AN INVESTIGATION OF THE ACOUSTICAL ABSORPTION CHARACTERISTICS OF A RECYCLED COCONUT MATERIAL WITH AN *IN SITU* AND IMPEDANCE TUBE METHODS

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Abstract. *In this paper the acoustical impedance and absorption coefficient of a fibrous acoustical material based on coconut fibers are investigated. The material is manufactured from recycled coconut shells. Recycling coconuts has many impacts, both social and environmental. From environmental point of view the production of coconut garbage in a country like Brazil is very big. It takes many years for full natural decomposition. Recycling of coconut has many applications, and the manufacturing of acoustical absorbent materials is one of those. From the social point of view transforming the recycled coconut into a product will create new companies and jobs. This paper investigates the absorption characteristics of a coconut based material and compares it to a commercial fiberglass material. Two methods are used in this comparisons: The standard impedance tube, and a relatively new in situ method for measuring impedance with a combined pressure and particle velocity sensors (with a wider frequency range then the impedance tube). The theoretical background of the in situ method and the effects of sample size and measurement room will also be presented. With this investigation it will be possible to draw more conclusions about the behavior and commercial applicability of the coconut based acoustical material.*

Keywords: *Sound absorption, impedance, in situ, coconut*

1. INTRODUCTION

Coconuts can have many commercial applications besides the food industry. One of the applications that is gaining importance is the use of coconut fibers to manufacture acoustic panels which are able to absorb sound energy in a wide frequency band. According to Soeiro (2004) the acoustical panel absorber, based on the coconut fiber is manufactured from the mesocarp of the coconut. The mesocarp is the fibrous and thickest part of the coconut. The white and liquid part of the coconut is used by the food industry. According to Santiago (2005) the production of coconut fibers is over 7,000 ton in Brazil. These fibers takes about 8 years to be naturally degraded. Obviouslly it represents a major impact for the enviroment. According to Giselle Moreira Silva (2008) the increasing concern of the industry with the use of renewable and green technologies puts the coconut acoustic material as a possible candidate for a car lining material, for example. The fact that materials based on vegetal fibers (such as those made of coconut) are renewable, cheaper and offer no risk to the human health during handling and processing also contributes to the potential of this technology.

In the previously quoted works of Soeiro (2004) and Giselle Moreira Silva (2008) coconut fibers were modeled and measured in the impedance tube. The models used to predict the acoustical behavior of the material were the Biot model (Biot (1956a) and (1956b)) and the Delany and Baseley model (Cox et al. (2005)) respectively. In these works the material was measured and simulated for a frequency range up to 3 kHz. The measured materials showed to have a fairly agreement with the theoretical models in this frequency range.

The purpose of this paper is to extend the measured frequency range up to 10 kHz using an *in situ* technique and a sensor which measures at the same position both the sound pressure and particle velocity. This sensor is commercially available by Microflown technologies (in the Netherlands). These *in situ* measurements will be compared with measurements in the impedance tube.

The paper is organized as follows. A review of the impedance tube technique will be presented, with considerations to its drawbacks. Following this a section describing the impedance *in situ* setup will be presented, with its considerations and some limitations. Results will be presented comparing the results obtained with the impedance tube and the *in situ* technique. The coconut fiber materials will also be compared with a commercial glasswool material. Most of these results will be presented in terms of the absorption coefficient.

2. IMPEDANCE TUBE TECHNIQUE

Figure 1 shows a schematic drawing of an impedance tube. This technique uses a tube excited in one end by a loudspeaker. In the other end of the tube the sample is mounted over a hard reflecting surface. The impedance and absorption can be measured by several techniques. Plane waves are assumed inside the tube, which is a good assumption as long as some conditions are satisfied. According to the international standard IS0 10534 the microphone's location should be sufficiently far from the sound source and the sample surface, so the plane wave assumption can stand. Another condition is that there is an upper and lower limit in the useful frequency range. The upper limit is established by the existence of axial acoustic modes only. For a circular tube this frequency limit is dependent on the diameter of the tube.

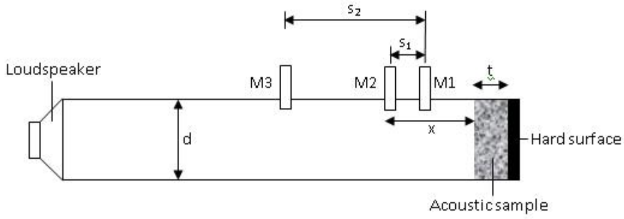

Figure 1. Impedance tube schematic drawing

$$f_u = \frac{c_0}{1.71d} \tag{1}$$

Where d is the impedance tube diameter and c_0 is the sound speed in the fluid.

Ross and Seybert (1977) derived a way to measure the surface impedance of the sample by the transfer function between two microphones located close to each other. Using two microphones is a fast measurement method but it has the disadvantage that the phase mismatch of the microphones can induce errors. Because of that, Chu (1986) proposed a way to measure the transfer function between two microphone's location using a single microphone. This method assumes that the process is stationary and avoids the phase mismatch between two microphones, but it is more time consuming because one has to change the microphone's location during the measurement of one sample.

The method using a single microphone was used in this study to avoid the phase mismatch. Measurements were done according to the international standard ISO 10534. In Fig. 1 one can see that three microphone positions were used. This was done because of the low frequency limitation due to a small microphone spacing. This limitation happens if the wavelength is too big, compared to microphone spacing, then the two microphones can not measure different sound pressures. This way the errors are too high. Increasing the microphone spacing allows one to extend measurements to low frequencies. On the other hand if the microphone spacing is too big it imposes a high frequency cut off. This upper limit can be smaller than the limit shown on Eq. 1, and in this case the frequency range is minimized. The upper frequency limit which one can measure due to microphone spacing is given in Eq. 2. In the case of this study s_1=0.065 m and d=0.09 m. Therefore the upper cutoff frequency chosen is approximately 2000 Hz.

$$f_{us} = \frac{0.45c_0}{s} \tag{2}$$

The low frequency limitation is given in Eq. 3. For s_1=0.065 m this frequency is f_l=263 Hz. Using the third microphone with a bigger spacing (s_2=0.35 m) the frequency range can be extended down to 50 Hz.

$$f_l = \frac{0.05c_0}{s} \tag{3}$$

For each microphone position (M1, M2 and M3) a transfer function between the exciting signal and the signal picked up by the microphone at M1, M2 and M3 is measured. In the end of one cycle of three measurements one has three transfer functions (H_{x1},H_{x2} and H_{x3}). The transfer functions between positions M1 and M2 and between M1 and M3 are then obtained by Eq. 4 and 5. H_{13} covers the lower frequency range from 100 to 400 Hz, and H_{12} covers the higher frequency range from 400 to 2000 Hz.

$$H_{12} = \frac{H_{x2}}{H_{x1}} \tag{4}$$

$$H_{13} = \frac{H_{x3}}{H_{x1}} \tag{5}$$

If one solve the acoustic field, assuming plane waves, the reflection coefficient is found in Eq. 6. This equation is the same for the lower frequency range but in this case $H12$ is replaced by $H13$.

$$R = \frac{H_{12} - e^{-iks}}{e^{iks} - H_{12}} e^{2ikx} \tag{6}$$

Where k is the wave number, s is the microphone spacing and x is the distance from the furthest microphone to the sample surface. The absorption coefficient is then calculated by Eq. 7.

$$\alpha = 1 - |R|^2 \tag{7}$$

Two of the drawbacks of the impedance tube technique is the frequency range limitation and the fact that this procedure is sample destructive. Some samples are difficult to cut (as the coconut samples), or even impossible to cut (such as perforated plates or very irregular absorbers).

There are other flaws regarding sample compression during mounting reported in the works of Kino and Ueno (2007) and Castagnede et al. (2000). A series of round-robin tests of impedance tube measurements in seven universities around the world is reported in the work of Horoshenkov et al. (2007). Deviation in the absorption coefficient reached 95% for one of the samples. The deviation was dependent on material type and uncertainties in the measurement of flow resistivity. Other reasons such as sample mounting conditions was attributed to the high deviations found. The authors suggested that the international standard ISO 10534 should be revised to account sample preparation.

3. *IN SITU* TECHNIQUE

In some situations it is important to know the impedance or absorption coefficient of a sample installed. This means that the sample should be measured at the environment where it is mounted. This is complicated because in these conditions the sensors used to measure are subjected to undesired sound reflections. There are several attempts in literature to overcome these problems. In the work of Mommertz (1995) the author used one microphone to measure the sound absorption coefficient. The free-field response (away from surfaces) was measured, and then a measurement close to the sample surface was taken. Using a time window and a subtraction technique (subtracting the the free-field sound pressure from the pressure near the sample) the author was able to get rid of undesired reflections (by the window), and to separate the incident and reflected sound pressures (by the subtraction technique). In another study from Ducourneau et al. (2008) the author used an array of microphones to measure absorption. Aiming the directivity of the array in two directions (towards the exciting source and towards the sample) the authors were also able to separate direct and reflected sound pressures and then calculate the reflection coefficient.

These attempts and others have the same problems in common. They are limited to samples with big areas, which is not true in many applications. The methods are low frequency limited because of sample size requirements, and due to the fact that microphones alone are sensitive to undesired reflections (as they are omnidirectional). Windowing can be used but the finite size of time windows also degrades the low frequency response. The two methods quoted can not accurately calculate the surface impedance, because one needs to know the sound field exciting the sensors. It must be said that there are methods in the literature that have incorporated a sound field calculation in order to measure the surface impedance, such as the work of Li and Hodgson (1997).

The alternative to the use of microphones alone is a relatively new sensor which measures sound pressure and particle velocity very close to each other. This sensor is commercially available by Microflown Technologies and it is called the *pu* probe. Its behavior is described in the works of de Bree et al. (2005) and Lanoye et al. (2006). With this sensor it is possible to measure very close to the sample, as can be seen in the work of Brandao et al. (2009). This reduces the sample size requirement and the sensitivity to undesired reflections (as the particle velocity sensor is not omnidirectional, and the measurement is taken very close to the surface of the absorber).

Figure 2 shows a photo and a schematic drawing of the impedance set-up used to measure the surface impedance *in situ*. This set-up is composed by a loudspeaker mounted on a spherical baffle, which behaves like a point source. The *pu* probe is then positioned at a distance h from the sample. The sound source is positioned in a distance h_s from the sample. Knowing these conditions, and that spherical waves are radiating from the loudspeaker one can solve the acoustic field near the sample. The pressure and particle velocity at a distance r from a sound source is given in Eqs. 8 and 9. The impedance measured in free-field conditions is given by Eq. 10, and the impedance measured at a distance h from the sample, by Eq. 11. These impedances are calculated dividing pressure and particle velocity in Eq. 8 and 9 with the proper values for r in each situation. The free field measurement is done pointing the impedance setup away from close reflecting surfaces in the room one is measuring.

$$p(r) = i\rho c_0 k \frac{Q}{4\pi r} e^{-ikr} \tag{8}$$

$$u(r) = \frac{Q}{4\pi} \frac{ikr+1}{r^2} e^{-ikr} \tag{9}$$

Where Q is the unknown source strength.

$$Z_{ff} = \frac{ik(h_s-h)}{ik(h_s-h)+1}\rho c_0 \tag{10}$$

$$Z_m = \frac{\frac{e^{-ik(h_s-h)}}{h_s-h} + R\,\frac{e^{-ik(h_s+h)}}{h_s+h}}{\frac{ik(h_s-h)+1}{ik(h_s-h)}\frac{e^{-ik(h_s-h)}}{h_s-h} + R\,\frac{ik(h_s+h)+1}{ik(h_s+h)}\frac{e^{-ik(h_s+h)}}{h_s+h}}\rho c_0 \tag{11}$$

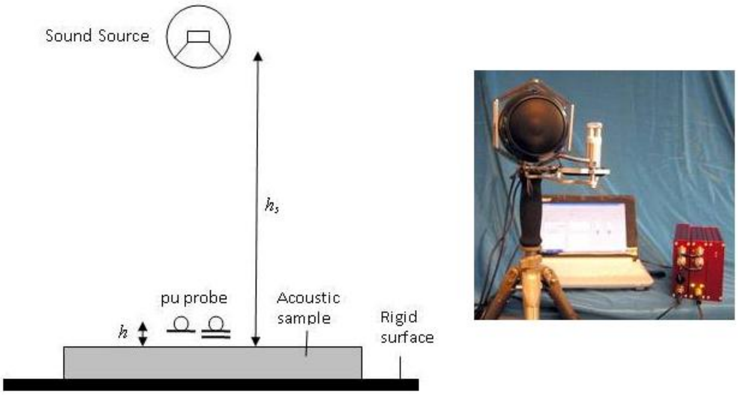

Figure 2. The impedance setup.

If the settings of amplifiers and sound card are kept constant during these two measurements Z_{ff} is used to correct the measured impedance Z_m. Thus dividing Zm by Z_{ff} and isolating R one finds the reflection coefficient for a spherical wave acoustic field. With the reflection coefficient and for $h = 0$ it is possible to calculate the surface impedance Z of the measured sample. It must be pointed out that this reflection coefficient assumes that the spherical waves reflects like a plane wave, which is not physically true. A more complex model which takes into account that spherical waves do not reflect like plane waves is shown in the work of Alvarez and Jacobsen (2008).

$$R = \frac{\frac{Z_m}{Z_{ff}} - 1}{\frac{Z_m}{Z_{ff}}(\frac{h_s - h}{h_s + h})(\frac{ik(h_s+h)+1}{ik(h_s-h)+1}) + 1}(\frac{h_s + h}{h_s - h})e^{ik2h} \tag{12}$$

$$Z = \frac{1+R}{1-R}\frac{ikh_s}{ikh_s + 1} \tag{13}$$

4. MEASUREMENT OF THE SAMPLES

Four different samples of coconut fiber material were measured with the *in situ* and impedance tube method. For the *in situ* technique, as the samples available were small in area, they were first measured in a semi-anechoic room. The performance of those samples were compared with a commercial Glasswool sample with a thickness of 2.5 cm. The four coconut samples varies in volumetric density and thickness. These data are shown in Tab. 1. The measured results are plotted in two ways: First comparing the impedance tube technique with the *in situ* technique, and then comparing the absorption coefficients of all the samples measured with the *in situ* technique.

Table 1. Coconut material data.

Sample	$\rho[Kg/m^3]$	Thickness (t [cm])
Coconut 1	2.5	1.0
Coconut 2	2.5	5.0
Coconut 3	8.9	1.0
Coconut 4	19.7	2.0

Figures 3 to 8 show the measured data comparing the impedance tube technique with the *in situ* technique. Most of these results are shown in terms of the absorption coefficient. Only Fig. 4 shows the measured data in terms of surface impedance.

The absorption coefficient measured with the impedance tube agrees fairly well with the *in situ* technique in most of the cases (in the frequency range of the impedance tube). Coconut 1 and 2 showed to have the worst agreement between the two techniques. This is probably related to the low density of the samples which might lead to problems during handling and mounting of the samples in the impedance tube. These cutting and mounting problems are avoided by the *in situ* technique.

The glasswool showed to have a good agreement for the absorption coefficient from 200 to 2000 Hz. There are some deviations below 200 Hz, which might be due to both impedance tube and *in situ* technique errors. The surface impedance shown in Fig. 4 shows agreement for the real part of surface impedance ($Re\{Z\}$), but the imaginary part ($Im\{Z\}$) is more deviating. This result is unexpected and a final answer to this matter is not possible yet. According to Alvarez and

Jacobsen (2008) it would be expected that this difference would be found in the real part of the surface impedance, and not in the imaginary part. More research is being carried out regarding this problem.

Coconut 3 and 4 (Figs. 7 and 8) showed to have a fairly good agreement between 200 and 2000 Hz for the two techniques. These samples have bigger volumetric density which might be the cause of better agreement.

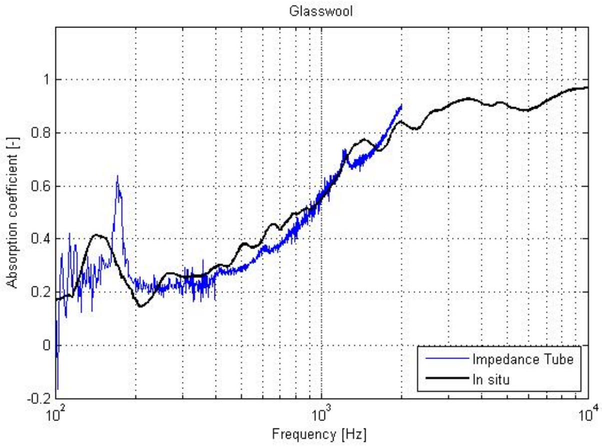

Figure 3. Absorption coefficient of glass wool (Impedance tube vs. *In situ*).

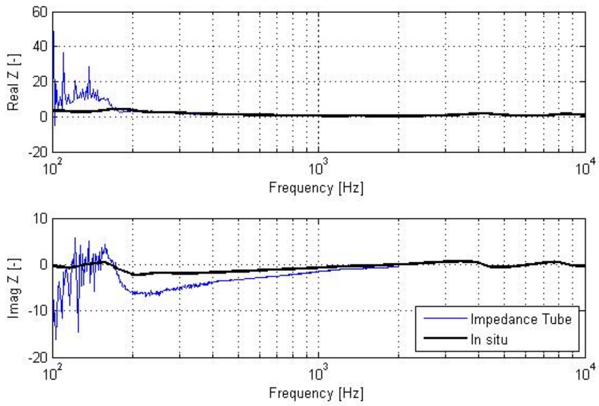

Figure 4. Surface impedance of glass wool (Impedance tube vs. *In situ*).

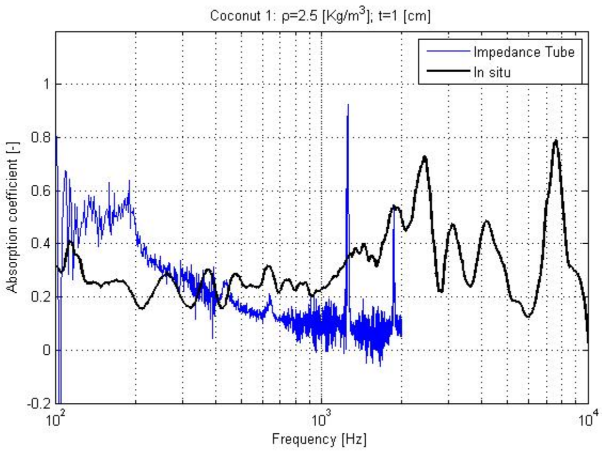

Figure 5. Absorption coefficient of coconut material 1 (Impedance tube vs. *In situ*).

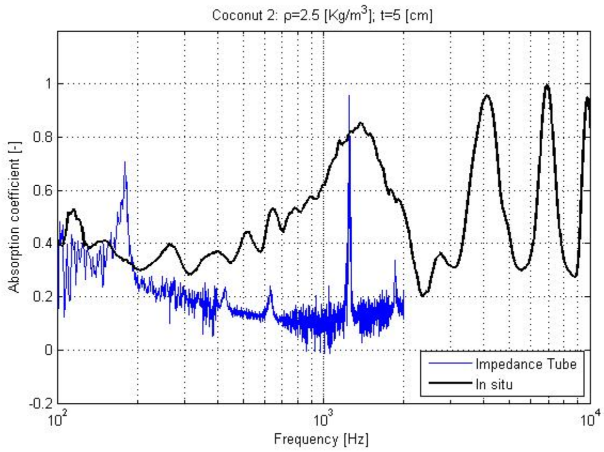

Figure 6. Absorption coefficient of coconut material 3 (Impedance tube vs. *In situ*).

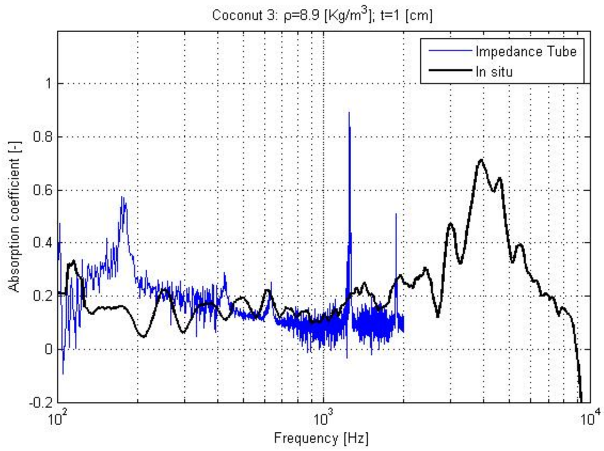

Figure 7. Absorption coefficient of coconut material 2 (Impedance tube vs. *In situ*).

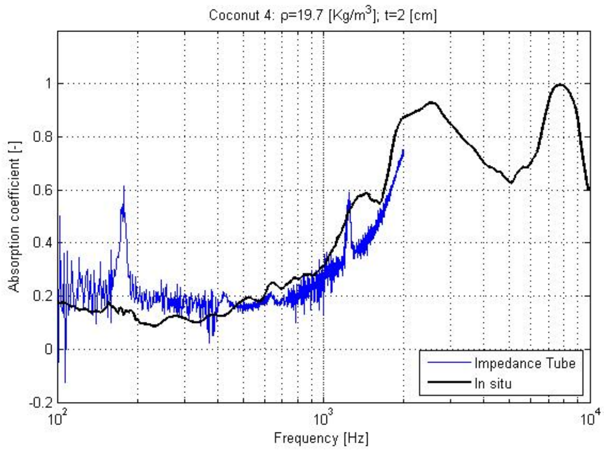

Figure 8. Absorption coefficient of coconut material 4 (Impedance tube vs. *In situ*).

Figure 9 shows all material absorption coefficients measured in the semi-anechoic chamber. The results shown that the coconut materials behave similar to common fibrous material only up to 1.5 kHz. Some samples like Coconut 1, 3 and 4 have an extended behavior up to 2 kHz. For higher frequencies there are strong resonances affecting the response of the coconut material. The absorption is not as high as the commercial glasswool due to these resonances, and because of that the Biot or Delany and Baseley model is not applicable to predict the behavior of coconut absorbent panels. Therefore, more research should be undertaken in order to predict this new type of acoustical material.

In spite of that the coconut materials seems to have a good potential for commercial applications as they have a high absorption characteristics. Materials with bigger density should be preferred as they show higher absorption. This is an advantage from the handling point of view, once materials with lower density seems to loose their fibers more easily. For architectural applications it is necessary to apply covering upon the materials for protection of the sample and aesthetic issues.

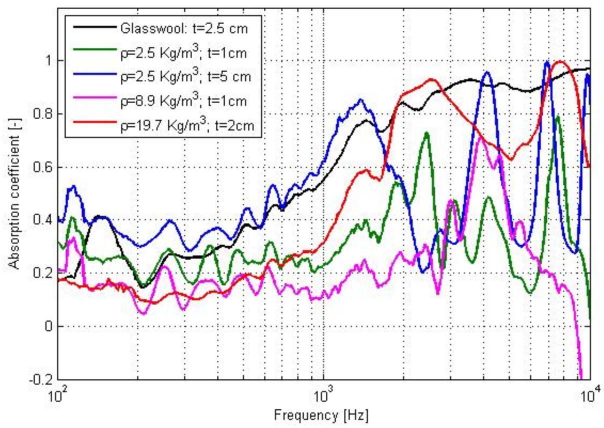

Figure 9. Absorption coefficient of all materials tested with the *in situ* technique.

Finally a comparison of the samples measured with the *in situ* technique is done for the glasswool and coconut 4 measured in the semi-anechoic room and in a regular small room. Figure 10 shows that the measurement took in the regular room is similar to the semi-anechoic room. The similarities are bigger for the glasswool, which has a higher absorption coefficient. The acoustic modes of the room appears as oscillations along the anechoic absorption curve. From past research it is known that less reverberant rooms show to have better agreement with anechoic measurements. Despite these differences the method can be used to measure *in situ* with good confidence. More research is being carried out in order to increase the accuracy of the *in situ* method.

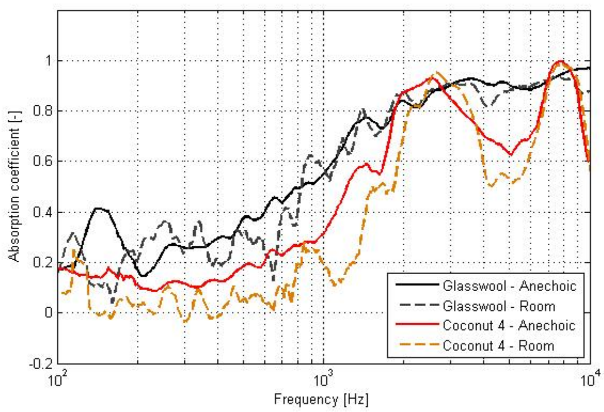

Figure 10. Absorption coefficient of glasswool and coconut 4 measured in the semi anechoic room and in a regular room.

5. CONCLUSIONS

In this study an acoustic material manufactured from coconut fibers was measured and compared with a commercial glasswool material. Measurements were taken in the impedance tube according to ISO 10534 and using a *pu* probe in an *in situ* technique. The measurements showed agreement for the two methods used in the frequency range of the impedance tube. Coconut materials with lower volumetric density showed to have less agreement for the two methods used. Also, coconut based materials seems to behave like a fibrous material up to 2 kHz. On the other hand they have a resonant behavior for higher frequencies. Therefore, in order to predict the acoustical response of coconut materials in higher frequencies a better model should be developed. In spite of these drawbacks coconut based materials offer a good potential for commercial applications. This material is also a green technology and the samples can be developed from recycling of coconut trash which might be a good environmental advantage as long as the chemicals used during the recycling process are not highly aggressive to the environment.

6. ACKNOWLEDGEMENTS

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