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DYNAMIC AND DAMPING PROPERTIES OF NOVEL BIO-COMPOSITES USING THE HAMMER EXCITATION VIBRATION TECHNIQUE

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ABSTRACT

The dynamic and damping properties of nine different wood-based bio-composites at varying volume fraction of Corn starch (CS), methylene diphenyl diisocyanate (MDI), microcrystalline cellulose (MCC), processing time and pressure have been studied. The samples used for the study consisted of southern yellow pine particles with 2% Corn starch (CS), 4% methylene diphenyl diisocyanate (MDI); 4% CS 4%MDI; - 4% MDI; - 2% CS 2% MDI; - 4% CS 4% MDI; - 2% microcrystalline cellulose (MCC) 4% MDI; - 4%CS2% MDI; - and 1% MCC 4% MDI; - (all on a solids basis). The panels were manufactured using a Dieffenbacher hot press at a temperature of 185oC. The dynamic and damping properties were determined using hammer excitation vibration technique. The responses were obtained from frequency and time domain for the fundamental natural frequency (fn), and the results obtained were consistent. The panel manufactured with 4% MDI and formed at relatively high pressure (10.5 MPa) had the highest average storage modulus (E'), and this shows that increasing manufacturing pressure and density of material contributed to the high elasticity of the material. The panel produced with 2% CS and 2% MDI had the highest damping ratio (ξ) and Loss factor (η) when compared with other wood samples, and this demonstrates that the CS contributed to the high damping of the material.

KEYWORDS: Wood-based bio-composites, vibration, damping, logarithmic decrement, loss factor, storage modulus, loss modulus.

INTRODUCTION

Over the past few decades, bio-composite materials have received a great attention from researchers and industrialists. A remarkable and distinctive feature of bio-composite is that it can be considered as carbon dioxide neutral materials, i.e. it does not release excess carbon dioxide into the environment when dumped (Roy et al. 2014). Wood-based bio-composites have been consistently used for many structural and non-structural applications like boat hulls, non-structural fascia panels, acoustic dampeners (especially in automobiles) and packaging materials due to their renewability, low cost, high strength to weight ratio, and customize mechanical properties. Hence, Wood-based bio-composites could be a viable ecological alternative to carbon, glass, and man-made petroleum-based fiber composites. This study involved an effort to enhance the use of renewable materials by investigating nine novel wood-based bio-composites, which were developed in collaboration with the Department of Sustainable Bioproducts at Mississippi State University.

In many applications, composite materials are used for energy absorption and noise attenuation applications subjected to dynamic loading, which is produced by vibration or wave propagation (Gibson 2014). Therefore, it is necessary to investigate the damping and dynamic properties of composite materials. A number of investigations have been carried out on the dynamic, damping and mechanical properties of wood-based composites (Brémaud et al. 2013, Bogren et al. 2006, Koruk et al. 2010, Luo et al. 2017, Poletto 2017, Sewda et al. 2013, Wert et al. 1984). Guan et al. (2016) investigated the dynamic viscoelasticity of wood composite panels using vibration detection test and cantilever beam vibration test. Bolmsvik et al. (2013) studied the damping assessment of a light wooden assembly with and without damping material. They found that good sound reduction can be achieved by using elastomers. Wang et al. (2012) investigated the measurement of the dynamic modulus of elasticity and damping ratio of wood-based composites using the cantilever beam vibration.

The previous researches on wood contribute to the body of knowledge of mechanical and damping characterization of wood. However, there is limited documentation on the dynamic and damping characterization of the wood-based composite by hammer excitation vibration technique.

The hammer excitation vibration technique is a reliable approach providing a quick non-destructive measurement of the dynamic modulus of elasticity(Ed) and damping ratio (ξ)of wood-based bio-composites. The purpose of this investigation was to evaluate the dynamic property, storage modulus (E') and the damping properties, damping ratio (ξ) and loss factor (η) of novel wood-based bio-composites with different constituent materials using the hammer excitation vibration technique. Results from this investigation will help to develop an understanding of how mechanical and damping properties vary with different material constituents in wood-based bio-composites. This work would assist in selecting the appropriate material based on the nature of load applications.

MATERIAL AND METHODS

Specimens were created from Southern yellow pine. The amount of mass used to create the panels was the same for each panel (approximately 2.95 kg) except for the panel created at a mat pressure of 10.5 MPa (with ram pressure of 27.58 MPa) where twice the amount of mass (5.9 kg) was used. The particles ranged in size from 2-3mm, and the temperature used to form the panels was approximately 185°C. A Dieffenbacher 915 x 915 mm hot press system located at the Sustainable Bioproducts Laboratory at Mississippi State University was used to create the panels used in this study. This hot press with steam injection capability was coupled with the Alberta Research Council's Pressman operation and monitoring software. The Dieffenbacher hot press forms panels based on the desired thickness, so each composite material had differing pressures which were required to produce a panel with a thickness of 6.35 mm. The varying pressure required to form the panel to the appropriate thickness was based on the ability of the composite material in the mat to be compressed to the appropriate thickness. Wood-based bio-composite samples created for the analysis of the dynamic and damping properties using the hammer excitation vibration technique were made from Corn starch (CS), microcrystalline cellulose (MCC) and a Methylene diphenyl diisocyanate (MDI) resin with different mass fractions (listed in Tab. 1).

Tab. 1: Constituent materials for wood-based bio-composites

Material	Approx. pressure (MPa)	Curing Time (Seconds)	Density (kg·m^{-3})
2% CS 4 % MDI	9.2	140	821.56
4% CS 4% MDI 600s	9.5	600	911.44
4%MDI	8.9	140	826.48
4% MDI 10.5 MPa (2x material was used)	10.5	140	1389.22
2% CS 2% MDI	8.7	140	854.78
4% CS 4% MDI	8.4	140	946.45
2% MCC 4% MDI	7.1	140	903.20
4% CS 2% MDI	9.2	140	941.42
1%MCC 4% MDI	9.2	140	980.86

MDI is an aromatic diisocyanate and was an efficient binder that has been used in the production of composite wood products for over 30 years. Corn starch is the starch derived from the corn (maize) grain or wheat, and microcrystalline cellulose (MCC) was formed from techniques described in a previous study Chauhan et al. (2009) using pure cotton. The hammer excitation vibration test technique sample dimensions were 317.5 mm in length x 25.4 mm in width x 6.35 mm in height (Fig. 1).

Fig. 1: Wood-based bio-composite hammer excitation vibration technique test samples.

Experimental testing

The dynamic response of wood-based bio-composites in a cantilever beam configuration was tested using hammer excitation located at the Structure and Dynamics Laboratory at the University of Mississippi. The accelerometer was located on the free end of the beam and was connected to both an oscilloscope and a signal analyzer with a conditioning amplifier. The impulse hammer was connected to a signal analyzer through the conditioning amplifier (Fig. 2).

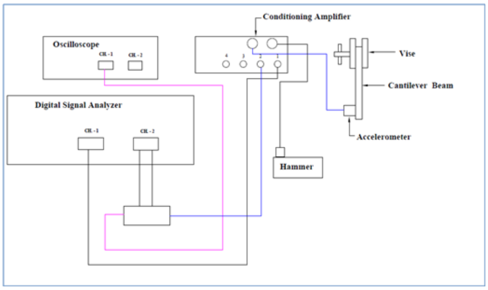


Fig. 2: Schematic of experimental set-up.

The dynamic response of the beam was initiated by the light impact of the excitation hammer on the beam. From the dynamic response, the logarithmic decrement and damped natural frequency were recorded from the oscilloscope. The natural frequencies (f_n) and damping ratio (ξ) of the beam were recorded from the spectrum analyzer.

Calculations of Damped Frequency (f_d) (Hz), Experiment Natural Frequency (f_n), Loss Factor (η), Storage Modulus (E'), Loss Modulus (E"), Damping ratio (ξ), Logarithmic decrement (δ).

Time domain analysis

Time domain is analyzing the data over a time period. Cathode-ray oscilloscope (CRO) was used to obtained responses.

The logarithmic decrement (δ) represents the rate at which the amplitude of a free damped vibration decreases. It is defined as the natural logarithm of the ratio of any two successive amplitudes. It is found from the time response of under damped vibration (oscilloscope or real-time analyzer).

The logarithmic decrement (δ) was calculated using Eq. 1 (Rao and Gupta 2012).

$$\delta = \frac{1}{n} \ln\left(\frac{x_0}{x_n}\right) \tag{1}$$

Where x_0 and x_n are amplitude at time t_0 and n refers to the number of cycles.

The damped natural frequency (f_d), The rate of free oscillation of a sensing element in the presence of damping is calculated using Eq. 2.

$$f_d = \frac{1}{\Delta t} \tag{2}$$

Where $\Delta t = t_n - t_0$

The damping ratio (ξ) is a material property that indicates whether a material will bounce back or return energy to a system. is calculated by using Eq. 3 (Rao and Gupta 2012).

$$\xi = \frac{\delta}{\sqrt{\delta^2 + 4\pi^2}} \tag{3}$$

The natural frequency (f_n) of the object which vibrates without any external force, calculated using Eq. 4 (Inman 2015).

$$\mathrm{f_n} = \frac{f_d}{\sqrt{1-\xi^2}} \tag{4}$$

The storage modulus (E') measures the stored energy, representing the elastic portion, calculated using Eq. 5 (Blewins 1979)

$$\mathrm{E}' = \frac{4\pi^2 \mathrm{f_n^2} \mathrm{L}^4 \rho \mathrm{A}}{(\lambda_n \mathrm{L})^4 \mathrm{I}} \tag{5}$$

This equation shows that the value of the natural frequency gives an evaluation of the storage modulus (E').

Where λ_n is the eigenvalue of the nth mode, I is the area moment of the inertia of beam cross- section, ρ is the beam of mass density, L is the length of the beam, and A is the beam cross- sectional area.

For a fixed free (Cantilever beam) boundary condition (Blewins 1979):

1st mode: $\lambda_1 L = 1.875$, 2nd mode $\lambda_2 L = 4.694$, 3rd mode $\lambda_3 L = 7.855$.

The loss factor (η) is a measure of intrinsic damping (resistance to vibration) is given by Eq. 6.

$$\eta = \frac{\mathrm{E}''}{\mathrm{E}'} = 2\xi \tag{6}$$

Where ξ is the damping ratio and E'' is the loss modulus, measures the energy dissipated.

Frequency domain analysis

The frequency domain refers to the analysis of mathematical functions or signals with respect to frequency, rather than time.

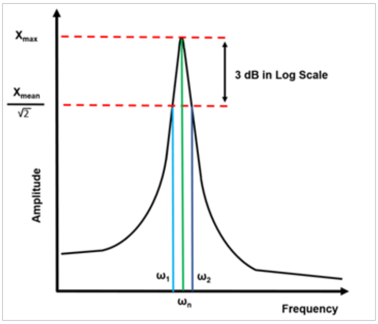


Fig. 3: Damping measurement using half-power bandwidth method.

Each of the frequencies produced from the signal analyzer corresponds to the peaks along the horizontal (frequency) axis. Damping can also be found from the frequency domain data with the half-power bandwidth method (Rao and Gupta 2012) shown in Fig. 3.

$$2\xi = \frac{\omega_2 - \omega_1}{\omega_n} = \frac{\mathrm{f_2} - \mathrm{f_1}}{\mathrm{f_n}} = \eta \tag{7}$$

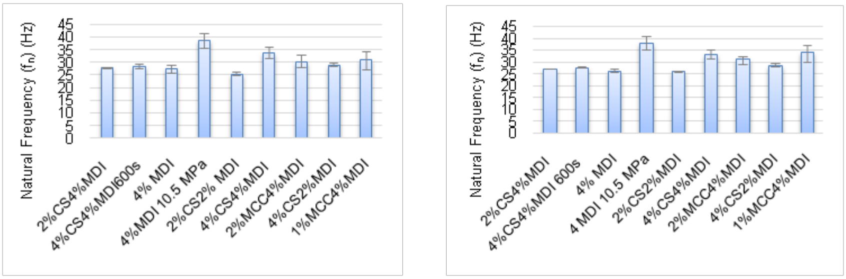
RESULTS AND DISCUSSIONS

Tab. 2 summarizes the average values of experimental results with the standard deviation of nine different types of wood-based bio-composites tested using the hammer excitation vibration technique.

Tab. 2: Mechanical properties of wood-based bio-composites

Material	Natural frequency (f_n) (Hz)		Storage modulus (E') (GPa)		Damping ratio (ξ)		Loss factor (η)	
	Frequency response	Time response	Frequency response	Time response	Frequency response	Time response	Frequency response	Time response
2% CS 4 % MDI	28 ± 0.25	27.31 ± 0.16	1.63 ± 0.06	1.55 ± 0.08	0.019 ± 0.003	0.024 ± 0.004	0.039 ± 0.007	0.048± 0.007
4% CS 4% MDI 600s	28.63 ± 0.90	27.74 ± 0.21	1.88 ± 0.15	1.76 ± 0.05	0.017 ± 0.006	0.023 ± 0.004	0.035 ± 0.01	0.040± 0.008
4%MDI	27.63 ± 1.64	26.38 ± 0.88	1.42 ± 0.31	1.28 ± 0.22	0.018 ± 0.003	0.025 ± 0.004	0.036 ± 0.03	0.050± 0.009
4% MDI 10.5 MPa (2x density)	39.041 ± 3	38.27 ± 2.79	3.35 ± 0.63	3.28 ± 0.45	0.016± 0.002	0.019 ± 0.001	0.031 ± 0.003	0.031± 0.003
2% CS 2% MDI	25.63 ± 0.75	26.21 ± 0.19	1.43 ± 0 .11	1.47 ± 0.01	0.043 ± 0.008	0.026 ± 0.005	0.085 ± 0.016	0.051± 0.009
4% CS 4% MDI	33.87 ± 2.13	33.43 ± 1.89	2.43 ± 0.54	2.36 ± 0.48	0.019 ± 0.002	0.023 ± 0.003	0.036 ± 0.003	0.043± 0.006
2% MCC 4% MDI	30.46 ± 2.52	31.48 ± 1.92	1.79 ± 0.22	1.88 ± 0.23	0.017 ± 0.002	0.023 ± 0.004	0.035 ± 0.033	0.042 ± 0.007
4% CS 2% MDI	29.13 ± 0.76	26.83 ± 3.82	1.90 ± 0.13	1.76 ± 0.12	0.016 ± 0.003	0.014 ± 0.009	0.025 ± 0.009	0.038 ± 0.004
1% MCC 4% MDI	34.25 ± 3.76	34.06 ± 3.71	2.58 ± 0.67	2.56± 0.61	0.017 ± 0.001	0.025 ± 0.008	0.035 ± 0.0024	0.062 ± 0.018

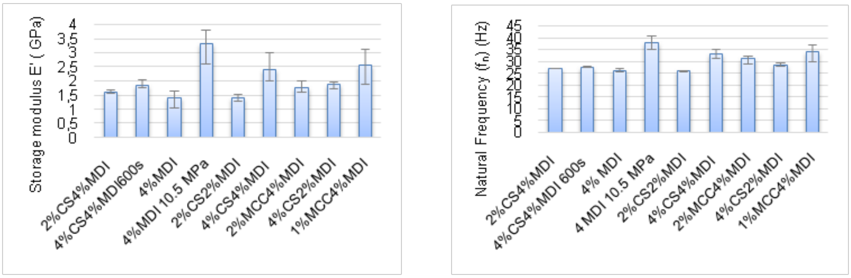
The average values of the fundamental natural frequencies (f_n) were found from the investigation of the wood-based bio-composites. Fig. 4a and Fig. 4b shows the average values of the fundamental natural frequency (f_n) with the standard deviation for the different types of wood-based bio-composites tested. Results show that the average natural frequencies (f_n) were different for different materials.



(a) Frequency response *(b) Time Response*

Fig. 4: Natural frequency (fn) of different wood-based bio-composites.

The storage modulus (E') in a composite material measures the amount of stored energy and represents the elastic portion of the material. The analysis shows that the average storage modulus (E') varied for the different types of wood-based bio-composites as shown in Fig. 5a and Fig. 5b.

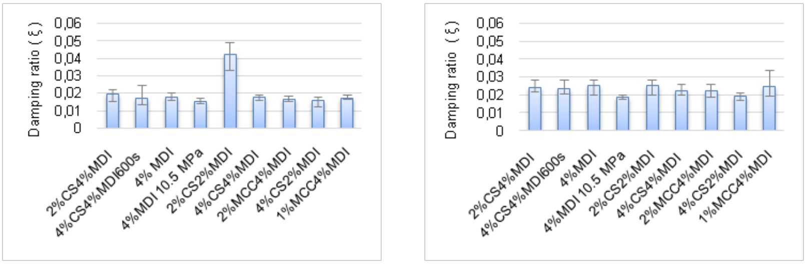


(a) Frequency response *(b) Time response*

Fig. 5: Storage modulus (E') of different wood-based bio-composites.

From the analysis of Fig. 5a, it was found that by increasing the constituent of MDI, a change occurred in the average storage modulus (E'). The wood-based bio-composite material that was made with 2% CS2% MDI had an average storage modulus (E') of 1.43 GPa, and by increasing the mass fraction of the MDI by 2% (solids basis), the observed average storage modulus (E') was 1.63 GPa for 2% CS 4% MDI. A 14% increase in the storage modulus (E') was achieved from the addition of more MDI. Furthermore, similar trends were observed for the composite with 4% CS2% MDI (1.90 GPa) and 4% CS4% MDI (2.43 GPa). This resulted in an increase of approximately 27.89% in the average storage modulus (E'). In addition, results show that increasing the pressure and density of the material during the manufacturing process of the wood-based bio-composites highly affected the average storage of modulus (E'). When the wood-based bio-composite materials were made of 4% MDI and the pressure was increased from 8.9 MPa to 10.5 MPa, the average mass density increased from 826.45 kg·m^{-3} to 1389.22k g·m^{-3}. The average storage modulus (E') increased from 1.42 GPa to 3.35 GPa, which shows an approximate 135.74% increase in the average storage modulus (E'). Increasing the manufacturing pressure of the wood-based bio-composites increased stiffness. Furthermore, from Fig. 5a and 5b, the addition of MCC were found to notably lower the average storage modulus (E'). Wood-based bio-composite material made with 1% MCC and 4% MDI had an average storage modulus (E') of 2.58 GPa. After increasing the mass fraction of MCC to 2% (solids basis) with 4% MDI, the observed average storage modulus (E') was 1.79 GPa, which shows a reduction of approximately 30.78% in the average storage modulus (E'). This could be because the higher MCC mass fraction caused a higher mass density and resulted in a lower natural frequency (fn), which also lowered the average storage modulus (E'). Increasing the processing time during the manufacturing of wood-based bio-composites decreased the average storage modulus (E'). Increasing the processing time from 140 seconds to 600 seconds for the wood-based bio-composites made of 4% CS4% MDI decreased the average storage modulus (E') from 2.42 to 1.88 GPa, a decrease of 22.5%. This could be because the longer processing time decreased the intermolecular bonding strength of the wood-based bio-composite (Ale´n et al.). Among different types of wood-based bio-composites, 4% MDI (2x density material with a pressure of 10.5 MPa) had the highest average storage modulus (E') of 3.35 GPa which was approximately 22.75%, 27.45%, 43.18%, 43.77%, 46.52%, 51.38%, 57.29%, and 57.58% higher when compared to the average storage modulus (E') of 1% MCC 4%MDI, 4% CS4% MDI, 4% CS 2%MDI, 4% CS4% MDI600S, 2% MCC 4%MDI, 2% CS 4%MDI, 2% CS 2%MDI, 4%MDI respectively. This result was due to high pressure causing the compaction of more material to create a higher mass density of the composite. This resulted in creating a higher natural frequency and a higher average storage modulus (E') of the wood-based bio-composite using 4% MDI with a pressure of 10.5 MPa. Increasing CS and MCC in MDI improved the average storage modulus (E') of the wood-based bio-composites. The trend of experimentally obtained values of average storage modulus (E') were in good correlation with the previous study of wood composite panel (Guan et al. 2016).

The damping ratio (ξ) is a dimensionless measure describing how oscillations in a system decay after a disturbance and is a frequently used ratio to measure damping in a system. The analysis shows that the average damping ratio (ξ) differed for the multiple types of wood-based bio-composites as shown in Fig. 6a and 6b. The results from Fig. 6a show that increasing the MDI percentage changed the average damping ratio (ξ). The composite material made of 2% CS 2% MDI had an average damping ratio (ξ) of 0.043 and by increasing the mass fraction of MDI to 2%, the observed damping ratio (ξ) decreased by 55.82% to 0.019 for the 2%CS 4% MDI composite. Furthermore, the composite material made of 4% CS 2%MDI had an average damping ratio (ξ) of 0.016 and by increasing the mass fraction of MDI to 2%, the average damping ratio increased by 12.5% to 0.018 for the 4% CS 4% MDI composite. Moreover, results show that increasing the pressure and density of the material during the manufacturing process slightly decreased the average damping ratio (ξ). When composite materials were made with 4% MDI and the average mass density and pressure were increased from 826.45 kg·m^{-3} and 8.9 MPa to 1389.22 kg·m^{-3} and, 10.5 MPa, the average damping ratio (ξ) decreased from 0.018 to 0.016. This shows an approximate 20% decrease in the average damping ratio. Furthermore, from Fig. 6a, the addition of the constituent MCC (both 1% and 2% solid content) with MDI, the average damping ratio (ξ) was found to be approximately 0.017. In addition, an average damping ratio (ξ) for the composite with 4% CS 4%MDI and a processing time of 600 seconds was 0.017. The data from the time response shows variation because of the nature of the test conducted, but nearly similar trends have been observed from time response data shown in Fig. 6b.These values are in good agreement with the previous investigation of wood-based composites (Wang et al. 2012).

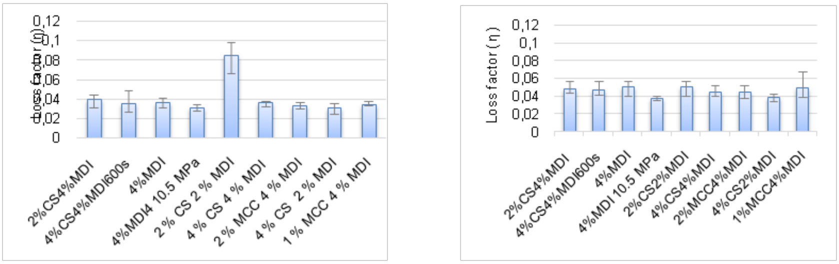


(a) Frequency response *(b) Time Response*

Fig. 6: Damping ratio (ξ) of different wood-based bio-composites.

The loss factor (η) is a measure of damping. Fig. 7a and 7b compare the average loss factor (η) deduced from the experimental results obtained for the various composites. The loss factor (η) of the nine different composites was dissimilar and was dependent on the type of additive used in the sample. The samples containing CS in MDI improved the average loss factor (η). Adding MCC in MDI decreased the average loss factor (η) for all panels that were created in the pressure range of 7.1-9.5 MPa.

The results from Fig. 7a show that the average loss factor (η) of the panel created using 4% MDI and 10.5 MPa was 0.031. This was the smallest value among the nine different types of composites tested. This suggests that the 4% MDI 10.5 MPa material is not a good damping material when compared to the other types of composites for the dissipation of vibrational energy. Moreover, it seems that the 2% CS 2%MDI had the highest average loss factor (η) of 0.085 and has an improvement of 172.44% when compared to the 4% MDI control sample. Therefore, the 2% CS 2%MDI sample was classified as having the best damping characteristic among the different types of composites which were tested. In addition, a nearly similar response was observed from the analysis of time domain data as shown in Fig. 7b.We found much higher values of loss factor (η) for tested wood-based bio-composites with respect to those reported by Bogren et al. (2006) for wood-fiber mats. The results imply that corn starch (CS) and microcrystalline cellulose (MCC) can be used to obtain good damping in structural applications.



(a) Frequency response *(b) Time Response*

Fig. 7: Loss factor (η) of different wood-based bio-composites.

CONCLUSIONS

Nine different types of wood-based bio-composite materials have been experimentally investigated using the hammer excitation vibration technique. It was observed that the structure of natural frequency (fn) totally depends on the mass density and stiffness of the composite. Furthermore, it could be concluded that the average storage modulus (E') of 4% MDI 10.5 MPa was found to be larger than the other composites due to the high mass density. This sample had the highest stiffness among all the composites. The damping varied with frequency, and the 2% CS 2% MDI had the highest average damping ratio (ξ) and average loss factor (η) among all the composites. The samples containing corn starch showed enhanced damping properties, and therefore corn starch can be a good constituent for making wood-based bio-composites for structural damping applications.

The future scope of work is to study the effect of increasing volume fraction of CS on dynamic and damping properties of wood-based bio-composites and perform experiments using response surface experimental design to explore the relationship between constituent materials, curing time and manufacturing pressure. In addition, to perform dynamic mechanical studies of composites and to study the material characteristics and energy absorption using a low-velocity impact machine.

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