$ 300 mm $\times$ 3 mm mold cavity was filled with the resin and curing ingredients and then the chopped *Agave vera-cruz* fiber was evenly distributed throughout the mold cavity. To cure the composites, the mold had to be kept closed under constant pressure for 24 h at 32 $^{\circ}\text{C}$. A typical polyester composite prepared from polyester resin and woven mat of *Agave vera-cruz* fiber is shown in Fig. 2. The four different combinations of the woven fabrics prepared from *Agave vera-cruz* fibers are given in Table 2. The strength of the rope mat polyester composites was determined by the weave pattern, fiber orientation, fiber direction and matrix-fiber bonding.

Table 1 Properties of polyester resin

Material	Appearance	Specific gravity	Acid value (mg KOH/g)	Tensile strength (MPa)	Tensile modulus (GPa)	Reference
Polyester resin	Yellow viscous liquid	1.12	25	18	0.5	Present work

Mechanical properties

The biocomposite panels prepared from woven fabric of *Agave vera-cruz* fiber rope were tested in the horizontal and vertical directions during loading of the composite specimens. The tensile tests were performed in accordance with ASTM standards using a digital UTM Tinius Olsen company, India (Tinius Olsen H50K) with a capacity of 5 kN and a crosshead speed of 2 mm/min. The specimens were cut from the biocomposite panels in accordance with ASTM 3039 M [29]. The digital UTM machine Tinius Olsen company, India (Tinius Olsen H50KL) with a capacity of 5 kN and a crosshead speed of 2 mm/min was used to perform the 3-point flexure test in accordance with ASTM D790 [30]. When a force was applied to the centre of the beam, the specimen, which was freely supported by the beam, breaks. The impact test specimens were evaluated using a Tinius Olsen company, India (Model: 104 Izod) digital impact tester in accordance with ASTM D256 [31].

The hardness of the biocomposites was assessed using a Barcol hardness tester (model: VBH2) in accordance with ASTM D2583 [32]. After placing the specimen under the indenter of the Barcol hardness tester, it was continuously compressed until the dial indicator reached its maximum. The depth of penetration was used to calculate the absolute Barcol values. The specimens must be at least one sixteenth of an inch thick.

Thermal conductivity

A protected heat flow meter (Unitherm Model No. 2022) was used to test the transverse thermal conductivity of the biocomposites in accordance with ASTM E1530 [33]. A test specimen with a diameter of 50 mm and a thickness of 3 mm was made from the manufactured biocomposite.

Heat deflection temperature (HDT)

The HDT was measured using the HDT-VSP tester in accordance with ASTM D648 [34]. The temperature readings were then recorded as HDT.

Morphological analysis

Fractography experiments were performed on the fracture surface of the biocomposite specimen after various mechanical tests at different magnifications in the SEM. To prepare the surface of the fractured specimen for morphological study, a thin section was cut and coated with gold. The SEM micrographs of the fractured specimens were taken using secondary imaging settings with a voltage ranging from 10 to 15 kV.

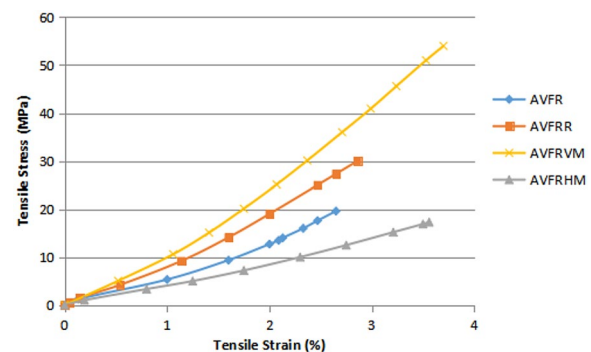


Fig. 3 Tensile stress vs strain curves *Agave vera-cruz*/polyester composites in various forms

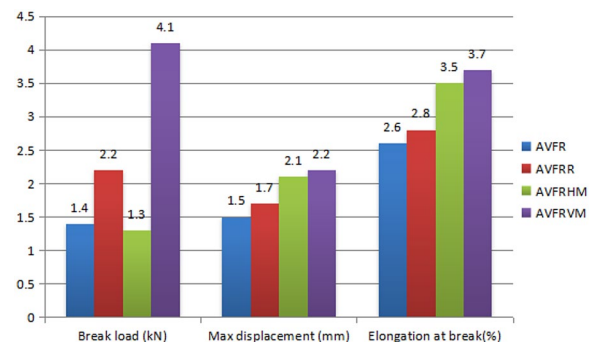


Fig. 4 Tensile properties of *Agave vera-cruz*/polyester composites in various forms

Results and discussion

Tensile properties

A typical stress–strain curve for the AVFR, AVFRR, AVFRHM, and AVFRVT biocomposites is shown in Fig. 3. For all the biocomposites, the stress reduced suddenly after reaching a high stress point. *Agave vera-cruz* fiber random, rope random and rope reinforced polyester biocomposites were analysed. The tensile properties such as breaking load, maximum displacement and percentage elongation at break for four different shapes are shown in Fig. 4. The breaking loads for the AVFR, AVFRR, AVFRHM and AVFRVM-reinforced polyester biocomposites were found to be 1.4 kN, 2.2 kN, 1.3 kN and 4.1 kN, respectively. The AVFRVM reinforced biocomposite had a high failure load (Fig. 4). It was almost 1.4 times higher than AVFR, 1.3 times higher than the AVFRR and 1.04 times higher than the AVFRHM biocomposite. The maximum displacement was also high for the AVFRVM reinforced biocomposite. It was approximately 1.4 times that of the AVFR, 1.3 times that of AVFRR and 1.04 times that of AVFRHM biocomposites. The percentage elongation at break for AVFR, AVFRR, AVFRHM and AVFRVM biocomposites were measured

to be 4.27%, 2.88%, 3.56% and 3.73%, respectively. It was found that the AVFRVM biocomposite had a slightly higher percentage elongation than the other three forms of biocomposite, meaning that the AVFRVM biocomposite can withstand more strain before the failure [35–37].

The tensile strength of the different types of biocomposites is given in Table 3. The tensile strength of the AVFRVM-reinforced biocomposites was 54.7 MPa, which was higher than that of the other biocomposites. It was about 64% higher than that of AVFR, 44% higher than that of AVFRR and 68% higher than that of the AVFRHM biocomposite. In order to achieve maximum tensile properties and to prevent fiber breakage during fiber extraction, the matrix and fibers had an improved interfacial bond [38, 39]. The tensile modulus of the different forms of biocomposites was calculated from the stress and strain values from the linear part of the graph. The tensile modulus of the AVFR, AVFRR, AVFRHM and AVFRVM biocomposites were found to be 0.73, 1.06, 0.49 and 1.47 GPa, respectively. From the above results, it is clearly indicated that the tensile modulus of the AVFRVM bio-composites was higher than that of other biocomposites. The tensile strength of the AVFRVM composites increased up to 67.5% higher than that of the bamboo fiber/polyester, 51.8% higher than that of the palmyra fiber/polyester, 57.5% higher than that of coir/polyester, 48.10% higher than that of *Roystonea regia* fiber/epoxy composites.

Flexural properties

The flexural properties such as ultimate load, maximum displacement and percent elongation at break of the biocomposites are presented in Table 4. It was found that the ultimate load of the AVFRVM biocomposite was higher than other biocomposites. It was about 6.5 times that of AVFR, 2.5 times that of the AVFRR and AVFRHM polyester biocomposite. The maximum displacement and percentage elongation were also high for the AVFRVM reinforced polyester biocomposite. The AVFR, AVFRR,

Table 4 Flexural properties of the different forms of biocomposites

Composite code	Break load (N)	Displacement (mm)	Elongation at break (%)
AVFR	70.1	2.6	0.5
AVFRR	166.6	2.1	0.4
AVFRHM	31.6	2.2	0.5
AVFRVM	268.3	9.1	2.0

AVFRHM and AVFRVM reinforced biocomposites had the flexural strengths of 82.5 MPa, 96.2 MPa, 37.4 MPa, and 316.6 MPa, respectively. This was approximately 88% higher than SFHM polyester biocomposites and 70% higher than the AVFR and AVFRR polyester biocomposites. Compared to other biocomposites, the AVFRVM reinforced biocomposites had the highest flexural strength. This may be due to the fabric orientation of the *Agave vera-cruz* fiber rope and the superior adhesion of the fibers to the polyester matrix compared to these other biocomposites [38–42]. Table 3 shows the flexural modulus of polyester biocomposites reinforced with woven fabric of the AVFR, AVFRR, AVFRHM and AVFRVM reinforced biocomposites showed flexural modulus of 14.5 GPa, 16.5 GPa, 7.3 GPa, and 18.1 GPa, respectively. This indicated that the AVFRVM reinforced biocomposites had slightly higher flexural strength compared to the other biocomposites. The flexural strength of the AVFRVM composites increased up to 89.9% higher than that of the bamboo fiber/polyester, 87.7% higher than that of *Roystonea regia* fiber/epoxy composites, 85.9% higher than that of the palmyra fiber/polyester, 82.9% higher than that of coir fiber/ polyester composites.

Impact properties

The variations in impact strength of the polyester biocomposites reinforced with AVFR, AVFRR, AVFRHM and AVFRVM are shown in Table 5. The aforementioned biocomposites were found to have impact strengths

Table 3 Tensile and flexural properties of different forms of composites

Sl no	Composite code	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural stress (MPa)	Flexural modulus (GPa)	References
	AVFR	20.5	0.73	82.5	14.5	Present work
	AVFRR	31.5	1.06	96.2	16.5	Present work
	AVFRHM	17.5	0.49	37.4	7.3	Present work
	AVFRVM	54.7	1.47	316.6	18.1	Present work
	Palmyra/polyester	26.2	1.40	44.4	1.4	[34]
	Roystonea regia/epoxy	28.4	2.80	38.4	3.8	[35]
	Bamboo/polyester	17.5	3.0	34.2	3.4	[36]
	Coir/polyester	22.7	3.83	53.4	4.8	[37]

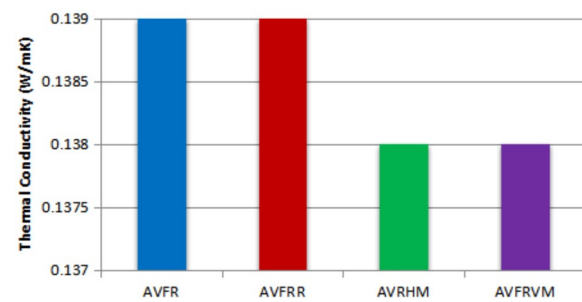
Table 5 Impact strength and hardness of different forms of composites

SI No.	Composite code	Impact strength (kJ/m ²)	Hardness (barcol)	References
	AVFR	27.6	19	Present work
	AVFRR	30.5	30	Present work
	AVFRHM	11.5	38	Present work
	AVFRVM	109.6	40	Present work
	Palmyra/polyester	6.8	–	[34]
	Jute/polyester	44.5	–	[35]
	Coir/polyester	40.6	–	[36]
	Bamboo/polyester	32.6	–	[37]

of 27.6 kJ/m², 30.5 kJ/m², 11.5 kJ/m², and 109.6 kJ/m², respectively. The mechanical properties of the biocomposites reinforced with each *Agave vera-cruz* fiber were found to have a higher impact strength than the biocomposites reinforced with some natural fibers such as palmyra, jute, coir, and bamboo (Table 5). The microfibrillar angle, or the angle between the fiber axis and the fibril angle, and the cellulose content of the natural fiber biocomposite affect its impact strength [43, 44]. As a result, the biocomposite reinforced with *Agave vera-cruz* fibers had a higher absorption capacity and a more uniform impact energy distribution [39, 45]. Due to its high absorption capacity and uniform impact energy distribution, the AVFRVM biocomposite exhibited higher impact strength than other biocomposites in the impact test. In comparison, it was approximately 74.59% higher than the AVFR, 71.95% higher than the AVFRR and 90% higher than the AVFRHM biocomposites. The impact strength of the AVFRVM composites increased about 18.01 times higher than that of the palmyra fiber/polyester, 3.04 times higher than that bamboo fiber/polyester, 2.72 times higher than that of coir fiber/polyester, 2.47 higher than that of the jute fiber/polyester composites.

Hardness properties

The variation in the hardness with respect to different shapes of reinforcing biocomposite is shown in Table 5. The hardness values of the polyester biocomposites reinforced with the AVFR, AVFRR, AVFRHM and AVFRVM were 19, 30, 38, and 40, respectively. Compared to the other three biocomposites, the AVFRVM biocomposites showed superior hardness. It was approximately 52.5% higher than that of the AVFR polyester biocomposites, 25% higher than that of the AVFRR biocomposites and 5% higher than that of the AVFRHM biocomposites. Better matrix-reinforcement bonding is demonstrated by the increased hardness of the AVFRVM biocomposites [46].

**Fig. 5** Thermal conductivity of *Agave vera-cruz*/polyester composites in various forms

Thermal conductivity properties

The thermal conductivity measurements for each of the four biocomposite types is presented in Fig. 5. The thermal conductivities of the AVFR, AVFRR, AVFRHM and AVFRVM biocomposites were found to be 0.139, 0.139, 0.138 and 0.138 Wm⁻¹ K⁻¹, respectively. In contrast to the AVFR and AVFRR biocomposites, the results indicate that the matrix and fiber ropes of *Agave vera-cruz* can be oriented in a fabric-like manner, which reduces the thermal properties of the AVFRHM and AVFRVM biocomposites. The thermal conductivity is reduced by 7.2% when the AVFR and AVFRR biocomposites are randomly oriented as opposed to the woven fabric orientation of the AVFRHM and AVFRVM biocomposites. Since the orientation of the fibers in the woven fabric of the AVFRHM and AVFRVM biocomposites was evenly distributed throughout the matrix, the heat transfer was restricted and the thermal conductivity was lower than that of the AVFR and AVFRR biocomposites. The reduced thermal conductivity of the AVFRHM and AVFRVM composites was an advantage when used near hot surfaces [47].

Heat deflection temperature

The results of the heat deflection temperature test for the manufactured biocomposites are presented in Fig. 6. The HDT of the AVFR, AVFRR, AVFRHM, and AVFRVM biocomposites were measured at 66 °C, 63 °C, 62 °C, and 77 °C, respectively. The HDT of the different biocomposite forms did not vary significantly (Fig. 6). As the rope orientation in the fabric was transverse to the load and longitudinal to the load in the vertical orientation in the fabric, the AVFRHM provided a lower HDT value. The AVFRVM reinforced polyester biocomposites, on the other hand, had the HDT values that were 14.2% higher than the AVFR, 18.18% higher than the AVFRR, and 19.48% higher than the AVFRHM biocomposites. As the material can tolerate higher

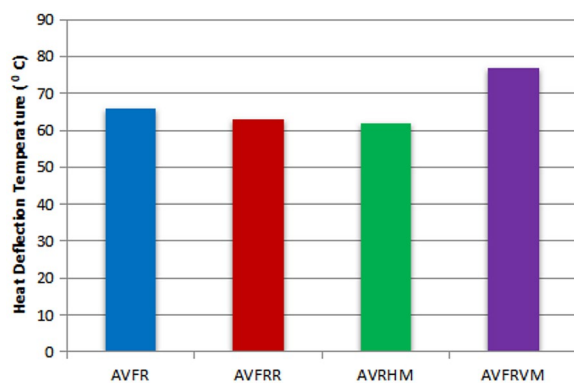


Fig. 6 Heat deflection temperature of *Agave vera-cruz* fiber/polyester composites in various forms

ambient temperatures without deflection, the higher HDT value of the AVFRVM reinforced biocomposite is an attractive feature [47, 48].

Morphological analysis

Figure 7 shows the SEM fractography of a tensile cracked specimen of biocomposites from *Agave vera-cruz* fiber rope. It shows the complicated crack propagation, fiber bending and fiber pull-out under cracked tensile stress. The strength of the biocomposites was enhanced by the resin surrounding the rope fibers. The extensive fracture in the *Agave vera-cruz* fiber-reinforced polyester biocomposite specimens produced after the bending test is shown in Fig. 7. A good bond between fiber and matrix was demonstrated by the brittle failure with matrix fracture resulting in reduced fiber pullout [39, 43–45]. Figure 8 illustrates how a rapid impact stress causes the

polyester resin and fabrics from *Agave vera-cruz* fiber rope to break, resulting in the failure of the biocomposite specimen.

Prototype applications

Bicycle seat

A saddle is the seat of a bicycle. The hard shell of most saddles is made of molded plastic, such as nylon, although carbon fiber can also be used; these synthetic materials are not environmentally friendly. Traditionally, leather has been used to make saddles, but the production of leather has a negative environmental impact, causing air and water pollution. Therefore, natural fiber material, which is environmentally friendly, is a preferable substitute. Based on the research results, a bicycle seat was produced using AVFRVM-reinforced polyester biocomposite. The AVFRVM biocomposite bicycle seat was produced using a hand lay-up process. Figure 9 shows the inside and outside views of the bicycle seat.

Table tennis racquet

Rubber is usually applied to two sides of the laminated wood table tennis racquet to improve the player's grip. For different levels of spin or speed, the racquet has different surfaces on each side. For example, a player may have a blade with spin-heavy rubber on one side and no spin on the other. One side of the racket must be red and the other black. Players have a wide variety of rubber sheets to choose from. The majority of professional tournament players will use a bespoke racket, although the manufacturer may sell rackets constructed with rubber. A player chooses a blank racket (one without

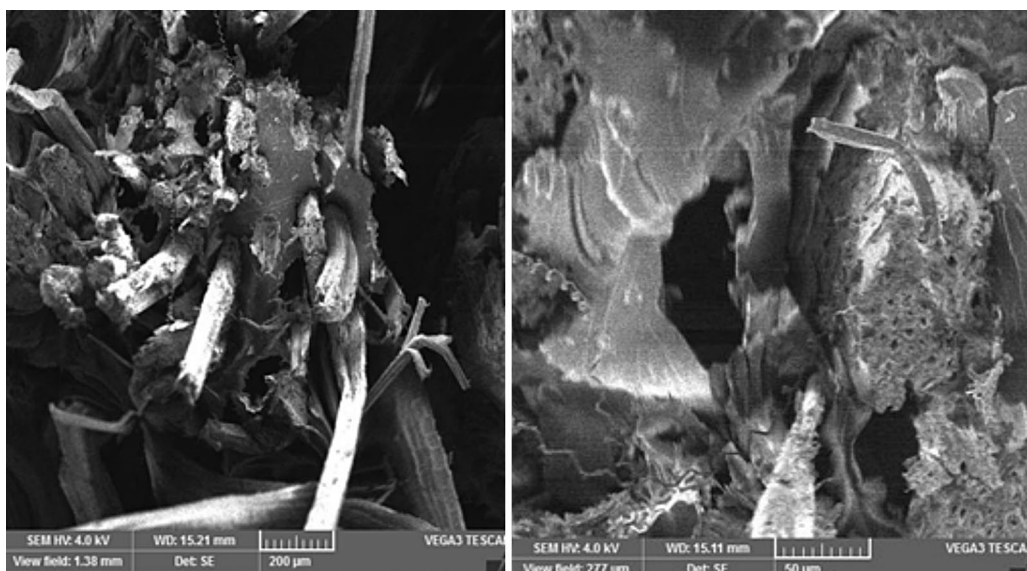


Fig. 7 SEM image of *Agave vera-cruz* fiber mat composites fractured specimens for the tensile test

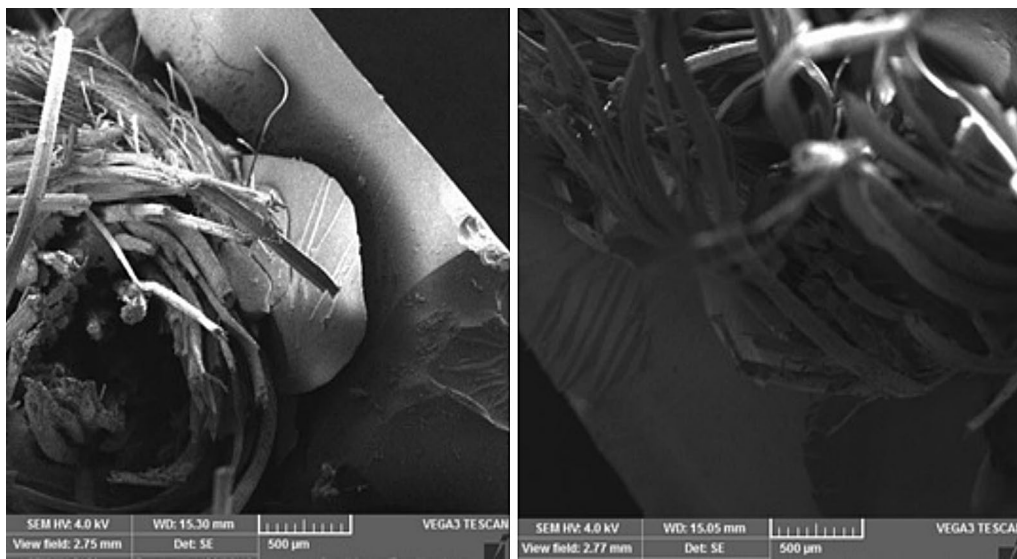


Fig. 8 A typical SEM image of fractured *Agave vera-cruz* fiber/polyester composite for the impact test



Fig. 9 Outer side view and Inner side view of cycle seat fabricated by AVFRVM polyester composite

rubber) according to his or her playing style. The speed of the blade depends on the type of wood or synthetic layers used in its construction. The amount of spin, speed, and other playing characteristics are influenced by the type of rubber used. The amount of deviation from the expected ball flight path is mostly caused by the racket construction and new rubber technologies. As the woven fabrics made from *Agave vera-cruz* fiber rope are environmentally friendly, they are preferable to laminated wood. The table tennis racquet made of polyester biocomposites reinforced with woven fabric of *Agave vera-cruz* fiber rope is shown in Fig. 10.

Conclusions

The mechanical and thermal properties of polyester biocomposites reinforced with *Agave vera-cruz* fiber were analysed in the horizontal and vertical directions. The mechanical and thermal properties of AVFRVM confirmed its good performance as an alternative reinforcing material to conventional synthetic hazardous fibers. It was observed that the AVFRVM biocomposites had superior properties to other forms of reinforcement, such as the AVFR and AVFRR biocomposites. Slight improvements in mechanical and thermal properties were obtained in AVFRR biocomposites compared to AVFR biocomposites. AVFR VM biocomposites in the vertical

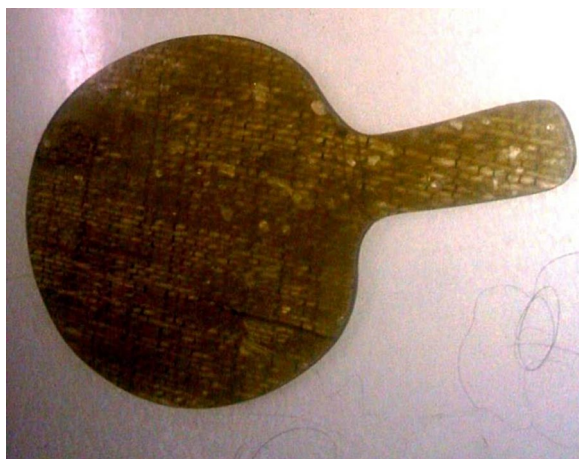


Fig. 10 Outer side view of blank table tennis racquet fabricated by AVFRVM polyester composite

direction had a higher tensile strength (54.7 MPa), flexural strength (316.6 MPa), impact strength (109.6 kJ/m²) and barcol hardness (40) than the other three forms of AVFR, AVFRR and AVFRHM polyester biocomposites. The AVFRVM biocomposites had the lowest thermal conductivity (0.138 Wm⁻¹ K⁻¹) and the highest heat deflection temperature (77 °C) than the other three forms of AVFR, AVFRR and AVFRHM polyester biocomposites. The SEM study of the fractured specimen confirmed that a good interfacial bonding between the natural fiber and polyester matrix, which played a vital role in improving the mechanical properties. A bicycle seat and a table tennis racket were successfully fabricated using the AVFRVM-reinforced biocomposite for sports applications.

Abbreviations

FRP	Fiber reinforced polymer
EFB	Empty fruit bunch
PCF	Peanut oil cake filler
AO	Aluminium oxide
TiO ₂	Titanium oxide
SC	Silicon carbide
HDT	Heat deflection temperature

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Author contributions

AN Balaji: Investigation, conceptualization, methodology, investigation; MKV Karthikeyan: research design, data analysis; V Vignesh: conceptualization, data curation, writing-reviewing and editing; AB Madhavan: writing an original draft; N Ayilimis; conceptualization, writing-reviewing and editing. Kwang-Hyun Ryu: Writing-reviewing and editing, Funding. Hyun-Joong Kim: Writing-reviewing and editing, Funding. All authors participated in interpreting and discussing the results. All authors reviewed and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed in the current study are available from the corresponding author upon reasonable request.

Declarations

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Consent for publication

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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