RES2101: Research and Development of Acoustic Timber Panels

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1. Executive Summary

- Using a combination of measurement and modelling two wood end grain sound absorption panels have been designed and tested.

- In order to develop and validate the model range of small wood end grain samples with simple modifications were tested in the impedance tube.

- These results were then compared to predictions from the model to verify the range over which it was reliable.

- Once this requirement was satisfied individual elements were designed to absorb sound in specific frequency ranges and then combined into arrays.

- The sound absorption of the arrays was then measured in the reverberation chamber to evaluate their performance.

- The measurements reported here were performed in a small reverberation chamber (48m3 volume, 81m2 area) taking guidance from BS EN ISO 354:2003. The requirements of this standard could not fully met due to the sample size and the dimensions of the chamber.

- This approach was taken because using larger samples at this stage of the research would have been impractical.

- The results are however expected to be indicative of the standard test and should therefore be a good basis for comparing the sound absorption of different end grain features and modifications.

- Good candidate designs can then be selected and tested fully according to BS EN ISO 354:2003 in the future.

- Two array types were tested:
    - Type 1: An array of rectangular wood end grain blocks modified to expose their internal end grain structure by drilling a central wave guide with intersecting side branches.
    - Type 2: Arrays of wood end grain discs stacked with a separation of 1cm between them. In this case when the discs are arranged into an array; the gaps between the discs creates the waveguide.

- The type 1 array of modified wood end grain samples achieved a sound absorption coefficient of 0.8 at a frequency of 400Hz. This is a significant improvement when compared to tests on samples of the same thickness but without modifications to the end grain.

- The mechanism for this improvement in low frequency sound absorption is resonance of the cavity formed by drilling the central waveguide and side branches.

- This effect is further enhanced by the porosity of the end grain that is exposed within the array elements.

- The type 2 array did not perform as well as the type 1 array at low frequencies as resonant effects were weaker but the sound absorption at higher frequencies was significantly better.

- The best results were obtained when the type 1 and type 2 arrays were combined. In this case the sound absorption coefficient in the frequency range 400-5000Hz was estimated to be between 0.7 and 0.8.

- This means above 400Hz 70-80% of sound energy incident on the sample was absorbed. For wood end grain without modifications (tested previously in the impedance tube) only 10% to 20% of incident sound energy was absorbed.

- Thus, the sound absorption properties of wood end grain have been significantly improved by simple modifications to the surface and internal structure to make highly effective sound absorption panels which are visually attractive and sustainable.

2. Introduction

In 2014 the University of Salford conducted testing for Coed Cymru to investigate the feasibility of using wood end grain as a sound absorption treatment, e.g. for interiors (http://www.endgrain.org.uk/research-testing/). It was found that the end grain of some species of wood has a surprising ability to absorb sound compared to other solid materials demonstrating potential for its use as an acoustic treatment. In two further studies, modifications to the surface structure were investigated and it was found that the sound absorption properties of wood end grain could be significantly enhanced with only minor modifications. The work demonstrated the potential of wood end grain as a visually attractive sound absorption material and it was recommended that a further study be conducted to optimise the acoustic performance by surface structuring based on a combined measurement/modelling approach.

In the study reported here a combination of measurement and modelling has been used to develop two wood end grain panel designs consisting of multiple small elements. In order to develop and validate the model used to design these panels a range of small wood end grain samples with simple modifications were tested in the impedance tube. These results were then compared to predictions from the model to verify the range over which it was valid and reliable. Once this requirement was satisfied individual elements were designed to absorb sound in specific frequency ranges and then combined into arrays. The sound absorption of the arrays was then measured in the reverberation chamber to evaluate their performance.

The measurements reported here were performed in a small reverberation chamber ($48m^3$ volume, $81m^2$ area) taking guidance from BS EN ISO 354:2003. The requirements of this standard were not fully met however due to the sample size and the dimensions of the chamber. This approach was taken because using larger samples at this stage of the research would have been impractical. The results are however expected to be indicative of the standard test and ought therefore to be a good basis for comparing the sound absorption of different end grain features and modifications.

3.   Materials Characterisation

The Acoustic Research Centre at the University of Salford has a strong track record of developing and testing of acoustic materials; demonstrated by numerous journal papers, patents and a spin out company. As a result of our research, methods of modelling porous and resonant materials have been developed which are utilised in this study to enhance the sound absorption of wood end grain.

In order for these models to be useful in designing sound absorbers it is first necessary to have a good understanding of the intrinsic material properties (which are required as inputs to the model). These properties include the Characteristic Impedance, Wavenumber, Porosity and flow resistivity. Provided below is a description of how these material properties were determined.

Flow Resistivity

The flow resistivity of the poplar wood end grain samples was determined using a test assembly developed in house which measures the rate of airflow incident on a test sample and the air pressure before and afterwards. A photograph of the flow resistivity rig is shown in Figure 1 below.

When tested in the flow resistivity rig the wood end grain was oriented so that it was in line with the direction of airflow. Due to the internal structure of the material, which is effectively a stack of fibres aligned in the direction of growth, the flow resistivity perpendicular to the trunk may be regarded as close to infinite whereas along the direction of growth a lower flow resistivity will be observed. This is an important property of wood end grain which allows it to absorb sound.

The purpose of the study is to exploit this by modifying the material to provide enhanced sound absorption.
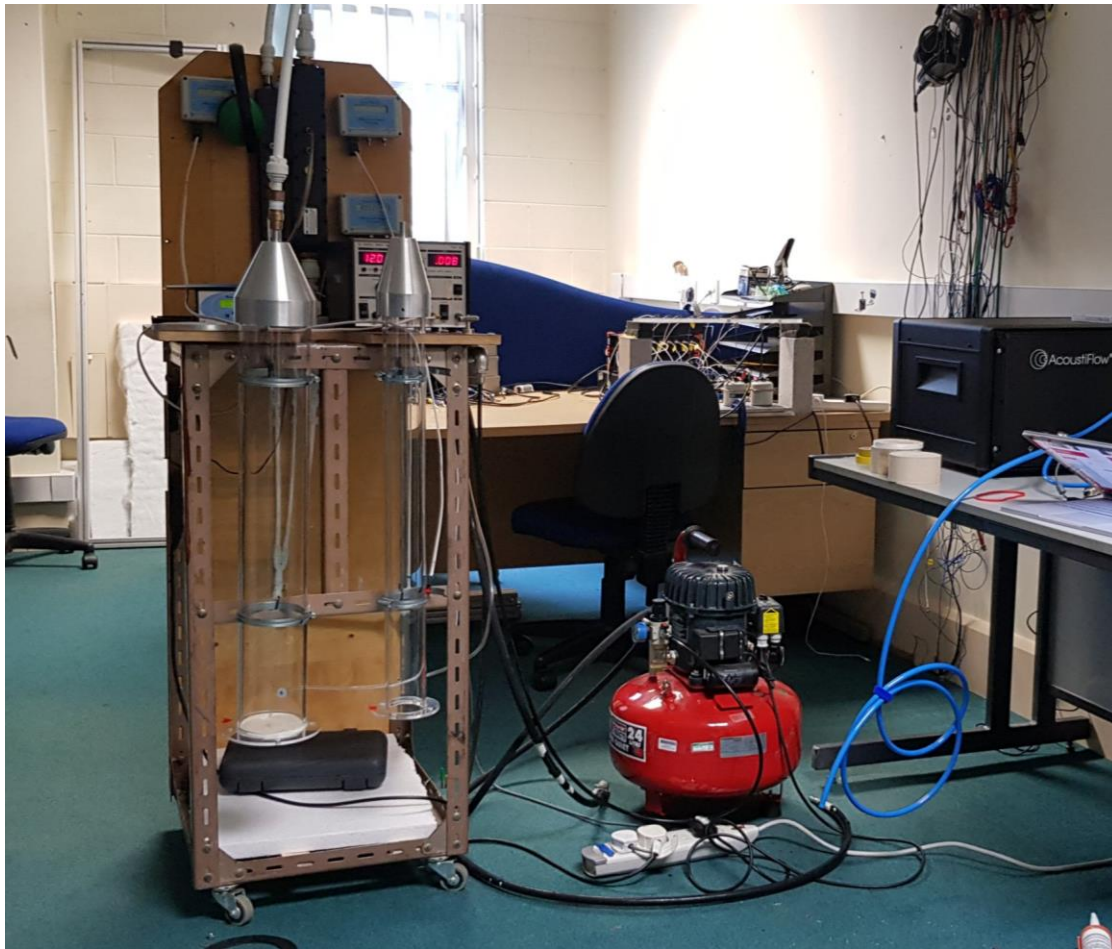
Figure 1: Photograph of the flow resistivity rig. The flow resistivity test rig is composed of an air compressor (right) connected via a laminar airflow rate sensor to a long transparent tube. Installed in the tube is a 10mm thick disc of poplar sealed around its edge. An differential pressure sensor is connected via a thin pipe to the inside of the tube so that the air pressure before and after the sample can be recorded. The combination of these measurements allows the flow resistivity to be calculated.

Porosity

A material's porosity is the ratio of solid volume to that which is free space that can be occupied by air. For example, the porosity of sponge can be determined by measuring its mass and then soaking the sponge (to saturation point), e.g. in water, and weighing again. The volume of saturating fluid, e.g. water, can then be determined and with its density being known the amount of free space within the material can be determined.

For some materials, such as wood end grain, the above method is not appropriate because the initial water content may not be fully known and because the duration required for the water to fully

penetrate cannot easily be determined. Furthermore, during the saturation process the material may swell/change shape making the material volume itself an additional variable.

In this study a similar method to the above was used. However, rather than using water as the saturating fluid atmospheric air was used. This was done by sealing the end grain sample (of known volume) within a cylinder (also of known volume) and then adding air to the cylinder in known quantities whilst measuring the pressure increase. From these measurements the porosity of the end grain sample could be estimated.

Characteristic Impedance, Wavenumber and Sound Absorption

The model, described in section 4, requires inputs of the characteristic impedance and wavenumber together with the flow resistivity and porosity. The impedance tube, see Figure 2, can be used to determine the characteristic impedance and wavenumber as well as the sound absorption coefficient.

Solid wood end grain samples of varying thickness were tested in the impedance tube to describe the material in terms of characteristic impedance and wavenumber. As mentioned previously this data is required as an input to the design model (see section 5). After these tests were completed a range of modified wood end grain samples were also tested to validate the model.

The modifications consisted of a single hole drilled in the direction of the end grain at the centre of each sample. In addition to this a number of side branches were also drilled perpendicular to the central hole in order to expose the internal end grain; the aim being to achieve a lower frequency sound absorption peak. A range of samples were tested to determine their sound absorption coefficient for validation of the model.

Figure 2: A Bruel and Kjaer Type 4206 was used to measure the characteristic impedance and wave number of solid end grain samples and to measure the sound absorption of modified end grain samples for validation of the model (see section 5).

4.   The Model

Wood grain possesses a network of capillaries which, for the purpose of modelling, are assumed to run along the sample thickness, in the direction normal to its surface. The radius of the identical capillaries is found by fitting the measured flow resistivity value. On its own, the wood grain is a poor sound absorber, presenting a large impedance mismatch with air and hence inducing a lot of reflections at the surface.

Drilling a larger hole in wood grain sample decreases impedance mismatch, thus creating a more effective way for sound to penetrate into the material. The energy of sound is then lost due to viscous and thermal losses within the larger perforation. This solution, however, does not bring the capillaries into play. Running in parallel to the main perforation, they remain inaccessible for sound. The solution which seems most effective is to exploit the sound losses both in the main perforation and in the capillaries. To achieve this, there needs to be a way of connecting the capillaries network with the perforation. This is done by creating a structure with the so called lateral (or side) pores. These pores run in the direction parallel to end grain surface, initiating at the walls of the main perforation and running towards the side surface of the end grain sample. In this case, the capillaries open up at the walls of side pores. Due to the lower impedance contrast between the side pores and the capillaries, sound is able to penetrate them thus creating an additional attenuation mechanism.

The side pores are known to increase the effective compressibility of air within the structure. More compressive gasses have lower sound speed in them and consequently longer wavelengths. This means that the length of the wood grain with the main perforation and the side pores resonates at lower frequencies as the frequency of the resonance is related to the wavelength. This effect is well known and has been described in several publications e.g. [1]. The effect is usually stronger if the side pores are presented at several locations along the thickness of the sample. It is even more effective if side cavities, instead of side pores are introduced, for instance by stacking the perforated plates separated by small air cavities [2].

The characteristic feature of the wood grain is the presence of the capillaries, which could be beneficial for sound absorption if the dimensions of the main and side pores (or side cavities) are chosen correctly. Positioning the wood grain samples next to each other on the planar surface could also be beneficial as this allows the interactions between the side pores (or cavities) in neighbouring samples.

The model has been developed for cylindrical side pores, positioned regularly along the thickness of wood grain sample and for the side cavities. The model has been based on Transfer Matrix approach (TMM), where each section of the main pore – loaded by side pores/ cavities and not – is modelled separately and characterised by a propagation matrix. The propagation matrix of the whole structure is then obtained by multiplying those of the subsequent sessions. This method is well established in acoustics and is commonly used for the description of layered structures [1]-[2].

5.   Model Validation

Following material characterisation (section 3) modified samples of wood end grain were tested in the impedance tube to determine their sound absorption coefficient. The sound absorption coefficient of these samples was also calculated using the model described in section 4. The material properties used in the model are given in Table 1 below.

Material Property	Value
Flow Resistivity	1.25×10^6 Pa s m^{-2}
Porosity	65 %
Characteristic/Surface Impedance	Frequency dependent

Table 1: Material characterisation values for poplar used in the model (see section 3)

The material properties in the table above were employed in the model to make predictions of the sound absorption coefficient for the modified samples provided. Shown in Figure 3 and Figure 4 are examples of the model's agreement with the impedance tube measurements.
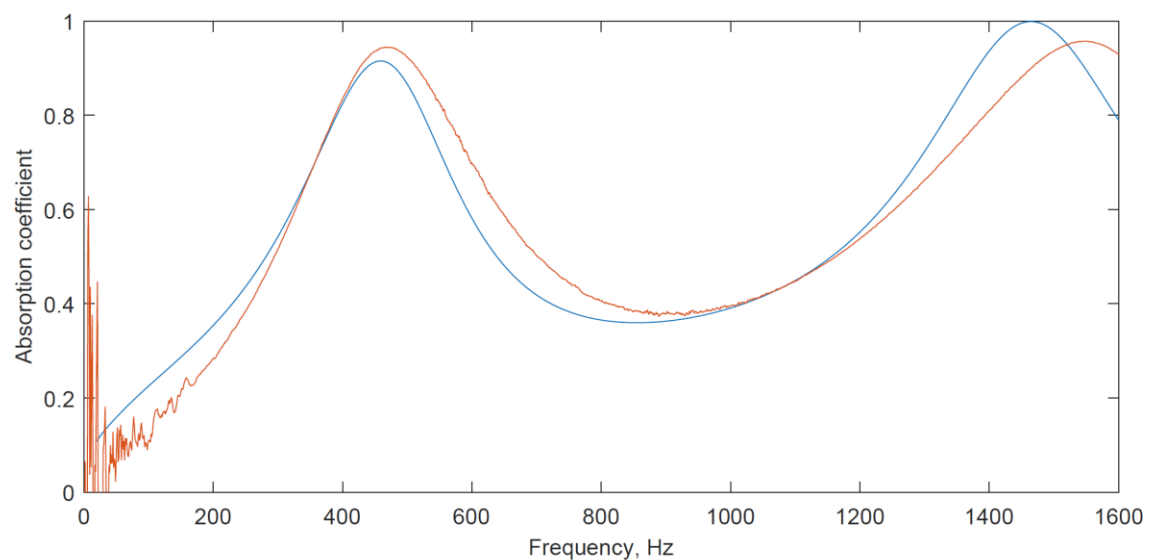
Figure 3: Example of the model's agreement with the measured sound absorption coefficient in the impedance tube. This wood end grain sample had a central hole in the direction of the end grain of 15mm diameter and sixteen side branches of 5mm diameter in two rows of eight evenly distributed over the 150mm sample length.
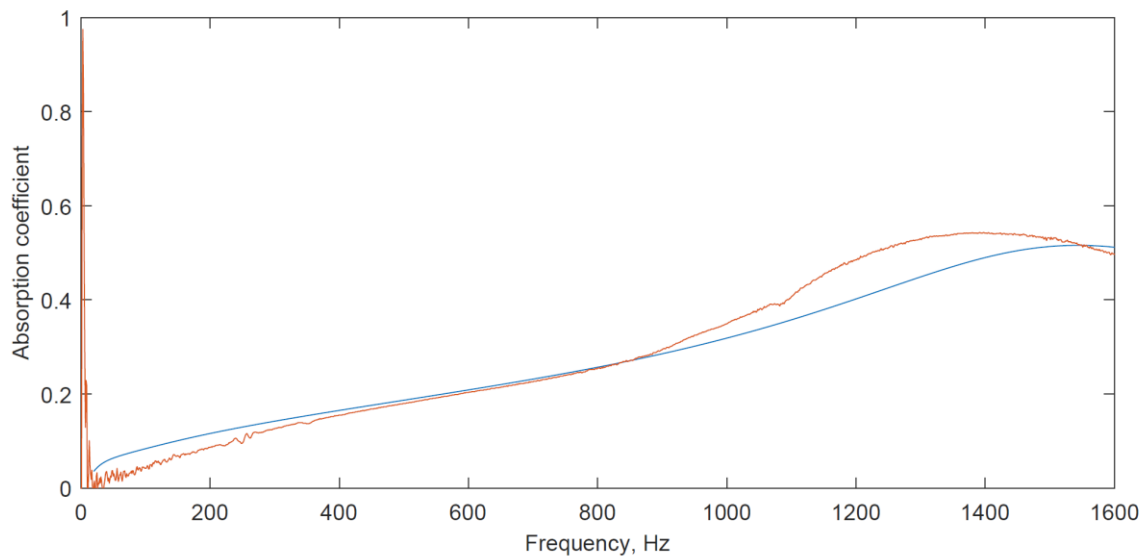
Figure 4: Example of the model's agreement with the measured sound absorption coefficient in the impedance tube. This wood end grain sample had a central hole in the direction of the end grain of 60mm diameter and four side branches of 20mm diameter in one layer.

In most cases tested the model demonstrated good agreement with the sound absorption data when using the material properties given in Table 1. It should however be noted that this was not the case for all samples tested.

It was found that for elements where there was a high density of side branches, and especially when they were closely packed in multiple close layers, the agreement between model and measurement was less reliable. For this reason, the model was only considered as being validated for modified end grain samples with sparse well separated layers of side branches. The model was then used (within its range of validity) to design elements of a sound absorption panel.

6.   Array Design 1

For practicality it was agreed that the principal array design would be based on rectangular blocks with different modifications that can be arranged into arrays of components with different sound absorption properties. Shown in Figure 1Figure 5 is a schematic to explain the design of the array elements.

NC – number of layers of side branches
NB – number of side branches per layer
SB – side branch diameter in (mm)
WG – central waveguide diameter (mm)
a – length (mm)
b – width (mm)
c – height (mm)
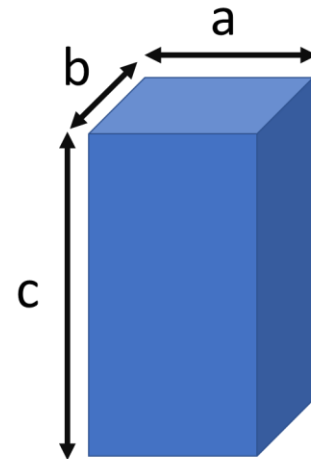
Figure 5: Array elements. Each of the array elements has a height, C, of 150mm and all are square with a=b in each case being either 50mm or 100mm. Each has a central hole or wave guide of diameter (WG) drilled in the direction of the end grain (vertically) and a number of side branches (NB) repeated over a number of layers (NC). The total number of side branches is NC x NB.

Table 1 below provides details of the elements of the array selected to form the timber end grain sound absorption panel. The aim when designing the panel was to include multiple resonant elements that offer significant sound absorption in the low frequency range. Shown in Figure 7 are the predicted normal incidence sound absorption coefficients of the individual elements.

As can be seen in Figure 7 the smaller (50mm x 50mm) elements of the array appear more effective as sound absorbers but they are more time consuming to manufacture. For this reason a combination of 100mm and 50mm elements were used in equal numbers but with the larger 100mm x 100mm elements making up 75% of the surface area. Alternative manufacturing techniques could be explored to further optimise the array by incorporating an increased number of smaller more detailed elements. Figure 8 shows a suggested arrangement of the array elements.

	No. Side branch layers (NC)	No. Side branches per layer (NB)	Side branch diameter (mm)	Wave guide diameter (mm)	Dimension a (mm)	Dimension b (mm)	Dimension c (mm)
Element 1	4	4	20	20	100	100	150
Element 2	4	2	20	40	100	100	150
Element 3	4	2	30	30	100	100	150
Element 4	N/A	0	N/A	N/A	50	50	150
Element 5	4	4	20	20	50	50	150
Element 6	4	4	10	25	50	50	150
Element 7	4	4	15	25	50	50	150

Table 2: Dimensions of the array elements and details of their modifications. See Figure 5. Each has a central hole or 'wave guide' (WG) drilled in the direction of the end grain (vertically) and a number of side branches repeated over a number of layers. The total number of side branches is NC x NB.
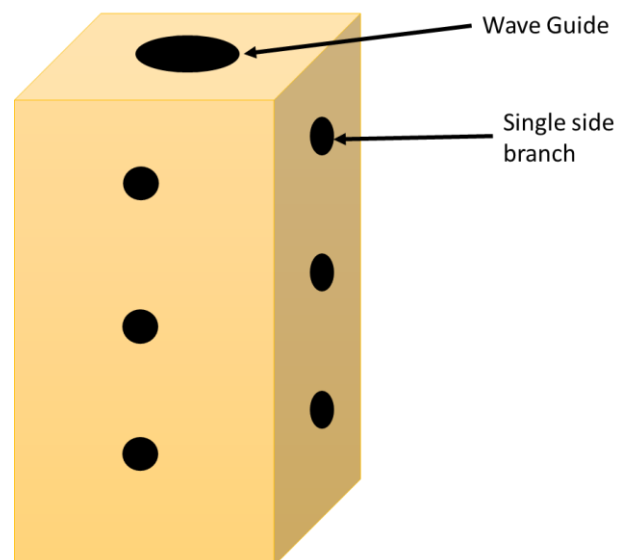
Figure 6: Illustration of an array element showing the central wave guide and side branches. In this case six side branches are visible, if the same pattern is repeated on the sides which are not visible there would be a total of 12 side branches in three layers 4.
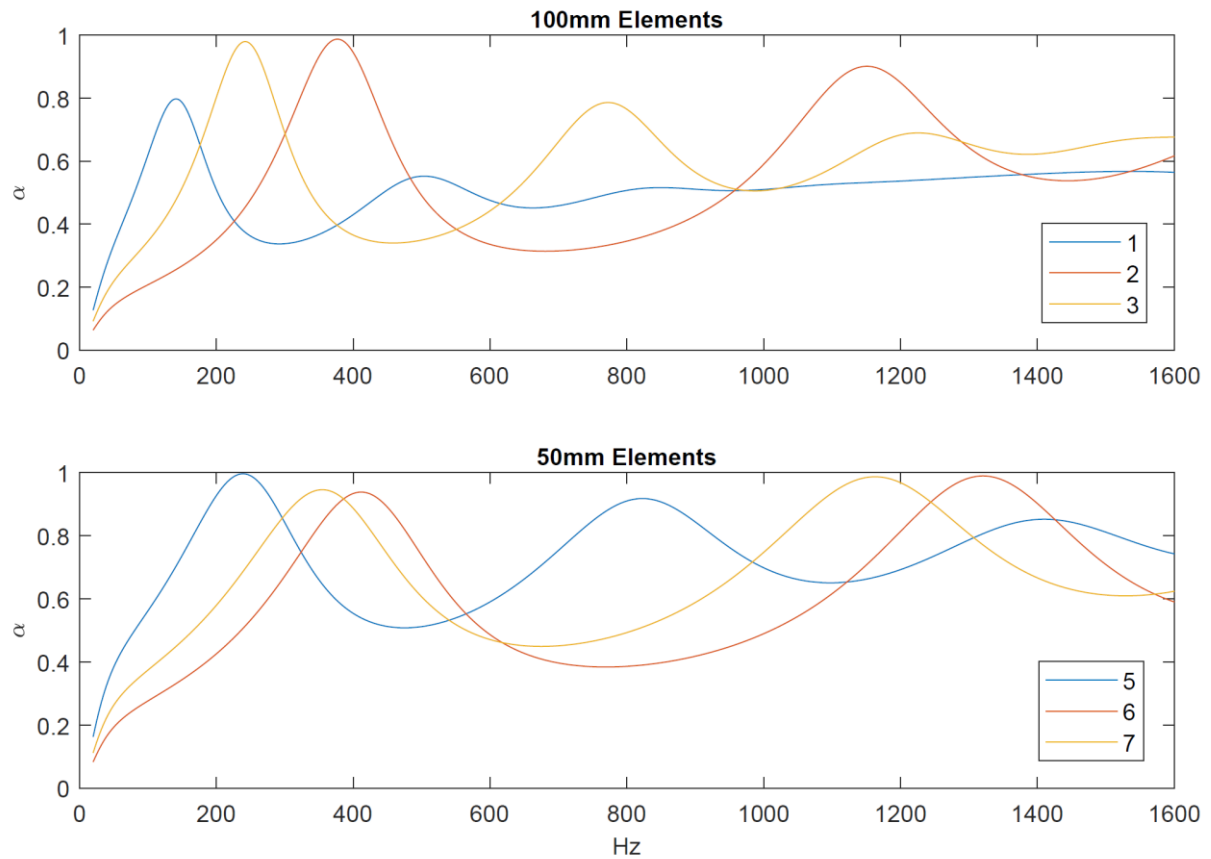
Figure 7: Sound absorption coefficients of the array elements in Table 2 predicted from the model. Array elements were selected to optimise sound absorption at low frequencies where typically thicker treatments are required because of the associated longer wavelengths of sound.

Figure 8: Arrangement of the Array elements. For every three 100mm x 100mm elements there are four 50mm x 50mm elements. It is not necessary to arrange them as above, but an even distribution is sensible unless there is specific knowledge of the application.

7.   Array Design 2

For array design 1 exposing the internal end grain was achieved by drilling a central hole in a block of wood end grain and by drilling additional holes perpendicular to it that intersect the central hole (the waveguide). Manufacturing such elements is time consuming and may not be cost effective.

A simple analogy to this is an assembly formed from multiple discs with exposed end grain stacked with spacers to control the separation between them. Such an array can be formed as shown in Figure 9 below.
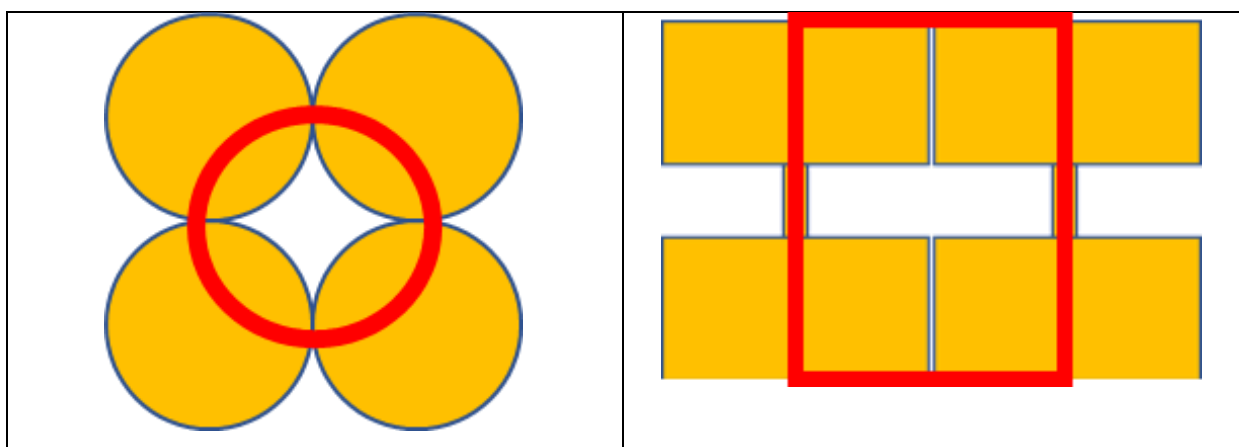
Figure 9: Alternative arrangement for an end grain absorber array. In this case a hole is created that runs parallel with the end grain by virtue of the space between the disc elements (top left) and the side branches are replaced with an entire plane of exposed end grain (top right). The red areas on the diagram are used to illustrate a comparison of the elements used in Array 1 (described in the previous section).

The optimisation of such an array is somewhat beyond the scope of the model available because the model assumes a rigid (solid wall) boundary condition between the array elements which will not be the case here. It is however interesting to explore this alternative array configuration due to the much-simplified manufacturing procedure and the artistic freedom it allows.

In the following section of the report the two array types are tested to estimate their random incidence sound absorption coefficient. A case is also included where the two array types are combined which is found to perform best overall.

8.   Sound Absorption Coefficient of the Panels

Presented in the following subsections are estimates of the sound absorption coefficient of the Array types 1 and 2 and a combination of them as detailed in the table below.

Test reference	Description	Array Type (1 or 2)	Surface area (m^2)
A1	Array 1 arranged into 1m x 1m sample (surface area includes the sides of the array)	Type 1	1.60
A2	Array 1 with elements of array 2 arranged around the outer edge (surface area includes the sides of the array) surrounded by elements of array 2. Sheep's wool is used in the empty slot.	Combination	2.12
A3	Array 1 with all elements laid on their sides (surface area includes the sides of the array). Tested out of interest.	N/A	1.90
A4	126 stacks of 25mm thick discs with 10mm spacers (surface area includes the sides of the array)	Type 2	0.733
A5	126 stacks of 25mm discs with 10mm spacers and a graduated profile (surface area includes the sides of the array)	Type 2	0.761

Table 3: Test reference labels with a brief description of each test including the array type and the surface area of the sample. In all cases the vertical sides of the array are included as potential sound absorption areas.

Test A1

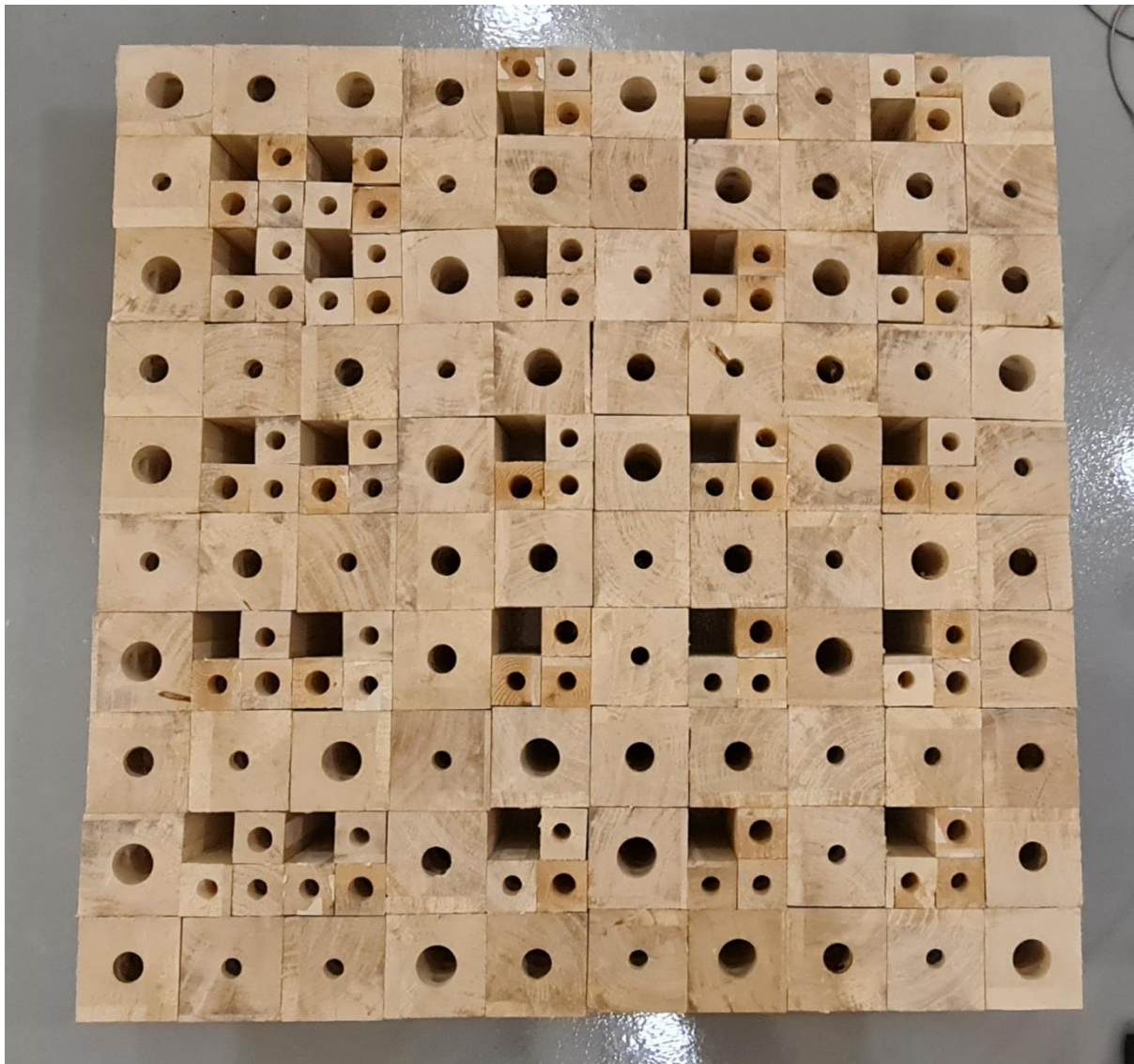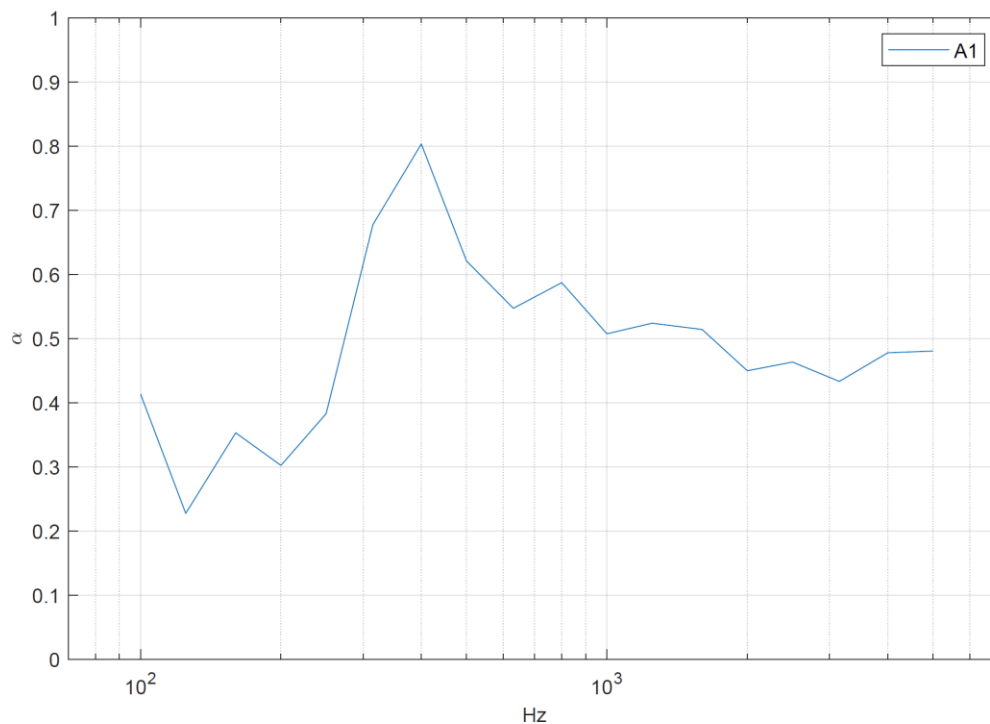| Test reference	Description	Array Type (1 or 2)	Surface area (m^2)
A1	Array 1 arranged into 1m x 1m sample (surface area includes the sides of the array)	Type 1	1.60

Figure 10: Photograph of specimen A1 arranged on the reverberation room floor for sound absorption testing.

Figure 11: Sound absorption of test sample A1 (see Table 3). The vertical axis represents the proportion of incident sound that is absorbed. A value of 1 is total absorption and a value of 0 is total reflection.

In previous studies the peak in sound absorption coefficient for an equivalent layer thickness occurred at 800Hz. Here we see a peak in the sound absorption coefficient at 400Hz for the same thickness layer.

In this case modifications to the end grain have significantly enhanced sound absorption at low frequencies. Typically, greater depth or thickness of material is required to achieve this but with modification of the internal structure an enhanced behaviour is achieved with equivalent dimensions.

Test A2

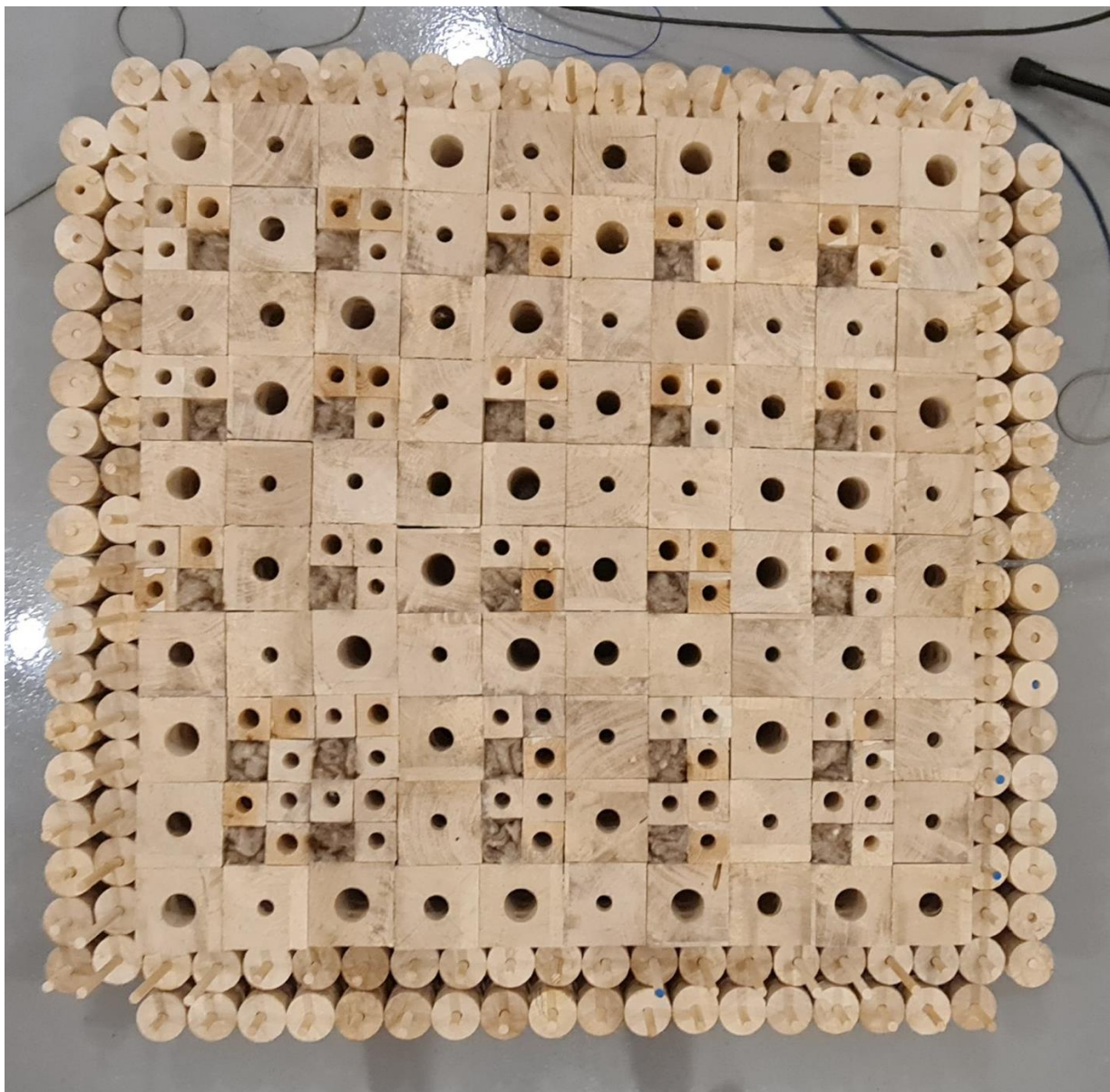| Test reference	Description	Array Type (1 or 2)	Surface area (m²)
A2	Array type 1 with elements of array type 2 arranged around the outer edge (surface area includes the sides of the array) surrounded by elements of array 2. Sheep's wool is used in the empty slot.	Combination	2.12

Figure 12: Photograph of specimen A2 arranged on the reverberation room floor for sound absorption testing.
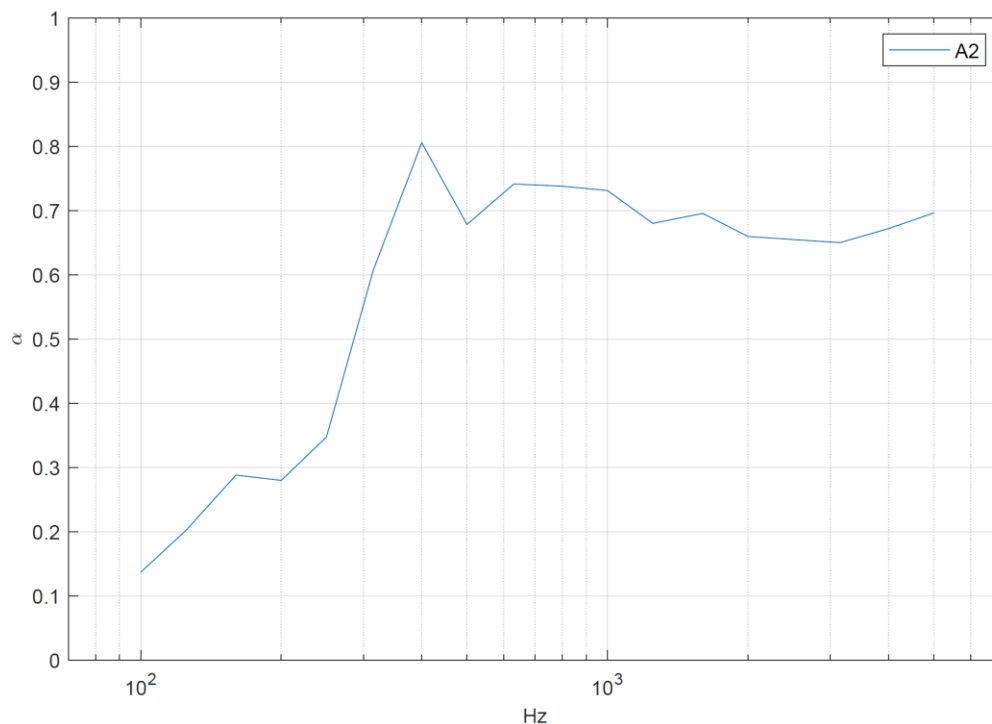
Figure 13: Sound absorption of test sample A2 (see Table 3). The vertical axis represents the proportion of incident sound that is absorbed. A value of 1 is total absorption and a value of 0 is total reflection.

Test A1 shows a high sound absorption at low frequencies which peaks at 400Hz. Whilst this is desirable the sound absorption of the end grain array does not compare well to open cell porous materials (e.g. mineral wool) above this frequency.

Combining array types 1 and 2 rectifies this issue to some extent as shown in Figure 13. The peak in low frequency sound absorption is maintained and sound absorption at higher frequencies is improved. A sound absorption coefficient between 0.7 and 0.8 is observed for all frequencies between 400 and 5000Hz meaning that in this frequency range 70-80% of incident sound energy is absorbed by the array.

Test A3

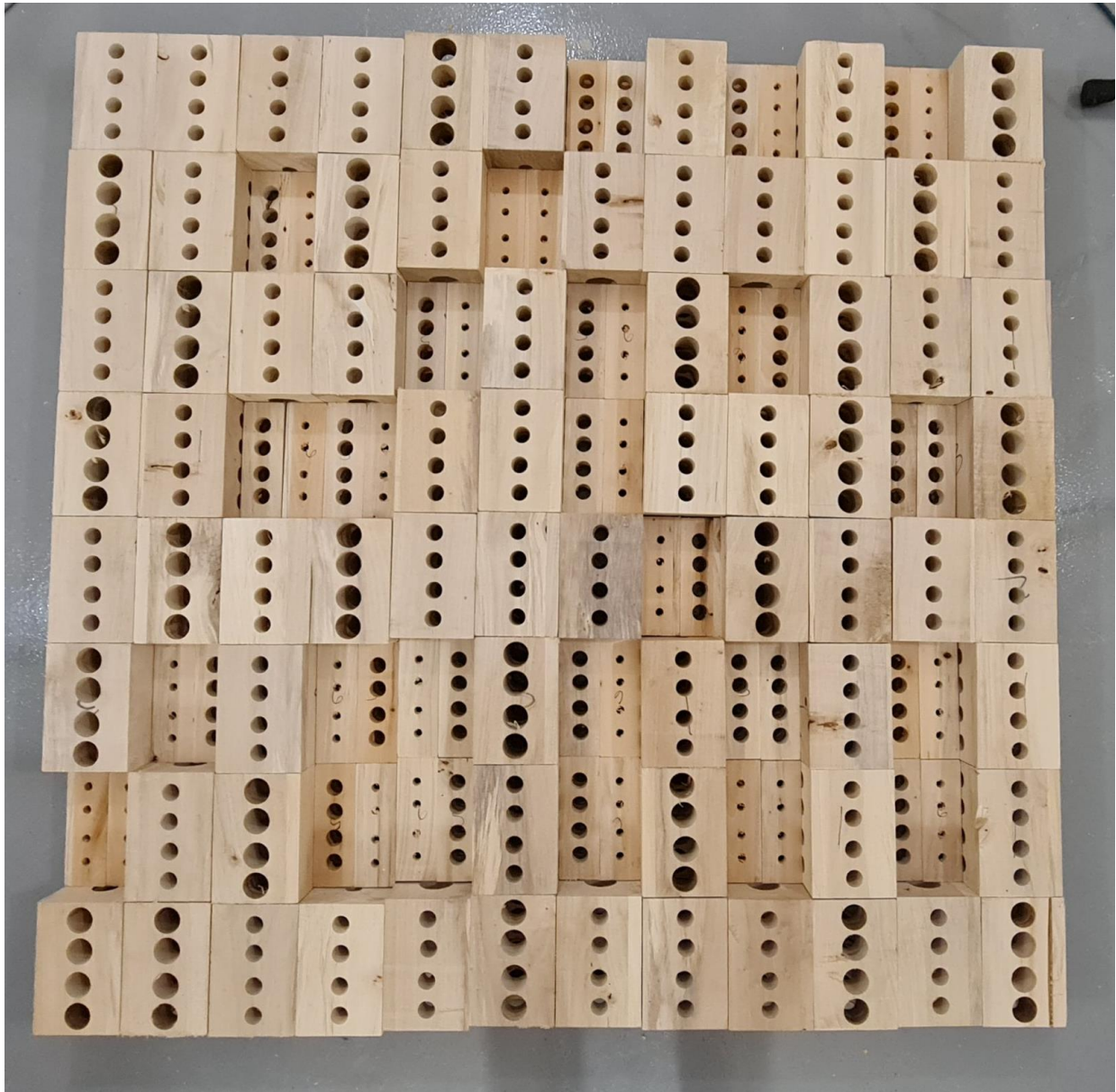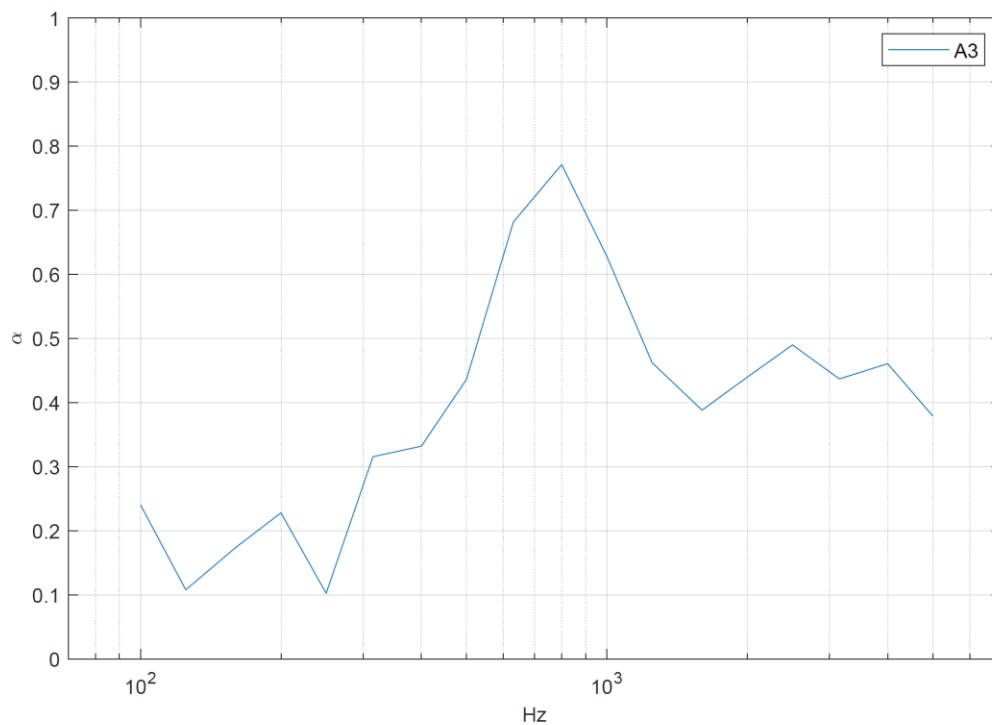| Test reference	Description	Array Type (1 or 2)	Surface area (m²)
A3	Array type 1 with all elements laid on their sides (surface area includes the sides of the array)	N/A	1.90

Figure 14: Photograph of specimen A3 arranged on the reverberation room floor for sound absorption testing.

Figure 15: Sound absorption of test sample A3 (see Table 3). The vertical axis represents the proportion of incident sound that is absorbed. A value of 1 is total absorption and a value of 0 is total reflection.

This is an interesting result that demonstrates the importance of combining theory and measurement in a rigorous way. Exactly the same elements as those used in Array (A1) are employed here in a different configuration (not the intended design). In this arrangement the array is less effective at absorbing low frequency sound energy despite occupying the same volume of space and using the same amount of material. This is evident from the frequency of the sound absorption peak which occurs at 800Hz rather then 400Hz as was the case for Array type 1 as it was intended.

Test A4

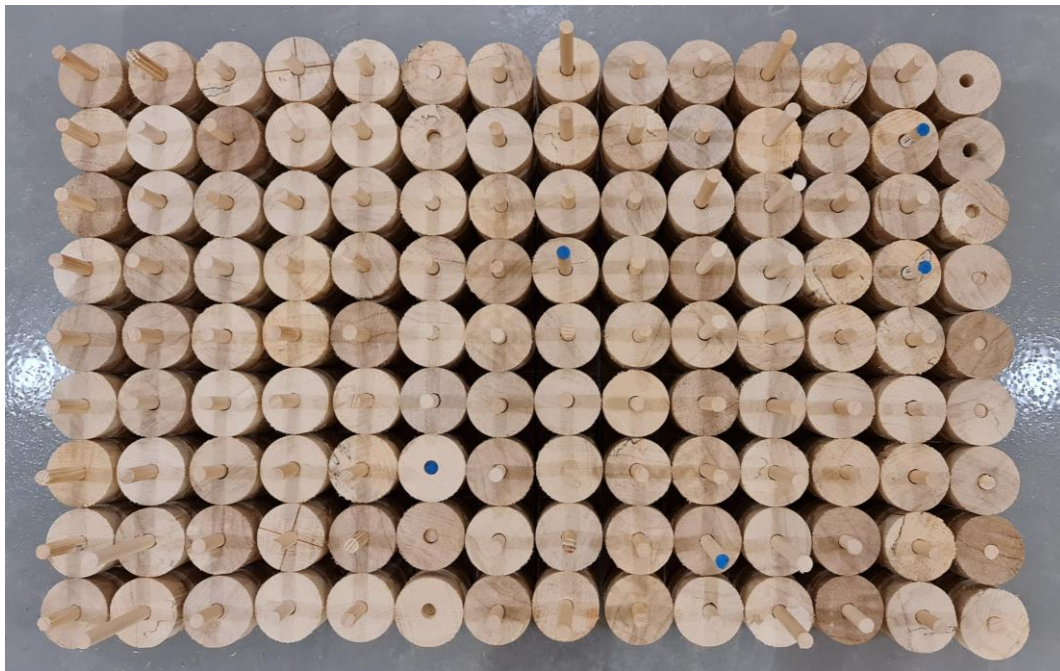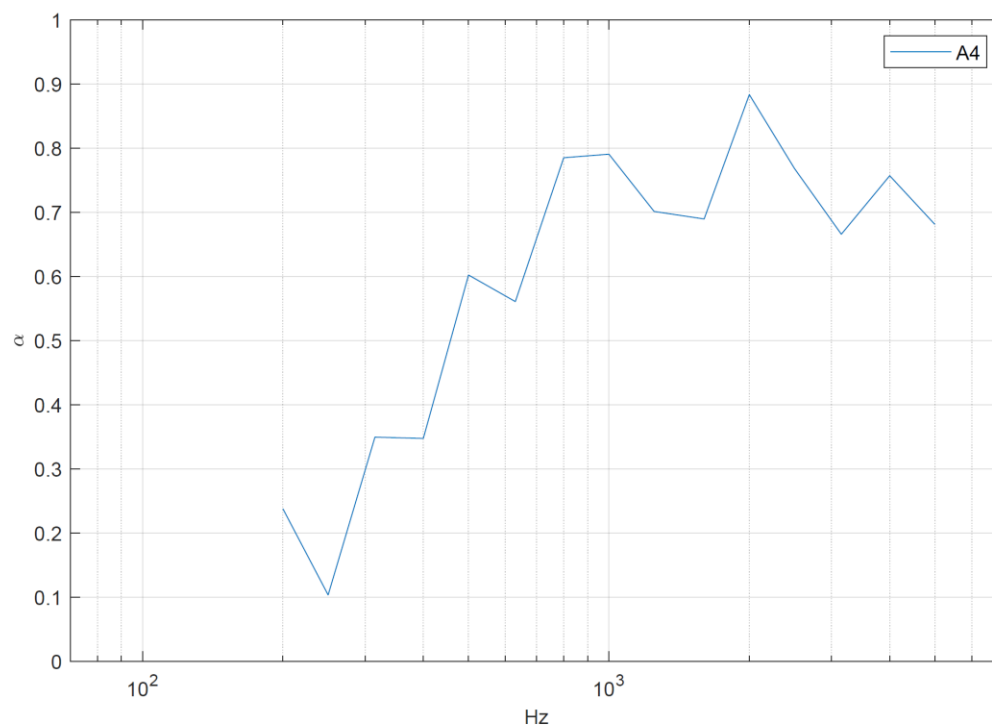| Test reference	Description	Array Type (1 or 2)	Surface area (m^2)
A4	126 stacks of 25mm thick discs with 10mm spacers (surface area includes the sides of the array). 3 layers in each stack.	Type 2	0.733

Figure 16: Photograph of specimen A4 arranged on the reverberation room floor for sound absorption testing.

Figure 17: Sound absorption of test sample A4 (see Table 3). The vertical axis represents the proportion of incident sound that is absorbed. A value of 1 is total absorption and a value of 0 is total reflection.

The type 2 array consists of multiple wood end grain discs separated by small spacers as shown in Figure 16. In the configuration tested here 126 stacks of three 25mm thick discs form the array.

Compared to array type 1 the sound absorption is poorer at low frequencies, i.e. below 1000Hz, but sound absorption is improved above this frequency. A likely reason for this is that the array elements are not separated from each other resulting in weaker resonances that contribute to low frequency sound absorption. Conversely, a larger area of wood end grain is revealed which improves sound absorption at higher frequencies.

Test A5

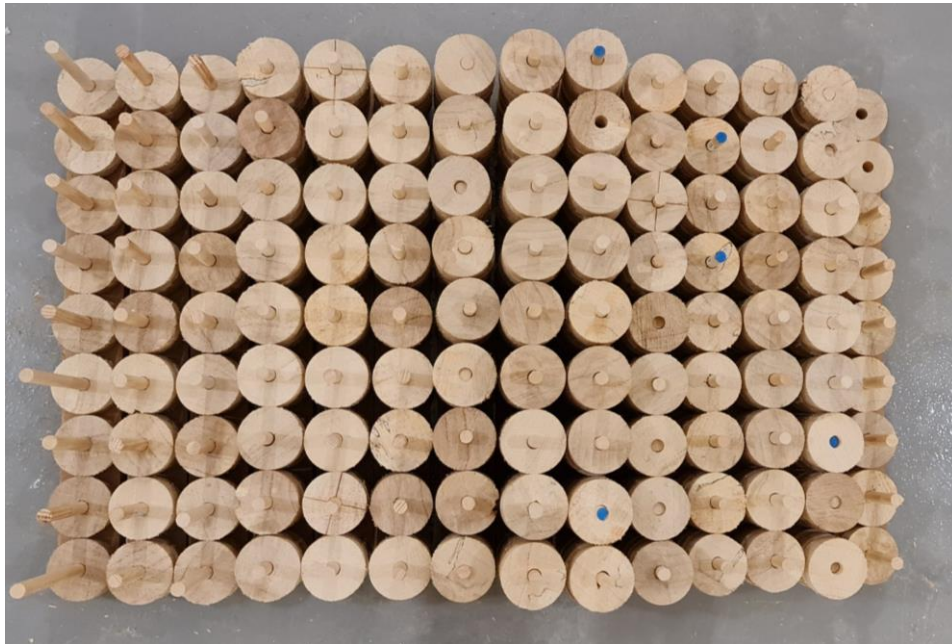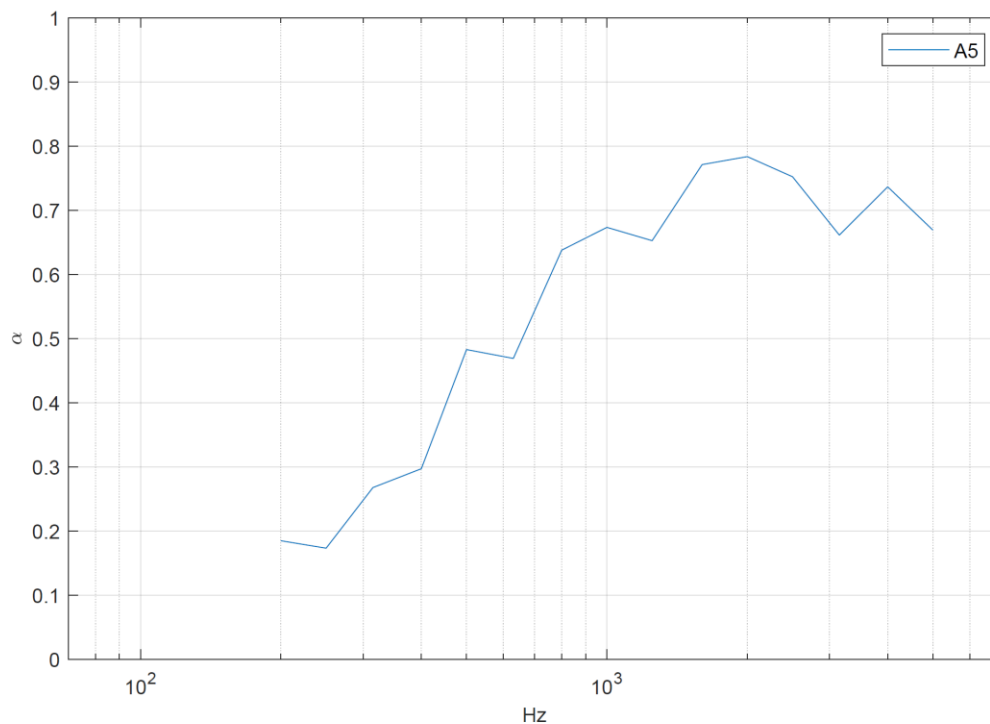| Test reference	Description	Array Type (1 or 2)	Surface area (m²)
A5	126 stacks of 25mm discs with 10mm spacers and a graduated profile (surface area includes the sides of the array)	Type 2	0.761

Figure 18: Photograph of specimen A5 arranged on the reverberation room floor for sound absorption testing.

Figure 19: Sound absorption of test sample A5 (see Table 3). The vertical axis represents the proportion of incident sound that is absorbed. A value of 1 is total absorption and a value of 0 is total reflection.

Sample A5 is also a type 2 array consisting of multiple 25mm thick end grain discs stacked with 1cm spacing but now using a graduated profile as shown in Figure 18. In this case the array performs slightly less well than was the case for sample A4 but a similar trend is seen; an improvement of high frequency sound absorption and be less effective than A1 in the low frequency range.

The main advantage of this type of array is the ease and flexibility of manufacture and when used in combination with array type 1 a broadband sound absorber can be achieved (see A2, Figure 13). Another advantage of this type of array is that it allows interesting and attractive profiles to be created resulting in a nice feature.

9.   References

1.   Acoustical properties of air-saturated porous material with periodically distributed dead-end pores, P. Leclaire, O. Umnova, T. Dupont, R. Panneton, J.Acoust.Soc.Am, 137, 1772-1782 (2015).

2.   A microstructure material design for low frequency sound absorption, T. Dupont, P. Leclaire, R. Panneton, O. Umnova Appl. Acoust.136, 86-93 (2018).