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An evaluation study of mycelium based acoustic absorbers grown on agricultural by-product substrates

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ABSTRACT

This research examines the use of a novel new renewable resource in acoustic absorption applications. The new material being tested is based on a fungi that is grown on semi-hydrophobic agricultural by-product substrates such as switch-grass, rice straw, sorghum stalks, flax shive, kenaf and hemp. The various substrates were tested as this novel composite is limited in the control over density, with the main control being the selection of the constituent parts. The testing of the material for use in acoustics utilized an impedance tube and measured the standing wave ratios in accordance to ISO standard 10534-1. The results of the study show the mycelium based boards are a promising bio-based composite alternative to standard traditional foam insulation board. Results suggest an optimal performance at the key automotive road noise frequency of 1000 Hz. A further advantage provided by this new material is that it can be produced economically in comparison to the traditional petroleum based foams with the further advantage of bio-degradation when the product is disposed of at its end-of-life use. Based upon this work, future research is planned to examine this novel new composite in other acoustic applications where shape modifications can further enhance the performance.

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1. Introduction

This research examines the use of a novel new renewable resource in acoustic absorption applications. The material under test is based on vegetative stage, mycelium, of a fungi in the phylum of Basidiomycetes, which is grown on semi-hydrophobic substrates such as cotton by-products, leaves, sticks and cotton burs and other low cost agricultural by-products such as switch-grass, rice straw, sorghum stalks, flax shive, kenaf and hemp. By growing the mycelium around agricultural by-products, the by-products provide food and a base structure for the fungi which in turn provides the binder to form the agricultural by-products into molded shapes that are low cost and suitable for such applications as packing material for shipping as well as construction insulation (Alma et al., 2005; Holt et al., 2012) in a manner that is competitive to more traditional particle board composites built using rice-straw and other agricultural by-products such as composites as reported by Yang et al. (2003) and Sampathrajan et al. (1991). The mycelium provides structural binding properties for the mixture through the growth of interconnecting fibrous threads that form chitin and Beta Glucan based structural oligosaccharides that bind the bulk agricultural materials into a composite board or complex shape capable of replacing non-renewable resource materials such as Styrofoam and poly-urethane foams.

A new application, for sound absorption panels, of this novel composite material is being examined in this study for use in the application of sound absorption panels. One proposed applications of interest for such panels are the potential for use in automotive sound absorption panels as well as more typical construction installations for acoustic noise damping. As automotive applications are one of the primary motivators for this investigation; testing was conducted to explore the sound absorption properties in the range from 300 Hz through to 4000 Hz as that range is the dominant road-noise spectrum of interest.

Of note is that the use of mycelium for a binder limits control over density, whereby the sound properties of these proposed boards are derived by the selection of the composite's constituent components. Thus, the main variable of interest to a producer, is the selection of the available substrates. However, it should also be noted that sizing of the particles also plays a role as the finer grinds limits the available oxygen to the mycelium and results in a denser board with less penetration of the mycelium fibers into the depths of the board. Thus, the grind of the material is expected to be a factor as acoustic properties are known to be influenced by the porosity, tortuosity, flow resistivity and the characteristics lengths (Takahashi and Tanaka, 2002; Park and Palumbo,

Abbreviations: ISO, International Organization for Standardization; Hz, Hertz.

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2009). Noting however that this study is the first foray into the potential for acoustic absorption panels for this novel new material, the investigation was limited to a broad survey of various mixtures of available agricultural by-product residues. The investigation examined numerous mixes comprising a wide variety of different agricultural by-products to determine the best mixtures for this application. While noting that most acoustic testing is currently performed via the two-microphone impedance-tube transfer-function method, ISO standard 10534-2 (1998), we note that the transition away from the old ISO 10534-1 (1996) standard was due primarily to the increase in ease and speed of testing rather than an improvement in accuracy. As accuracy was a key criteria for our testing, the testing for this study utilized the more accurate original ISO standard 10534-1 (1996), with further application details found in Beranek (1988, 1996), McIntosh et al. (1990) and Rossing (2007). In ascertaining which frequencies the panels should be tested for, a literature search revealed that the dominant road noise, based on a −3 dB 1/2 power cut-off, typically ranges from 500 to 1600 Hz for large trucks and over a narrower region from 800 to 1600 Hz for typical consumer grade automobiles (Mak et al., 2012; Sandberg, 2001, 2003; Sandberg and Ejsmont, 2002; Soto et al., 1994). Noting from Jarzinski (1990) and Jiang et al. (2009) that sound vibration absorption is affected by particle sizes and polymer properties, a wide range of agricultural by-products were testing during the course of this research ranging from cotton, kenaf, sorghum, hemp, rice and switch grass. The specific objectives of this research were to determine the sound absorption characteristics of the composite formed by the interaction of agricultural by-products with mycelium to produce acoustic absorption panels.

2. Materials and methods

2.1. Mycelium based panels

The test subjects were generated by growing fungi, of the phylum of Basidiomycetes, on top of agricultural by-products that were fiberized to different size ratios by means of either a hammer or attrition mill followed by screanning to exclude particles less than 0.853 mm (#20 mesh screen). The agricultural by-products were tested as both sole constituents and in 50–50% mixtures ratios comprised of the following {Rice Straw, Hemp Pith, Kenaf Fiber, Switch Grass, Sorghum Fiber, Cotton Bur Fiber and Flax Shive}.

The mycelium was grown onto the by-products via the process reported by Holt et al. (2012), which consisted of the main processing steps of:

- fiberized agricultural by-products,
- steam processing the fiberized agricultural by-products to render mold spores inert,
- inoculating the stream processed fibers with Basidiomycetes based fungi,
- placing the inoculated fibers into 16 cm × 16 cm molds at a depth sufficient to generate a finished nominal thickness of 2.5 cm,
- growing fungi on the fiberized by-products in a controlled environment chamber under dark warm humid conditions for 4–6 days.

2.2. Acoustic testing

In developing the requisite impedance tube apparatus for the acoustic testing, it was observed that while the distance between maxima's as well as mimina locations adhered to theoretically expected distances; a significant offset was observed between the minima locations to the maxima locations that were likely occurring due to non-linearity's in the system. To avoid this non-linearity, the testing protocol selected for this study was the previous acoustic impedance tube testing standard, ISO 10534-1 (1996), due to its inherent accuracy advantage over the later ISO standard, as it provides a direct measure in place of a 2 point extrapolation via a model based estimate. Of particular note in the development of the testing protocol was the reference in the literature, ASTM E1050 (2010) which discuses attenuation along the length of the tube that attenuates the maxima the further away from the reflection plug. To address this concern, the magnitude of the attenuation was tested to obtain a correction factor, alpha, by measuring the pressure amplitude as a function of the distance along the tube to provide the tube attenuation coefficient. This testing however revealed that if the maxima peaks were limited to the first or second peak closest peaks to the reflected specimen, it was found that the attenuation was minimal across the frequency range of interest for our tube, and could be assumed to be negligible for the purposes of this testing. As part of the validation testing of this assumption, a plain brass plug, providing a pure 99.9% reflection, was tested for reflection coefficient at both the first and second maxima peaks which produced results that were found to be within less than 1% deviation between the peaks across the frequency range of interest. Given this, the protocol for this study followed the ISO 10534-1 (1996) recommendation for measuring, with respect the reflection specimen, the first pressure minima, followed by the next closest pressure maxima.

The equipment utilized in the construction of the impedance testing was[1]:

- Hewlett Packard, Santa Clara, CA, 33120A signal generator.
- Agilent, Santa Clara, CA, DSO1024 digital oscilloscope.
- Peavey, Meridian, MS, Power Amplifier IPR-1600 DSP.
- Crowne Audio, Elkhart, IN, 15 cm diameter speaker.
- Behringer, Behringer City, China, two cascaded equalizers, to provide a full range of attenuation of ±24 dBu.
- Analog Devices, Norwood, MA, Electret microphone amplifier provided by Analog Devices integrated circuit: SSM2166.
- Electret phantom power was set to 3.3 V.
- Olympus America, Center Valley, PA, Electret microphone.
- Extech Instruments, Nashua, NH, NIST traceable Sound Level Meter 407732.
- Extech Instruments, Nashua, NH, NIST traceable Piston Sound Level Calibrator 407722.
- Impedance tube was constructed out of PVC schedule 80 with an inner diameter of 4.76 cm.
- The reflection plug was machined to a tight, but movable, fit out of 3 deep solid brass.
- Samples were attached to the brass plug via a hot glue developed for use with plastics, ceramics and metals, model #9-80459 by Craftsman, Sears Holding Co., Hoffman Estates, IL.
- Relative humidity for each test was obtained with a National Institute of Standards and Technology, "NIST", traceable humidity sensor manufactured by the Control Company, Friendswood, TX, an ISO 17025 Calibration Lab that holds an A2LA Accreditation. We would also note that we verified the Control Company's humidity sensor against a high-end General Eastern chilled dewpoint humidity sensor model Hygro-M2.

2.3. Experimental methods

The experimental test was conducted per standard method supplied in ISO 10534-1 with the following added necessary procedures that are not covered in the standard method protocol:

- Initial system configuration was developed by placing the microphone in free space on a mount immediately in front of the speaker and adjusting the two cascaded equalizers until a uniform sound level was obtained for each frequency of interest, with the power amplifier and signal generator held to a fixed voltage and power level. This initial configuration was performed only one time at the initial system setup.

- Noting that the primary measurement of the standing wave ratio, “SWR”, reading relies on a linear response for the measurement of sound pressure levels, “SPL”. Tests were conducted at each frequency to ensure the system’s cascaded voltage to power amplifier to speaker to microphone and microphone pre-amplifier combinations provided a linear response, with respect to the sound pressure level, across signal range of interest. This portion of the testing utilized an Extech, NIST traceable, 407732 sound power meter to verify pressure amplitudes versus system’s predicted sound pressure levels.

In practice during every run,

- Signal generator was tuned to one of the test frequencies comprised of {250, 310, 400, 630, 1000, 1600, 2500, 4000 Hz}.
- At each frequency of microphone distance from the plug was adjusted to the strongest of either the first or second maxima. After the maxima was located the signal generator voltage was adjusted until the microphone reading was nominally at 855 mV, ±25 mV, which represents the strongest signal available from the SSM2166 in the linear range before the signal undergoes signal compression. The reading at the maxima was then stored as the max for the SWR formula. After the maxima was found, the microphone distance was adjusted to the closest minima where again the amplified microphone voltage was recorded. Using both the minima voltage and the maxima voltage the SWR and reflection coefficient, “Γ“, for that frequency was determined.
- After the SWR is measured, for each frequency, the reflection coefficient and absorption coefficient is calculated, per Eqs. (1)–(3).

$$S_{\mathrm{wr}} = \frac{P_{\mathrm{maxima}}}{P_{\mathrm{minima}}} \tag{1}$$

$$\Gamma = \frac{(S_{\mathrm{wr}}+1)}{(S_{\mathrm{wr}}+1)} \tag{2}$$

$$\alpha = 1 - \Gamma^2 \tag{3}$$

where α is the attenuation coefficient (amount of pressure wave that is absorbed); Γ is the reflection coefficient (amount of pressure wave that is reflected); S_{wr} is the standing wave ratio (fundamental measurement of standing waves); P_{minima} is the minimum SPL in impedance tube; P_{maxima} is the maximum SPL in impedance tube.

Of particular note, from Eq. (1), is that the SWR is a ratio. Thus, it can be seen that the absolute magnitude is not important as any gain term will cancel out, thereby alleviating the need to track the various gains for each frequency. Thus, the initial protocol of determining a separate gain for each frequency was abandoned in favor of adjusting the system’s input voltage to set the acoustic power such that the microphone pre-amplifier was still in the linear region of operation for the pre-amplifier. This testing protocol was followed for each specimen, which was replicated 3 times on each test material. In addition to the acoustic testing, each replicate was measured for thickness, volume and density. For future reference in case an impedance value is needed, room temperature and relative humidity was also recorded per requirements specified in the ISO standard method.

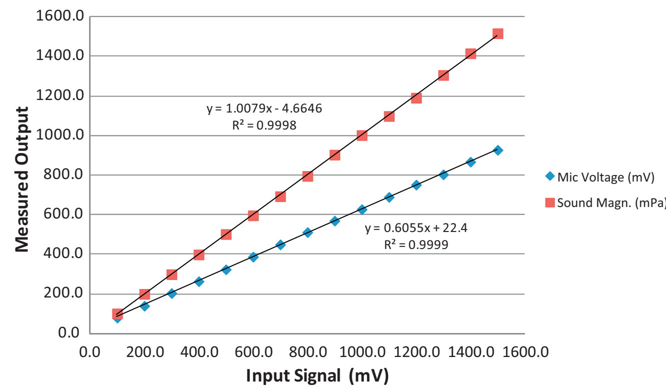

Fig. 1. Results from the amplified microphone gain calibration test at 1000 Hz. Test compared input signal (mV) to microphone output (mV) as well as the SPL response from an NIST traceable sound meter (dB) which was converted from SPL (dB) to pressure (mPa).

3. Results and discussions

3.1. Acoustic testing

During the initial setup phase of the system, tests were conducted to ensure a linear response for the system across the acoustic power range of interest at every frequency that was tested. Fig. 1 details the linear response, showing a coefficient of determination of $r^2 = 0.9996$ with a bias of 2.4 mV (milli-volts) and a standard error of ±27.2 mV.

Noting the E-1050 acoustic impedance, two-microphone method, suggests awareness of the need to potentially correct for attenuation along the length of the tube, tests were conducted to examine the attenuation coefficient at each subsequent maxima location starting at the brass plug and moving the microphone progressively away from plug reflector. Of particular note was the observation that, in accordance to ISO 10534-1 (1996), the greatest maxima was observed to occur at the first closest pressure maxima beyond the first minima, with respect to the sample’s location. It was also noted that the difference in SWR’s obtained between the highest two of the nearest three maxima’s were in agreement with each other within 1–2% with the best response found by using the first maxima past the first minima, which also suggests that in our system the tube attenuation provided a minimal impact on results and could be safely neglected. Fig. 2 shows the results of the testing that was performed at 1600 Hz.

Noting that the brass plug provides a near ideal reflecting surface, while the results of the uncorrected response of the brass plug were typically within 1–2% of 100%; to ensure highest accuracy the

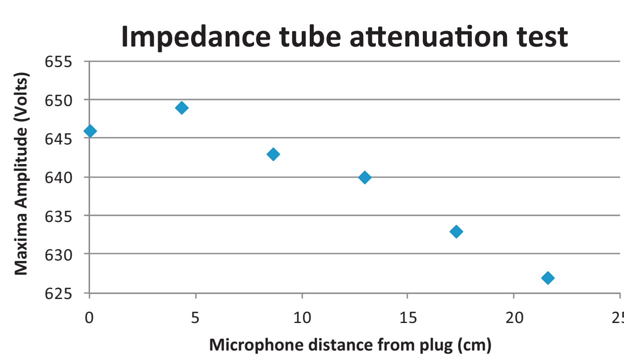

Fig. 2. Test examining the attenuation at maxima locations as a function of microphone distance from hard brass reflector, providing a near perfect reflection at 1600 Hz.

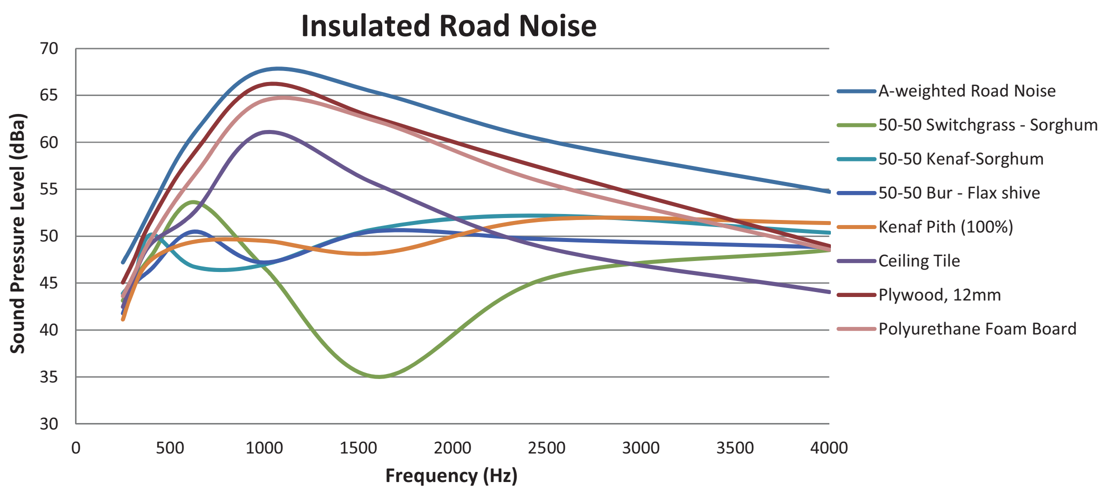

Fig. 3. Test comparing the audio spectrum, A-weighted with typical road noise excitation, between mycelium based acoustic absorption boards ranging from best to worst performers alongside a few traditional absorbers for reference, such as plywood and a typical 25 mm thick poly-urethane insulation board.

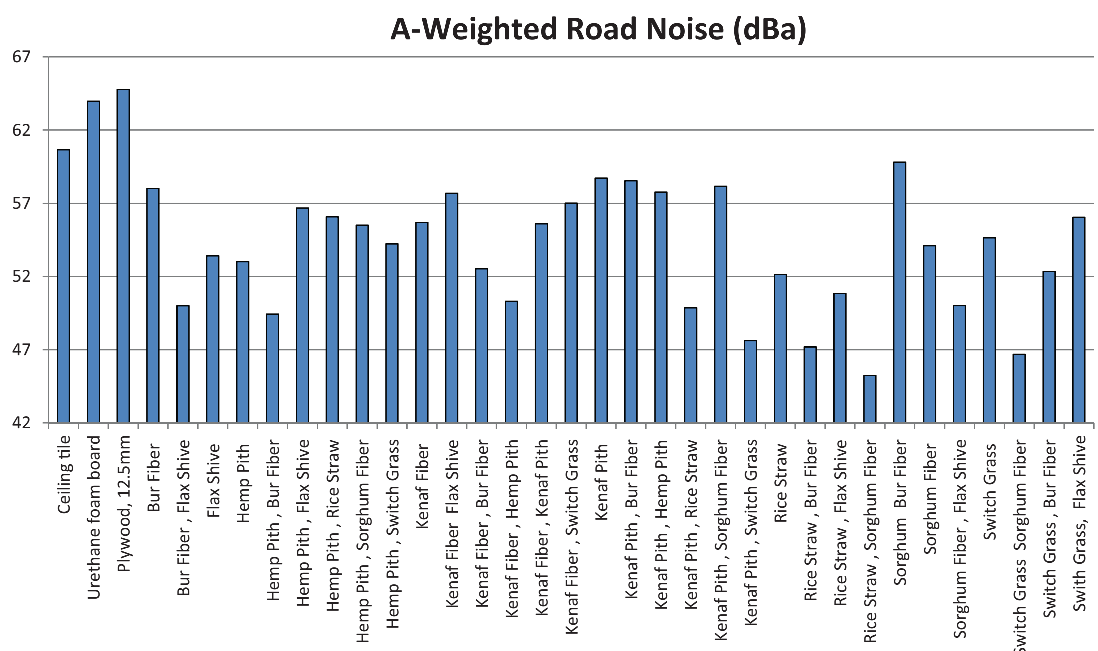

Fig. 4. Results of the entire group of composite mixtures that were tested. Results shown are the acoustic performance for perceptual response of road noise for each of the tested composite mixtures (integrated A-weighted response with typical road noise excitation).

results were normalized to the brass plug response at each frequency and the maxima and minima integer n locations were held fixed for each frequency and each tested specimen. This was done in accordance to measurement correction techniques typically utilized to improve measurements, such as are commonly employed when testing with microwave network analyzers (Pozar, 1998).

To gain some insight into the performance of the mycelium based acoustic insulation boards, tests were also conducted using 15 mm thick plywood samples and 25 mm thick polyurethane construction grade foam insulation board and a typical acoustic ceiling tile. Comparative results are detailed in Fig. 3 against a range from the low performers and to the high performers from the acoustic mycelium based samples. As can be appreciated, 10 dB represents a doubling of the perceptual volume, the mycelium based samples tests suggest promise for a significant improvement over standard construction grade materials, and even a standard fiber based acoustic ceiling tile, especially in the region of 1000 Hz which is the critical frequency range for absorption of road noise. The entire

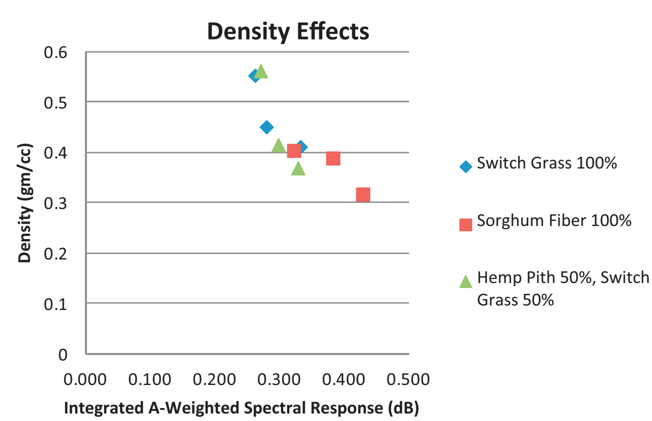

Fig. 5. An inverse relation to density was observed between replications on a per case basis. There was not however a significant impact of density on a global basis.

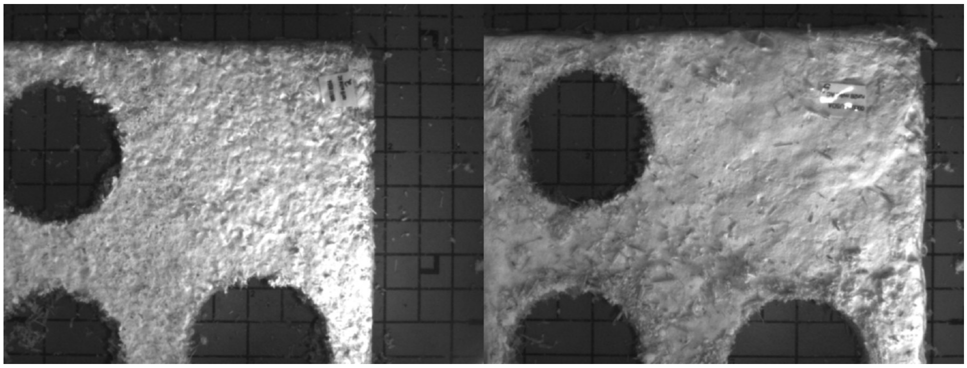

Fig. 6. Comparison images of the varying surface texture that occurred when mycelium was grown on various substrates. On the left is a picture of 50% kenaf pith and 50% cotton bur fiber that produced a nice compact dense board, but a rough surface texture. On the right is a picture for 50% kenaf pith and switch grass that yielded a smoother surface texture.

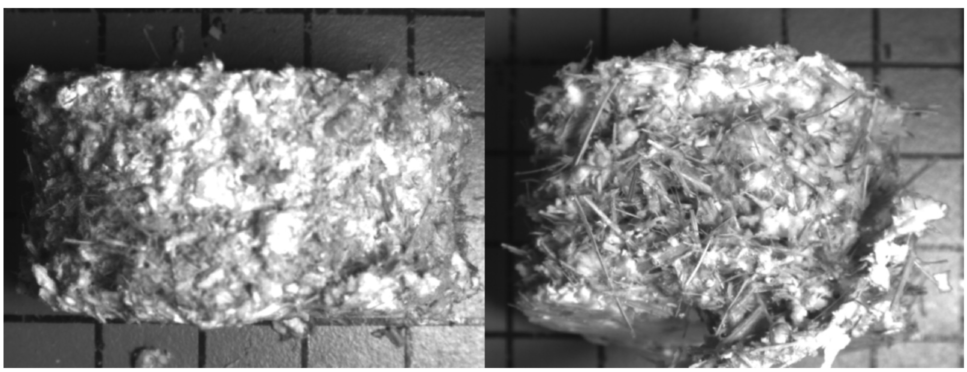

Fig. 7. Zoomed side view comparison of two of the cut-out biscuits showing full penetration of the mycelium on the left that produced a high quality dense board with good machining qualities, 50% kenaf pith/cotton bur fiber versus 50% switch grass/sorghum fiber which resulted in poor penetration leading to a loose, friable biscuit with poor machining qualities, as pictured on the right.

spectrum of tests are shown as an integrated A-weighted response in Fig. 4.

In looking at the performance of the various mixtures, one of the test parameters that was quantified was board density. The mean density of the entire set of boards was found to be 0.340 g/cm^3 with a standard deviation of $\pm$0.066 g/cm^3. It should be noted that while within individual replicates from a single board, some showed an inverse relation between acoustic absorption and density as detailed in Fig. 5. However, when measured across the entire group, the correlation to density was not significant with the largest performance correlation being tied to the specific material interaction with mycelium.

3.2. Surface quality and machining characteristics

One of the primary characteristics of interest in the development of the mycelium based acoustic boards is the esthetic quality factor where, depending upon the substrate material the mycelium is grown on, results in significant differences in the surface quality of the produced boards. To illustrate this, lighting was setup at 90° and 180° to bring out the surface texture of two boards that ended up with very different results ranging from a smooth velvety surface, to one with a rough hard texture with the only differing element being due to the underlying substrate material (Fig. 6).

Similarly, a cross-sectional view detailed in Fig. 7 shows that in some substrates, such as 50% kenaf pith and 50% cotton bur fiber, the mycelium did a very good job of penetrating throughout the material, which led to a high quality board with good machining qualities. In other substrates, just by changing one of the blended constituents from 50% kenaf pith to that of a 50% switch grass changed the response such that the resulting board exhibited very poor penetration of the mycellim that in turn resulted in a low grade weak board that was readily fractured upon machining into test biscuits (Fig. 7).

4. Conclusions

The results of the study indicate the mycelium based boards showed promise in providing a unique alternative to that provided by traditional standard foam insulation boards. Of note is that one of the primary objectives of this research was to ascertain which of the agricultural by-product mixtures is the best for future work; as well as to gain a basis into potential of this novel material for use as an acoustic absorber. Results from the testing suggests that a great deal of flexibility with materials exists when implementing a design for mycelium based acoustic absorption panels. This conclusion is further supported by noting that even the low performer, such as 100% cotton bur fiber yielded better than 70–75% acoustic absorption at the peak frequency of interest of 1000 Hz. In summary, all test subjects performed well leaving the best choice as to the most economic solution along with a bias toward board strength and other physical properties of interest to the particular application, that will be explored in future work. Of particular interest for future work is examine the best performers and then examine the relation between acoustic properties as by-product sizing is expected to influence the acoustic performances, as porosity, tortuosity, flow resistivity and characteristic lengths, are known to influence acoustic properties.

In comparison to the traditional petroleum based foams, the mycelium based acoustic absorbers shows promise to provide a low cost high performing alternative, to traditional foam based boards, that also include the advantage of bio-degradation for environmentally conscious disposal when the product is at its end-of-life use. Based upon this work, future research is planned to examine this novel new composite in other acoustic applications where shape modifications can further enhance the performance.

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