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# DEVELOPMENT OF ACOUSTIC MATERIALS USING COIR FIBRE AND NATURAL FIBRE COMPOSITE PANELS

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**RINGKASAN:** *Kertas kerja ini membentangkan pembangunan bahan penyerap bunyi yang baru dari bahan tempatan terutama yang berasaskan serat. Bahan mentah yang digunakan sebagai penyerap adalah serat dari sabut kelapa yang dilapis dengan panel komposit berasaskan serat dari bahan asli. Panel-panel tersebut diperbuat dari serat kelapa sawit (SKS) dan sekam padi (SP) yang diadun dengan poliester tak-tepu (PT) atau matriks polipropilena (PP). Ciri-ciri akustik struktur komposit yang terhasil diperolehi dengan menggunakan tiub galangan berdasarkan kaedah rangkap pindah pada julat frekuensi antara 125Hz hingga 4000Hz. Keputusan umum menunjukkan bahawa struktur panel komposit berasaskan serat sabut kelapa adalah bahan penhadang dan penyerap bunyi yang berpotensi dengan kadar tidak kurang dari nilai 50% serapan bunyi. Peningkatan prestasi serapan bunyi diseluruh julat frekuensi yang diuji diperolehi dengan menggunakan panel SP-PP yang lebih luwes manakala serapan tinggi pada frekuensi rendah diperolehi menggunakan panel yang diperbuat dari 50% nisbah SKS/SP didalam campuran PT. Keputusan dari hasil ujikaji dianalisa berasaskan perubahan nilai dua ciri akustik iaitu, galangan tentu permukaan normal dan lepasan tentu permukaan normal. Hasil dari penyelidikan ini menawarkan bahan pilihan yang baik dari segi kos-prestasi berbanding dengan bahan sedia ada yang mahal untuk mengawal kebisingan. Selain itu, penemuan dari kajian ini juga boleh membantu meningkatkan nilai bahan buangan didalam industri perladangan.*

**ABSTRACT:** This paper presents the development of novel sound absorbing materials based on natural indigenous resources particularly that of fibrous nature. The raw material used as the main absorbing component was coir mat backed by natural fibre composite panels. The panels were made from oil palm frond fibre (OPF) and rice husk (RH) bounded in either unsaturated polyester (UP) or polypropylene (PP) matrix. The acoustical properties of the composite structures were determined in an impedance tube based on the two-microphone transfer function method in the frequency range of 125Hz to 4000Hz. Overall results indicate that the coir mat-composite panel structure is a potential absorbent-barrier with not less than 50% of sound absorption. General improvements were achieved in the absorption properties over the entire frequency range using the more flexible RH-PP panel while superior low frequency absorption was attained using panel made of 50% volume fraction of OPF/RH mixture in UP. The experimental results were analysed based on the variation of two essential acoustical properties i.e. the normal specific surface impedance and normal surface admittance values. The product of this research offers exceptional cost-performance balance to the existing, relatively expensive noise control industry while reducing waste disposal problems in the plantation industry.

**KEYWORDS:** Acoustic materials, sound absorption, natural fibre, acoustic impedance, acoustic admittance.

## INTRODUCTION

Engineering problems related to noise and vibration control are often tackled using four major classes of materials i.e. absorbing materials, barrier materials, vibration damping materials and silencers (Harris, 1991). Their use depends on specific treatment strategies which might involve any or all elements of the noise transmission chain ( Figure 1).

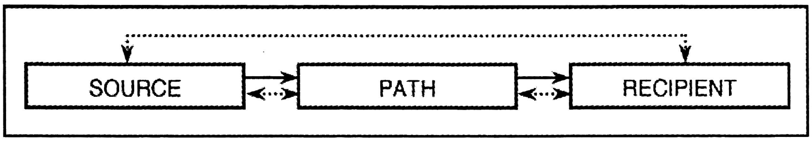


**Figure 1.** *Noise transmission chain(→) and interactions between elements of the sound transmission ( ··→)*

Most sound absorbing materials are naturally porous and allow sufficient sound energy transmission into them to be dissipated. At present, almost any commercially available sound absorptive material utilises mineral or glass fibre as the base material. Rockwool and fibreglass are the common choice of materials used in architectural and industrial noise control applications today. However, these materials do have their limitations too. Some intrinsic features of conventional sound absorbers, especially asbestos, pose risks concerning health and skin irritation (Ballagh, 1996). Furthermore, they are often imported from major exporters abroad at a very high cost. Alternative approaches are being diligently researched to design and develop proxy materials that are specifically aimed at eliminating the health impact caused by the commercial materials but possess equally good sound absorption properties.

The continuous effort to reduce and recycle waste residues predominantly from the plantation related sectors has contributed significantly towards development of various sophisticated agro-based products such as biodegradable plastics (Mohanty *et al.*, 2000), automotive components such as engine covers and composite boards (Brent *et al.*, 1997). Of these, utilisation of naturally occurring materials in acoustical applications has been increasingly explored.

Shoshani and Rosenhouse (1990) used woven fabrics made of cotton and wool as sound absorbing materials. These materials were found to be effective when applied as the covering surface to other noise absorbers such as perforated metal plate or rockwool. Wassilieff (1996) developed a novel sound absorber using loose wood fibres and shavings packed into a sample holder or compressed using PVA as the binder. The main difficulty encountered in developing the compressed panels was related to the production of a low density, homogeneous sample with relatively pervious front surface. Ballagh (1996) proposed wool as a potential substitute for the traditional materials. Woollen materials show increment in transmission loss of stud walls up to 6 dB besides the possibility of achieving high absorption coefficients for control of room reverberation.

In the case of indirect transmission path from the noise source to the recipient, sound absorption materials can be effectively used to attenuate noise and suppress multiple reflections in an enclosed space. The mechanism of sound energy dissipation via frictional energy losses inside a porous absorptive material is understood. One obvious constraint of any efficient sound absorber is its functionality merely as a noise-absorbing component with virtually no restriction posed to the possible transmission of sound through it. Therefore, special acoustic material designated as absorbent-barrier, which consists of thin, semi-rigid panel backing the principal absorptive material component, is sometimes chosen for critical applications. Solid mass added inside the panel functions as a sound block to prevent transmission of sound through the absorbent-barrier. Moreover, the transmitted sound is reflected back to the absorbent to be further dissipated.

The aim of this work was to develop novel sound absorbing materials utilising entirely local agro-based resources. The absorbing material is designed to be a composite structure where prefabricated coir mat is used as the main absorptive component backed by thin composite panels in various compositions of fibres extracted from indigenous, natural resources. Besides varying the fibre volume fraction, $\% v_f$ of the composite panels, two types of binder matrixes were utilised to determine their specific effects on the acoustical properties of the composite absorptive materials. The acoustical properties of the fabricated materials were determined experimentally. The information gained will be particularly useful to establish suitable applications for these novel, inexpensive materials.

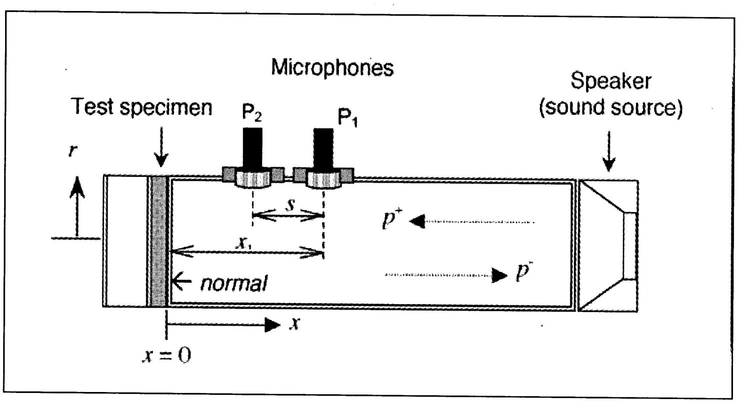


**Figure 2.** *The impedance tube set-up*

Referring to Figure 2 above, harmonic acoustic waves of pure tones are generated by the speaker at the right end. This produces one dimensional acoustic field inside the tube. The generated sound wave will propagate towards the test specimen that is mounted on the left. Upon impinging the surface of the material, some portion of the acoustical energy will be reflected while the rest will be absorbed. This is, of course, assuming that there is nearly no energy being transmitted across the material i.e. structure borne sound radiation. Assuring that the specimen is snugly mounted on the specimen holder fulfills this assumption. The phase interference between the incident and reflected sound wave produces a complex standing wave pattern that can be decomposed. This is achieved by using two microphones to obtain the transfer function of the complex acoustic pressure signals, $H_{12}$ between the two microphones. $H_{12}$ represents the ratio of the Fourier transform of acoustic pressure measured at the microphone nearer to the test specimen (microphone 2), $p_2$, to that measured by the microphone closer to the sound source (microphone 1), $p_1$, at discrete frequencies, i.e.

$$H_{12} = \frac{p_2}{p_1}$$

Reflection is caused by the impedance mismatch between the propagating medium (air) inside the tube and the material surface. Abiding the condition $kr >> 1$, where $k$ is the wave number and $r$, the radius of the tube, the propagating wavefront towards the specimen are considered to be plane i.e. plane wave and consequently, the impedance of concern is the characteristic impedance of air. The amplitude of the reflected wave depends on the acoustic impedance of the material surface. The amount of reflection therefore can be inferred from the determination of acoustic impedance. Thus, the surface of a material can be acoustically characterised in terms of its acoustic impedance. A local reaction model is often regarded for the determination of sound absorption by a plane surface. In this model, it is assumed that the normal component of the particle velocity, $\vec{v}_n$ , at any defined points on the material surface is linearly related to the local sound pressure, p (Fahy, 1984). In other words, the acoustic field at given point of the surface is determined only by the properties of the surface at this point. In retrospect, these properties are summarised and termed as the normal specific acoustic impedance, $Z_n$, which is a function of the incidence frequency as given below (Lefebvre, 1999).

$$Z_n(\omega) = \frac{p(\omega)}{\vec{v}_n(\omega)} \tag{1}$$

Specification of the normal specific acoustic impedance of the facade of a material is deemed necessary to express the interaction between an incident sound wave and the material because this parameter characterises the basic reflection properties of any sound absorbent material.

Figure 2 shows the superposition of incident $(p^+)$ and reflected $(p^-)$ waves in the opposite directions. The resulting pressure, $p(x)$ and normal velocity, $v_n(x)$ along the abscissa can be derived as follows:

$$p(x) = Ae^{-jkx} + A'e^{jkx} \tag{2}$$

$$v_n(x) = \frac{A}{\rho_\circ c} e^{-jkx} - \frac{A'}{\rho_\circ c} e^{jkx} \tag{3}$$

where the amplitudes of the incident and reflected acoustic pressure is denoted by A and A', respectively. $\rho_{o}c$ is the characteristic impedance of air (415 kg $m^{-2}$ $s^{-1}$ at 293K).

By employing Eq.(1), the normal specific acoustic impedance is given by:

$$Z_n(\omega) = \frac{\rho_o c\,(Ae^{-jkx} + A'e^{jkx})}{Ae^{-jkx} - A'e^{jkx}} \tag{4}$$

At $x = 0$, Eq.(4) gives,

$$Z_n(\omega) = \rho_o c\ \frac{(A + A')}{(A - A')} \tag{5}$$

By substituting $R_n$, the normal incidence reflection factor, for $\frac{A'}{A}$ in Eq. (5), one has

$$\frac{Z_n(\omega)}{\rho^{\circ}c} = \frac{1 + R_n(\omega)}{1 + R_n(\omega)} = \zeta(\omega) \tag{6}$$

where $\zeta(\omega)$ is the dimensionless (normalized) normal specific impedance of the material surface. The real and imaginary part of the complex normal specific impedance is called resistance and reactance, respectively. The resistance value is necessarily a positive quantity. A comprehensive elaboration on this point is given by Filippi (1999). Normalisation of the specific impedance implies the physical significance of the values of resistance and reactance. The inverse of $Z_n$ is called the normal specific acoustic admittance ratio, $G_n$, which is a measure of the ease of sound transmission into the material. The real and imaginary part of $G_n$ is known as conductance and susceptance, respectively. Normal acoustic absorption coefficient, $\alpha_n$, is related to the reflection coefficient, $|R_n|^2$ as follows:

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

$R_n$ can be deduced from the measurement of $H_{12}$,[11]

$$R_n = \frac{H_{12} - e^{-jks}}{e^{jks} - H_{12}}\, e^{2jk_o x_1} \tag{8}$$

where $x_1$ is the distance between the specimen surface to the further microphone and $s$ is the microphone separation distance.

## TEST MATERIAL

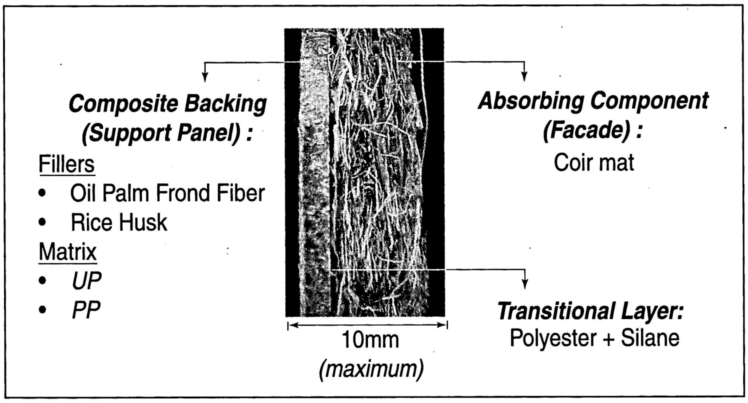


***Figure 3.*** *Design of the composite absorbing structure*

The design of the composite absorbing structure is shown in Figure 3. The overall nominal thickness of the test materials is 10mm. The facade of the material is a factory-produced coir fibre mat (CF mat) made from long coconut fibre and sprayed with latex to keep the fibres intact. This fibrous and fuzzy material will function as the main sound absorbing component. The support panel is a composite material itself that is bonded to the coir mat by a fine transitional layer of polyester and silane mixture. Three different composite systems were fabricated using high $\%V_f$ of crushed oil palm frond fibre (OPF) and rice husk (RH). Unsaturated polyester (UP) and polypropylene (PP) were chosen as the binding agents. Thus, three test materials were developed based on the specifications listed in Table 1 below.

**Table 1.** Composite systems for supporting panel

| Sample | Absorbing component | Support Panel | | $\%V_f$ |
|---|---|---|---|---|
| | | Fibre | Matrix | |
| 1 | CF mat | (OPF + RH) | *UP* | 70 (50 + 50) |
| 2 | CF mat | (OPF + RH) | *UP* | 70 (70 + 30) |
| 3 | CF mat | RH | *PP* | 50 |

## FABRICATION

The composite backing panels were fabricated employing suitable processing techniques for the types of matrix used i.e. thermoset (*UP*) and thermoplastic (*PP*) polymers. Hand lay-up coupled with compression moulding technique was utilised to fabricate the UP based samples. OPF and RH were initially dried at 333 K for 24 hours. Appropriate amount of OPF and RH were then thoroughly mixed and dispersed in *UP*. The cross-linking process of *UP* is initiated using 1% methyl-ethyl-ketone-peroxide. The mixture was discharged and carefully suffused into a cylindrical cavity mould of 3 mm thickness. This preparation was placed on a manual compression moulding unit and compacted at room temperature (302 K) for at least 8 hours. Pressure ranging 30 - 50 MPa was applied according to the $\% v_f$ level. Hot pressing method was used to fabricate the *PP* based sample. RH and *PP* were originally mixed using an extruder at 453 K and compressed by an automatic hot press machine. The processing temperature and pressure was 453 K and 15 MPa, respectively. A mixture of polyester and 1% silane coupling agent was finely applied to the support panel surface to bond the CF mat against it.

## PROCEDURE

The acoustical properties of the test materials i.e. normal incidence absorption coefficient, $\alpha_n$, normal specific surface impedance and admittance ratios were determined in an impedance tube using the two-microphone transfer function method. Transfer function method in accordance to the ISO 10534-2 (1998) standard was used since it is proven to be a rapid and accurate technique which does not need large sample sections as required by the reverberation room method (Fahy, 1984; Chu, 1991). The properties were measured as a function of incident sound frequency at six discrete, octave band centre frequencies ranging from 125 Hz to 4000 Hz. Two impedance tubes, which differ in internal diameter (ID), were fabricated. The maximum measurement frequency for the bigger tube with ID = 90 mm is 1000 Hz while the smaller tube with ID = 25 mm works up to 4000 Hz. The cut-off frequencies were also used as a basis to calculate the appropriate microphone separation distance, $\Delta\delta$ , based on the finite different approximation principles. Sound pressure signals from the two microphones were acquired using 01dB-SYMPHONIE®, a 32bit PC-based digital acquisition unit, and processed by dedicated software namely, dBFA32® to determine the transfer function of the pressure signals with an accuracy of 0.01%. The entire process of signal acquisition and processing was accomplished in real time mode. Transfer function data obtained from the dBFA32® were then transferred to a specially written MATLAB® program to calculate the acoustical properties.

Effect of the support panel rigidity on the sound absorption properties of the CF mat was investigated. Support panel of sample 3 that contains *PP* matrix (thermoplastic) is more flexible than the support panels for sample 1 and sample 2, which are based on *UP* matrix (thermoset). Effect of increment of RH content in samples 1 and 2 on the sound absorption properties was also investigated. Besides this, a reference sample i.e. CF mat of 10mm thickness (without the support panel) was tested for comparison purposes. Noise Reduction Coefficient (*NRC*), that is the arithmetic mean of $\alpha_n$ at 250 Hz, 500 Hz, 1 kHz and 2 kHz, is used as a rating index to evaluate the sound absorption performance of the samples with regard to the reference sample.

## RESULTS AND DISCUSSION

Normal incidence sound absorption coefficient for both sides of the absorptive composite structure was determined individually. Figure 4 and Figure 5 show the absorption coefficient curve as a function of test frequency for the facade (CF mat component) and support panels, respectively. The entire test samples show similar trend as the reference sample i.e. CF mat. However, the values of $\alpha_n$ at the resonance frequency, 2 kHz is slightly greater for sample 1 and sample 2 as summarised in Table 2. Samples 1, 2 and 3 have the same thickness as CF mat and therefore a comparative analysis can be made in terms of the effect of different support panels on the absorption properties of the porous CF mat. The analysis will involve critical comparison of the effect of varying panel rigidity on the sound absorption performance of the CF mat with specific reference to the test frequency and the panels' reflection properties. The basis for argument revolves around two influencing aspects. Firstly, the panels' stiffness properties, which depends on the filler content and type of matrix. Secondly, the normal specific surface impedance and admittance ratios that is pertinent to the absorption mechanism.

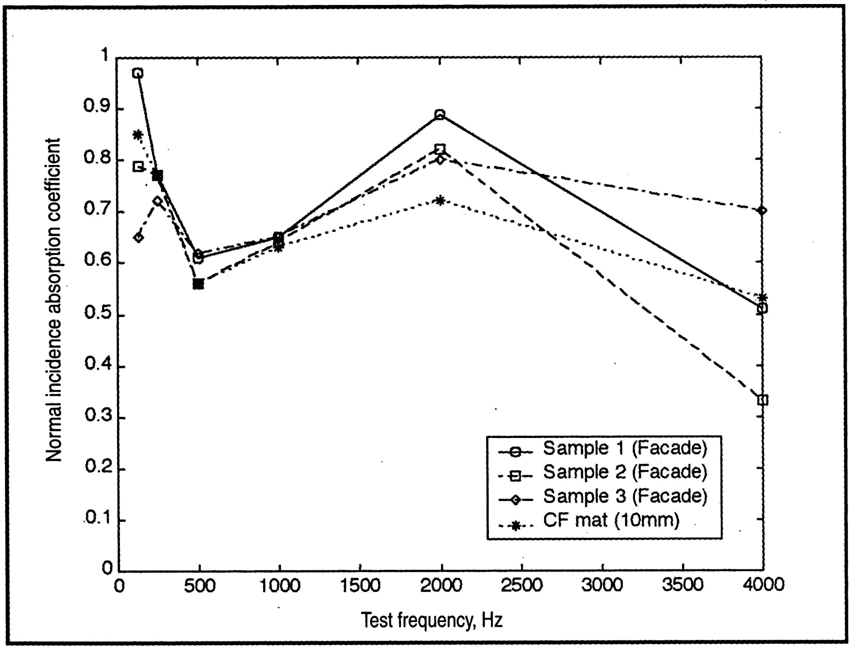


**Figure 4.** *Normal Incidence Sound Absorption Coefficient Plot of the CF Mat Components*

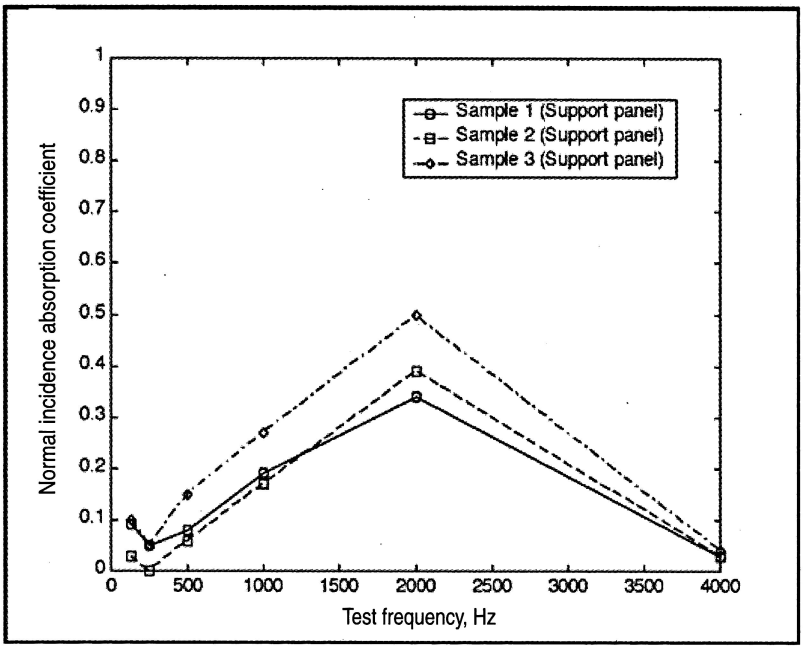


***Figure 5.*** *Normal Incidence Sound Absorption Coefficient Plot of the Support Panels*

**Table 2.** The NRC Values of the Test Samples

| Sample | Thickness, mm | $\alpha_n$ | | | | | | ***NRC*** |
|---|---|---|---|---|---|---|---|---|
| | | **125 Hz** | **250 Hz** | **500 Hz** | **1 kHz** | **2 kHz** | **4 kHz** | |
| 1 | 10 | 0.97 | 0.77 | 0.61 | 0.65 | 0.89 | 0.51 | 0.73 |
| 2 | 10 | 0.79 | 0.77 | 0.56 | 0.64 | 0.82 | 0.33 | 0.70 |
| 3 | 10 | 0.65 | 0.72 | 0.62 | 0.65 | 0.80 | 0.70 | 0.70 |
| CF Mat | 10 | 0.85 | 0.77 | 0.56 | 0.63 | 0.72 | 0.53 | 0.67 |

Table 2 shows that sound absorption, especially at 125 Hz and 2 kHz has improved significantly. Sample 1 is capable of absorbing 97% of incident sound energy at 125 Hz. Panel absorption also plays crucial part in this superior low frequency performance. Although the decrement at 250 Hz and 500 Hz is present, it is improving at higher frequencies as shown in the table. One apparent drawback that persists in both samples is the low absorption at 4 kHz. The overall performance of coir mat can be improved by introducing a semi-rigid backing panel. The improvement is evident from the increment of the *NRC* indicator for sample 1 compared to that of CF mat alone.

It can be observed from Figure 6 that the variation of the real part of the normalised specific impedance ratio i.e. resistance curve exhibits a trend that is somewhat inverse to that of the absorption coefficient shown in Figure 1. This proves that higher surface resistance is detrimental to the acoustic absorption characteristics. The positive values of resistance imply that there is a flow of energy flux through the boundary element of the specimen. In contrast, the absorption curve pattern is resembled by the conductance curve as seen in Figure 8. Drop of $\alpha_n$ at 4 kHz is related to the sudden increment in the resistance value, which is also evident from the drastic decrement in the conductance value. On the contrary, higher conductance value at 2 kHz yields good sound absorption with slight resistance posed to the impinging sound energy.

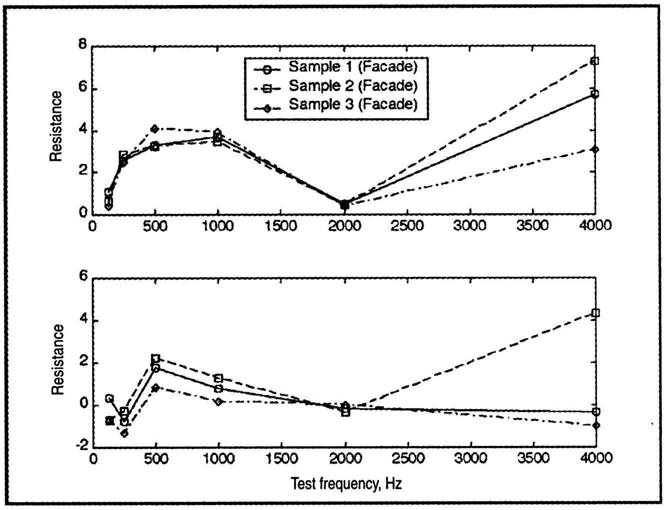


***Figure 6.*** *Normalised Specific Acoustic Impedance* $(Z/\rho_o c)$ *Plot of the CF Mat Components*

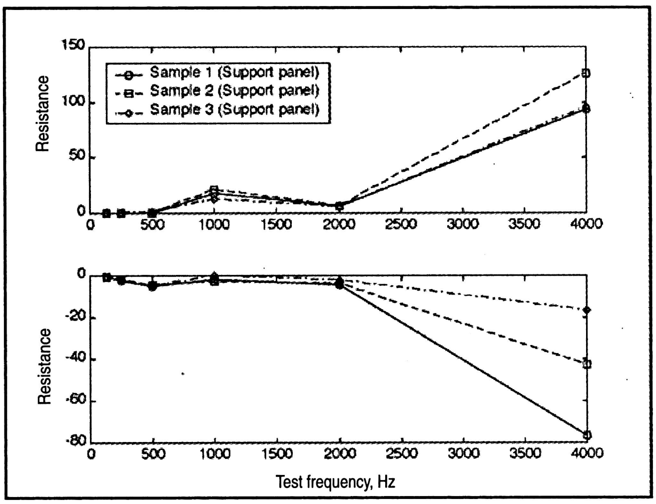


***Figure 7.*** *Normalised Specific Acoustic Impedance* $(Z/\rho_o c)$ *Plot of the Support Panels*

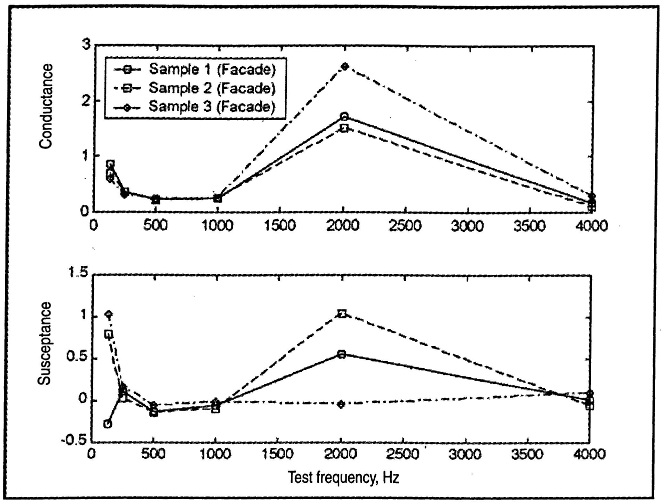


***Figure 8.*** *Normalised Specific Acoustic Admittance ($G\rho_o c$) Plot of the CF Mat Components*

The support panel of sample 1, on the other hand, is relatively a reflective material compared to its absorbing component. This is because the CF mat component is a porous material that allows the transmission of incidence sound energy more readily to be dissipated while the hard, solid surface of the support panel hinders sound transmission through it. High reflections occur at 250 Hz and 4 kHz. The reflecting trait of the support panels is generally signified by their symmetrical normalised specific impedance curve as shown in Figure 7. Referring to Eq. (6), as the reflection factor increases, the normal specific impedance will also increase. This is experimentally proven in this case. The values of the resistance of the support panel are much higher than for the facade material and the reactance values are all greater in magnitude. These were the reasons for the low absorption coefficient values of the support panels which is consistent with the theoretical relationship provided by Eq. (7). Lower conductance, on the other hand, characterises the physical front surface of the support panel, which is relatively hard and closed. Hence, sound energy transmission into the material is rather restricted causing the absorption mechanism to be insignificant or stalled. The variation of the conductance values explains the increment of sound absorption at 2 kHz and its drop at 4 kHz.

The overall trend of sound absorption for sample 2 is similar to sample 1 but in a smaller magnitude. At 125 Hz, only 79% of the incident energy are absorbed. This is equivalent to a reduction of about 20%. The reduction vaguely indicates the lack of the backing panel's function to provide sufficient flexibility to absorb low frequency sound. Greater amount of fine RH inclusion compared to OPF i.e. 70 %$v_f$ makes the panel more rigid, as observed in another experiment (Rowell *et al.*, 1997). At 250 Hz, 500 Hz and 1 kHz, this sample performs almost competitively with the reference sample, CF mat. But the value of $\alpha_n$ is lower at 4 kHz compared to sample 1 and CF mat alone.

The absorption trend of the support panel of sample 2 is similar to that of sample 1 but generally in a lower scale. The values of absorption coefficient at 125 Hz - 1 kHz range is almost inferior to the values of sample 1-support panel. Hence, sample 2-support panel is a better reflector in this frequency range. Nevertheless, the value of absorption coefficient at 2 kHz is higher. Zero absorption registered at 250 Hz cannot be entirely attributed to the panel's acoustical response but could also be due to other factors including execution of the test method or deficiency related to the impedance tube apparatus. This problem will be treated separately in another paper.

The maximum absorption of sample 3 occurs at 2 kHz but its value is slightly lower than sample 2. Sample 3 exhibits an apparent shift in low frequency absorption compared to sample 1 and sample 2, i.e. from 125 Hz to 250 Hz. Performance trend from 250 Hz onwards is akin to that of sample 1 and sample 2. The uniqueness of sample 3 is its high absorption of 72% at 4 kHz. Increased flexibility of the structure supported by a supple backing panel causes this augmentation of high frequency absorption.

Sample 3 is comparable to sample 1 in terms of RH content. Since the matrix is a flexible *PP*, the support panel of sample 3 is generally more absorptive than its counterpart in sample 1 and sample 2 at all frequencies. Increment of sound absorption at 250 Hz, 500 Hz and 1 kHz is observed for the sample 3-support panel. This is particularly useful to improve the high frequency absorption of the CF mat.

## CONCLUSION

The novel acoustic materials that were developed in this research provide a convenient solution as absorbent barrier wherein one side of the material absorbs sound finely while the other reflects sound energy. Requirements pertaining to specific application and critical regions that have to be masked from intrusion of noise determines which part of the composite acoustic absorber to be exposed to the noise source. Functional optimisation of the composite absorptive material is possible. Rigidity of the support panel can be altered by varying the %$v_f$ or the type of polymer matrix used to enhance the sound absorption performance of CF mat at higher frequencies. Support panel made from *PP* is more flexible and reflect 50% of incident sound energy while panels based on *UP* is rigid and reflect more than 60%. The flexibility of thin composite panels can be utilised to design a sound absorbing system that yields efficient mid and high frequency absorption. It is anticipated that the utilisation of abundant agricultural residues would reduce, to some extent, waste disposal problems faced by the plantation or its related sector. Exploitation of agricultural wastes on a large scale will most likely create new wealth generating and economical ventures in the rural plantation areas.

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