Characterization of cissus quadrangularis fiber polymer composites along with properties analysis

Sankarasubramanian M* and Pitchipoop P©
Department of Mechanical Engineering, PSR Engineering College, Sivakasi—626140, India
* Author to whom any correspondence should be addressed.
E-mail: sankara.mss@gmail.com

Keywords: fiber polymer composites, Cissus Quadrangularis, water absorption, mechanical properties and unsaturated polyester composite

Abstract
The natural fibers such as coir, flax, oil palm, jute etc are widely used in civil construction and automobile industries based on their advantages like eco friendliness as well as their enhanced performances whereas the synthetic fibers namely kevlar, carbon and glass yield higher production costs. Hence in this present work, a new natural fiber, the Cissus Quadrangularis, which is made from the Cissus Quadrangularis plant, has been introduced and it is bio-degradable, renewable, and eco friendly. The chemical composition, density, mechanical properties and water absorption potential of fiber bundles are investigated and impressive results are obtained. The composite material has been fabricated by the fiber with different weight percentage in the form of powder and its characterizations and the mechanical properties have been studied. The results reveal that the fabricated composite is suitable for structural applications and a better replacement of synthetic fibers. The mechanical features of Cissus Quadrangularis are reinforced with unsaturated polyester composite and it is optimized by changing the fiber content.

1. Introduction
Recently, the utilization of Natural Fiber Reinforced Polymer (NFRP) based composites has been increasing rapidly in the field of automotive and construction sectors. The synthetic material fibers are usually substituted with natural fibers in composites because of their environmental benefits. In the industries, the composite materials play a significant role day by day and it has lot of advantages in terms of strength, light weight, durability, design flexibility, eco-friendly and corrosion resistance [1]. Several investigations have been positioned based on the natural fiber consolidations including flax, jute, oil palm empty fruit bunch, ramie, kenaf, leaves fibers, pineapple, rubber wood, sisal, coir, date palm, bamboo, sugar palm, hemp and so on. The hemp fiber is relatively cheap to yield and process among the natural fibers and it is mainly available in Asia and Europe [2]. According to the mechanical properties, the hemp fibers are categorized into non-cellulosic fiber that makes a perfect strengthening.

The particle and the fiber reinforced composites are the important types of polymer matrix composites. Further, the fiber reinforced composite has been categorized into discontinuous fiber and continuous fiber respectively [3]. The construction, structural and the automotive components are the important fields of applications of natural fiber reinforced polymer composite. The natural fiber has lower density and it easily replaces the synthetic fiber as well as it is biodegradable and easily available everywhere. The wood and jute fibers possess excellent reinforcing abilities according to proper polymers along with their compounds [4]. Based on the ease of fabrication, the fiber polymer composites are used in many applications in the case of structural materials. The longer and shorter fiber polymer composites have various fiber orientations and length, which vary based on their properties [5].

Recycling of synthetic fiber reinforced plastic becomes complex, since it contains carbon and glass [6]. The fiber plastic and the synthetic fibers such as carbon, glass and kevlar are costly compared to natural fibers for similar performance in terms of specific tensile strength and flexural. The machinability in case of tool wear,
surface topography and surface damages optimization requires a deep investigation of natural fiber composites. Consequently, most of the researchers have used leaves and plant stems as reinforcements in fiber polymer composites because of their capabilities and performances [7]. In this article, a new natural fiber of *Cissus Quadrangularis* has been introduced and this *Cissus Quadrangularis* provides better performances in terms of mechanical property testing.

2. Related works

The mixture of small amount of substance with various polymer forms and other materials has been suggested by Devnani et al [8]. The efficiency of material consistency, including flame retardancy, water absorption, mechanical and thermal properties has been improved. Nano fillers, that improve various properties of original materials without minimizing the density of the materials, are one of the additives in solid form. To improve the compatibility between the natural fibers and the polymer matrix, various types of surface treatment mechanisms such as maleate binding, acetylation, and alkylation have been used.

Vel murugan et al [9] have reported the mechanical properties of composite materials. The manufacture of composites has been carried out by nylon fillers with natural fibers such as spider silk fibers, jute, and matrix. The key purpose of their research is the influence of different kinds of measurements of natural fibers. Flexural, tensile strength and hardness are tested experimentally. When compared the flexural examination of spider silk and nylon filler, the nylon filler with jute reinforcement has offered the highest flexural strength and hardness. Arul Jeya Kumar et al [10] have studied the mechanical and the morphological characterizations of Basalt/*Cissus Quadrangularis* hybrid fiber composites. They have developed three mixtures by varying the weight percentages and are reinforced in polyactic acid to analyse different properties. The study on the mechanical properties of composites has proved that high tensile, flexural and impact strength of the composites are observed as the weight percentage of basalt and cissus fiber is increased in polyactic acid.

The evolutions of reinforced polymeric artificial fiber and different natural composites have been suggested by Sekaran et al [11]. The materials are developed as natural fiber reinforced polymer composites by strengthening the matrix with natural fiber. The epoxy resin with aloevera and silas has been used to prepare the composite laminate through hand layup technique. The aloevera natural fiber reinforced composites and the drilled silal delamination are studied by the means of carbide tip drill bit. The drilled natural fiber composite delamination and the surface hardness are evaluated. Liu et al [12] have replaced the synthesizing fibers into natural cellulose fibers in bio-polymer composites. The natural cellulosic fibers have been derived from corn waste stalk and processed at different concentrations with silane solution. Experimentally, the morphology of Corn Stalk Fiber (CSF) and the mechanical efficiency of CSF are validated in terms of impact fracture and impact strength surface. With the support of silane treatments, the impact strength of polymer composites and the interfacial bonding of the fiber matrix are increased.

Afolabi et al [13] have investigated the natural cellulose fiber that is obtained from screw pine or Pandanus Tectorius leaves. The Pandanus Tectorius leaf fibers are extracted and thereby, the reinforcement in polymer composite is experimented for engineering applications. The cellulose fibers with their mechanical properties such as mixed alkaline bleaching, bleaching and alkaline treatments are tested. The soaking time and the concentration percentage of cellulose fiber get increased. While compared to the untreated cellulose fiber, the amalgamation of alkali bleach cellulose fiber composite provides nearly 40% more tensile strength.

Hariprasad et al [14] have attempted to study the mechanical properties of various fibers from milkweed, banana, Kusha grass, silas and hay fiber mixed with polypropylene in the ratio of 10:90 by weight. It is reported that the hay fiber has better tensile strength and hardness compared to other fibers. In addition, the acoustic characterization has been carried out by varying the thickness of the composite. After the experimentation, there is no effect on increasing the thickness at higher acoustic frequencies.

Vignesh et al [15] have fabricated the natural fiber polyester composites by reinforcing Indian mallow fiber in random orientation by varying the fiber reinforcement from 10%–50% by weight. These composites are evaluated for its mechanical properties and thermal properties and it is stated that 50% fiber reinforced composite has provided optimum mechanical properties and it withstands up to 84°C while conducting heat deflection test.

Balogun et al [16] have evaluated the mechanical properties and the friction co-efficient of polypropylene based fiber reinforced composites with particles from Entada mannii fiber. The composites are prepared by mixing the fiber ash and fiber particles in different proportions and the analysis is carried out. In this trail, it has been proved that the hybrid reinforced composites have provided better result in mechanical tests whereas single reinforced composite has shown better friction co-efficient.

Vinu kumar et al [17] have studied the mechanical, dynamic mechanical and sound acoustic behaviors of flax woven fabric reinforced epoxy composites by reinforcing the alkali treated custom made basket woven
fabric at 0, 25, 35 and 45 weight percentages and observed that 45% composite shows higher tensile, flexural and hardness strength. The same composites have been subjected to dynamic mechanical analysis at five different frequencies by varying the temperature and it is evident that 35% composite has provided better improvement in storage modulus when operated at higher frequency.

Most of the researchers are ideal in choosing short fiber to enhance the mechanical properties of the composites. In the present investigation, the fiber is crushed into powder form to make the composite. The
characteristics of fiber are studied and the composites are fabricated. The fabricated composites are subjected to various tests to explore the mechanical properties. The structural analysis has been done additionally to verify the bonding between the fiber and the matrix by means of scanning electron microscopy.

3. Materials and methods

This section presents the complete procedure of how the experiment has been conducted and the various tools used for the experiment.

3.1. Fiber plant

A perennial grape family vine, *Cissus Quadrangularis* [18, 19], has usually been considered to be the so-called veldt grape, devil’s backbone, adamant creeper, the asthisamharaka, the hadjod, and the piranda. This is the native of tropical Asia, Arabia, and most of Africa. Figure 1 presents the *Cissus Quadrangularis* plant in its own habitat. For the experimentation, the plant has been taken from locally grown areas in India. The chopped *Cissus Quadrangularis* stems are depicted in figure 2 and they are soaked in water as shown in figure 3 for a time period of 2 weeks to degrade the microbes. The cellular content of the *Cissus Quadrangularis* plant is up to 83.04% and it has a tensile strength value from 2299 MPa to 5462 MPa [13]. The percentage of fiber reinforcement has been changed to optimize the mechanical characteristics of *Cissus Quadrangularis* fiber polymer composite.

The main aim of the usage of fiber is to replace the harmful E-glass fiber [20] for an ecofriendly environment. To prevent the moisture retention capacity, the *Cissus Quadrangularis* fiber has been sun-dried. After withering of fleshy layer, the unwanted strands are eliminated using a metal brush in order to obtain uniform fibers of maximum content. The mechanical characteristics of fiber polymer composite have been evaluated using the standard experimental investigation techniques. The mixture is fashioned by adding 98% of isophthalic resin, 1% of Methyl Ethyl Ketone Peroxide (MEKP) aggregate and 1% of Cobalt Octoate accelerator in a basin with a help of a stirrer. The resin is tested both in liquid and solid forms at room temperature. The testing specimen has been prepared using a 300 × 300 x 3 mm mould through compression molding process. The powdered fiber (figure 4) is then carefully dropped in a uniform pattern and pre-pressed without deteriorating the structure of fiber with different combinations of weight (10%, 20%, 30%, and 40%). After the completion of this process, the liquid resin (Yellow Viscous Liquid) at 25°C is allowed to pass through the fiber. The grooved roller degasses the fiber morphology and it is cured in normal temperature under 399 kN load. 0.17% wax content shares a higher bonding capacity and a hard fiber surface. Figures 5(a)–(d) depict the SEM images of composite plates produced for different fiber variations.
3.2. Anatomy of the stem
To analyze the structure of healthy *Cissus Quadrangularis* stems, they have been thoroughly investigated under a polar microscope \[21\]. The stems are broken into a length of 9 × 9 mm and they are immersed into a solution (15% formaldehyde, 70% ethyl alcohol, and 15% acetic acid) for 1 day to conserve the tissue structure. A graded tertiary butyl alcohol has been used for dehydration and it is embedded with paraffin. After this process, the microstructural specimen has been obtained.

3.3. Chemical Characteristics of fiber
The standard procedure followed by National Renewable Energy Laboratory (NREL) has been used to obtain the chemical characteristics such as cellulose, lignin, and hemicellulose. To identify the moisture content, the specimen is dried in an oven at 103°C for five hours. The cellulose and the lignin properties present in the *Cissus Quadrangularis* fiber polymer composite are 81.38% and 15.92%, respectively. These properties show good mechanical strength of *Cissus Quadrangularis* fiber polymer composite. The low level of hemicellulose content increases the strength of the fiber and prevents the breakdown of cellulose microfibers. The low lignin content preserves the fiber structure and the arrangement and 1.20% of wax content exhibits a higher binding capacity as well as a tough fiber surface. The fiber contains 1.67% of ash.

3.4. Powdered fiber composition
The powdered fiber has been subjected to 45% relative humidity and then, kept at 28°C for two hours inside the testing chamber. A very steady relative humidity will be created by maintaining constant dew point and air temperature. To identify the moisture content, 3g of the sample is taken, it is dried in an oven at 62°C for three hours and it is cooled in the silicon gel desiccator. Heating and cooling are performed with repeated motions until there occurs less than 1 mg of variation between the two successive measurements. The Moisture Content (MC) is evaluated using equation (1).

Figure 6. *Cissus Quadrangularis* fiber’s scanning electron micrographs for different testing specimens.
\[ MC(\%) = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}} \]  

The untreated *Cissus Quadrangularis* fiber polymer composite is measured by the pycnometer process, where the distilled water is taken as the immersion liquid, and the equation (2) is used to determine the density of *Cissus Quadrangularis* fiber polymer composite.

\[ D_{\text{CQDFPC}} = \left( \frac{\mu_2 - \mu_1}{(\mu_3 - \mu_1)(\mu_4 - \mu_2)} \right) \times D_W \]  

In equation (2), the masses are represented as \( \mu_1, \mu_2, \mu_3, \) and \( \mu_4. \) The parameter \( \mu_1 \) represents a void pycnometer, the parameter \( \mu_2 \) denotes a pycnometer filled with *Cissus Quadrangularis* fiber, the parameter \( \mu_3 \) is a pycnometer filled with distilled water, and parameter \( \mu_4 \) illustrates the pycnometer filled with both distilled water and *Cissus Quadrangularis* fiber. The density of distilled water is measured using \( D_W. \) The moisture content and the density of *Cissus Quadrangularis* fiber are 5.01% and 1.213 g cm\(^{-3}\), respectively.

### 3.5. Surface morphology of *cissus quadrangularis* fiber

A scanning electron microscope (HITACHI Model S3000H) has been used to verify the surface morphology of *Cissus Quadrangularis* fiber. In order to prevent the charging of electron rays during the test, the specimens are covered with a platinum layer. The SEM experiments are carried out with an acceleration power of 10 kV of electron beam. The surface morphology of fiber is an important consideration for defining the fiber’s ability to be a strong reinforcement and to survive.

The scanning electron micrographs of different test specimens are presented in figure 6. The roughness of the surface helps to boost the surface contact area so that, the fibers adhere to the matrix in a better way, during composite processing. It is noted that starch grains and the impurities are cleaned by pre-casting fiber treatments. This fiber is made more rigid by the existence of complex lateral pores. Hence, the mechanical properties are improved.

### 3.6. Standard test equipment used

The standard test equipment used to conduct the experiment is explained in the subsequent sections.

(i) **Universal testing machine (UTM):**

   The tensile and the compressive strengths of the additives are measured by the use of a universal testing machine (UTM) [22]. The UTM is a flexible and beneficial measuring tool that is able to assess the fabric houses comprising tensile power, elasticity, stiffness, the power of overall performance, elastic and plastic deformation, bending pressure, and tightening.

(ii) **Impact testing machine:**

   Impact testing machine measures the ability of an object to withstand heavy loads and it is also used to evaluate a component or a material’s working life [23]. Two standard forms of impact tests are available: Charpy and IZOD [24]. A pendulum impact tester has been used to examine the cracking behavior of *Cissus Quadrangularis* fiber polymer composite, during impact loading.

(iii) **Hardness testing machine:**

   Three common types of scientific hardness tests [25] are conducted by hardening machines: the Brinell hardness test, the Rockwell hardness test, and the Vickers hardness test. The hardness test by Rockwell is the most commonly used technique and it is easy to perform as well as more reliable than the other tests.

### 4. Results and discussion

The materials used to conduct the experiment are provided below along with the test results obtained for tensile, flexural, impact, hardness test, and water absorption capacity of *Cissus Quadrangularis* powder reinforced polymer composite. The reinforcement material is the fiber in the form of powder with 600 microns.

#### 4.1. Tensile test results

Tensile testing is a destructive testing method that provides information about the metallic material’s tensile strength, yield strength and ductility. In this test, the force needed to crack a composite and the degree to which the specimen persists or continues to the point of breakage are determined. Composite tensile testing typically takes the form of simple tension or flat-sandwich stress testing according to the standards such as ISO 527-4, ISO
Table 1. Results of Tensile Test.

| Parameters                             | 10% Combination | 20% Combination | 30% Combination | 40% Combination |
|----------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Area (cm²)                             | 1.00            | 1.00            | 1.00            | 1.00            |
| Yield Force (Kg)                       | 14.30           | 5.60            | 7.90            | 30.00           |
| Yield Elongation (mm)                  | 0.63            | 0.52            | 1.74            | 1.11            |
| Break Force (Kg)                       | 67.5            | 33.8            | 17.4            | 41.4            |
| Break Elongation (mm)                  | 3.65            | 7.67            | 19.94           | 1.85            |
| Tensile Strength at Yield (Kg/cm²)     | 14.30           | 5.60            | 7.90            | 60.00           |
| Tensile Strength at Break (Kg cm⁻²)    | 67.50           | 33.80           | 17.4            | 82.80           |
| % Elongation                           | 12.17           | 15.34           | 39.88           | 3.70            |

Figure 7. Tensile Test Results. (a) 10% sample (b) 20% sample, (c) 30% sample, and (d) 40% sample.
Table 2. Flexural Test Results.

| Parameters                | 10% Combination | 20% Combination | 30% Combination | 40% Combination |
|---------------------------|-----------------|-----------------|-----------------|-----------------|
| Max. Force (Kg)           | 11.90           | 5.60            | 3.70            | 1.90            |
| Max. Elongation (mm)      | 17.83           | 17.30           | 14.55           | 18.09           |
| Flexural Strength (N mm$^{-2}$) | 14.06          | 6.61            | 4.37            | 2.24            |
| Flexural modulus (N mm$^{-1}$) | 163.01        | 79.46           | 60.50           | 25.29           |

Figure 8. Graphical analysis of flexural test Results. (a) 10% sample (b) 20% sample, (c) 30% sample and (d) 40% sample.

Table 3. Results of hardness test.

| Samples    | 10% Combination (RHN) | 20% Combination (RHN) | 30% Combination (RHN) | 40% Combination (RHN) |
|------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Sample 1   | 31.4                  | 30.6                  | 36.8                  | 34.7                  |
| Sample 2   | 33.0                  | 31.9                  | 38.8                  | 34.39                 |
| Sample 3   | 34.02                 | 32.82                 | 40.45                 | 35.12                 |
| Average    | 32.8                  | 31.77                 | 38.68                 | 34.74                 |

Table 4. Results of Impact Test.

| Specimen   | Impact value          |
|------------|-----------------------|
| 10% Combination | 1.207 joules         |
| 20% Combination | 2.548 joules         |
| 30% Combination | 1.947 joules         |
| 40% Combination | 2.237 joules         |

527-5, ASTM D 638, ASTM D 3039, and ASTM C 297. Tensile testing also includes tensile stress (at yield and break), tensile modulus, tensile pressure, yield elongation, break elongation, and percent elongation. Additionally, the tensile measure provides superior axial-load-string alignment to assess the optimum tensile strength in the direction parallel to the fiber path, especially it is very important in the aerospace industry, where composites are often used with high-tensile-stress structures. There are currently several validated gripping mechanisms available and they include manual, pneumatic and hydraulic actuation for atmospheric, sub-
ambient and high-temperature applications ranging from 200°C to 600 °C. Table 1 demonstrates the results of tensile test.

The tensile test results of different sample sizes are presented in figures 7(a)–(d). The measurements such as grip length-50 mm, gauge length-150 mm, sample width-25 mm, sample thickness-3 mm and speed of testing-1 mm min−1 are same for every tensile test results obtained. 30% combination of specimen shows that the Cissus Quadrangularis fiber is strong and possesses much elongation capacity compared to the remaining specimens.

4.2. Flexural test results

A flexure test does not measure the critical material properties compared to a compression test or a tensile test. All the three fundamental stresses are encountered when a specimen is involved under flexural pressure. A flexure test is most commonly used to measure the flexural strength and the flexural modulus [26]. Flexural force is defined as the maximum stress on the compression or tension side of the specimen in the outermost fiber. The flexural test results of the Cissus Quadrangularis fiber are presented in table 2. The Cissus Quadrangularis fiber with a 10% combination tends to have greater flexural strength compared to other specimens. The flexural strength of 40% combination is low compared to other combinations (figure 8).

The flexural test results obtained show the homogeneous nature of Cissus Quadrangularis fiber polymer composite. From the graphical analysis, it is clear that both the tensile and the flexural strengths are similar and the polymer provides high strength for fiber content.

| Time Taken (Hour) | Distilled water | Salt water | Rain water | River water |
|-------------------|----------------|------------|------------|-------------|
| 2                 | 4.40%          | 4.30%      | 4.25%      | 4.40%       |
| 4                 | 4.49%          | 4.39%      | 4.37%      | 4.49%       |
| 6                 | 4.75%          | 4.45%      | 4.40%      | 4.53%       |
| 8                 | 4.85%          | 4.55%      | 4.45%      | 4.65%       |
| 10                | 4.98%          | 4.68%      | 4.46%      | 4.76%       |
| 12                | 5.01%          | 4.68%      | 4.49%      | 4.89%       |
| 14                | 5.01%          | 4.68%      | 4.49%      | 4.89%       |
| 16                | 5.01%          | 4.68%      | 4.49%      | 4.89%       |
| 18                | 5.01%          | 4.68%      | 4.49%      | 4.89%       |
| 20                | 5.01%          | 4.68%      | 4.49%      | 4.89%       |

Table 5. Water absorption capacity of Cissus Quadrangularis Fiber at various streams under regular time intervals.

![Figure 9. Water absorption capacity of Cissus Quadrangularis Fiber in different aqueous environments.](image-url)
4.3. Hardness test results
The material hardness measurement measures the strength of a substance by evaluating its penetration resistance. The findings of the hardness test will particularly be helpful in choosing the materials, as the hardness value measured shows how quickly the material can be machined and how well it can wear [27]. The results of the hardness test with different combinations of Cissus Quadrangularis fiber polymer composites are presented in table 3. 30% combination shows higher hardness test result. It also indicates that the material can be machined well and it is less prone to tear.

4.4. Impact test results
Instrumented impact measurement systems have been developed with electronic sensing instruments and it can continuously monitor the load of the test specimen in terms of time and deformation of the specimen before fracture [28].

During the whole duration of an impact test, the instruments may report tension or pressure. The data acquisition method offer total coverage rather than a single estimated amount of the effect test history. The impact test results of different combinations of Cissus Quadrangularis fiber polymer composites are portrayed in table 4. The results demonstrate that irrespective of the combinations of Cissus Quadrangularis fiber polymer composite, higher strength has been gained at each combination. The impact values obtained for both 20% and 40% specimens show that the Cissus Quadrangularis fiber polymer composite possesses low amount of brittleness and ductile fracture and subsequently, these qualities depict the toughness of Cissus Quadrangularis fiber polymer composite.

4.5. Water absorption capacity
The water absorption capacity is experimented by considering thirty percentage of fiber content of Cissus Quadrangularis reinforced polymer composite as shown in Table 5 and figure 9. Four aqueous environments namely distilled water, salt water, rain water and river water are used. The pH values of each aqueous environment namely distilled water, salt water, river water, and rainwater are retrieved as 7.1, 8.3, 7.5, and 5.6, respectively. The micro void present in the natural fiber polymer composite shows increasing water absorption capacity and it simultaneously reduces the encapsulation of the compound. The good matrix bonding capacity of Cissus Quadrangularis reinforced polymer can even pass through the microvoids and it reduces the moisture absorption tendency. The moisture absorption capability of every aqueous solution obtained is approximately equal to 5.01%, which is relatively high compared to the reinforced polyester matrix composites [29, 30].

5. Conclusion
This study illustrates the optimization of mechanical features of Cissus Quadrangularis reinforced with an unsaturated polyester composite by changing the fiber content. Standard techniques have been used to assess the physicochemical and mechanical properties of the material. The preparation of Cissus Quadrangularis processed reinforced unsaturated polyester composites has been studied and the mechanical properties such as tensile, flexural, impact and hardness of different fiber contents are analyzed. The experimental results prove that the properties of Cissus Quadrangularis fiber produce better results than the other natural fibers discussed in various literatures. The micro void present in the composite of natural fiber polymer indicates improved ability of water absorption and at the same time, it decreases the encapsulation of the compound. The strong matrix bonding ability of the reinforced Cissus Quadrangularis polymer can also move through the microvoids and reduce the propensity of absorbing moisture. In contrast to the reinforced polyester matrix composites, the moisture absorption of any aqueous solution obtained is around 5.01 percent, which is relatively high. As a result, this composite can be used in the automobile industry and in its associated fields as pumpers, as front cabinet, as a roof sheet, as a body sheet, as an illumination frame, as two-wheeler mudguards, and so on. In future, multiobjective optimization technique can be incorporated to optimize the combination of parameters.

Data availability statement
No new data were created or analysed in this study.

ORCID iDs
Sankarasubramanian M https://orcid.org/0000-0002-6916-5095
Pitchipoo P https://orcid.org/0000-0002-2850-6084
References

[1] Krishnasamy S, Thiagamani S M K, Kumar C M, Nagarajan R, Shahrroze R M, Siengchin S, Ismail S O and Indira Devi M P 2019 Recent advances in thermal properties of hybrid cellulose fiber reinforced polymer composites Int. J. Biol. Macromol. 141 1–13

[2] Mochane M J, Tekgoz C M, Mokhtar T H, Mubea A, Sadiku E F, Ray S S, Ibrahim I D and Daramola O O 2019 Recent progress on natural fiber hybrid composites for advanced applications: a review in EXPRESS Polymer Letters 13 (2) 159–198

[3] Atta A 2020 Enhanced dielectric properties of flexible Cu/polymer nanocomposite films Surface Innovations 9 (1) 17–24

[4] Wang D, Onawumi P Y, Ismail S O, Dhakal H N, Popov I, Silberschmidt V V and Roy A A 2019 ‘Machinability of natural-fibre reinforced polymer composites: conventional vs ultrasonically-assisted machining Composites Part A: Applied Science and Manufacturing, 119 188–95

[5] Madhu P, Sanjay M R, Jawaid M, Siengchin S, Khan A and Pruncu C I 2020 A new study on effect of various chemical treatments on Agave Americana fiber for composite reinforcement: physico-chemical, thermal, mechanical and morphological properties Polym. Test. 85 106437

[6] Indran S, Raj R D E, Daniel B S S and Binoo J S 2018 Comprehensive characterization of natural Cissus quadrangularis stem fiber composites as an alternate for conventional FRP composites Mater. Today: Proc. 14 35–40

[7] Mayandi K, Rajini N, Pitchipoo P, Jappes J T W and Rajulu A V 2018 Properties of untreated and chemically treated Cissus quadrangularis natural fibers and their composites with polyester as the matrix Polym. Compos. 39 876–86

[8] Joseph J, Munda P R, Kumar M, Sidpara A M and Paul J 2020 Sustainable conducting polymer composites: study of mechanical and tribological properties of natural fiber reinforced PVA composites with carbon nanofillers Polymer-Plastics Technology and Materials 59 1088–99

[9] Velmurugan V, Kumar D D and Thanikaikalasaran S 2020 ‘Experimental evaluation of mechanical properties of natural fibre reinforced polymer composites Materials Today: Proc. 15 1079–86

[10] Arul Jeya Kumar A and Prakash M 2020 ‘Mechanical and morphological characterization of basalt/Cissus quadrangularis hybrid fiber reinforced polyolactic acid composites Proceedings of IMechE Part C, Journal of Mechanical Engineering Science 234 2895–407

[11] Shadrach Jeya Sekaran A and Palani Kumar K 2019 Study on drilling of woven sisal and aloe vera natural fibre polymer composite Mater. Today Proc. 16 640–6

[12] Liu L, Lv X, Bao J, Xie J, Tang X, Che J, Ma Y and Tong J 2019 Characterization of silane treated and untreated natural cellulose fibre from corn stalk waste as potential reinforcement in polymer composites Carbohydrate Polym. 218 179–87

[13] Afabi O L, Megat-Yusoff P S M, Arif Z M and Hamizol M S 2019 Fabrication of pandanus tectorius (screw-pine) natural fiber using vacuum resin infusion for polymer composite applications, Journal of Materials Research and Technology 8 3102–31

[14] Hariprasad K, Ravichandran K, Jayaseelan V and Muthuramalingam T 2020 Acoustic and mechanical characterisation of polypropylene composites reinforced by natural fibres for automotive applications Journal of Materials Research and Technology 9 14029–35

[15] Vignesh V, Balaji A N, Nagaprassad N, Sanjay M R, Khan A, Asiri A M, Ashraf G M and Siengchin S 2021 Indian mallow fiber reinforced polyester composites: mechanical and thermal properties Journal of Materials Research and Technology 1 274–84

[16] Balogun O P, Alaneem K K, Acedidian A A and Omomoyiobo J A 2020 Mechanical properties and friction coefficient of hybridpolypropylene Entada mannii composites Material Research Express 7 115301

[17] Kumar S M V, Kumar K L S, Jalal H S and Rajamurugan. G 2020 Mechanical, DMA and sound acoustic behaviour of flax wovenfabric reinforced epoxy composites Material Research Express 7 085362

[18] Chemnapan J, Sankaranarayanan A and Arjunan. S 2020 ‘Evaluation of antimicrobial activity of cissus quadrangularis L. stem extracts against avian pathogens and determination of its bioactive constituents using GC-MS Journal of Scientific Research 64

[19] Zhao F, Li G, Osterle W, Häuserl I, Zhang G, Wang T and Wang Q 2016 Tribological investigations of glass fiber reinforced epoxy composites under oil lubrication conditions Tribol. Int. 103 208–17

[20] Mohanty J R, Das S N and Das H C 2014 Tribological behavior of acrylic acid–modified date palm leaf–reinforced polyvinyl alcohol composite Tribol. Trans. 57 546–52

[21] Chegdani F, Takabi B, El Mansori M, Tai B L and Bukkapatnam S T 2020 Effect of flax fiber orientation on machining behavior and surface finish of natural fiber reinforced polymer composites J. Manuf. Processes 54 337–46

[22] Kwesim H, Choi S, Kim Y and Nam K 2006 Development of a new UTM (universal testing machine) system for the NANO/MICRO in-process measurement International Journal of Modern Physics B, 20 4432–8

[23] Lin Y Wu et al. 2016 Influence of diameter–thickness ratio on alloy Zr–4 tube under low-energy impact fretting wear. Materials Today Communications 8 79–90

[24] Ismail S O, Dhakal H N, Popov I and Beaudrand J 2016 Comprehensive study on machinability of sustainable and conventional fiber reinforced polymer composites Engineering Science and Technology, an International Journal 19 2043–52

[25] Furuta E, Kaieda M and Takada A 2018 Hardness test apparatus and hardness testing method U.S. Patent No. 10,001,432

[26] Dukhan N, Rayess N and Hadley J 2010 Characterization of aluminum foam–polypropylene interpenetrating phase composites: flexural test results Mech. Mater. 42 134–41

[27] Shahdad S A, McCabe J F, Bull S, Rusby S and Wassell R W 2007 Hardness measured with traditional Vickers and Martens hardness methods Dent. Mater. 23 1079–85

[28] Trotta A, Annadith A N, Burek R O, Pelgrims B and Iven J 2018 ‘Evaluation of the head-helmet sliding properties in an impact test J. Biomech. 75 28–34

[29] Maslinda A B, Majid M A, Ridzuan M M J, Afendi M and Gibson A G 2017 Effect of water absorption on the mechanical properties of hybrid interwoven cellulose–cellulose fibre reinforced epoxy composites Compos. Struct. 167 227–37

[30] Choo W K, Kim H I, Kang S J, Lee Y S, Han J H and Kim B J 2016 Mechanical interfacial adhesion of carbon fibers-reinforced polarized–polypropylene matrix composites: effects of silane coupling agents Carbon letters 17 79–84