WOOD RESEARCH doi.org/10.37763/wr.1336-4561/68.1.6882
ISSN 1336-4561 e-ISSN 2729-8906
68(1): 2023 68-82 pp.

ACOUSTIC ABSORBERS MADE OF WOOD FIBER COMPOSITES DEVELOPED BY COMPRESSION MOLDING AND ADDITIVE MANUFACTURING

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(RECEIVED AUGUST 2022)

ABSTRACT

This research aims to address the noise pollution by developing an acoustic absorber made of polylactic acid (PLA)/polyhydroxyalkanoates (PHA)-wood fibers (PLA/PHA-WF) by compression molding (CM) and additive manufacturing (AM). Physical, mechanical, thermal, water absorption, and biodegradation properties of the developed acoustic absorbers by CM and AM were characterized and compared. Upon providing an air gap, thin absorbers developed by AM exhibit an increased and narrow acoustic peak than the CM absorbers because of the Helmholtz resonance effect due to the decreased density and increased porosity in the AM absorber. The results also show that the mechanical and thermal properties of the absorbers developed by CM and AM were almost similar and absorber developed by AM shows an increased rate of water absorption and biodegradation compared to absorber developed by CM due to the presence of porosity in the AM structure.

KEYWORDS: Additive manufacturing, compression molding, acoustics, acoustic absorbers, wood fiber composites.

INTRODUCTION

In this era of globalization and modernization, the noise level gradually gets louder in an uncontrolled manner. People started to realize that noise can affect a person, both psychologically and physiologically (Jiang and Li 2018). Research shows that prolonged exposure to noise may cause stress elevation, temper tolerance reduction, intractable sleeping problems, and, if worse, might lead to irreparable hearing complications. Hence, it is essential to ensure that noise exposure is at a tolerable limit since it is practically impossible to eliminate noise (Munzel et al. 2018). There are numerous methods for noise control. The most common method is to install an acoustic absorber to solve the acoustic problem within a specific space or room, as it is the most practical and cost-effective solution (Ryu et al. 2018). There are mainly two types of acoustic absorbers; they are porous absorbers and resonant absorbers. Resonance absorbers are further classified into membrane and Helmholtz absorbers. A Helmholtz absorber, also known as a Helmholtz resonator, is an absorber with an open hole (or neck or port) containing air inside. Because of the springiness of the air inside, a volume of air in and near the open hole vibrates at the Helmholtz resonance (Yang et al. 2014).

An acoustic absorber is commonly made of synthetic materials, and these synthetic materials are frequently derived from petrochemical resources and require high temperatures for manufacturing, which may contribute to increases in carbon footprint (Chen and Burns 2006). The above reason encourages researchers to use natural fibers and its composites for acoustic applications. Natural fibers are proven to be good acoustic absorbers and can be an option to replace synthetic materials-based acoustic absorbers (Sekar et al. 2019). Over the last 10-15 years, in particular, wood architecture has grown, and new wood building systems and design strategies have been developed. New innovative wood and concrete panels are used in building applications, with wood providing thermal insulation and sound absorption and concrete acting as a binder and providing structure strength (Asdrubali et al. 2017). There are numerous types of wood available, and wood obtained from poplar (Negro et al. 2016) and pine (Amel et al. 2016), in particular, has been widely considered for acoustic applications.

There are a lot of methods employed in developing acoustic absorbers. Recently, additive manufacturing is one of the tools that have been used for developing acoustic absorbers for various reasons. Additive manufacturing (AM) is one of the esteemed techniques that have rooted its impact in almost all fields. Only a few thermoplastic polymers such as acrylonitrile butadiene styrene, polyamide, polyethylene terephthalate, polyvinyl alcohol, PLA, and PHA can match the melting temperature of the fused deposition modeling (FDM) process (Mohan et al.

2017). PLA based natural fiber filaments have received attention in recent years because of their renewability and biodegradability (Bermudez et al. 2021). (Stoof and Pickering 2017) initiated the use of natural fiber-reinforced composites in the field of AM by FDM for the first time. The authors have used fibers from hemp and harakeke as reinforcement for PLA. The authors have successfully printed the natural fiber composites and found that the 3D printed part contains voids (pores, cracks, or gaps) between the deposition layers. The authors also investigated the mechanical properties of the printed absorber and revealed that there was a decrease in mechanical properties. The presence of voids in the printed absorber caused a reduction in mechanical properties. The majority of research dealt with 3D printing the natural fiber-based structures using FDM technology noticed voids formation on their structures. A review paper written by (Sekar et al. 2019) concluded that these void formation between the deposition layers could be useful in acoustic applications. Compression molding has been also widely used in the development of acoustic absorbers where (Daeipour 2017) fabricated acoustic absorbers made of polyethylene reinforced with a different fiber content of wood obtained from poplar by compression molding. It was concluded that the maximum sound absorption was observed from 2000 Hz onwards. (Jayamani et al. 2014) produced acoustic absorbers made of polypropylene reinforced with rice straw and kenaf fiber by compression molding. They have concluded that the acoustic absorption of the developed absorbers made of polypropylene reinforced with rice straw and kenaf fibers was almost similar. (Sekar et al. 2021) demonstrated the alteration of inner porosity by varying the infill density in the 3D printed acoustic absorbers. They have concluded that altering the infill densities makes the absorbers to control noise at different spectrums. They have also 3D printed acoustic absorbers with varying thickness and found that the thin absorber follows the mechanism of Helmholtz resonator. In this study, the acoustic performance of the mentioned thin 3D printed absorbers will be compared with the conventional compression molded acoustic absorbers to understand the mechanism of acoustic absorption in the compression molded and additive manufactured structures. In addition, physical, mechanical, thermal, water absorption and biodegradation properties of the developed acoustic absorbers will also be investigated.

MATERIAL AND METHODS

Polylactic acid/polyhydroxyalkanoates-wood fibers (PLA/PHA-WF) composite was commercially available in the form of filament and hence outsourced from ColorFabb, DK Belfeld, Netherlands under the trade name woodfill. PLA/PHA-WF filament contains 15 wt.% of recycled fine wood fibers obtained from pine trees as reported by (Le Duigou et al. 2016). The filament has a standard diameter of 1.75 ± 0.05 mm, and the density of the filament is 1.15 $g \cdot cm^{-3}$ with a melting temperature of greater than 155°C.

Filaments were hot pressed by GT-7014-H hydraulic molding press with a mold thickness of 1.5 mm, considering the filament's melting temperature, which is 210°C at a pressure of 15 bars for 2 min followed by cold press for 2 min. The molded absorber was then laser cut to a diameter of 33.4 mm to fit in the impedance tube. Later, another absorber was 3D printed using the Raise 3D N2 Plus printer. It uses FDM technology to print the absorber layer by layer. The absorber was 3D printed considering the melting temperature of 210°C at a rate of 70 $mm \cdot s^{-1}$. The printing conditions had been selected from the recommended datasheet provided by ColorFabb. The absorber was 3D printed with the default grid pattern having 100% infill density. Tab. 1 shows the specification of the compression molded and 3D printed acoustic absorbers. Fig. 1 shows the compression molded and 3D printed acoustic absorbers.

Tab. 1: Specifications of the acoustic absorbers made of PLA/PHA-WF.

Sample ID	Mold thickness, (mm)	Sample thickness, *t* (mm)
PLA/PHA-WF-CM-1.5	1.50	1.50 ± 0.10
PLA/PHA-WF-AM-1.5	-	1.50 ± 0.10

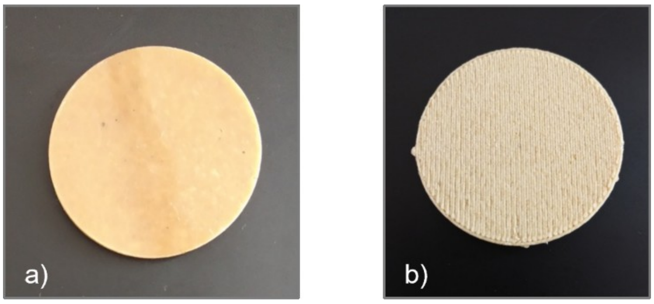


Fig. 1: Acoustic absorbers: a) Compression molded, b) 3D printed.

Physical characterization

The density of the successfully developed acoustic absorbers was measured using the Mettler Toledo ME204 density meter referring to the ASTM D792 testing standard. The measurement of density works on the Archimedes immersion technique. The density of acoustic absorbers was obtained experimentally using the results of two measurements, i.e. mass of sample in the air and mass of the sample in distilled water at 25 ± 2°C with the relative humidity of 65 ± 5%. The density of the sample (ρ_s) was calculated experimentally as per Eq. 1:

$$\rho_s = \frac{u}{u-v}\,\rho_w \tag{1}$$

where: u - the mass of sample in the air (g), v - the mass of sample immersed in water (g) and ρ_w - the density of water ($g \cdot mm^{-3}$).

In general, porosity can be determined by four methods, namely, calculating porosity theoretically by volumes, calculating porosity theoretically by densities, calculating porosity experimentally by saturation, and calculating porosity in the field by taking core samples. In this research, porosity was evaluated by correlating the densities of compression molded and additive manufactured samples (Le Duigou et al. 2016). Porosity was calculated by using Eq. 2:

$$Porosity\ (\%) = \frac{Density\ of\ CM\ sample - Density\ of\ AM\ sample}{Density\ of\ CM\ sample}\ X\ 100 \tag{2}$$

Morphology

The surface of the compression molded and additive manufactured PLA/PHA-WF absorbers were observed using SWIFT M5 Multi Phase 100 optical microscope, which uses 6 V, a 20 W halogen bulb for illumination and a variable pressure scanning electron microscope (SEM). The microscope used was the HITACHI S-3400N. The samples were sputtered by gold using QUORUM, Q150RS with 30 mA of current for the sputtering time of 38 s. The tooling factor used for sputtering was 1:10. After sputtering, all the samples were observed at different magnifications factors at an accelerating voltage of 10 kV.

Acoustical characterization

The sound absorption coefficient (SAC) of the acoustic absorbers which are successfully developed by compression molding and additive manufacturing was measured using a two-microphone impedance tube method as per the ISO 10534 standard. Tab. 2 shows the parameters considered during the measurement of SAC.

Tab. 2: Parameters considered during measurement of SAC.

Parameter	Value
Ambient temperature	25 ± 2°C
Relative humidity	65 ± 5%
Speed of sound	$343\ m \cdot s^{-1}$
Air density	$1.20\ kg \cdot m^{-3}$
Frequency range	500 to 4500 Hz

The microphones were calibrated with a sound calibrator prior to the experiment to ensure that the sound pressure inside the tube was accurately measured. The measurement was repeated three times to ensure repeatability. The sample was removed and reinserted into the sample holder for each measurement, and the variability was found to be negligible for all samples. All the results were obtained within a frequency range of 500 Hz to 4500 Hz, a valid frequency based on the tube diameter and microphone distance. Fig. 2 shows the setup of the acoustic testing. The setup consists of a computer, impedance tube, two microphones, plunger, amplifier, and a signal analyzer. The computer used in this setup acts as a noise generator, data acquisition system, and display. Software in the computer generates the noise signal required by the impedance tube, which is then fed to the tube. The computer receives the A and B microphone signals, which aids in the calculation of incident and reflected sound wave pressure values. Based on the difference in pressure values, the computer's sound absorption software calculates the sound absorption coefficient.

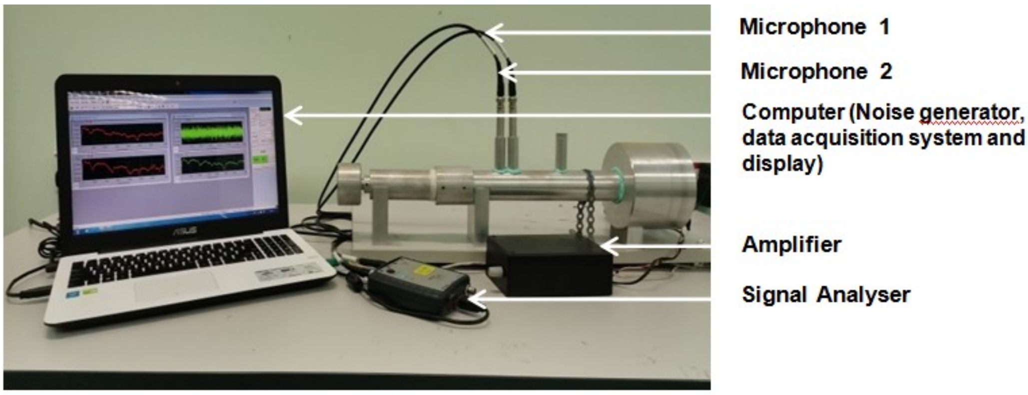


Fig. 2: Setup of the acoustic testing.

Mechanical characterization

Tensile strength is one of the important parameters that determine the strength of the product. The conditions and the specifications of the tensile testing were selected as per ASTM D638. The dog-bone samples were tested for tensile strength using an Instron Universal Testing Machine (load cell of 50 kN) at the speed of 20 $mm \cdot min^{-1}$.

Thermal characterization

Thermogravimetric analysis (TGA) was carried out as per ASTM E1131 using a Pyris Diamond TGA 8000 from PerkinElmer. Samples weighing around (5 ± 1 mg) taken from the acoustic absorbers underwent thermal scanning under the nitrogen atmosphere at a rate of 20 $ml \cdot min^{-1}$ from 25°C to 600°C with the heating rate of 10°$C \cdot min^{-1}$. TGA curves were used to calculate the temperature at 10% weight loss ($T_{10\%}$), and residue at 600°C ($R_{600°C}$). The maximum thermal degradation temperature (T_{max}) was calculated from the first derivative of the respective curves.

Water absorption

Acoustic absorber samples were tested for water absorption. The conditions and the methods for the water absorption test were conducted as per ASTM D570. Acoustic absorbers were initially dried in an oven for 1 hour at 110°C. Later, acoustic absorbers were taken for the long-term immersion technique as per the ASTM D570. Acoustic absorbers were immersed in 100 ml of distilled water for 24 hours, taken out, dried, and weighed (W_i) using a top-loading balance machine with a repeatability of 0.001 g, and immersed in the container for two weeks (336 hours). The absorbers were taken out after 2 weeks and weighed (W_f). This change in weight over time helps in understanding the water absorption of the absorbers. Water uptake (W_u) in (%) of the absorbers can be calculated by the following Eq. 3 (David and Azlan 2018):

$$W_u\ (\%) = \frac{W_f - W_i}{W_i} \times 100 \qquad (3)$$

where: W_i - the initial weight of the absorbers (g), and W_f - the final weight of the absorbers after immersion (g).

Biodegradation

A soil burial test was conducted as reported by (Harmaen et al. 2014) to explain the degradation properties of the absorbers. Absorbers were buried under the soil for 4 weeks. Organic soil outsourced from Kim Wei Nursery, Malaysia, was used. It contains coco peat, red burnt soil, fine sand, charcoal, and microbes as constituents. The average atmospheric temperature was around 30°C, with 80% humidity. The buried absorbers were taken out after each week, washed cleanly, and are placed in an oven at 50°C for 12 hours before being weighed. Loss of weight over the buried time helps in understanding the degradation properties of the absorbers. The weight loss (W_{loss}) in (%) of the absorbers can be calculated by the following Eq. 4 (Harmaen et al. 2014):

$$W_{loss}\,(\%) = \frac{W_i - W_f}{W_i} \times 100 \tag{4}$$

where: W_{loss} - weight loss in (%), W_i - the initial weight of the absorbers (g), and W_f - the final weight of the absorbers (g).

RESULTS AND DISCUSSION

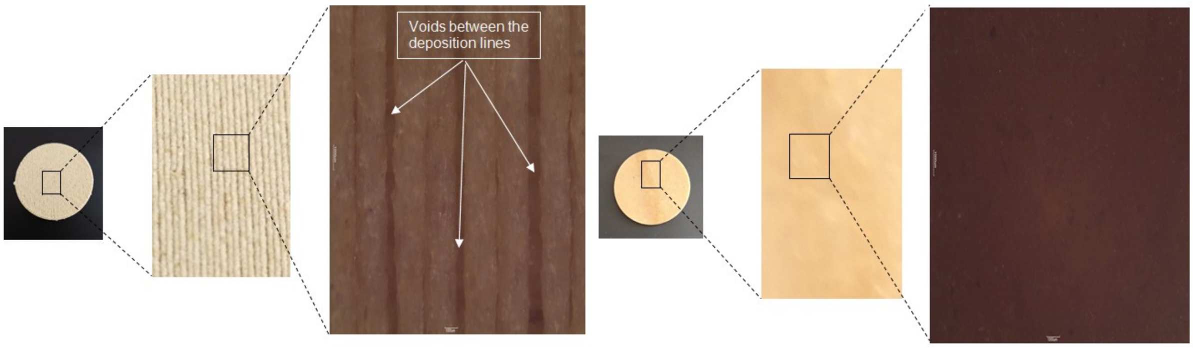
Physical properties of the acoustic absorbers

In the case of acoustic absorbers made of PLA/PHA-WF, the density of the compression molded absorber was 1.20 g·cm^{-3} and the density of the additive manufactured absorber was 0.98 g·cm^{-3}. The densities of the absorbers were listed in Tab. 3. It can be seen that the additive manufactured absorber exhibits decreased density than the compression molded absorbers.

Tab. 3: Densities of the acoustic absorbers made of PLA/PHA-WF.

Sample ID	Density (g·cm^{-3})
PLA/PHA-WF-CM-1.5	1.20 ± 0.16
PLA/PHA-WF-AM-1.5	0.98 ± 0.04

This decreased density is due to the increased porosity in the additive manufactured absorber. The void formation between the deposition layers of the additive manufactured absorber had caused 18% of porosity than the compression molded absorber whose porosity is assumed to be less (or) zero. This is in accordance with the research of (Le Duigou et al. 2016) where they have investigated the same woodfill filament and have reported that the additive manufactured structure exhibits relatively high porosity, around 20% than the compression molded structure. Most of the research dealt with 3D printing of PLA-based natural fiber filaments by FDM technology has reported this similar void formation among the deposition layers (Sekar et al. 2019). Fig. 3 shows the microscopic view of the additive manufactured and compression molded absorbers. Fig. 3a shows the microscopic view of the additive manufactured absorber showing voids between their deposition layers. Fig. 3b shows the microscopic (optical) view of the compression molded absorber with no (or) fewer voids in it.



a) b)

Fig. 3: Microscopic view of: a) the additive manufactured absorber showing voids, b) the compression molded absorber with no (or) fewer voids in it.

Fig. 4a shows the SEM image of the porosity exhibited by the PLA/PHA-WF-AM-1.5 and Fig. 4b shows the orientation of wood fibers in the 3D printed structure.

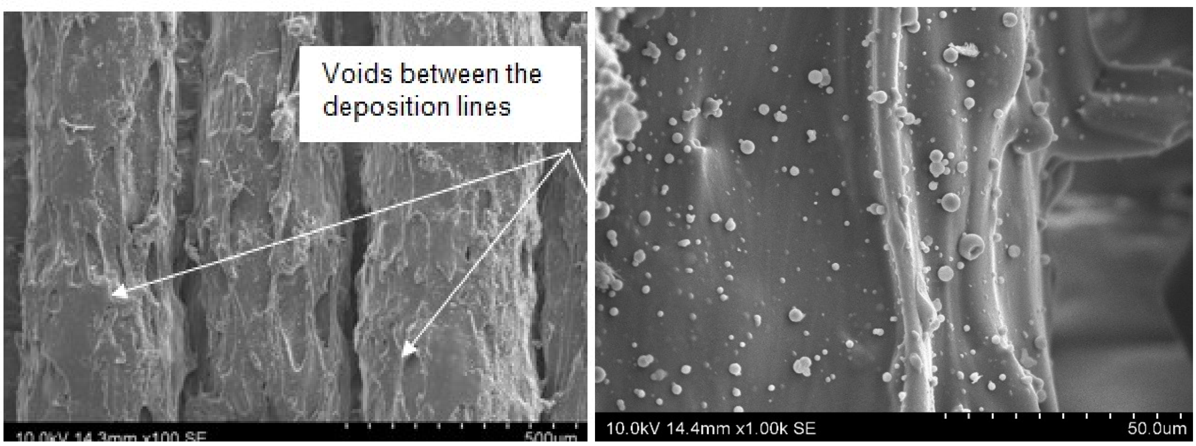


Fig. 4: a) SEM image of the porosity exhibited by the PLA/PHA-WF-AM-1.5 (100x), b) Orientation of wood fibers in the 3D printed structure.

Acoustical property of the acoustic absorbers

This section presents the acoustic absorption of the absorbers made of PLA/PHA-WF by compression molding and additive manufacturing. Fig. 5 shows the SAC of the compression molded and additive manufactured acoustic absorbers with and without air gap comparatively. It can be seen from Fig. 5 that the compressed molded absorber exhibits wider peaks of acoustic absorption with an air gap and there was no peak of acoustic absorption noticed without an air gap. This can be justified by the one-quarter wavelength theory, where the porous absorbers have to be one-fourth of a wavelength thick to absorb effectively at a broader spectrum. If not, an air gap must be provided for effective absorption (Kuczmarski and Johnston 2011). Compression molded absorbers made of PLA/PHA-WF with an air gap of 5 mm show the maximum SAC of 0.57 at 1784 Hz. Also, it can be seen from Fig. 5 that the additive manufactured sample exhibits increased acoustic absorption compared to the molded acoustic absorber in the mid to high-frequency spectrum without an air gap. In this case, the increased SAC of the additive manufactured sample is due to the increased porosity exhibited by the additive manufactured absorbers than the compression molded absorbers. This porosity (void formation) in the additive manufactured sample allows the acoustic wave to enter, followed by collision and dissipation. This helps the additive manufactured absorbers offer higher SAC than compression molded absorbers, especially at mid to high-frequency spectrum.

Upon providing an air gap, the additive manufactured porous absorbers follow the mechanism of the Helmholtz resonator, exhibiting a narrow peak of acoustic absorption due to the presence of micro-holes (voids) as seen in Fig. 3 and the presence of the back air gap with a maximum SAC of 0.81 at 1611 Hz. The absorption happened due to the friction between the air and the hole's inner surface (resistive part) and the air's inertial motion inside the hole (reactive part). The back air layer acts as the spring. This feature makes the additive manufactured absorbers exhibit the highest SAC more than the compression molded absorbers but is limited to a narrow bandwidth.

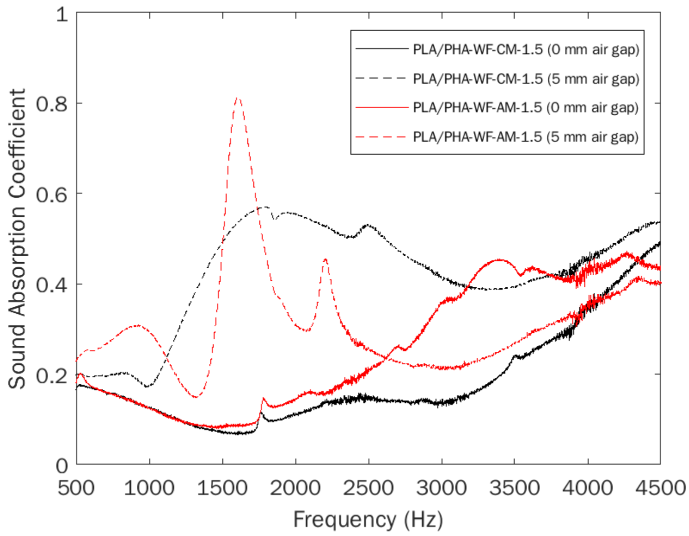


Fig. 5: SAC of the compression molded and additive manufactured acoustic absorbers with and without air gap comparatively.

Mechanical property of the acoustic absorbers

Fig. 6 shows the tensile strength of an acoustic absorber made of PLA/PHA-WF developed by compression molding and additive manufacturing. It can be seen from Fig. 6 that the tensile strength of the PLA/PHA-WF-CM (23.64 ± 1.20 MPa) was higher than the tensile strength of the PLA/PHA-WF-AM (21.65 ± 1.55 MPa). There was a slight increase in tensile strength seen for the acoustic absorbers developed by compression molding than the acoustic absorbers developed by additive manufacturing.

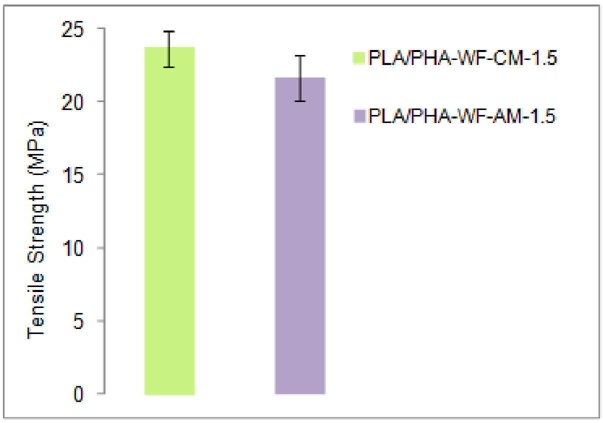


Fig. 6: Tensile strength of an acoustic absorber made of PLA/PHA-WF developed by compression molding and additive manufacturing.

The porosity exhibited by the additive manufactured structure was attributed to the decrease in tensile strength for the PLA/PHA-WF-AM. During tensile loading, the porosity caused by the voids between the deposition layers creates a deficit on the structure, and there will be less material left to hold the structure compared to the compression molded structure, which is more solid. However, the amount of material that holds the composite in the additive manufactured structure would have aligned the orientation of wood fibers in the direction of tensile loading as seen in Fig. 4b, reducing the tensile strength difference compared to the compression molded structure, where the orientation of wood fibers in the matrix during the molding process would be randomized. The results are in accordance with (Le Duigou et al. 2016).

Thermal property of the acoustic absorbers

Fig. 7 shows the thermal behavior of PLA/PHA-WF produced by compression molding and additive manufacturing. PLA/PHB-WF composite exhibited a two-step degradation profile regardless of the processing technique. PLA/PHA blends tend to have an intermediate trend between the thermal degradation curves of individual PLA and PHA polymers which could be attributed to the hydrolysis reaction catalyzed by the carboxyl end groups of polyester as a result of thermal degradation (Frone et al. 2020). There was no significant difference in the thermal behavior of the PLA/PHA-WF composites produced by compression molding and additive manufacturing. However, a small increase in thermal degradation temperature starting from the $T_{10\%}$ for the PLA/PHA-WF produced by additive manufacturing was noted as seen in Tab. 4. This could be due to the orientation effect of wood fibers (Frone et al. 2020). The orientation of fibers in the matrix influences the thermal behavior of the composites. The orientation of the wood fibers in the composites will be aligned to the direction of the 3D printing process as seen in Fig. 4b whereas the orientation of wood fibers in the compression molded composites will be randomized.

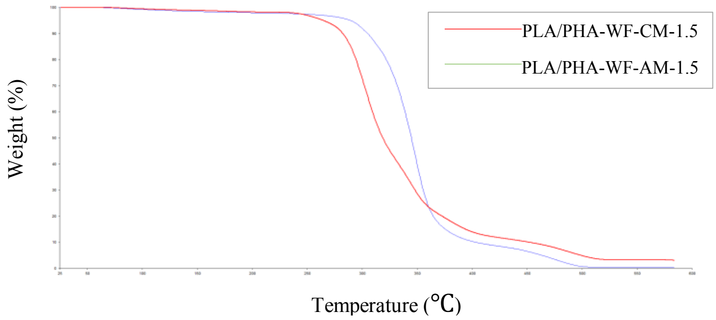


Fig. 7: TGA curves of PLA/PHA-WF absorbers produced by compression molding and additive manufacturing.

Tab. 4: TGA data of PLA/PHA-WF composites produced by CM and AM.

Sample ID	$T_{10\%}$ (°C)	T_{max} (°C)	$R_{600°C}$ (%)
PLA/PHA-WF-CM-1.5	280.61	303.92	0.16
PLA/PHA-WF-AM-1.5	304.01	347.65	0.02

Water absorption property of the acoustic absorbers

Fig. 8a shows the water uptake percentage of acoustic absorbers made of PLA/PHA-WF developed by compression molding compared with an acoustic absorber made of PLA/PHA-WF developed by additive manufacturing after 2 weeks. It was found that the water uptake percentage of the acoustic absorber developed by additive manufacturing (6.5 ± 0.66 %) was higher than the water uptake percentage of the acoustic absorber developed by compression molding (2.8 ± 0.54 %). There was around a 3% increase in water uptake percentage of the absorbers developed by additive manufacturing than the absorbers developed by compression molding.

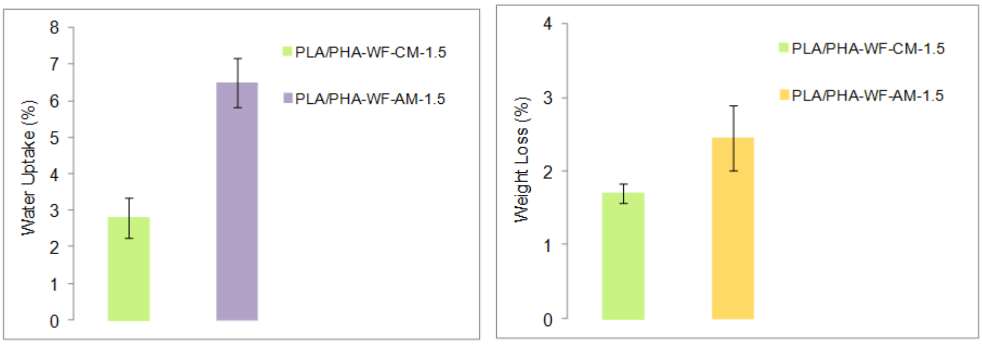


Fig. 8: a) Water uptake (%) after 2 weeks of acoustic absorber made of PLA/PHA-WF developed by compression molding and additive manufacturing, b) Weight loss (%) of acoustic absorber made of PLA/PHA-WF developed by compression molding and additive manufacturing.

The increased porosity (voids between the deposition layers) of the additive manufactured absorbers allows water molecules to pass through. This resulted in a higher water uptake percentage for the additively manufactured acoustic absorber than for the compression molded acoustic absorber. The results are in accordance with (Le Duigou et al. 2016).

Biodegradation property of the acoustic absorber

Fig. 8b shows the weight loss percentage of acoustic absorbers made of PLA/PHA-WF developed by compression molding compared with an acoustic absorber made of PLA/PHA-WF developed by additive manufacturing after 4 weeks.

It can be noted from Fig. 8b that both the absorbers made of PLA/PHA-WF by CM and AM exhibited weight loss at the end of the 4^{th} week. This can be justified by the fact that both the polymers, PLA and PHA under aerobic conditions, degrade into carbon dioxide and water. The presence of natural fibers like wood in the polymer blends would increase the hydrophilic site and support the biodegradation as well thereby leading to weight reduction. It can also be noted that the weight loss percentage of the acoustic absorbers made of AM was higher (2.45± 0.45 %) than the weight loss percentage of the acoustic absorbers made of CM (1.70 ± 0.13 %). The increase in weight loss percentage is attributed due to the increase in porosity of the AM structures. This porosity in the AM structure allows constituents of the soil to enter in thereby increasing the rate of biodegradation.

CONCLUSIONS

Acoustic absorbers made of wood fiber composite were successfully developed by CM and AM. The developed acoustic absorbers were measured for its physical, mechanical, thermal, water absorption and biodegradation properties: *(1)* Upon providing an air gap, thin porous acoustic absorber made of PLA/PHA-WF developed by AM behaves as a perforated absorber exhibiting narrow peak of acoustic absorption obeying the Helmholtz resonance mechanism due to the presence of porosity in their structures whereas the thin acoustic absorber developed by CM behaves as a porous absorber with a wider peak of acoustic absorption. *(2)* The mechanical and thermal properties of the absorbers made of PLA/PHA-WF developed by CM and AM were almost similar. The tensile strength of the developed absorbers was almost in accordance with the tensile strength of a few of the commercially available acoustic absorbers such as commercial ceiling board (Ajiwe et al. 1998), medium density fiberboard (Narlıoğlu et al. 2018), and hardboards (Hunt and Vick 1999). The results from the TGA show that the acoustic absorbers will not thermally degrade under ambient conditions and were thermally stable under maximum processing temperature (210°C). *(3)* Acoustic absorber made of PLA/PHA-WF developed by AM shows an increased rate of water absorption and biodegradation compared to absorbers developed by CM due to the presence of porosity in the AM structure. Future work will be more into developing the acoustic absorbers with a reduced rate of water absorption without compromising the acoustic properties.

There are 3D printers in the current research which have proved the possibilities of 3D printing bigger structures such as houses and bridges (Hossain et al. 2020, Schuldt et al. 2021). Hence, the possibility of 3D printing an acoustic absorber of bigger sizes will be not an issue. However, the current idea is to fabricate a portion of the acoustic absorbers in the form of tiles and assemble them at the desired place.

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