Sustainable Acoustic Absorbers from the Biomass

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Abstract

The suitability of biomass materials as novel and sustainable sound absorbent treatments has been investigated. Current models for the characterization of porous absorbers have been used to identify candidate materials and impedance tube measurements are carried out for a number of these materials and the results are presented. Examination of the acoustical characteristics of natural fibres has confirmed their effectiveness as porous sound absorbers with properties similar to those of conventional absorbers made from rock wool or fiberglass. Examination of the acoustical performance of different configurations of whole reeds has revealed that these also possess considerable potential for application as sound absorbers with particularly good low frequency absorption characteristics. The combination of fibrous materials and whole reeds offer the possibility of developing a range of very effective absorbers which act across the complete audio frequency range.

Introduction

Acoustic absorbers are widely used in noise control to reduce sound reflected from surfaces. This paper describes work carried out as part of the EU sponsored Hoilwood project to identify a sustainable absorptive treatment to complement the sustainable structural components of a proposed noise barrier system made from thermally treated European hardwood. Two potential sources of sustainable absorbers were identified: materials from the biomass and recycled materials. In this paper the properties and potential of the latter are examined. The term biomass refers to living and recently dead biological material. Biomass materials are inherently sustainable as they constitute part of the normal carbon and nitrogen cycles. Thus, provided only renewable energy is employed during processing, they are virtually carbon neutral. Similarly, if the use of highly toxic chemicals for protection against deterioration due to biological attack from fungi or insects is avoided then they can be disposed of after use by returning to the natural cycles by simple composting.

A number approaches are commonly used to obtain a sound absorbing finish. The first is by the use porous material. This frequently consists of glass fibre or mineral wool in which some form of binding agent is used to hold the fibres together and to maintain dimensional stability. A second approach to ensuring structural integrity and dimensional stability is to produce rigid panels constructed with open textured porous materials. The frequencies at which the absorption is a maximum for porous absorbers are typically high, with the materials only being effective for frequencies above 1kHz.

In investigating the potential of biomass materials as sound absorbers, the first step was to identify the characteristics of conventional absorbers from an examination of earlier work. From this study two possible forms of absorber were identified: materials with a highly homogeneous pore structure, typified by fibrous materials, and those with a more heterogeneous pore structure, typically granular materials.

There are a number of potential homogeneous candidate materials available from the biomass in the form of organic fibres, either vegetable or animal in origin, which constitute obvious candidates for the direct replacement of the glass and mineral wool fibres used for conventional sound absorbers. Many of these have a long history of use in fabrics (cotton, wool, flax, silk), as floor coverings (wool, reeds), sacking (jute, hessian) and ropes (hemp) [1]. A selection of these materials will be examined in this paper.

Biomass derived heterogeneous materials are currently available as commercial products manufactured from cementitious materials with a granular structure. In addition, recent work has been carried out on the development of heterogeneous absorbers in the form of crumb rubber particles and clay particles. In this work we investigate the acoustical properties of layers of un-shredded straw or reeds in which the pore distribution characteristics occurring are highly heterogeneous. The pores arise from spaces between the individual stems and the non uniformity of the cross sections of individual lengths. This results in a large number of slit like pores, parallel to the straw or reed lengths, which communicate with large cavities between the individual straws or reeds.

Biomass Options for Sustainable Noise Absorbers

Natural fibres can be obtained from plants or animals. Plant fibres are extracted from the leaf, the inner bark or fruit/seed crop whilst animal fibres are obtained in the form of wool, hair or the material of insect cocoons. Plant sources of fibre include cotton, hemp, kenaf, ramie, sisal, flax, linen, lime, jute, seagrass, bamboo and abaca. Animal sources of fibre include sheep, alpaca, llama, goat, and camel, and can be either wool or hair. Insect fibre is predominantly from silkworm cocoons.

Plant fibres are long, stretched, thick-walled cells whose composition is principally cellulose. The cellulose molecules consist of glucose units linked together in long chains, which in turn are linked together in bundles called microfibrils, glued together with pectin. Hemicelluloses and lignin are also found in all plant fibres. Hemicelluloses are polysaccharides bonded together in relatively short, branching chains. They are intimately associated with the cellulose microfibrils, embedding the cellulose in a matrix. Lignin is the compound which gives rigidity to a plant. Without lignin, plants could not attain great heights or the rigidity found in some crops such as straw. The fibres may be chemically modified, for example, viscose or cellophane.

In general, natural fibres can be grouped into two categories: soft fibres and hard fibres. Most soft fibres come from the bast portion of the plant which lies directly under the outer bark or skin and is where the transport of the products of photosynthesis and the development of stabilizing structures take place. The fibres are usually freed from the stalk by a process termed retting. The released fibre bundles are frequently used without additional separation, however, flax and ramie strands, are usually separated into individual fibre cells, or true plant fibres. Hemp, Flax, Jute and Ramie are soft fibres.

Hard fibres are comprised not only of the bast but also partly of the hardened wood core of the plant and the hardness of the fibres is caused by the deposit of lignin in the cell walls. Hard fibres generally come from the leaves of monocot (single seed-leaf) species, for example Sisal agave, fibre banana and diverse palms.

There is a great variation in fibre dimensions and the various types of raw material are separated using processes to generate fibres suitable for specific end products, e.g., bast or stem fibres are mainly used in the textile or rope industries because both require long fibre.

There are a number potential homogeneous candidate materials in the form of organic fibres, either vegetable or animal in origin. Many of these have a long history of use in fabrics (cotton, wool, flax, silk), as floor coverings (wool, reeds), sacking (jute, hessian) and ropes (hemp) [1].

Commercial products with a granular structure manufactured from biomass materials in the form of various board products consisting of shredded and compressed wood, straw, reed or cork particles are already available. Wassilieff [2] has shown how the performance of wood based materials can be predicted from application of the Attenborough [3] model.

The pore distribution characteristics occurring in layers of un-shredded straw or reeds are highly heterogeneous. In the case of straw and reeds, the pores arise from the non uniformity of the cross sections of individual lengths. This results in a large number of slit like pores, parallel to the straw or reed lengths, which communicate with large cavities between the individual straws or reeds. In this paper we describe an investigation of the acoustical performance of a number of different orientations of reeds and relate these to an established model for the prediction of the acoustical properties of materials with a heterogeneous pore structure.

From examination of Table 1 it can be seen that the basic plant fibres divide into two sub groups depending upon the mean fibre radius. Hemp, sisal and jute are relatively coarse with fibre diameters approaching 100 µm with a value in excess of 200 for the jute µm. The cotton, flax and ramie have fibre diameters in the range 13-25 µm. It is the finer nature of these fibres that has resulted in their use for clothing. The density of the matrix material, however, only varies slightly which reflects the fact that they are all largely composed of cellulose. The bulk density varies between the samples and, given the relatively slight variation in the density of the matrix material, reflects the degree of compaction to which the samples have been subjected. Thus, the hemp matts, a product manufactured as animal bedding, were bound using latex which was clearly visible on micrographs. The binding process appears to have been performed under greater pressure to give a material with a relatively high bulk density. In contrast the bulk density of the sisal was low as it was hand compacted and, given the coarseness and stiffness of the fibres, only a relatively limited degree of compaction could be achieved.

Flax is a bast fibre with a long history of use for clothing due to its relatively small diameter when compared with hemp and jute.. The flax fibre was supplied in the form of 'Roves' of carded fibre (as prepared for spinning). These were pulled apart into short lengths and packed into the sample holder.

The boll or seed pod of the cotton plant contains the white cotton fibres. Once the seed pod has opened the raw cotton fibres dry out and can be harvested and made into textile fabrics and other cotton containing products. The raw cotton tested was unprocessed raw American cotton and this was again packed into the sample holder. It can be seen from Table 1 that it has the smallest diameter of all the unprocessed plant fibres examined.

PARAMETERS DETERMINING THE PERFORMANCE OF SOUND ABSORBENT MATERIALS

The intensity of plane wave reflected from an absorbent surface is smaller than that of the incident wave by a factor of $|R|^2$ where R is the sound pressure reflection coefficient. The absorption coefficient, α, is thus given by:

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

The reflection coefficient is given by:

$$R = \frac{z_s - \rho_0 c}{z_s + \rho_0 c} \tag{2}$$

Where zs is the surface impedance of the surface and p0c is the characteristic impedance of the propagating medium.

In the case of a single layer of porous absorber of depth *d* with a rigid backing the surface impedance z_s is given by:

$$z_s = -jz_c \cot(k_c d) \tag{3}$$

Where the z_c is the characteristic impedance and k_c is the complex wave number of the absorptive material.

Thus it is the complex impedance and complex wave number that determine the absorptive characteristics of a material.

Conventional porous sound absorbers come in a variety of forms and their performance depends upon their pore structure. The most common form of porous sound absorbers are highly porous and homogeneous in structure and consist of fibrous materials and open cell foams. Various models have been devised for determining the complex impedance and complex wave number for these materials based upon just one parameter, flow resistivity, σ,. This is determined by the pore size and porosity, which in turn are dependent on the size and shape of the fibre.

Fibrous materials constitute a large proportion of porous sound absorbers in common use and a number of empirical models have been developed which build upon the work of Delany and Bazely, presented in Equations 4 and 5 and employ the single non-acoustical parameter of flow resistivity. Delany and Bazley obtained simple power-law relations obtained by best-fitting a large amount of experimental data to a range of fibrous porous absorbers. They also provided a graph for estimating the airflow resistivity of a fibrous material from its bulk density. Although a good empirical match was achieved, these relationships are only applicable over a well defined frequency range and where the porosity, ε, is close to 1.

The relationships found by Delany and Bazley [4]are presented below.

$$z_c = \rho_o c\left(1 + 0.0571\left(\frac{\rho_o f}{\sigma}\right)^{-0.754} - j0.087\left(\frac{\rho_o f}{\sigma}\right)^{-0.732} \right) \tag{4}$$

$$k_c = \omega / c \left(1 + 0.0978\left(\frac{\rho_o f}{\sigma}\right)^{-0.7} - j0.189\left(\frac{\rho_o f}{\sigma}\right)^{-0.595} \right) \tag{5}$$

Where ρ o is the density of air, σ is the flow resistivity and f is the frequency.

The Delany-Bazely relationships were obtained from measurements on a range of glass and mineral fibre materials for which the fibre diameters were typically 1-10 µm. Garai and Pompoli [5] suggested that the Delany-Bazely model was unsuitable for predicting the acoustical characteristics of polymer fibres for which the diameters ranged from 18 to 48 µm. They carried out a similar set of tests on polymer fibres to those of Delany and Bazely to obtain the following expressions:

$$z_c = \rho_o c\left(1 + 0.078\left(\frac{\rho_o f}{\sigma}\right)^{-0.623} - j0.074\left(\frac{\rho_o f}{\sigma}\right)^{-0.660} \right) \tag{6}$$

$$k_c = \omega / c \left(1 + 0.121\left(\frac{\rho_o f}{\sigma}\right)^{-0.53} - j0.159\left(\frac{\rho_o f}{\sigma}\right)^{-0.571} \right) \tag{7}$$

The flow resistivity is a property of the fibre diameter and porosity of the material and several empirical relationships have been developed for the calculation of flow resistivity.

Examples of relationships for sound incident perpendicular to the direction of the fibres, as reported by Mechel [6] are as follows:

$$\sigma = \frac{10.56\eta(1-\varepsilon)^{1.531}}{a^2\varepsilon^3} \tag{8}$$

and

$$\sigma = \frac{6.8\eta(1-\varepsilon)^{1.296}}{a^2\varepsilon^3} \tag{9}$$

Where η is the viscosity of air (equal to 1.84 x 10-5 poiseuille), *a* is the radius of the fibres and ε is the porosity which is the volume fraction occupied by pores in the material. Equation 8 relates to fibre radii ranging from 6 to 10 µm and Equation 10 to fibre radii from 20 to 30 µm.

For a material having only a small amount of binder and assuming the presence of no closed cells, the porosity, ε, is given by:

$$\varepsilon = 1 - \rho B/\rho m \tag{10}$$

Bies and Hansen [7] have presented the following expression which relates the flow resistivity to the bulk density, ρ, of the porous absorber for fibre glass and mineral fibres:

$$\sigma = \frac{3.18\times 10^{-9}}{4a^2\rho^{-1.53}} \tag{11}$$

The above expression was obtained from measurements on fibre glass and mineral fibre for which the fibre diameter is very small. Garai and Pompoli [8] made measurements of the flow resistivity of a number of polymer fibres for which the fibre diameter varied between18 to 48 µm with a mean value of 33 µm. They obtained the following expression for flow resistivity:

$$\sigma = \frac{28.3\times 10^{-9}}{4a^2\rho^{-1.404}} \tag{12}$$

From examination of Table 1 it can be seen that the range of diameters typical of many natural fibres is similar to that of the polymers. In addition, the density of the matrix material of natural fibres is generally in the range 1,300-1,500 kgm-3 which is closer to that of polymers, typically approximately 1000 kgm-3, than to that of glass or minerals which are both typically approximately 2,600 kgm-3. Thus, given the similarity of the densities of the matrix materials and the typical fibre diameters, the expression produced by Garai and Pompoli might be more applicable to the natural fibres than those reported by Mechel.

Additional parameters are necessary for accurate calculations of the characteristic impedance and wave number of porous materials with structures which are more complex than those discussed above. They are generally developed from considerations of viscous and thermal effects on the sound propagation in circular pores and between parallel plates. Models for these materials thus require more detail to account for the interaction between the sound waves and the pores of the material. Predictive models for materials in this category may require up to four of the following parameters: flow resistivity, porosity, tortuosity, pore shape factor and the standard deviation of the pore size distribution.

The tortuosity, T_s, takes into account the orientation of the pores relative to the incident sound wave which also has a effect on the sound propagation in the pores. This parameter cannot be calculated accurately and in practice T_s is measured.

The pore shape factor, s_f, takes into account the dependence of the propagation of sound in the pore on the shape of the pore, as it affects the viscous and thermal interaction effects. For simple pore shapes s_f can be determined analytically. However for most absorbers the pore shapes are complicated and s_f has to be measured, usually by best-fitting the acoustic measurements of the effective density and bulk modulus of the material.

The microstructural approach, as employed Zwikker and Kosten [9] , involves deriving the wave propagation inside individual pores from first principles and then generalising the results to the macroscopic scale. The viscous and thermal effects are separately leading to the concepts of complex density, ρb, and complex compressibility, Cb, from which the characteristic impedance and complex wave number can be calculated as follows:

$$z_c = \left[\frac{\rho_b(\omega)}{C_b(\omega)}\right]^{\frac{1}{2}} \tag{6}$$

$$k_c = i\omega\left[\rho_b(\omega)C_b(\omega)\right]^{\frac{1}{2}} \tag{7}$$

Biot[10, 11] and Smith et al[12] introduced a dynamic shape factor to allow for a pore shape with a range of cross sections. For application to bulk media, Dupuit relationships [13] were applied using a modification which included the effect of tortuosity. Other models have been developed by Attenborough[3], Stinson[14], and Allard and Champoux[15] which all use flow resistivity, porosity, tortuosity and the shape factor to predict the performance of a porous absorber.

The structure of highly heterogeneous materials is characterised by a wide variation in the pore size distribution which tends to have more effect on their performance than the shape and tortuosity of the pores. Thus the characterisation of materials with a highly heterogeneous pore structure requires the incorporation of a parameter to account for the pore size distribution in the material structure. A model to describe heterogeneous material structures has been presented by Horoshenkov, Attenborough and Chandler-Wilde [16].

The Measurement Systems

Acoustic measurements of an absorber material can be carried out in a laboratory using the impedance tube or reverberation chamber methods.

With the impedance tube measurements are based on the two-microphone transfer-function method according to ISO 10534–2 [17] and ASTM E1050–98 [18] international standards. It is possible to obtain fast and accurate measurements of normal incidence parameters using small samples that are easy to assemble/disassemble.

The reverberation chamber method is the basis of EN 20354 [19] and measures the absorption properties of a material sound waves at random incidence. The method is based on measuring the reverberation time in a room before and after the introduction of the test samples. The absorption of the sample material is found by comparing the reverberation time measurements, taken without the sample in the room, to the reverberation time measurements taken with the sample in the room.

The impedance tube method has a number of advantages over the reverberation chamber method. First, the apparatus itself is much smaller and therefore more practical. Secondly, only a small sized sample is required for the tests, and thirdly it allows the surface impedance to be determined in addition to the absorption coefficient. The disadvantages are first, that the properties are only measured for sound at normal incidence to the sample although it is possible to apply a correction to obtain an approximate value of the random incidence absorption coefficient. Secondly, uncertainties are introduced when measuring heterogeneous materials as the constitution and pore structure of samples taken from a larger area may vary considerably. Thirdly, two different material samples are required for measurements over a large frequency range.

In the reverberation chamber method sound arrives at the material from arbitrary angles and hence the measured absorption properties are more representative of the performance of the material under real conditions. However, the method requires large samples of the material under investigation as it is not possible to get accurate data from small samples. The edges of the sample constitute a possible source of error when it comes to using the reverberation chamber method. During the process of getting the measurements, some of the sound is diffracted from the edges of sample which leads to excess absorption predictions. To reduce this problem, the usual practice is to cover the material edges or use rectangular shaped materials.

The impedance tube was employed in this work for measurements on homogeneous materials. The measurements presented in this paper were made on 50mm thick samples of materials using the Brüel & Kjær Impedance Tube Kit Type 4206. Tube measurements were based on the two-microphone transfer-function method described in ISO 10534-2 [20].

The reverberation chamber was employed to measure the absorption properties of heterogeneous materials. The reverberation chamber at the Acoustics Research Unit at the University of Liverpool measures 5m x 5m x 4.8m and thus has a volume of 120m3. EN 20354 [19] specifies a minimum volume of 150 m3 and therefore the Liverpool facility does not satisfy this requirement. However, in practice it is sufficiently close to the recommended value that measurements will be accurate apart from at the very lowest frequencies.

Measurement Results

Fibrous Materials

Table 1 contains a summary of the sample materials examined. It can be seen that the plant based materials have very similar densities as they consist of the same basic principal components, cellulose, hemi-cellulose and lignin. Variations in the densities are due to different proportions of these components as their densities vary with values of 1397 and 1559 and 1520 kg/m3 being reported for lignin, hemicellulose and cellulose respectively [21] . Thus, the lower values of density for hemp and sisal result from a greater proportion of lignin than in other fibres.

The bulk density of the samples for the large tube was measured and the small tube samples were made to the same bulk density. Micrographs of the fibres were made and the mean fibre diameter was measured from the micrographs (only a small sample size, typically three or four fibres). Samples of the lighter coloured materials were dyed prior to preparing micrographs to aid visibility. The density of the matrix material was obtained from published literature allowing the porosity of the samples to be calculated. The results of these measurements are summarised in Table 1.

Measurements were made of all samples using the impedance tube method. The samples were hand compacted in the tube sample holder to give a sample thickness of 50mm. After the measurements dad been performed the weight of the test sample was measured and use with Equation 4 to obtain an estimate of the porosity of the sample. Micrographs were taken of each sample and used with a calibration graticule to obtain information regarding the fibre diameters.

Basic Plant Fibres

From examination of Equations 8, 9, 11 and 12 it is apparent that the factors that determine the absorption characteristics of fibrous absorbers are the fibre diameters and the porosity. The latter is a function of the degree to which the material is consolidated or compacted. In this work a variety of natural fibres were obtained and a systematic investigation of their absorptive properties was carried out.

Figure 1 shows the measured absorption coefficient as a function of frequency for cotton, soya, wool and sisal, each having a thickness of 50mm.

It can be seen that the cotton and soya fibres have absorption properties which are similar to those of rock wool or fibre glass of the same thickness but that the wool and sisal fibres are much less effective. This is probably due to the nature of the fibres of each material. The cotton and soya fibres are both very fine with average diameters of 14 and 12 microns respectively and are easily compressed. The wool and sisal fibres are coarser with average diameters of 37 and 213 microns respectively. The wool fibres also have a natural “springiness” which makes compression of the materials much more difficult resulting in greater porosity.

Also shown on Figure 1 are the predicted absorption characteristics for these materials. Equations 9 and 12 were employed to calculate the flow resistivity and equations 4-7 were used to calculate the absorption characteristics.

It can be seen that all models predict values of absorption coefficient that are considerably less than that measured for the sisal. The agreement is better for the wool sample and is particularly good when the Garai and Pompoli expressions are used to calculate both the flow resistivity and the absorption characteristics. It should be noted that mean fibre diameter and density of the matrix material of the wool is very close to that of the polymers investigated by Garai and Pompoli. Although the predicted absorption characteristics for the soya and cotton samples tend to follow the general trends of the measured data, the agreement is not good.

It can be concluded that existing prediction models have limited applicability when dealing with most natural fibres. This is probably due to the diameters of these fibres differing considerably from those on which the predictive models have been developed.

Natural fibres can undergo a number of processes such as carding in which the raw fibres are aligned by a combing process and fibres with large diameters removed. Figure 2 shows the measured data for both raw and carded jute fibres. The raw material had a slightly greater mean fibre diameter and higher bulk density which reflects the greater difficulty in compacting the more ordered bundles of fibres arising from the carding process. It can be seen that effect of carding is to reduce slightly the absorption coefficient at most frequencies. Also shown on Figure 2 are the predicted characteristics using the Delany-Bazely and Garai-Pompoli models and it can be seen that both models tend to under predict the absorption coefficient.

The only animal fibre tested was wool. There is considerable interest in developing new applications for wool as developments in synthetic fibres have adversely affected its original market as a fibre for clothing to the extent that wool is now a by-product of the farming of sheep for food.

Wool is composed of more than 20 amino acids, which form long chains, or polymers, of protein. It also contains small amounts of fat, calcium and sodium. The coiled springs of wool's molecular chains contribute to the fibre's resilience. As it grows from the sheep's skin, wool naturally groups into staples which each contain many thousands of fibres.

Wool was available in two forms: firstly as unprocessed sheep wool, breed of sheep unknown and also in the form of a wool batt marketed as a thermal insulation batt and also as an acoustic absorber for use in stud walls. The measured diameters of the sample fibres were larger than those normally used for clothing where diameters less than 25 µm are preferred. The matrix density is comparable to that of the soy silk which reflects the protein based composition. The bulk density is low which reflects the difficulty experienced in hand compacting due to the springy nature of this fibre.

Figure 3 shows the measured absorption characteristics of the raw wool and the wool batts and the predictions of the different models. Again, it can be seen that both models tend to under predict the absorption coefficient.

Hemp is a coarse bast fibre with very long fibre lengths hence its use in ropes and twine. The fibre was supplied as ‘strick’ which consists of long bundles of fibres. These were cut into shorter lengths and packed into the sample holders. The fibres often appear to be quite flat so the quoted dimensions are more likely to be reflect maximum widths rather than true diameters.

Hemp was available in the form of hemp mats and hemp batts. The hemp batts were 85% hemp fibres bound into a ‘batt’ with a 15% polyester binder. The polyester appears to be in the form of fibres mixed in with the hemp then heated to fuse the batt together. The polyester fibres were ignored for the purposes of estimating the fibre size although they could be seen on the micrograph.

Figure 4 shows the measured absorption characteristics for the hemp samples. It can be seen that the performance for the densely compacted mats is poor even at the high frequencies whilst the relatively less compacted batt shows characteristics typical of conventional mineral wool batts.

Fibres from processed plant material.

It is possible to process the basic material of the plants to produce synthetic fibres. Three sample materials were available for testing: bamboo fibre, Tencel and soya silk

Bamboo fibre is a textile fibre fabricated from natural bamboo **a**nd other additives and is made from the pulp of bamboo plants. It is not made from the fibres of the plant, but is a synthetic viscose made from bamboo cellulose.

Tencel is a trade name for a variant of Lyocel which is manufactured by dissolving and extruding cellulose extracted from wood. Fibres appear to be very uniform and were supplied in the form of a ‘rove’. Tencel is a cellulose fiber made from wood pulp from trees it is produced via a special "solvent-spinning" process using a non-toxic solvent.

Soy Silk is fibre made from tofu manufacturing waste. Soy protein is liquefied and then extruded into long, continuous fibers that are then cut and processed like any other spinning fibre.

Soya fibres are relatively new fibre made from extruded soya protein by an industrial process. The fibres are claimed to be naturally resistant to biological attack. Developed (as a protein fibre) to have similar properties to silk.

From examination of Table 1 it can be seen that the matrix density of Tencel is similar to that of the basic plant fibres discussed above which again reflects the fact that the basic component is cellulose. However, the matrix density of the soy silk is similar and this is surprising as the basic components are proteins.

Figure 5 shows the measured absorption characteristics of the processed fibres and the predictions of the various models.

Heterogeneous Materials

There are already examples of biomass materials employed in the manufacture of sound absorbent materials. They may be used in shredded form either bound together by means of a process which releases natural sugars that then act as a glue or, for more durable solution, bound together with small amount of cement. Alternatively the biomass material can be reduced to its basic fibres which are then compressed and bound together in the form of a board product. Wassilieff [2] has presented the results of a detailed study of such materials and demonstrated how their properties may be predicted using Attenborough’s model hence they will not be considered in this paper. However, an alternative will be examined consisting of aligned lengths of whole reed or straw stems.

Two basic configurations were examined, the first was end on configuration in which the cut ends of the material are perpendicular to the incident sound, as shown in Figure 6a. The second was the transverse configuration in which the reed stems are perpendicular to the incident sound as shown in Figure 6b. Because of the irregular nature of the reed cylinder there are slit like gaps between reeds as can be seen in Figure 6b and these will link through to the large voids between reeds that are visible in Figure 6a.

The “end-on” structure consists of blind (i.e. with a closed end) tubes with large prismatic voids between them. The tubes are hollow with a small internal diameter and it is to be expected that there will be dissipative losses as sound propagates in these tubes. The tubes also contain pith which might be expected to contribute to the sound absorption. Because of the lined tube structure, reeds arranged in this orientation do not conform well to the heterogeneous model and might be expected to act more like a homogeneous material. However, as the holes in the reed are blind and although they might be expected to make a significant contribution to the sound absorption, it is not clear how they might affect the effective bulk flow resistivity.

Figure 7 shows the measured absorption coefficient of 50mm long bundles of straw and reed as a function of frequency for the “end on” configuration. The absorption characteristics of the reeds and the straw are similar but the reeds are slightly more effective. For both materials well defined peak values of absorption coefficient can be seen at approximately 1250-1600HZ and 5,000Hz with an equally well defined trough at approximately 3,150Hz. A length of 50mm corresponds to a quarter wavelength at approximately 1600 Hz, three quarter wavelength at approximately 4,800Hz and a half wavelength at approximately 3,300 Hz. Thus it may be surmised that the observed characteristics are affected by resonance effects. This was investigated by repeating the measurements with reeds of lengths 8.5cm, 10cm and 15cm. The measured data is shown in Figure 8.

Measurements of these reed configurations were only made with the larger tube of the Impedance tube measuring system as some the size of the reed stems (typically around 5cm in diameter) was such that there was potentially considerable variation in the porous nature of different samples when used with the 29mm diameter tube. It can be seen from Figure 8 that the effect of increasing the length of the reed stems was to reduce the frequencies at which the first peak and the first trough in the absorption characteristics. Simple calculations revealed that the relationships between length of the stems and the wavelengths corresponding to the frequencies of the peak and the trough held for the new red lengths. As the frequency at which the absorption peak corresponded to the reed length equally approximately one quarter wavelength it would appear that either the hollow reed or the cavity between reeds was acting as a quarter wave resonator. The hollow ends of the 8.5 cm reeds, therefore, were sealed off with putty and the measurements repeated. The results are also shown in Figure 8. It can be seen that the effect of sealing the reeds is to increase the absorption coefficient at most frequencies and to lower the peak frequency slightly. It can thus be concluded that the narrow space between the reed stems is the most important aspect of this configuration.

It should be noted that obtaining consistent results from impedance tube measurements with samples of reed and straw proved difficult for two reasons. The first was the need to seal the sample edges very carefully. If this was not done then odd additional peaks and troughs were observed in the measured absorption characteristics. Secondly, there was considerable variability between different lengths of reeds or straw such that if two different but nominally identical samples were prepared the pore structure could be very different. Nevertheless, the results do demonstrate the potential of reeds and straw layers as porous absorbers and suggest that measurements on larger samples in a reverberation chamber would be valuable.

Figure 10 shows the results of measurements made with 12 m2 of reeds cut to an approximate length of 14cm. It can be seen that this reed configuration was very effective at absorbing sound at frequencies above 250Hz. The expected peak at around 600Hz, the frequency for which 14cm corresponds to the quarter wavelength, cannot be observed. This is probably due to the slight variations in the lengths of the reed stems leading to a broadening of the frequency response.

It proved very difficult to cut the number of reeds required (approximately 500,000) to make such a large sample and the only way it could be done was by cutting up 5cm thick, wire bound reed mats into strips. The need to maintain the wire in place so that the samples could be relatively easily handled restricted the dimensions to which the reeds could be cut. In addition, the use of a circular saw with these mats limited the consistency of the cutting procedure. Thus the second configuration which consists of using aligned reeds “as delivered” may be the more practical option.

The measured values of the absorption coefficient as a function of frequency for layers of reeds and straw perpendicular to the incident sound field as measured in the impedance tube are shown in Figure 11. Measurements of these reed configurations were again only made with the larger tube of the Impedance tube measuring system as there was potentially considerable variation in the porous nature of different samples when used with the 29mm diameter tube.

It can be seen that the values of absorption coefficient are small at low frequencies and although they rise with increasing frequency, they exhibit significant peaks and this characteristic is typical of a material having a heterogeneous pore structure. The results show a pronounced peak in the characteristics at 630 Hz for reeds and 800Hz for straw. This is probably due to the difference in the typical tube diameters of reeds and sraw.

The impedance tube measurements have indicated that reeds have some potential for application to a noise barrier. However, the small samples employed in the impedance tube cannot be assumed to accurately replicate the pore structure to be found in large mats and hence reverberation room measurements were essential. The results obtained for reed thicknesses of 35mm, 50mm, 100mm and 150mm are shown in Figure 12. The thicknesses were built up with layers of 5cm thick reed mats and a 3.5cm thick reed roll. The double and triple layers of mats were both arranged with all mats aligned in the same direction as not only does this configuration seem to give a slightly better performance but it is probably the most practicable for manufacturing purposes.

At low frequencies it can be seen that the effect of increasing the thickness of the reed layer is to move the frequency at which the absorption coefficient peaks downwards and to introduce additional peaks. There is a slight increase in the low frequency absorption coefficient for the 150mm thick configuration.

At high frequencies there is a slight increase in the absorption coefficient with increasing layer thickness. The increase is greater for an increase from 50mm thick to 100mm thick than for an increase from 100mm thick to 150mm thick. It is probable that there would be an additional increase if the thickness were to be made larger but this would small.

Composite Absorbers

The results of the previous sections have shown that fibrous absorbers can be used as the basis of high frequency absorption and that highly heterogeneous porous materials in the form of aligned reeds can provide very good low frequency and moderate medium and high frequency sound absorption. This reflects the situation with conventional sound absorbers where fibrous materials such as mineral wool provide high frequency absorption and other systems, notably panels over air spaces, provide low frequency absorption. In some circumstances, such as in broadcast studios, a considerable amount of sound absorption is required over the entire audio frequency range and the limited area available for the application of treatment results in the use of composite absorbers [5]. These typically consist of a limp panel over an air space covered with a thick layer of porous absorber. The depth of such treatment can be considerable [5]. The performance of the aligned reeds at low frequencies is similar to that of panel absorbers hence the effect of combining reeds and porous absorbers was investigated.

Figure 13 shows the results measured in the reverberation chamber of the absorption coefficients for absorber systems consisting of 5 and 10cm layers of reeds under a 7cm thick hemp batt. It can be seen that the good low frequency performance of the reeds, especially for a thickness of 10cm, is maintained but complemented by the good high frequency performance of the hemp. The result is a composite absorber which is relatively shallow but comparable in performance with the very specialised systems employed in broadcast studios [5].

One of the problems with using Biomass fibres for acoustic absorbers is the need to bind the fibres together without the use of unsustainable substances. An alternative to adhesive binding is to use a mechanical system to hold the fibres in place. As there are gaps between aligned reeds due to irregularities in their sections, it is possible that a reed layer placed in front of fibrous material could act as a perforated protective panel and perhaps also provide some additional absorption. Measurements were therefore made of 100mm thick fibre glass covered a thin reed screen consisting of a single layer of reeds. The results are shown in Figure 14 along with the absorption coefficient of the basic fibre glass.

It can be seen that the single reed screen, being acoustically more transparent, allows the sound to reach the fibre glass and as a result the absorption coefficient of the composite arrangement is very similar to that of the fibre glass alone.

Although the combination of the single layer of reeds plus 100mm fibre glass results excellent absorptive characteristics, it is probable that the single reed layer would not be sufficiently durable. A further set of measurements were therefore carried out with double layers of single reed screens. The measured results are also shown in Figure 14.

The effect of the additional reed layer is very small and it is possible that further layers could be added to improve the durability of the system without significantly compromising the acoustical performance.

Conclusions

The suitability of biomass materials as novel and sustainable sound absorbent treatments has been investigated. Current models for the characterization of porous absorbers have been used to identify candidate materials and impedance tube measurements are carried out for a number of these materials and the results are presented. Examination of the acoustical characteristics of natural fibres has confirmed their effectiveness as porous sound absorbers with properties similar to those of conventional absorbers made from rock wool or fiberglass. Examination of the acoustical performance of different configurations of whole reeds has revealed that these also possess considerable potential for application of sound absorbers with particularly good low frequency absorption characteristics. The combination of fibrous materials and whole reeds offer the possibility of developing a range of very effective absorbers which act across the complete audio frequency range.

Data have been obtained relating to the acoustical absorption characteristics of a range of sustainable biomass materials. The biomass offers many options including fibres, wood based products and different configurations of straw and reed.

The use of natural fibres offers a way of producing very absorbent material whose acoustical absorption properties are determined by the typical fibre diameter and the degree of consolidation. The need to consolidate fibres requires the use of either a binder (glue) or some form of structural framework. Natural fibres are also susceptible to attack by fungi or insects and may constitute a fire risk. There are chemical solutions to many of these problems but they may conflict with the goal of developing a sustainable product.

Wood based products can either be in the form of large wood fragments, typically wood shavings, in a cement matrix (wood wool slabs) or made from wood fibres. The wood fibre solutions have the same good and bad points (good acoustic performance countered by susceptibility to insect and fungi attack, need for binders etc) as the other biomass fibres. Wood wool slabs have good structural properties and, it is claimed, are not susceptible to insect and fungi attack. However, there sound absorptive properties tend to be relatively poor. Also, the cement binder is not normally considered a sustainable material.

Straw and reeds have been found capable of acting as remarkably efficient sound absorbers. Both straw and reeds have a long history of use as a roofing material and have displayed good resistance to insect and fungi attack in this very adverse situation. There are different possible configurations that could be employed. Potentially the most efficient in terms of sound absorption is the configuration in which the cut ends of the straw or reeds face the incident sound. However, this would require a relatively more complex manufacturing procedure than that normally associated with the production of straw and reed. This configuration would also require a binder or structural framework. In addition, the exposed cut ends would probably be more susceptible to insect and fungi attack than the alternative discussed below. The other possible configuration is with the straw or reed lying so that the incident sound is perpendicular to their lengths. Although this is acoustically slightly less efficient it can be employed without a binder in a simple retaining system. The straw or reeds could also be aligned to shed water and thus the long life associated with roofing systems might be replicated in the noise barrier situation.

In practical applications, however, other performance criteria have to be achieved. Of particular importance in situations in which porous absorbers might be employed are durability and fire resistance. The biomass materials examined in this work have been largely composed of cellulose and are not generally attractive as food to insects. However, if exposed to water they can be subject to fungal attack. In a dry building this will present no problem but might preclude their application in some environments. With regard to fire risk, cellulose based materials such as hemp thermal insulation and re-cycled newspapers used as thermal insulation, are routinely treated with fire retardant chemicals to make them safe.

Some 50mm thick reed panels have been exposed to the Liverpool climate for twelve months and these have been tested to assess the effect of exposure on their acoustic performance. The results are shown below in Figure 45. It can be seen that the effect of exposure to climate for a year has resulted in slight increase in the high frequency absorption coefficient. This is probably due to flaking of the surfaces of the outer reeds resulting in a softer, more porous external surface of the panels.

Another practical consideration is the need to develop suitable binders to hold the fibres together without adversely affecting the absorption characteristics. A binder is needed both to reduce the possibility of a material shedding fibres and also to ensure that it maintains its shape. For example, in this work it was found that the natural springiness of wool tended to limit how much it could be compressed and this affected the resulting porosity. A suitable binder could hold the material in a more compressed form. In addition, fibrous materials without a binder could tend to move over time due to the effect of gravity.

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TABLE

Substance	Fibre diameter (m)		Density (Kgm-3)		Porosity
	mean	standard deviation	Matrix material	Bulk sample	
Basic Plant Fibres					
Hemp batts	9.39E-05	3.48E-05	1.48E+03	7.59E+01	9.49E-01
Hemp mats	7.70E-05	7.07E-06	1.48E+03	1.00E+02	9.33E-01
Hemp fibre	1.68E-04	1.16E-04	1.48E+03	8.84E+01	9.40E-01
Flax fibre	2.18E-05	2.05E-05	1.50E+03	7.84E+01	9.48E-01
Raw cotton	1.35E-05	8.96E-07	1.53E+03	4.05E+01	9.73E-01
Sisal fibre	2.13E-04	6.14E-05	1.41E+03	3.86E+01	9.73E-01
Ramie ‘tops’ fibre	2.44E-05	1.21E-05	1.50E+03	9.61E+01	9.36E-01
Jute raw fibre	8.12E-05	3.70E-05	1.37E+03	6.56E+01	9.52E-01
Jute carded fibre	6.21E-05	1.74E-05	1.37E+03	4.91E+01	9.64E-01
Processed Plant Fibres					
Bamboo fibre	1.21E-05	9.91E-07	1.32E+3	5.81E+01	9.56E-01
Soya fibre	1.19E-05	2.32E-06	1.29E+03	4.67E+01	9.64E-01
Tencel	1.47E-05	1.56E-06	1.53E+03	1.13E+02	9.26E-01
“Woodflex” wood fibre batt	4.48E-04	9.46E-05	6.00E+02	4.92E+01	9.18E-01
Animal Fibres					
Raw wool	3.71E-05	9.09E-06	1.30E+03	1.98E+01	9.85E-01
Wool batts	6.30E-05	1.58E-05	1.30E+03	2.57E+01	9.80E-01

Table 1 Physical properties of fibre samples

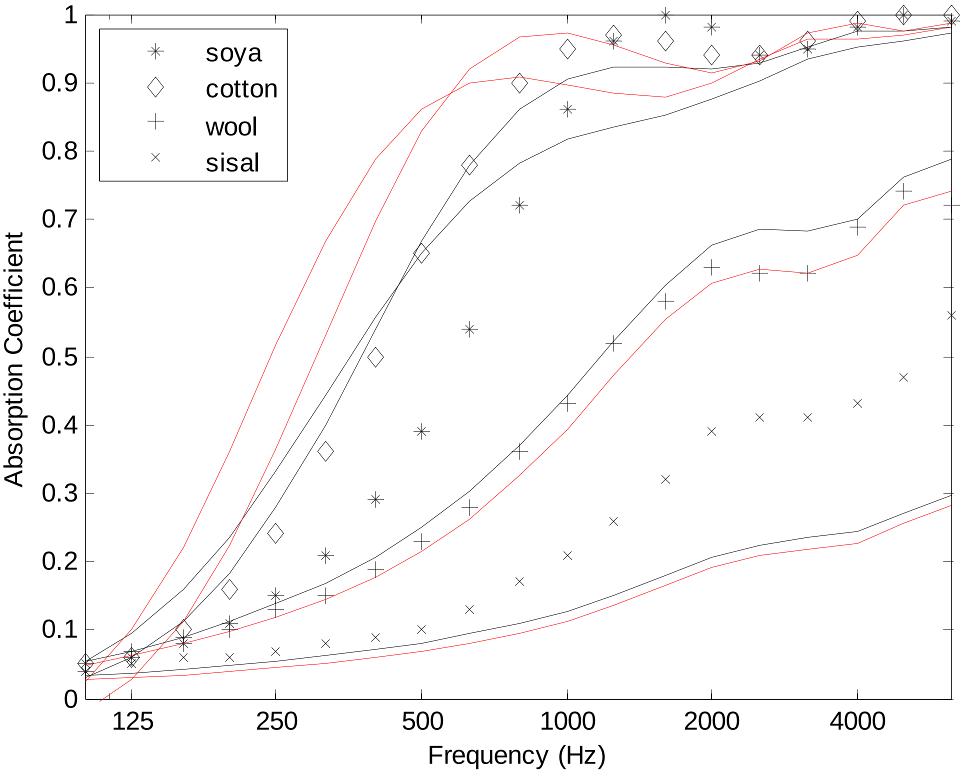


Figure 1: Measured Absorption Coefficient of soya silk, raw cotton, raw wool and sisal.

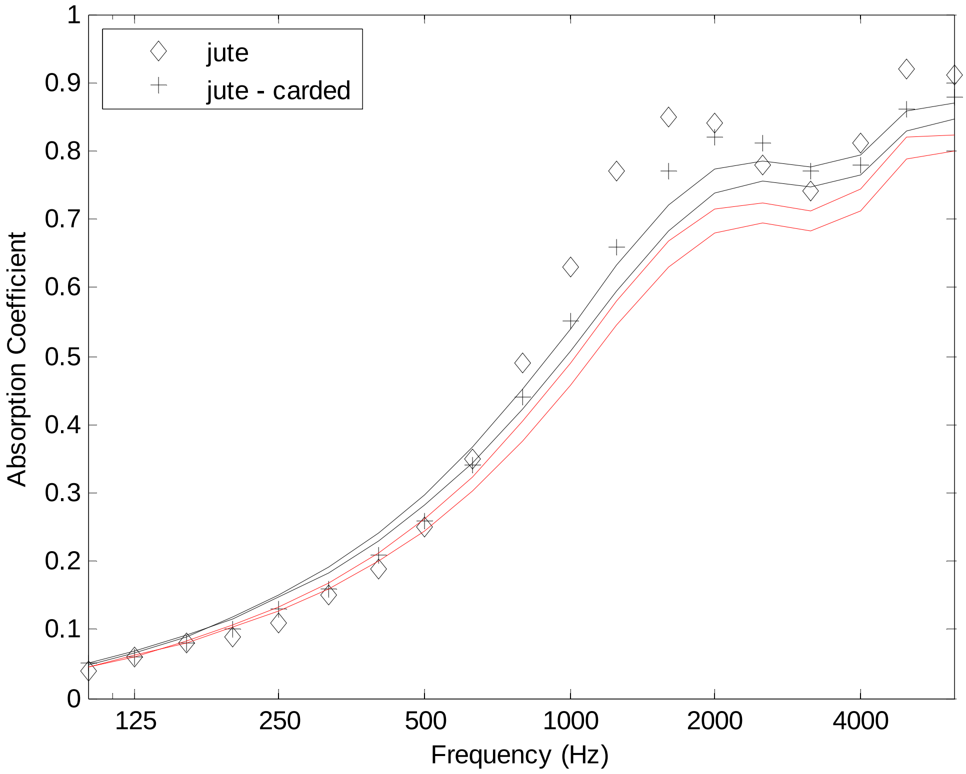


Figure 2: Absorption Coefficient of Raw and Carded Jute Fibre

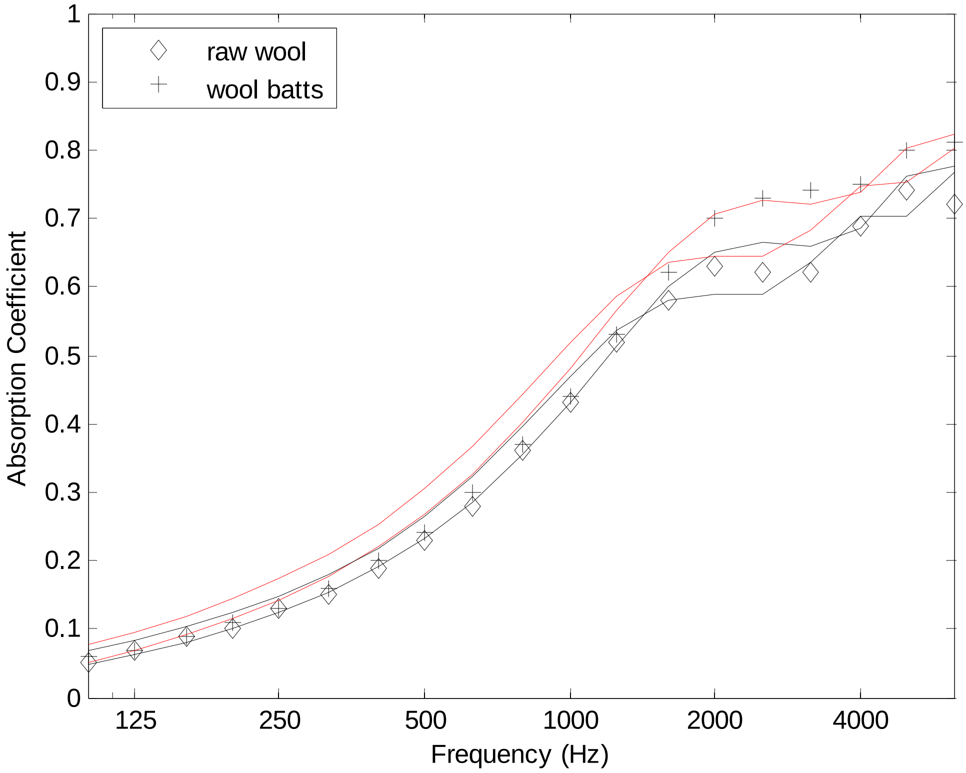


Figure 3 Absorption Coefficient of Raw Wool and Wool Batt

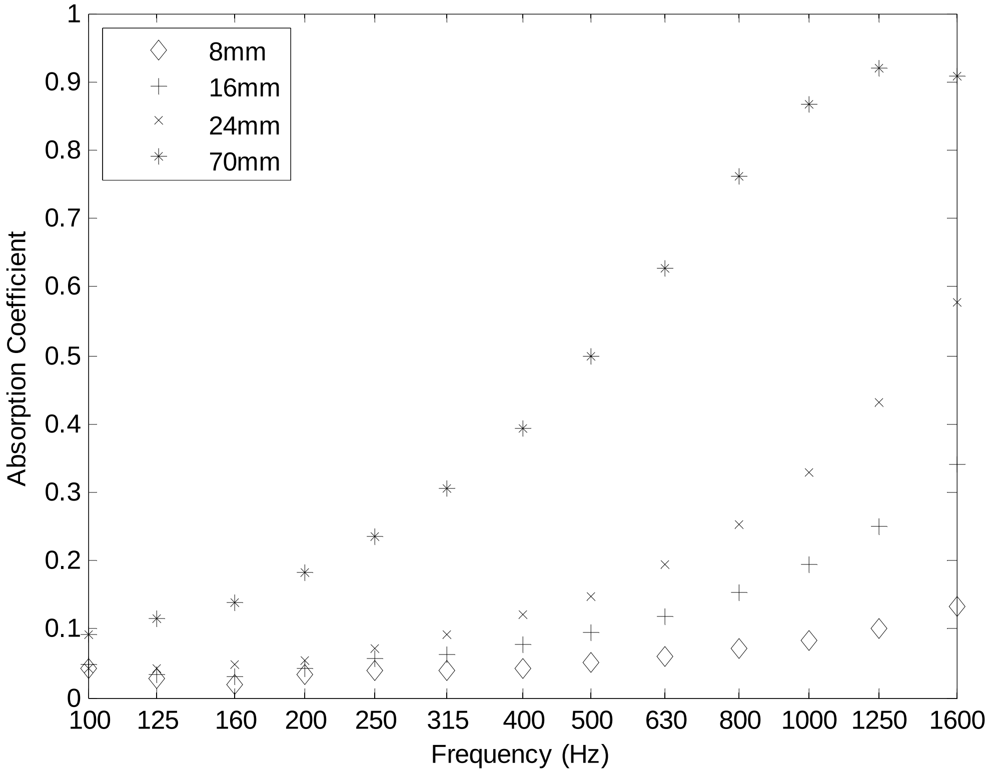


Figure 4: Absorption Coefficient of Hemp mats and Hemp Batts

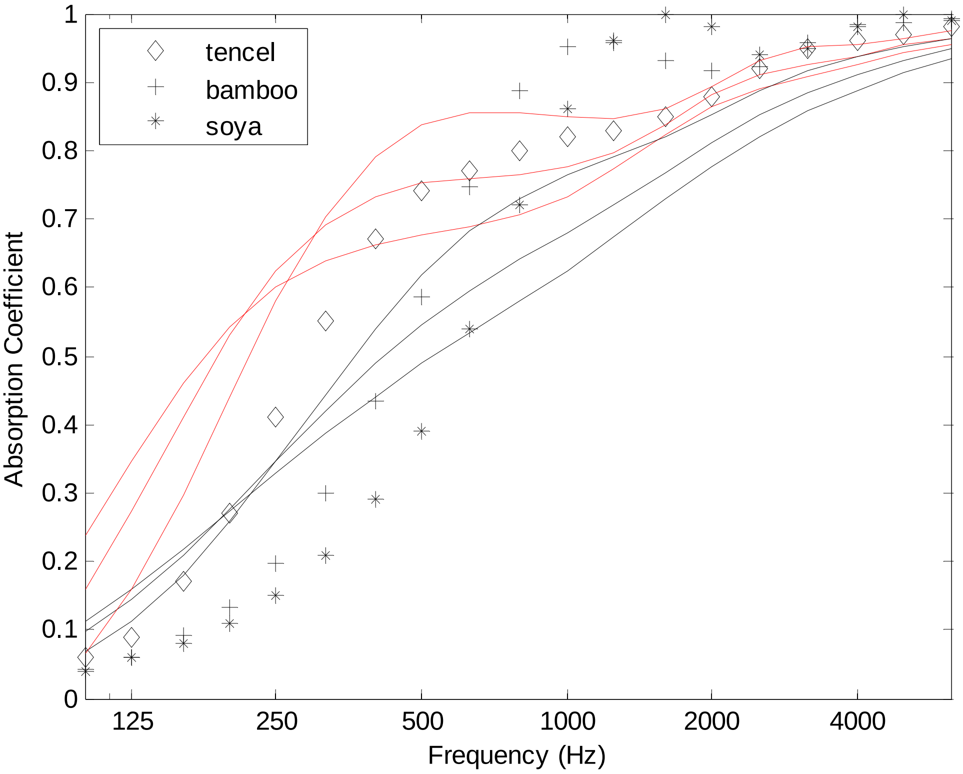
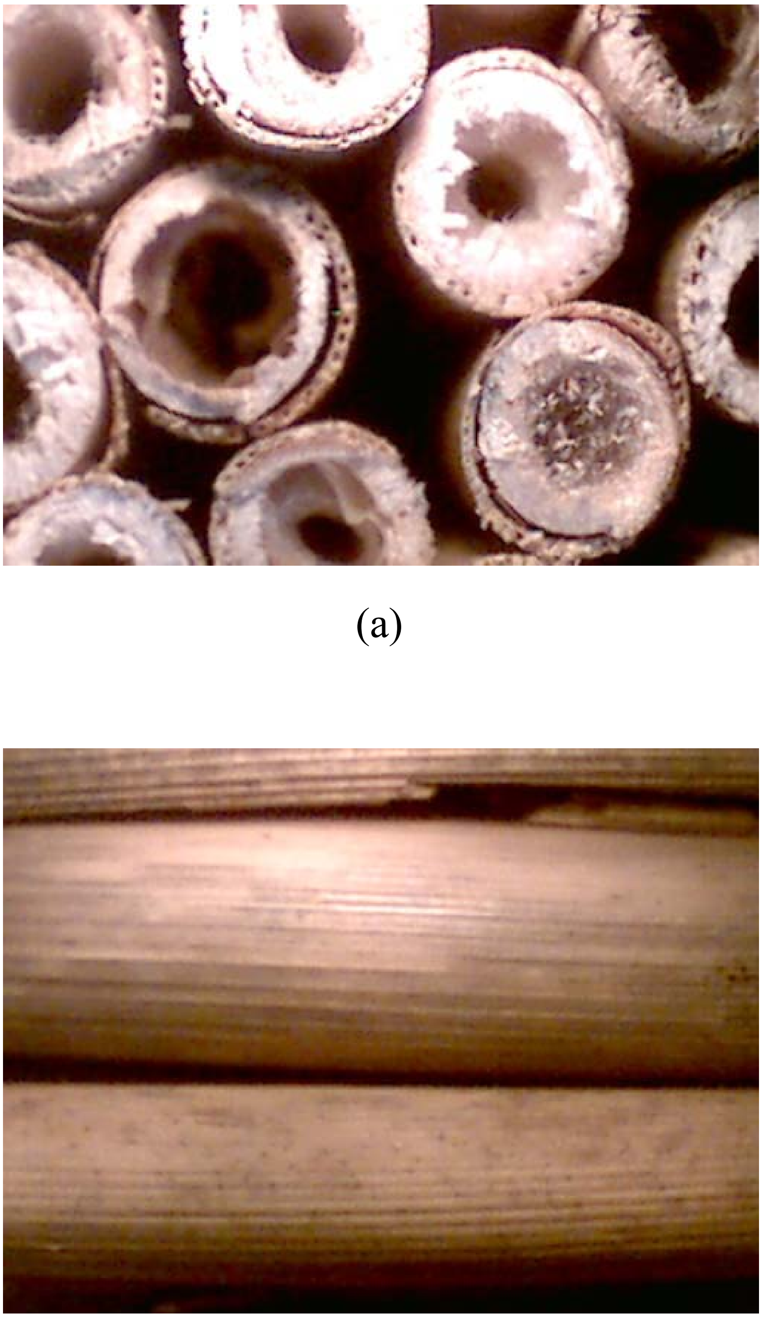


Figure 5: Absorption Coefficient of Fibres from Processed Plant Material



(a)

(b)

Figure 6 : (a) Showing cut ends of reeds; (b) Showing gaps between aligned reeds

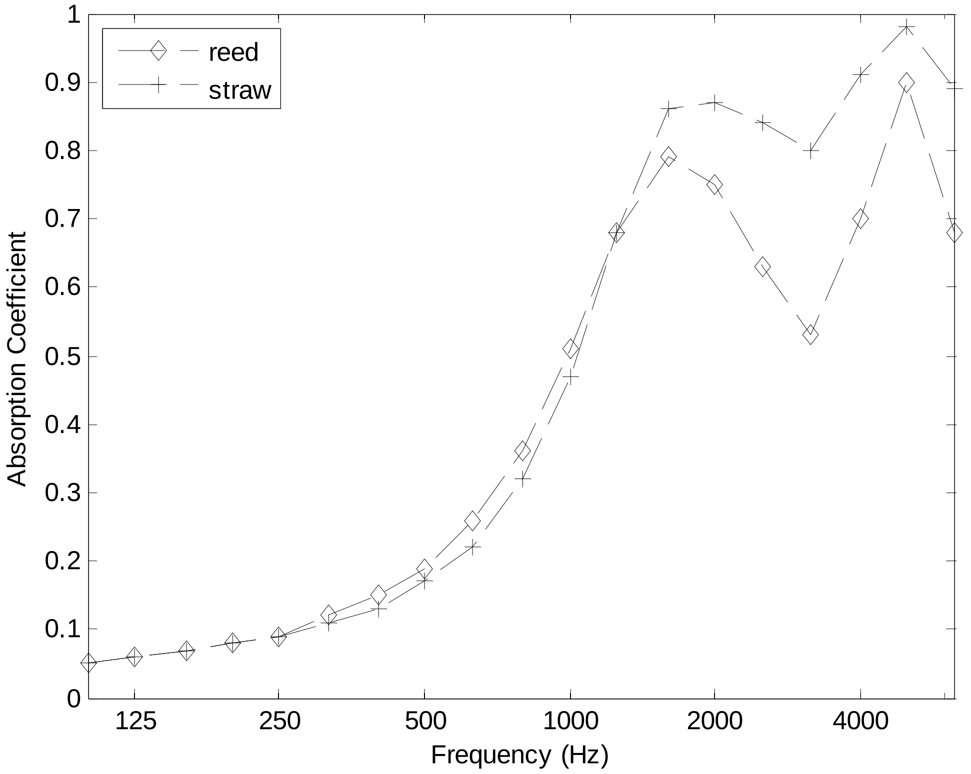


Figure 7: Absorption Characteristics of End-on Straw and Reed Bundles

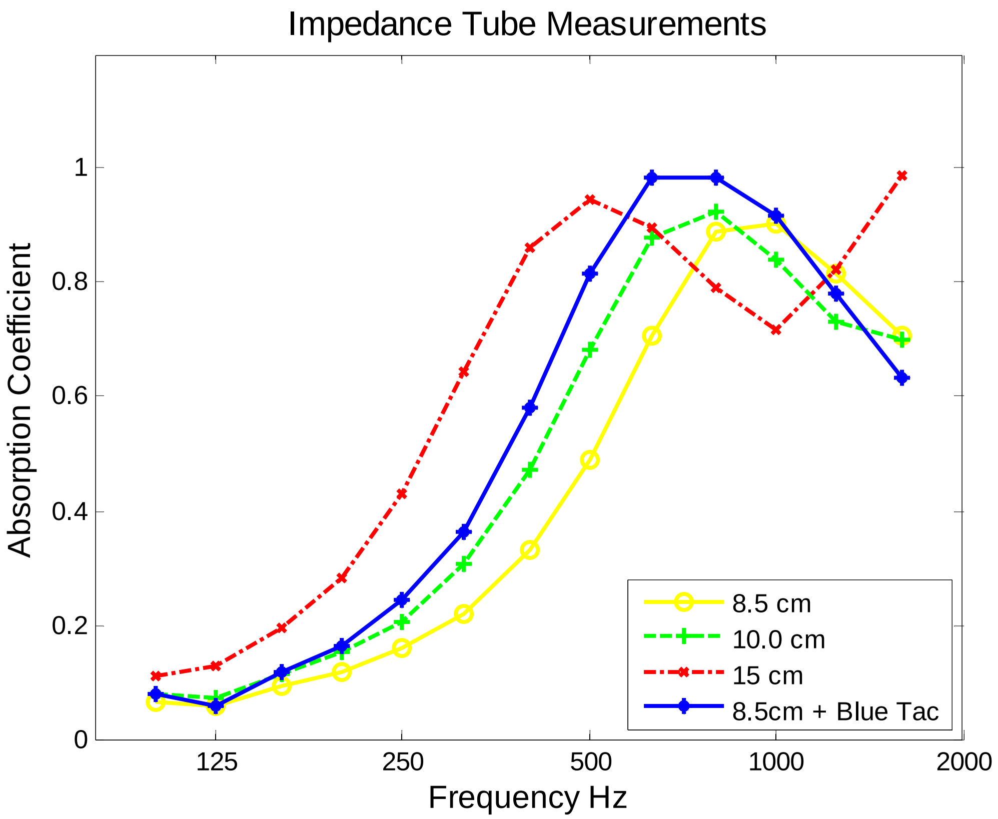


Figure 8: Absorption Characteristics of End-on Reeds Bundles of Different Lengths

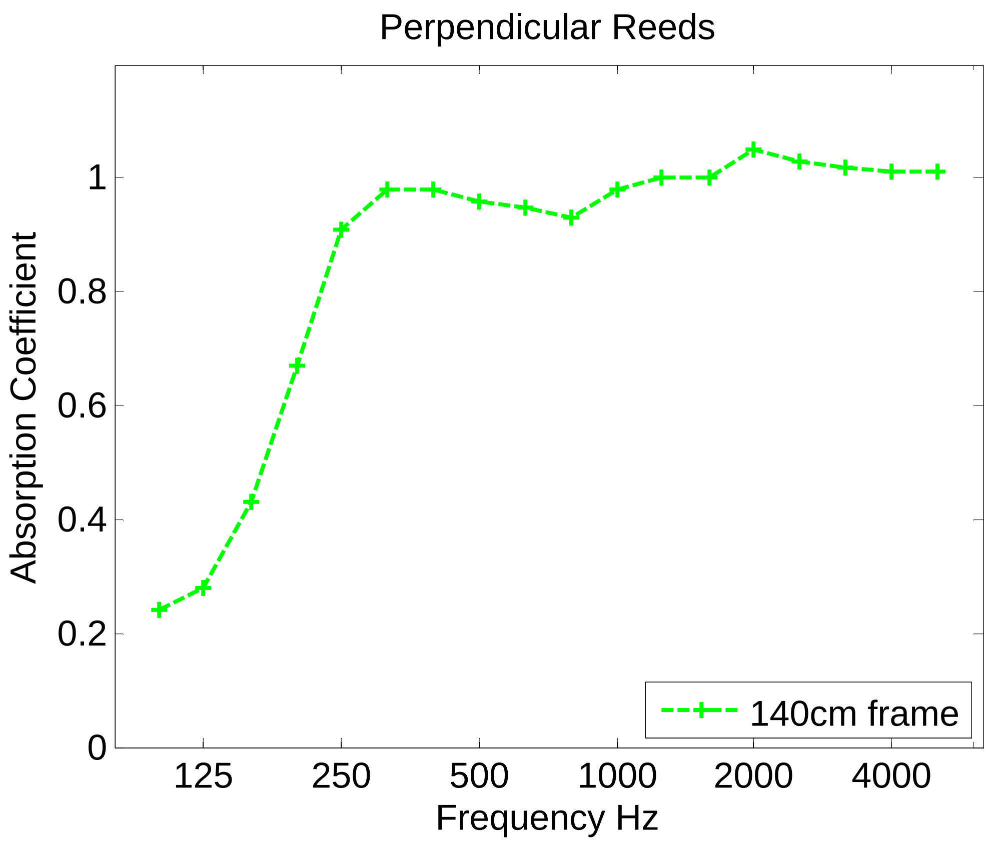


Figure 9: Absorption Characteristics of End-on Straw and Reed Bundles Measured in Reverberation Room.

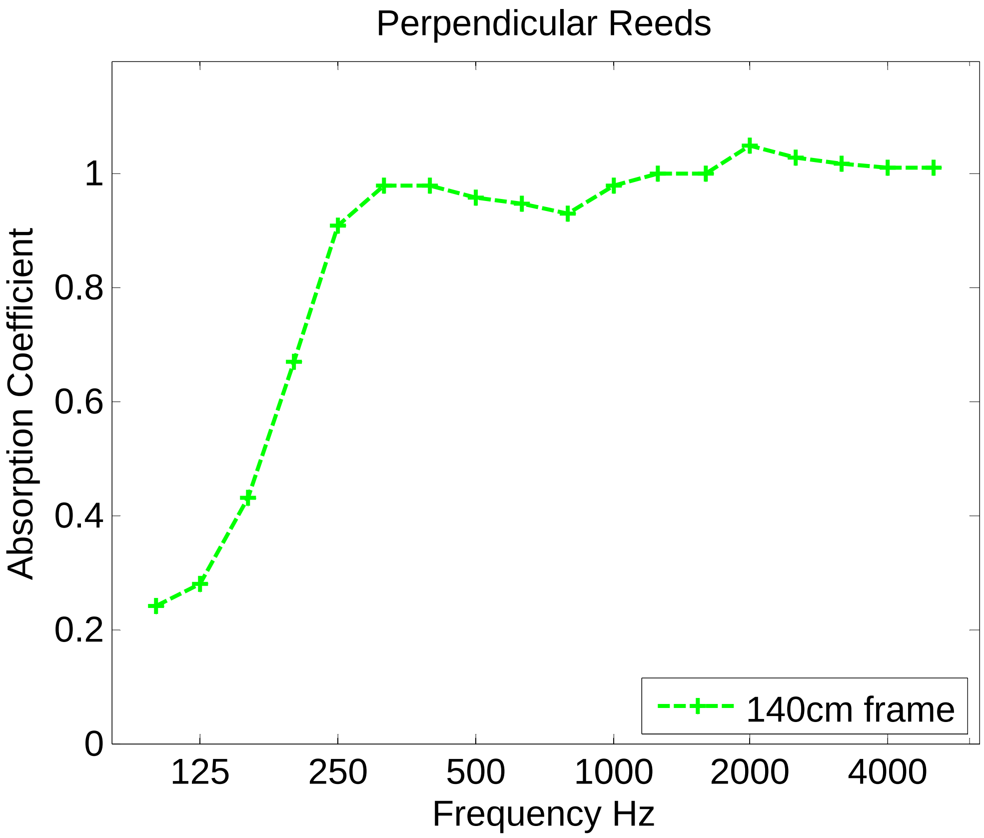


Figure 10: Absorption Characteristics of End-on Straw and Reed Bundles Measured in Reverberation Room.

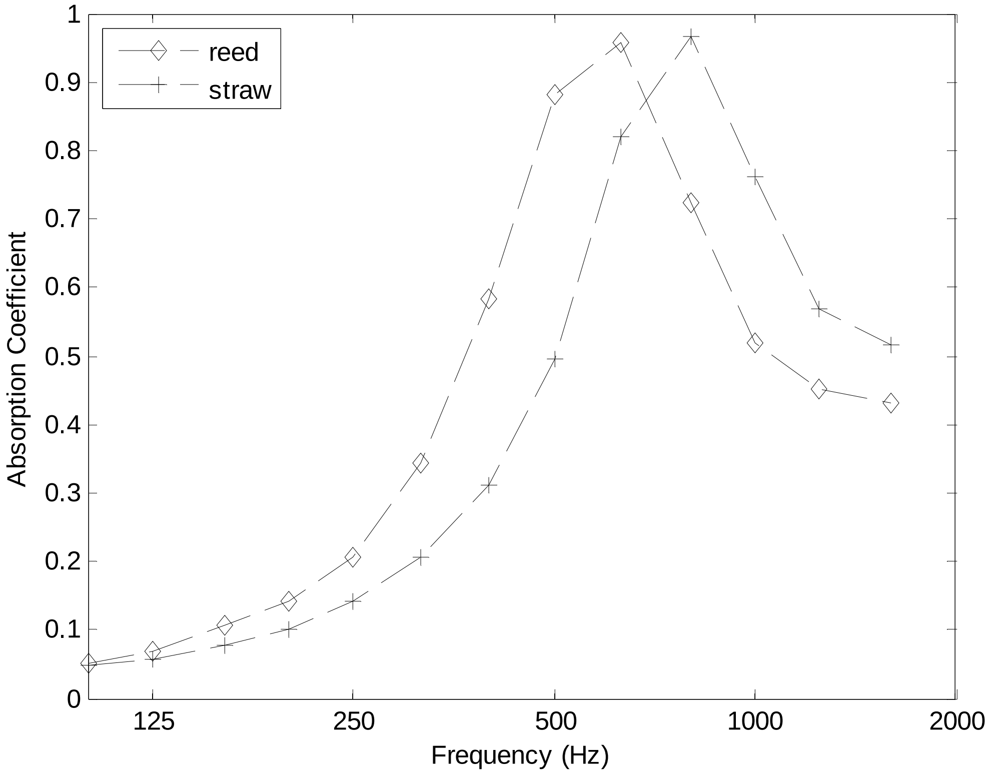


Figure 11: Absorption Characteristics of Straw and Reed Bundles Aligned Perpendicular to the Incident Sound.

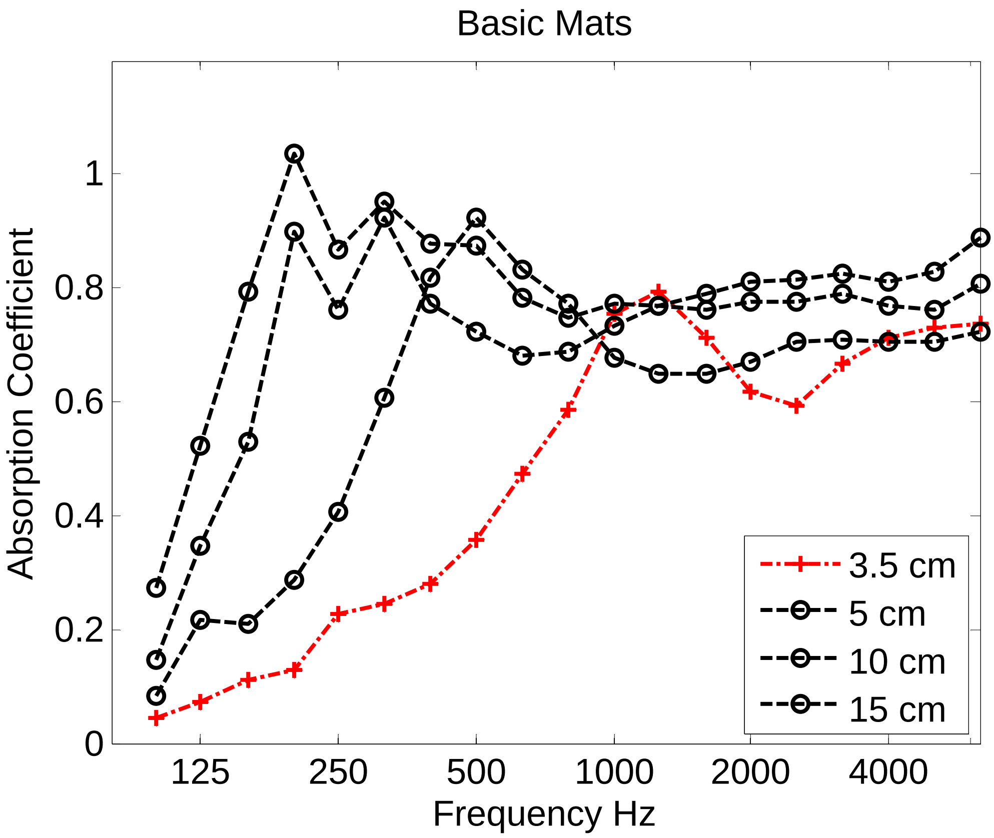


Figure 12: Absorption Characteristics of Aligned Reeds of Different Thickness Measured in Reverberation Room.

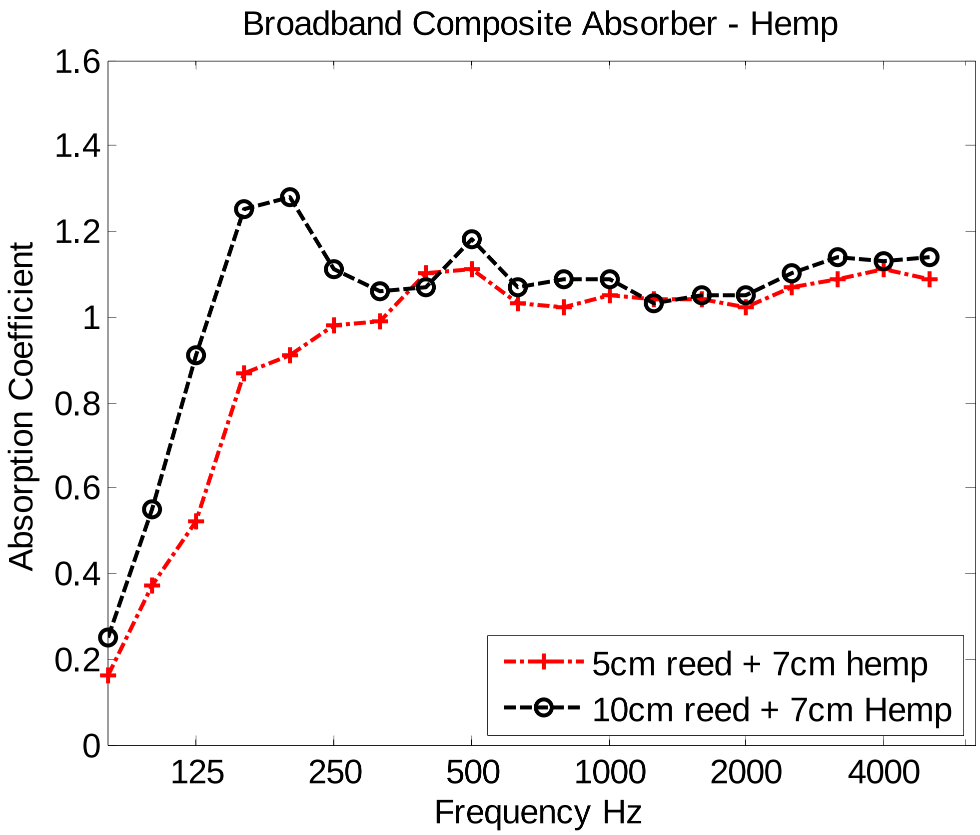


Figure 13: Broadband Composite Sound Absorber Consisting of Reed Underlay and Hemp Batt on Top.

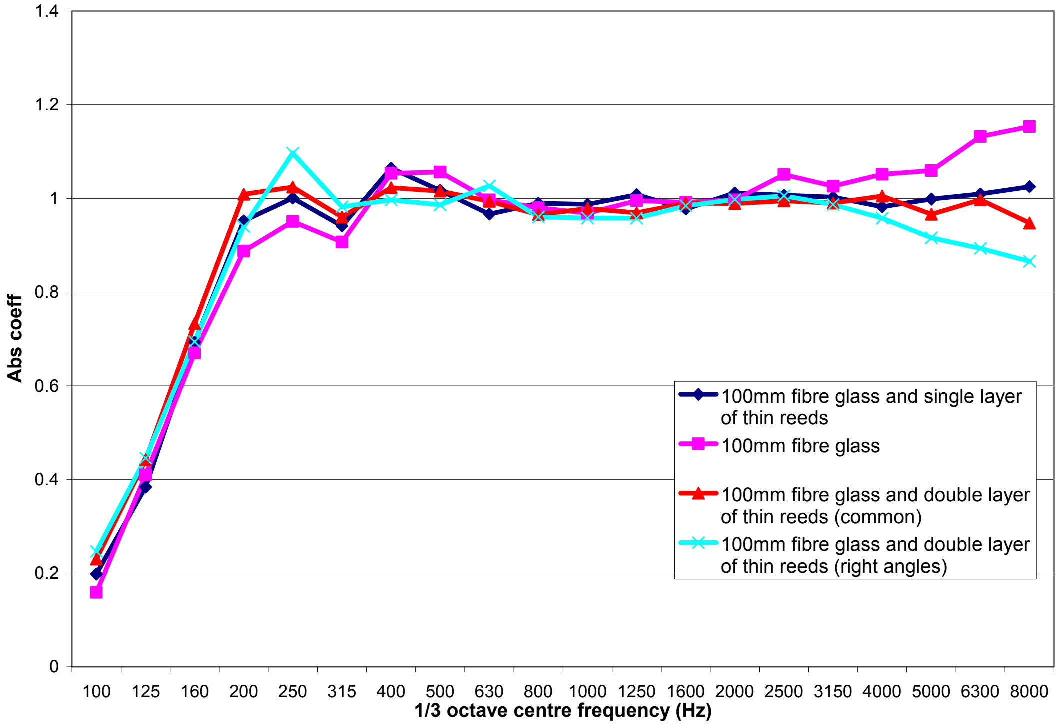


Figure 14: **Absorption coefficient of composite systems compared to that of 100mm thick fibre glass: single layer of reed on top of 100mm thick fibre glass; double layer of reed on top of 100mm thick fibre glass with common orientation; double layer of reed on top of 100mm thick fibre glass with transverse orientation.**