Experimental Analysis of Coir Fiber Sheet Reinforced Epoxy Resin Composite

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Abstract. In recent years, the industrial demand for composite materials is increasing rapidly. However, most composite materials are produced from synthetic fibers and resins. As a result, the current production of composite materials still has many problems and the most worrying concern is the environment and human health. From those challenges, natural fiber composite is gradually becoming a worldwide research and development trend. Natural fibers are an abundant and renewable resource, so their cost is relatively low compared with other conventional fibers. They are eco-friendly, biodegradable and reduce the problem of solid waste production when used to replace non-degradable fillers. The objective of this study is to approach and learn about natural fiber composite, which is divided into two main stages. In the first one, we learn about natural fibers and matrixes of natural fiber composites. In the second stage, material testing experiments were performed on the coir fiber sheet reinforced epoxy resin composites to determine their mechanical properties as well as to find the mechanical properties of the coir fiber sheet using the rule of mixtures theory. The experimental results show that the non-split coir fiber sheet has the similar properties with ones of single coir fiber and results in a higher mechanical performance compared to the split coir fiber sheet. Additionally, the results show a medium stiffness, small density and low-cost composite material. Therefore, the further purpose of this study is to apply natural fiber composites in aeronautical engineering such as manufacturing small unmanned aerial vehicle.

Keywords: Natural fiber composite, Polymer matrix, Coir fiber, Tensile test, Rule of mixtures.

1. Introduction
A composite material is a material made from two or more different component materials in order to make use of the advantages of components to produce the material having superior properties compared to individual components. About history, simple natural composite fiber materials exist from a long time ago. It can be found in wood in which cellulose fibers are held together by lignin. The connection of cellulose is responsible for adequate strength and density in plants and trees.

Nowadays, composite material industry has been developing strongly all over the world with many remarkable achievements and new inventions. However, in addition to development, many negative issues have risen, specifically the negative impact on the environment and human health. Consequently, research and development of natural fiber composite (NFC) are of interest. With many valuable features and advantages of NFC such as low specific gravity, low cost in production process, relatively high in strength and stiffness and especially eco-friendly and biodegradable [1-2], which is
less harmful to both human and environment, the application of natural fibers for reinforcement in composite materials has increased significantly in the past few years.

Natural fibers include all those derived from plants, animals and mineral resources [3]. In the scope of this study, we focus on studying and understanding the mechanical properties of natural plant-derived fibers. Natural fibers derived from plants are mainly composed of cellulose such as cotton, jute, flax, hemp, sugarcane, bamboo and many other plant fibers. These fibers are taken from different parts of the plant such as fibers from the seeds (cotton fibers), the leaves (sisal fibers), the bark (flax, hemp, jute, rattan or even banana and sugarcane fibers), the fruits (coconut fibers from coconut husks) and fibers from stems (bamboo, grass, wood fibers) [3]. In those mentioned fibers above, the ones are taken from the bark and stem will have the best mechanical properties and have great potential in the process of making reinforced fibers from natural fiber composites (NFCs).

2. Natural vegetable fibers
In this study, the authors introduce and learn about the mechanical properties of natural fibers that can be exploited in Vietnam.

2.1. Cotton fiber
Cotton fibers are soft and evenly spun; fibers are taken from the seeds of cotton plants - a shrub that normally grows in tropical and subtropical regions. In Vietnam, cotton trees are mostly grown in the Central Highlands and Southeast. Cotton fibers are friendly to human skin and hypoallergenic, which makes cotton fibers become an important ingredient in the textile industry. In addition, with relatively good mechanical properties, cotton fibers are also used today as reinforcing components in composite materials.

2.2. Jute fiber
Jute is a long and soft plant fiber that can be pulled into coarse, hard yarn. The fibers are relatively white to slightly brown and are 1 to 4 meters long. Some advantages of jute yarn are: it is 100% biodegradable and recyclable, so it is very friendly to the environment; it has high tensile strength, low elongation. In Vietnam, jute trees are grown in the Red River Delta region and Vietnam is one of the top ten jute producing countries according to the 2014 report. Just like cotton, jute yarns are mainly used in the garment and packaging industry. Besides, thanks to the available mechanical properties, jute fiber is also now studied and applied in the composite material industry.

2.3. Banana fiber
Banana fibers, which are derived from banana bark, have the following characteristics: it is a very strong fiber; it is similar to bamboo fiber but better fineness and smaller elongation; it is lightweight; it absorbs strong moisture but releases moisture very quickly; it can biodegrade. In Vietnam, banana trees are grown in many areas and it can be said that they are easy to grow and exploit. In previous years, the application of banana fiber is very limited and is mainly used to manufacture items such as ropes and carpets. However, recently, after studying the properties of banana fiber, with good mechanical properties and its usability, it is also used to make reinforced fibers in NFCs.

2.4. Bamboo fiber
Bamboo fibers are mainly cellulose fibers, extracted or made from natural bamboo. Bamboo has higher compressive strength than wood, brick or concrete and tensile strength can be compared with steel. Bamboo fibers come in different forms such as hardened strips produced by cutting bamboo stems into thin strips; rayon, also known as semi-synthetic fibers, are created by regenerating cellulose extracted from bamboo; Smooth fiber is produced by a machine-assisted process. Bamboo has a great economic and cultural significance in South Asia, Southeast Asia, East Asia and especially for Vietnam. Bamboo has many uses such as manufacturing food, building materials, household items,
agricultural tools, etc. Today, with valuable mechanical properties, bamboo fibers are being researched to have applicable in NFCs.

2.5. Coir fiber
Coconut fiber, also known as coir, is a natural fiber extracted from the part between the hard-inner crust and the outer layer of the coconut. There are two types of coconut fiber: brown coconut fiber extracted from the old coconut husk; White coconut fiber is extracted from young coconut shells. The brown coir fiber is strong and highly abrasion resistant. The white coir fiber is smoother, but also weaker. Since ancient times, coir fiber has been used by humans for many different purposes such as making clothes, making ropes, making carpet coverings, etc. Today, with available mechanical properties, coir fiber is also researched and applied in the natural fiber composite industry.

Table 1 shows that the mechanical properties of coir fiber are lower than other natural fibers that can be exploited in Vietnam. However, because of recent available market reasons in Ho Chi Minh City, coir fiber in the form of the sheet is chosen to fabricate composite material on which perform the experiments.

| Fiber     | Coir   | Cotton | Jute   | Banana       | Bamboo       |
|-----------|--------|--------|--------|--------------|--------------|
| Density (g/cm³) | 1.2    | 1.5 – 1.6 | 1.3 – 1.5 | 1.35         | 0.6 – 1.1    |
| Length (mm)    | 20 – 150 | 10 – 60 | 1.5 – 120 | 150          | 100          |
| Diameter (µm)  | 100 – 450 | –      | 40 – 350 | 50 – 250     | 240 – 330    |
| Tensile strength (MPa) | 131 – 503 | 287 – 800 | 393 – 800 | 600          | 503          |
| Young’s modulus (GPa) | 4 – 6   | 5.5 – 12.6 | 10 – 55  | 17.85        | 35.91        |
| Elongation at break (%) | 15 – 30 | 7 – 8   | 1.5 – 1.8 | 3.36         | 1.4          |

3. Polymer matrices in natural fiber composite

3.1. Polyethylene
Polyethylene (PE) is a thermoplastic polymer with a variable crystal structure and an extremely large range of applications. Polyethylene (PE) is often classified into many major compounds, most commonly Low-Density Polyethylene (LDPE), Linear Low-Density Polyethylene (LLDPE), High-Density Polyethylene (HDPE) and Ultra High Molecular Weight Polypropylene (UHMWPE). Among them, LDPE and HDPE, which have applicable mechanical properties, are usually used a lot in making matrices for NFCs.

3.2. Polypropylene
Polypropylene (PP) is a thermoplastic polymer produced via chain-growth polymerization from propylene monomer. Its properties are similar to polyethylene, but it is slightly harder and better resistant to heat. It is a material having good mechanical properties and high chemical resistance. Thanks to suitable mechanical properties, polypropylene is also commonly used as a matrix in NFCs.
3.3. Phenol formaldehyde resin
Phenol-formaldehyde resins, also known as phenolic resins, are some synthetic resins created by producing a reaction between phenol and formaldehyde. Thanks to appropriate mechanical properties, phenol formaldehyde resin has also been studied for application as a matrix in NFCs.

3.4. Epoxy resin
Epoxy resins, also known as polyepoxides, which have favorable mechanical properties, high heat and chemical resistance along with good strength and adhesion, are used for many different purposes. Applications of epoxy resins are very wide, such as coatings, adhesives, electronic applications, and especially it is used in aerospace industry as a matrix for composite materials with the reinforcement of fibers like glass fiber, carbon fiber and Kevlar fiber. In addition, it is now also used for research and application as a matrix in NFCs.

Table 2 shows mechanical properties of common matrix materials in NFCs.

| Table 2: The mechanical properties of epoxy resin compared to other polymer matrices [8-10] |
|---------------------------------------------|---------|---------|---------|---------|---------|
| Polymer matrix                            | LDPE    | HDPE    | PP      | Phenolic resin | Epoxy resin |
| Density (g/cm³)                           | 0.91 – 0.93 | 0.94 – 0.96 | 0.9 – 0.92 | 1.21     | 1.1 – 1.4 |
| Tensile strength (MPa)                    | 5 – 25  | 15 – 40 | 25 – 40 | 45       | 35 – 100  |
| Young’s modulus (GPa)                     | 0.1 – 0.3 | 0.5 – 1.3 | 0.9 – 2 | 6.5      | 3 – 6     |
| Elongation at break (%)                   | 400     | 150     | 80      | 1.2      | 1 – 6     |
| Strain at yield (%)                       | 19      | 15      | –       | –        | –         |
| Poisson’s ratio                           | –       | 0.46    | 0.43    | –        | 0.3       |

4. Experiments
4.1. Experimental system
Experiments are performed on the miniature testing machine, which is designed and manufactured by our own research team as shown in Fig. 1. In this testing machine, a loadcell is responsible for data acquisition of load and a strain gauge takes data of longitudinal strain during testing. Thanks to the data from the loadcell and the strain gauge, the stress-strain curve is defined, from which we can determine the values of tensile strength and Young’s modulus. Because the test system has just two data acquisition channels, the transverse strain is not be measured. So, the system also incorporates another strain measurement method based on the Digital Image Correlation (DIC). The results from strain measurement by DIC allows to define the Poisson’s ratio and then the shear modulus. However, the accuracy of this method depends on the resolution of image.
Fig. 1: The system used to test mechanical properties of composites

4.2. Experimental standard
Currently, for the tensile testing of composite materials, it is common to use standard ASTM D3039. However, for some other composite materials, the proposed standard is ASTM D638. In summary, ASTM D3039 is recommended for highly oriented and/or high tensile modulus fiber reinforced polymer composites. ASTM D638 is recommended for randomly oriented, discontinuous, moldable, or low reinforcement volume composites or composites with tensile modulus less than 20000 MPa. From those factors, for the coir fiber sheet reinforced epoxy resin composites, the standard chosen for tensile testing is ASTM D638. All the tests are conducted under displacement control at loading rate of 5 mm/min.

4.3. Specimens
In this study, coir fiber was selected in the form of a sheet (coir tape) with a width of 20 cm and a thickness of 1-2 mm (Fig. 2). There is no given specification for this coir tape.

Fig. 2: The coir fiber sheet (coir fiber tape)

The YDL 586 type epoxy resin is used with the specifications provided by the company including:

- Young’s Modulus: 2.8 - 3.4 GPa
- Tensile strength: 60 - 70 MPa
- Elongation at break: 4 - 7%

The coir/epoxy composite material sheets are fabricated by the compression molding method. The dumbbell specimens are machined out from these sheets with the dimensions following the standard ASTM D638 - Type I as shown in Fig. 3. The width and length of the gauge length is 13 mm and 57 mm respectively.

After that, the strain gauge is stuck on surface of specimen. In addition, to be able to measure simultaneously the strain by DIC, four points are also marked on surface of specimen at the effective position (the middle of specimens) with the distance of about 10mm apart as shown in Fig. 4.
4.4. Digital Image Correlation
In DIC method, strains are computed from the displacement of four marks laid at the surface of the specimen.

The longitudinal and transverse strains are calculated following Eq. (1) and (2),

\[ \varepsilon_l = \frac{y_i - y_o}{y_o} \]  

\[ \varepsilon_t = \frac{x_i - x_o}{x_o} \]  

where \( y_i \) and \( y_o \), \( x_i \) and \( x_o \) respectively stand for the current and initial distance between longitudinal and transverse marks.

Thus, the Poisson’s ratio is defined by Eq. (3),
\begin{equation}
\nu_{12} = \frac{E_2}{E_1} \tag{3}
\end{equation}

\section*{4.5. Rule of mixtures}
Rule of Mixtures (RoMs) is a method of approach to approximate estimation of composite material properties, based on an assumption that a composite property is the volume weighted average of the phases (matrix and dispersed phase) properties. It is the simplest method to determine the elastic properties for a unidirectional composite material. The Young’s modulus of the matrix and fiber are taken as \( E_m \) and \( E_f \), similarly Poisson’s ratios are taken as \( \nu_m \) and \( \nu_f \). The quantities of two components inside composite in terms of volume fraction is,

**Longitudinal properties,**
\begin{align}
E &= E_mV_m + E_fV_f \tag{4} \\
\nu_{12} &= \nu_mV_m + \nu_fV_f \tag{5}
\end{align}

Where \( V_m \) and \( V_f \) are volume fractions.

**Transverse properties,**
\begin{align}
E_2 &= \frac{E_mE_f}{E_mV_f + E_fV_m} \tag{6} \\
\nu_{2i} &= \frac{\nu_mE_f}{E_f} \tag{7}
\end{align}

**Shear properties,**
\begin{align}
G_{12} &= \frac{G_mG_f}{G_mV_f + G_fV_m} \tag{8}
\end{align}

Where \( G_f = \frac{E_f}{2(1+\nu_f)} \) \tag{9}
\begin{align}
G_m &= \frac{E_m}{2(1+\nu_m)} \tag{10}
\end{align}

RoMs also allows to determine inversely the mechanicals properties of component materials when the properties of composite are given.

\section*{5. Experimental results}
The goal of study is not only to determine the mechanical properties of composite materials but also to determine the mechanical properties of components including coir fiber and epoxy resin. In addition, it is also important to study the effect of the distribution and percentage of fiber volume on the mechanical properties of the composite material. With the current experimental conditions, it is not possible to measure the mechanical properties of single coir fiber, so the properties of the fiber are attributed to the properties of the coconut sheet by theoretical calculation. To solve these requirements, the experiments are performed on three specimen groups including epoxy resin group and two composite groups.

\subsection*{5.1. Density and volume fraction}
To determine the mechanical properties of composite materials, it is required the density of the component materials as well as the percentage of fiber volume.
The determination of density of epoxy resin and coir fiber is carried out according to the following steps:

- Step 1: Determine the density of epoxy resin using electronic scales and volumetric flasks.
- Step 2: Before fabricating composite sheet, measure the surface dimension and the mass of coir fiber sheet.
- Step 3: After fabricating composite sheet, cut the composite sheet according to the surface shape of the original coir fiber sheet. Then measure the mass of cut composite sheet.
- Step 4: The mass of epoxy resin in composite is the difference between the mass of composite sheet in step 3 and the mass of coir fiber sheet in step 2. With the measured density of epoxy resin in step 1, calculate the volume of epoxy resin.
- Step 5: Cut the composite sheet into small specimens and then measure their thickness and deduce the average thickness of the composite sheet, thereby calculating the volume of the composite sheet.
- Step 6: The volume of the composite sheet in step 5 minus the volume of epoxy resin in step 4 is equal to the volume of the coir fiber sheet.
- Step 7: From the mass of coir fiber sheet in step 2 and volume of coir fiber sheet in step 6, calculate the density of coir fiber.

Table 3 presents the measured density of epoxy resin, coir fiber and composite.

| Specimens | Epoxy | Composite 1 | Composite 2 |
|-----------|-------|-------------|-------------|
|           | Coir fiber | Coir fiber | Composite | Composite |
| $\rho$ (g/cm$^3$) | 1.15 | 0.98 | 1.13 | 0.93 | 1.12 |

| Reference [6-10] | 1.1 – 1.4 | 1.2 | 1.2 |

From the measured weight fraction and density of component materials with assumption that the volume of void is null, the volume fraction of components in composite groups is calculated and presented in Table 4.

| Specimens | Composite 1 | Composite 2 |
|-----------|-------------|-------------|
|           | Coir fiber | Epoxy | Coir fiber | Epoxy |
| $V$ (%)   | 9 | 91 | 15 | 85 |

5.2. Epoxy resin
For epoxy resin, tensile tests were performed on 3 specimens, which have similar thickness. Fig 6 shows three curves of stress-strain of three epoxy resin specimens obtained from the signals of loadcell and strain gauge. It is observed that three curves are superposed.
Fig. 6: The curve of stress-strain of epoxy resin specimens

From these curves, in the elastic linear region, the Young’s modulus of the epoxy specimens is determined as in Fig. 7.

Fig. 7: Linear elastic region of epoxy specimens

For non-linear region, the material has somewhat reduced mechanical properties, so all specimens tend to be highly deformed with a small corresponding force change. Besides, there is a large difference between the specimens in this region and the reasons explained from the effect of flaws in the specimen as well as the effects in the process of setting up experiments such as breaks within the grips, specimen slippage.

For this group, resolution of camera is 2000x3000 pixels which corresponds to 230 pixels for gauge length 10 mm between marks. This resolution is fine enough to measure Poisson’s ratio by DIC method. In addition, the theory of isotropic elastic materials is used to determine the shear modulus of epoxy resin. The properties of epoxy resin are given in Table 5.

**Table 5: The properties of epoxy resin from experiments and theory**

| Specimens | Epoxy resin | Standard deviation | Reference [8-10] | Error (%) |
|-----------|-------------|--------------------|------------------|-----------|
| $E(MPa) = \frac{\sigma}{\varepsilon}$ | 2976 | 48.9 | 2800 – 3400 | 4.1 |
| $\nu = -\frac{\varepsilon_x}{\varepsilon_y}$ | 0.31 | – | 0.3 | 3.3 |
| $G(MPa) = \frac{E}{2(1 + \nu)}$ | 1145 | – | 1192 | 3.9 |

In comparison with the values from reference, the difference is small (less than 5%). So, it can be concluded that the experimental results of epoxy resin group are reliable.

In addition, in the non-linear regions, there are other important properties such as yield strength, tensile strength and fracture. However, because of the properties of all materials in this study as well as the limit of maximum applied force of the testing machine, all those properties are not obtained.
5.3. Composite groups
The first group are made from split coir fiber sheet with volume fraction of fiber calculated about 9%. Similar to the epoxy resin group, tensile tests were performed on 3 specimens, which have the fiber distribution higher than the remaining specimens. Fig. 8 shows three curves of stress-strain of three 9% fiber composite specimens obtained from the signals of loadcell and strain gauge. It is observed that three curves are superposed.

![Fig. 8: The curve of stress-strain of 9% fiber composite specimens](image)

For this group, resolution of camera is also 2000x3000 pixels, but gauge length 10 mm between marks just corresponds to 150 pixels. This resolution is not fine enough to measure Poisson’s ratio by DIC method.

For the second composite group, the specimens are made from non-split coir fiber sheet with a denser distribution of fibers than the 9% fiber composite group, so it is expected to show the correct properties of the material. Therefore, tensile tests were performed on 6 specimens, which have the volume fraction of fiber about 15%. Fig. 9 shows six curves of stress-strain of six 15% fiber composite specimens obtained from the signals of loadcell and strain gauge. It is observed that six curves are also superposed.

![Fig. 9: The curve of stress-strain of 15% fiber composite specimens](image)

For this group, resolution of camera is also 2000x3000 pixels, but in this case, gauge length 10 mm corresponds to 460 pixels. This resolution is really fine to measure Poisson’s ratio by DIC method.

The properties of two coir fiber sheet composite groups are given in Table 6.

| Table 6: The properties of coir fiber composites from experiments |
|---------------------------------------------------------------|
| Specimens | 9% fiber composite | 15% fiber composite |
| $E_{11} (MPa) = \frac{\sigma}{\varepsilon}$ | 2726 | 3168 |
Additionally, the rule of mixtures allows to determine mechanical properties of the split and non-split coir fiber sheets as in Table 7. Because of the lack of Poisson’s ratio of 9% fiber composite group, for the split coir fiber sheet, just the Young’s modulus is defined.

Table 7: The mechanical properties of coir fiber sheet from RoMs theory

|                        | Split coir fiber sheet | Non-split coir fiber sheet | Reference [4,6-7] |
|------------------------|------------------------|----------------------------|-------------------|
| $E_f = \frac{E - (1 - f)E_x}{f}$ | 0.517 GPa              | 4.251 GPa                  | 4 – 6 GPa         |
| $\nu_f = \frac{\nu_{12} - (1 - f)\nu_{xx}}{f}$ | –                     | 0.11                       |                   |
| $G_f = \frac{E_f}{2(1 + \nu_f)}$ | –                     | 1915                       |                   |

The results show that the split coir fiber sheet does not reinforce the mechanical properties of the composite material but reduces them. The cause maybe from factors such as fiber distribution, fiber orientation and composite manufacturing process. Therefore, the mechanical properties of split coir fiber sheet calculated in theory are also very low.

Besides, it can be concluded that the non-split coir fiber sheet shows the similar properties with ones of single coir fiber and results in a higher mechanical performance compared to the manufacture of composite materials from split coir fiber sheet. Additionally, with the result of Young’s modulus of coir fiber sheet, it can be concluded that the Young’s modulus of single coir fiber will be greater than 4251 MPa.

5.4. Comparison and validation of results

Firstly, to evaluate the reliability of strain measurement, strains measured by two different methods (strain gauge and DIC) in the 15% fiber composite group are compared. The results show that the strain from the DIC (points in Fig 10) is near to the resulting curve from the strain gauge. So, it can be concluded that the strain results from both measurement methods are reliable.

Fig 10: The comparison of two strain measurement methods

Because the composite materials in this study are made of coir fibers in form of sheet and having random orientation, they are not only an orthotropic composite as usually but also considered to be in-plane isotropic elastic material. Therefore, their shear modulus can be calculated in two different ways corresponding for two material behaviors. Table 8 shows the shear modulus of 15% fiber composite
calculated from two different ways. The difference between two values of shear modulus is small (less than 5%), it can be concluded that the experimental results of 15% fiber composite group are reliable.

| Specimens | 15% fiber composite |
|-----------|----------------------|
| \(G_{12}(MPa) = \frac{E}{2(1+v_{12})}\) | 1257 |
| \(G_{12}(MPa) = \left(\frac{f}{G_f} + 1 - f \frac{G_r}{G_m}\right)^{-1}\) | 1218 |
| Error (%) | 3.1 |

6. Conclusion
Experimental analysis of the coir fiber sheet reinforced epoxy resin composites is realized in this study. Because of the limit of maximum applied force of test machine, only the Young’s modulus, the Poisson’s ratio and the shear modulus are determined for composites and component materials. The results show a medium stiffness, small density and low-cost composite material. The improvements like fiber treatment, fiber distribution and orientation as well as manufacturing technology of composite material could help to raise the properties of coir/epoxy composites. Moreover, the coir fibers in Vietnam are really common and affordable. Therefore, the study of mechanical properties of coir fiber composite opens the possibility of application in many fields, even aeronautical technology.

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