Micromodeling Natural Fiber Composites: Predicting Mechanical Properties of Reinforced Thermoplastic

Dr. Juan Miguel Díaz Mendoza[1], Dra. Delia Julieta Valles Rosales[2],
Dr. Juan Francisco Hernandez-Paz[3], M.I David Atayde Campos[1]

Abstract— Mechanical properties of natural fiber composites had been analyzed in the last two decades. However, composites are manufactured to determine their mechanical properties experimentally, since weight ratios and other factor can affect these properties. Using micromechanical models from Reuss, Voigt, Einstein, Hirsch, Halpin-Tsai and Facca modified series model can predict tensile strength. Injection molded samples were fabricated per ASTM D638 and tested using a universal testing machine. Weight ratio values of each micromechanical model from pecan shell were compared to experimental data. The predicted values from micromechanical models, were adequate to the experimental results.

Key words—mechanical properties, composites, statistical design, tensile test.

Introduction

Thermoplastics reinforced with natural fibers have been studied in the last two decades. Many of these composites have been analyzed with different types of reinforcements. The reinforcement has been made using fibers from pine wood, plants such as cotton, rapeseed, sisal, flax among others. The fibers many mixed with olefin plastics such as polypropylene, polyethylene, polyvinyl, among others. The studies made with thermoplastic composites have analyzed the type of shape and length of the fiber used to obtain better mechanical properties than the matrix. In a study by (Adhikary et al., 2008) for example used wood dust to study recycled high density polyethylene (HDPE) with wood pine dust. Others works have used long and short fibers where the length of the fiber is key in the mechanical response of tensile strength and other mechanical properties. A work from (Stark & Berger, 1997) analyzed pine wood flour properties considering particle size using mesh standard. Their results indicate smaller particle size have higher tensile response. A study with fiber length Mijiyama et al. (2017) used long fiber for polypropylene and birch and aspen fibers to improve mechanical properties. Oliver-Ortega et al. (2018) used rapeseed short fiber to reinforce polypropylene to improve mechanical properties as material suitable for construction material. In other study by Belgacem et al. (Belgacem et al., 2021) they analyzed the mechanical properties of Date palm short fibers with polypropylene.

Mechanical properties of composites have been predicted using several micromechanical models. However, the predicted values by the models have a variable correlation with experimental data; in fact, some of the models have a linear response which does not fit with the composite test data. Various studies (Adhikary et al., 2008; Facca et al., 2007; Kalaprasad et al., 1997; Oliver-Ortega et al., 2018) have analyzed tensile properties based on experimental testing and theoretical modeling using model from Reuss, Vought, Hirsch, Halpin-Tsai, Modified Bowyer and Bader's model, among others, where predicted values of the composites

Regarding works of composites from waste, few have been reported. Some works reported were focused on pecan and peanut shell (Essabir et al., 2015), (Maldas et al., 1992) These composites had different responses. In these works, the composites were coupled with different types of coupling agents based in the matrix type which most were polyolefin and poly-lactic acid. As for pecan wood particle composite no work was found. The lack of information of mechanical properties of pecan wood plastic composites of reinforced high-density polyethylene (HDPE) gave the opportunity to work in a study to assess the mechanical properties of such material for potential application in different uses in construction or automotive. In this work, development and predicting mechanical properties of WPCs based in pecan wood and pine wood flour are studied. The objective of the research is to use micro mechanic model to predict tensile properties of pine wood and pecan wood of the composite using HDPE and compare the results with the reported data from pecan wood and pine wood experimentation. The analysis was based in two fibers the pecan wood and pine wood with two mesh sizes 40 and 60. Weight ratios of 30 y 40%.

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[1] El Dr. Juan Miguel Díaz Mendoza y el M.I David Atayde Campos son Profesores del departamento de Ingeniería Industrial y manufactura en la Universidad Autónoma de Cd. Juárez, Chihuahua México. juan.diaz@uacj.mx, datayde@uacj.mx.

[2] La Dra. Delia Julieta Valles Rosales es Profesora de Ingeniería Industrial en la New México State University, Las Cruces NM, USA. dvalles@nmsu.edu

[3] El Dr. Juan Francisco Hernández Paz es Profesor del departamento ciencias básicas en Ingeniería de Física y materiales de la Universidad Autónoma de Cd. Juárez, Chihuahua México. juan.hernandez.paz@uacj.mx

Experimental Methods and Materials

In this section, a methodology is presented of the proposed approach to estimate the tensile strength of the composites for predicting tensile response and evaluate data with tested values.

Fabrication runs

The production of samples was considering HDPE with two factors: pine wood and pecan wood, two mesh sizes 40 and 60 and two weight contents 30% and 40%, Table 1 shows the runs to fabricate samples. The weight factor was selected were based in several works from (Mijiyawa, Demagna, Bohuslav, & Erchiqui, 2015), (Stark & Berger, 1997), (Essabir et al. 2015) among others. The particle size was selected based on the review of particle size paper from (Stark & Berger, 1997) and (Cruz-Salgado et al., 2016)where is not clear if small or bigger particle has higher tensile strengh response.

Run	Fiber	Weight	Size
1	P	40	60
2	P	40	40
3	w	40	60
4	w	40	40
5	P	30	40
6	P	30	60
7	w	30	60
8	w	30	40

Table 1 Table of production runs (w: pine; P: pecan wood)

Mill flour process

The process preparation started with the milling process using a commercial mill from Meadows Mill Inc. Model 250E-5780-12. Pecan wood was milled in the mill machine using 1/16 in. screen as initial step. The pine wood flour was from commercial company the American wood Company using 40 and 60 mesh. Matrix was HDPE from ExxonMobil part number HD6733, and coupling agent was Poly bond 3009. The flour from pecan wood was processed using a commercial sieve machine from Tech-Lab model TL6008. The coupling agent value of 3.5% of MAPE (Polybond 3009) was considered from several papers where the average value was selected among 2 to 5% and this was the final value. Sieve screen of 40 and 60 mesh were used. The samples were produced in a two-step process which used a twin extruder to mix the polymer, coupling agent and the flour. Both flours were dried for 24 hrs. at 80 °C prior to injection molding process.

Injection Molding

The extrusion machine was a 15cc twin co-rotating screws by Xplore model DSM 15 cc capacity. The samples were molded in a single piston injection molding unit. The injection molding machine was a Xplore DSM 12 cc heating chamber, model Micro 12 cc IMM figure 5.2 with the following parameters:

-Set up mold temperature according to material specification and from previous process data, it was at 45°C
- Molding temperature at 190°C

The data of materials is shown in table 2.

Property	Pecan wood	Pine wood	HDPE
Tensile at yield	54.1 Mpa	57.9MPa	24.5 MPa
Elastic Modulus	11.93 GPa	8.9 GPa	0.75 GPa
Poisson Ratio	0.38	0.38	0.46
Density(g/cm^3)	0.67	0.44	0.98

Table 2 Materials mechanical properties

Mechanical testing

All samples were stored in a zip plastic bag with proper identification of run number and material combination. The mechanical testing of tensile and flexural strength was made using the universal tester Instron machine model 5882 with Blu hill software for the data collection in CVS format. The machine was set up at 1mm/min speed head. Using the load data, tensile strength calculation was based on the general equation:

$$\sigma = \frac{F}{A} \qquad (1)$$

Where σ= tensile stress, F= Force and A= Area of the section
The area was estimated from measuring the cross section of the sample Type V (dog bone shape) in the testing cross section area see figure 1.

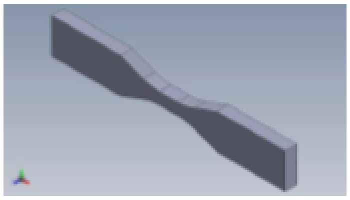

Figure 1. SolidWorks model per ASTM 638-14 type V

The tensile testing was performed using ASTM D638-14. According to the standards a require minimum of 5 samples per run is needed to determine the tensile strength.

Predicting mechanical properties

Predicting mechanical properties of composites is an area of high interest in the industry and developing models that can make good prediction are being studied in the past decades. Micromechanical models used to predict tensile strength are several. However, in this study will use the following:
Voight (Series) which is the most considered to estimate values as is considered in layers.

$$\sigma_c = \sigma f V f + \sigma m V m \qquad 2)$$

The parallel series (Reuss) is also used when fibers are acting along the stress direction.

$$\sigma_c = \frac{\sigma_m * \sigma_f}{\sigma_m V f + \sigma_f V m} \qquad 3)$$

A combination of these models is the Hirsch equation where uses a factor to adjust the equation.

$$\sigma_c = x(\sigma m V m + \sigma f V f) + (1-x)\left(\frac{\sigma m \sigma f}{\sigma m V f + \sigma f V m}\right) \qquad 4)$$

The value of x was estimated of 0.1 for random fibers.
For the Halpin-Tsai equation is an adjusted model of parallel model:

$$\sigma_c = \sigma m\left(\frac{1 + A n V f}{1 - n V f}\right) \qquad 5)$$

Where n is the n is:

$$n = \frac{\left(\frac{\sigma f}{\sigma m}\right) + 1}{\left(\frac{\sigma f}{\sigma m}\right) + A} \qquad 6)$$

And A is a factor from Einstein coefficient K with value of 12.2.
The following is the (Facca et al., 2007) equation which uses adjust factors for shape and length:

$$\sigma_c = \tau V f l/d + \sigma_m(1 - V f) \qquad 7)$$

The Einstein equation has only one factor of tensile strength from matrix, which is correct with the Vf volume fraction.

$$\sigma_c = \sigma m\left(1 + V f^{2/3}\right) \qquad 8)$$

Where in all equations σ_c is the tensile strength of the composite, σm tensile of the matrix, σf tensile of fiber, Vf volume fraction of fiber, Vm volume fraction of matrix; the τ interfacial shear stress of fiber, l length of fiber, and d diameter parameters are for the Facca equation.

Results and Discussion

Samples were tested for tensile strength. Table 3 shows the dimensional data for each particle size. The experimental testing the tensile data of pine wood and pecan wood both have better tensile strength than matrix. The results indicate a good bonding process between fiber and HDPE since values are higher than matrix values of 24.5 mega pascals (MPa).

MESH	WEIGHTS	Diameter	Lc
40	30, 40%	0.425mm	0.5mm
60	30, 40%	0.250mm	0.4mm

Table 3 Particle dimensional data.

The use of a coupling agent has improved the interfacial adhesion of both materials. The response from test data concurs with (Adhikary et al., 2008; Mijiyawa et al., 2015; Stark & Berger, 1997) where fiber characteristics have significant effect on tensile response. The table 4 shows the results of the micromechanical analysis to predict tensile strength for both fibers at 40 mesh size with two weight ratios, and the experimental test data. The table shows the effect of the fiber type in the response, where the pine wood has the highest tensile values compares to pecan wood. These results are similar in the analysis by (Neagu et al., 2006) and others on different fiber had significant different mechanical properties.

Weight Ratio	Test 40 Mesh	Voigt	Reuss	Einstein	Halpin-Tsai	Hirsch	Facca
Pecan							
0	24.50	24.50	24.50	24.5	24.50	24.50	24.50
0.3	32.380	35.59	30.81	37.23	34.99	32.72	29.5071
0.4	35.480	38.77	33.28	39.57	37.10	35.48	30.947
Pine							
0.3	34.60	37.01	31.25	37.23	36.25	33.55	29.5071
0.4	36.62	40.61	33.94	39.57	38.63	36.61	30.947

Table 4 Micromechanical and test values of tensile strength for 40 mesh.

The values of tensile strength for 60 mesh were also calculated using the micromechanical models mentioned above. The results for mesh 60 are in table 5, values of both fibers have better values than base values of HDPE. Each of the micromechanical model to predicted values are under or overpredicting the response. This implies that there are other factors that could be affecting the model for better predict the tensile response.

Weight Ratio	Test 60 Mesh	Voigt	Reuss	Einstein	Halpin-Tsai	Hirsch	Facca
Pecan							
0	24.50	24.50	24.50	24.5	24.50	24.50	24.50
0.3	27.98	35.59	30.81	37.23	34.99	32.72	25.0498
0.4	37.51	38.77	33.28	39.57	37.10	35.48	25.2079
Pine							
0.3	34.66	37.01	31.25	37.23	36.25	31.83	25.04
0.4	41.90	40.61	33.94	39.57	38.63	36.61	25.20

Table 5 Micromechanical and test values of tensile strength for 60 mesh.

According to Stark and Berger (Stark & Berger, 1997). smaller particle size could have higher response. In this study, the test results of 60 mesh are higher values than 40 mesh for pine wood, which concurs with them. One factor that could be affecting the response is the coupling agent since other work by Adhikary et al. (Adhikary et al., 2008) with similar fiber (pine wood) and using HDPE response values are lower than the reported in this study. For pecan wood results are mixed since at 30% weight, 40 mesh has higher tensile strength.

Is observed that most micromechanical models have values overpredicted at 60 mesh at 30% for both fibers as is in figure 2. This is significant since micromechanical models most of them does not correct for shape and size.

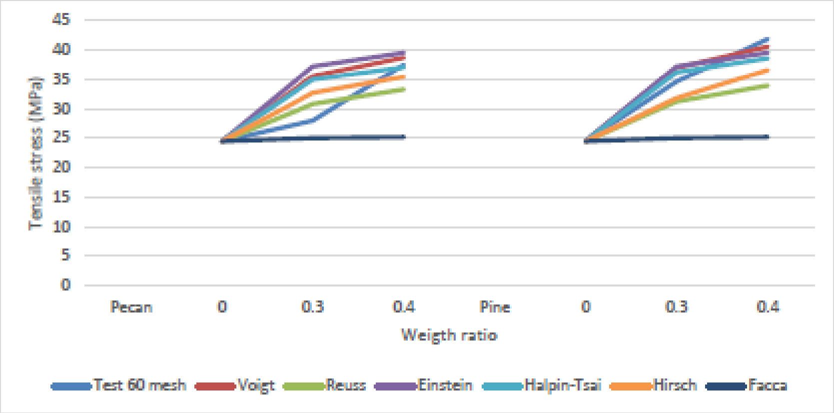

Figure 2. Tensile stress prediction for pecan and pine at 60 mesh.

For the 40% weight most are underpredicting the tensile value for both fibers. In the analysis for 40 mesh the values, the Hirsch model is the one that best fits the test data, as is observed in the figure 3. This is observed for both weight ratios. An observation in the micromechanical model of Facca et al. (Facca et al., 2007) used; is underpredicting the tensile strength response for both fibers in all the parameters of weight and mesh.

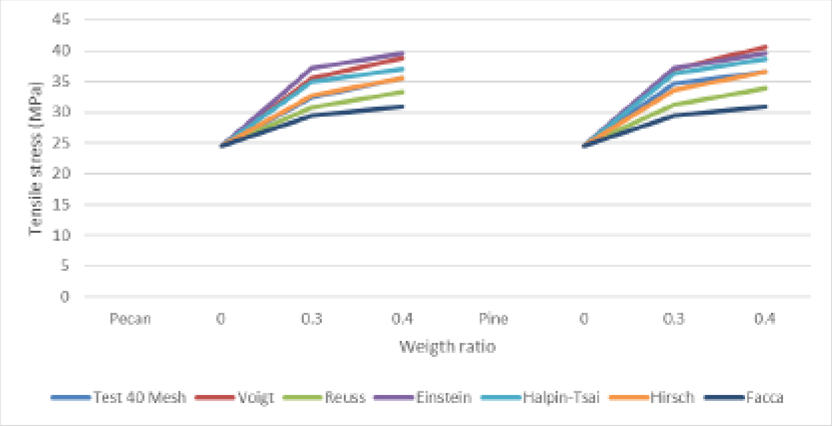

Figure 3. Tensile stress prediction for pecan and pine at 40 mesh.

This values can be affected by the shape factor that is used. The Model that is mentioned uses a cylindrical shape for the fiber. However, the response does not fit the tested values. This could be affected by the factor of shape and length which are used to correct the tensile response.

However, the results illustrate that these micromechanical models most do not fit experimental data. The model of Facca et al. with correction factor, all values are underpredicted.

Final comments

Summary of results

In this study was analyzed the response of two fibers in composites based in pine flour and pecan wood. The study analyzed the effect of both particle size on predicting tensile response The Hirsch model has best fit only for 40 mesh. The other model lack of fit was observed with the tested data.

Conclusions

The results show a lack of fit between test data and predicted values. The factor of particle size in the bonding mechanism in wood plastic composites is necessary to be understood to improve the mechanical response. Additionally, it is paramount to analyzed more in depth the particle size effect since results in this study have mixed response; smaller particle size had the higher response for pine, but for pecan fiber is mixed. Most of the micromechanical models have lack of fit in the response; this could be caused for no correction factor for particle size.

Recommendations

For those interested in composites with natural fibers will be recommended to investigate these factors: particle factors of shape and length that may affect the predicting response of micromechanical models.

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