Maximizing sound absorbing performance of PU foam by the layered GO nanoplatelets loading

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The sound absorption performance of graphene oxide (GO) impregnated polyurethane (PU) foam was studied. PU foams are fabricated to have a wide range of GO loading density by step-by-step impregnation method. It was determined that the flow resistance and the sound absorption coefficient were increased as a function of GO loading, and other foam properties as well. In addition to impregnating GO with a simple structure, a method for optimizing the spatial arrangement of GO impregnated PU was presented. The impregnation structure with the optimal sound absorption rate was suggested by controlling the impregnation structure in the multilayer structure of the porous polyurethane sponge. To this end, we developed a computer algorithm to find the optimal sound absorption structure. Through the simulation, the average sound absorption coefficient between 500 Hz to 4 kHz was maximized as 0.91 by only 56mm thick PU foam, which was verified by the impedance tube measurement. Also, various possibilities were revealed through extensive experiments and simulations.

1 Introduction

As the importance of noise control increases, there is a continuous need for more effective sound absorbing materials. [1] Although all materials can absorb sound as a passive medium, the materials with high sound absorption capability among these materials are very limited. The most efficient sound absorbing materials are mainly porous or fibrous, consisting of open, semi-open or closed pore structures interconnected with regular or irregular shapes. [2]

In general, porous materials have structural characteristics with channels through which sound waves can enter the material. The principle of sound dissipation is that energy is lost due to heat loss due to friction between the air molecules and the pore walls and viscosity loss due to the viscosity of the air flow in the material. This energy consumption principle gives the porous material a wide frequency band for sound absorption. [3,4] The porous structure is a suitable form for dissipating this energy. In particular, it has the advantage of being relatively easy to manufacture and light due to its low density. [5]

Among various porous materials, polyurethane foam (PU) is the most widely used material due to its effective acoustic damping and low cost. In addition, polyurethane is a material that can be manufactured in a variety of soft foams, high elastic foams, or other porous materials, as required. The sound waves penetrate into the pores of the porous PU and are dissipated by viscous friction and heat exchange occurring in the interconnected pores inside. However, in the open cell type PU foam, it is known that it is very difficult to obtain excellent sound absorption performance in a wide frequency range when the sound absorbing material is thin. To overcome this, optimization of the sound absorbing capability has been attempted through optimization of the porous structure itself. [6] Meanwhile, a method of mixing PU with other materials has been attempted. Various optimization methods have been added to the method of improving the sound absorption performance by mixing the material with the PU, thus providing a basis for maximizing the sound absorption performance. [7, 5] Recently, nanomaterials have been noted as a material to be mixed to improve the sound absorption capability of the porous material. In particular, additives such as graphene oxide (GO) and carbon nanotubes (CNT) have been found to be very effective. [8-14]

In this study, graphene oxide (GO) was added into PU foam to maximize sound absorption capability. Especially, the layer optimization method was applied. In particular, through the optimal arrangement of the layers, it was possible to noticeably improve the sound absorption performance in the low frequency range. As a result, the GO impregnated multi-layer PU foam system can have excellent sound absorption coefficient over the entire frequency range, thus industrial application of the result is expected in near future.

2 Theory and Strategy

2.1 Strategy for maximizing sound absorbing coefficient by multi-layer arrangement

To optimize the sound absorption coefficient, the layers were divided into *n* layers, and each layer was able to combine sound absorbing materials impregnated with GO up to 6 times. Multi-layer sound absorbing material absorption coefficient calculation is performed by a MATLAB code constructed based on a matrix model from references. [15, 16] The optimization routine was coded separately so that the combination with the maximum average sound absorption coefficient could be selected. The average sound absorption coefficient was obtained through the following equation.

$$\overline{\alpha}=\frac{\alpha_{500\,Hz}+\alpha_{1\,kHz}+\alpha_{2\,kHz}+\alpha_{4\,kHz}}{4}$$

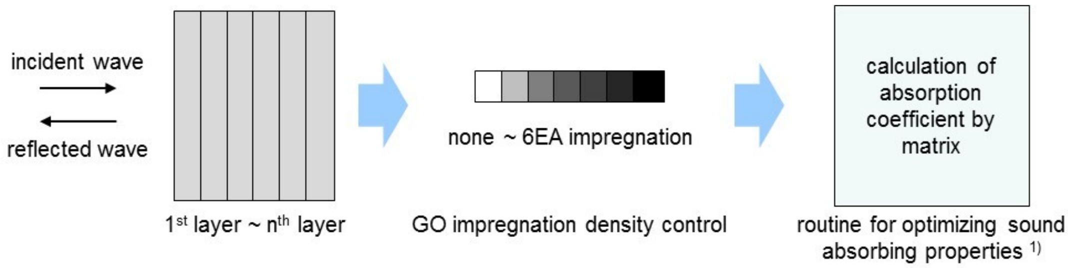


Figure **1**: Strategy for maximizing sound absorbing coefficient by multi-layer arrangement

2.2 Impregnation of graphene oxide into PU foam

To verify the calculated sound absorption coefficient experimentally, thin layers of GO impregnated PU foam were prepared. To impregnated GO into PU foam, vacuum impregnation method was applied. The thickness of each layer was set to 4 mm. Therefore, the thickness of the eight layers corresponds to 32 mm. Since each layer is impregnated with GO in 7 steps (0-6 times), a total of 7^8 = 5,764,801 combinations are derived. The sound absorption coefficient was measured using an impedance tube. As shown in Fig. 3, as the number of impregnations increased, the weight of impregnated GO increased linearly. On the other hand, the flow resistivity shows a tendency to increase rapidly as the amount of impregnation increases.

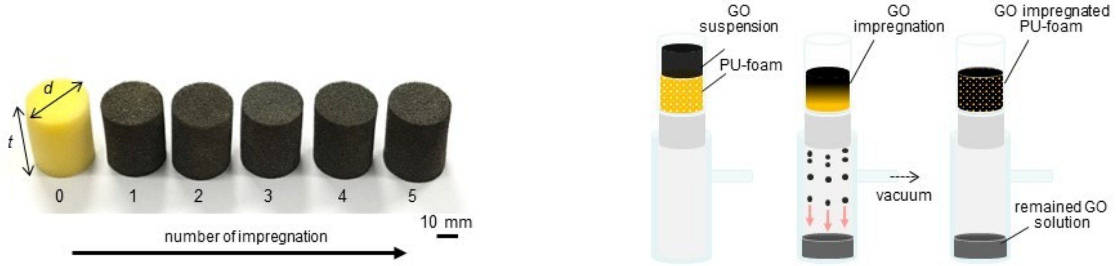


Figure **2**: GO impregnated PU foam (left), illustration of vacuum impregnation (right)

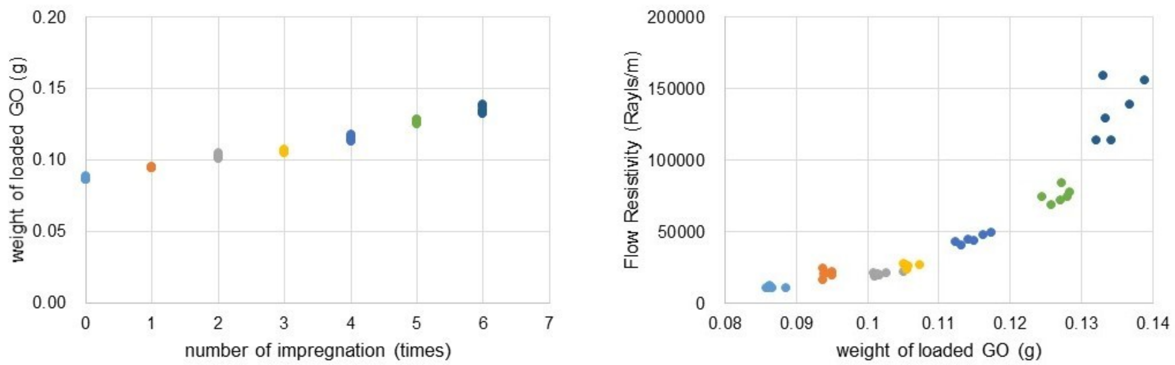
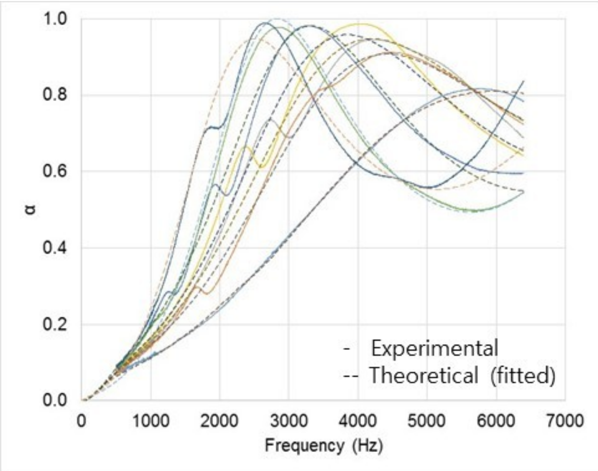


Figure 3: Weight of GO upon impregnation (left), flow resistivity as a function of loaded GO (right)

2.3 Foam properties of GO loaded PU foam

Determination of foam properties is very important in order to apply the elastic porous material theory. In this study, the bulk density, porosity, Young's modulus, and flow resistivity were measured or estimated from experiment. The tortuosity, viscous characteristic length, and thermal characteristic length were derived through fitting procedure. In the left panel of Fig. 4 shows the results of the fitting process to estimate the form properties. As shown in the right panel of Fig. 4, the fitted tortuosities are proportional to the density of impregnated GO. Table 1 below summarizes the foam properties measured or estimated according to the impregnation steps of all steps of GO impregnation. It is clearly shown in the table that Young's modulus, flow resistivity, and tortuosity increse as the number of GO impregnation increases.



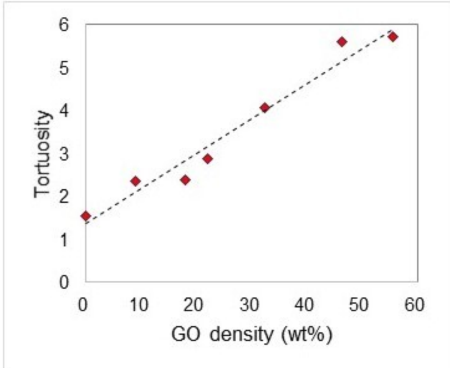


Figure 4: Fiited curves for foam parameters estimation (left), fitted tortuosites as a function of GO loading density (right)

Number of impregnation (times)	Bulk density (kg/m^3)	porosity	Young's Modulus (kPa)	Flow resistivity (Pa s/m^2)	Tortuosity	Viscous Characteristic Length	Thermal Characteristic Length
0	32.78	0.9697	48.6	10817.4	1.55	1.00E-04	2.70E-04
1	35.70	0.9682	438.7	17489.2	2.36	1.00E-04	2.00E-04
2	38.65	0.9668	831.8	20177.3	2.39	8.00E-05	2.00E-04
3	40.02	0.9661	1014.8	26039.5	2.87	9.00E-05	2.00E-04
4	43.42	0.9644	1468.8	44500.3	4.06	1.20E-04	2.00E-04
5	48.00	0.9622	2080.4	74944.4	5.59	1.00E-04	7.20E-04
6	50.99	0.9607	2479.7	130080.6	5.71	6.00E-05	6.50E-04

Table 1: measured and predicted foam properties

3 Result and Discussion

3.1 Sound absorption curves by thickness increase

Before examining the optimal combination of layers, the calculation result of the sound absorption curve with the increase in thickness was compared with the measurement result to examine the validity of the theory and measurement. Each layer was set as 4mm thick 5 times of GO impregnated PU foam. The sound absorption curves were measured from 1 layer up to 6 layer (24 mm) and compared with the calculation. As shown in the following results, it can be seen that the experimental results are well explained even by simply inputting foam properties without applying a separate optimization. Therefore, we can be sure that the subsequent optimization process can have sufficient probability with the experiment.

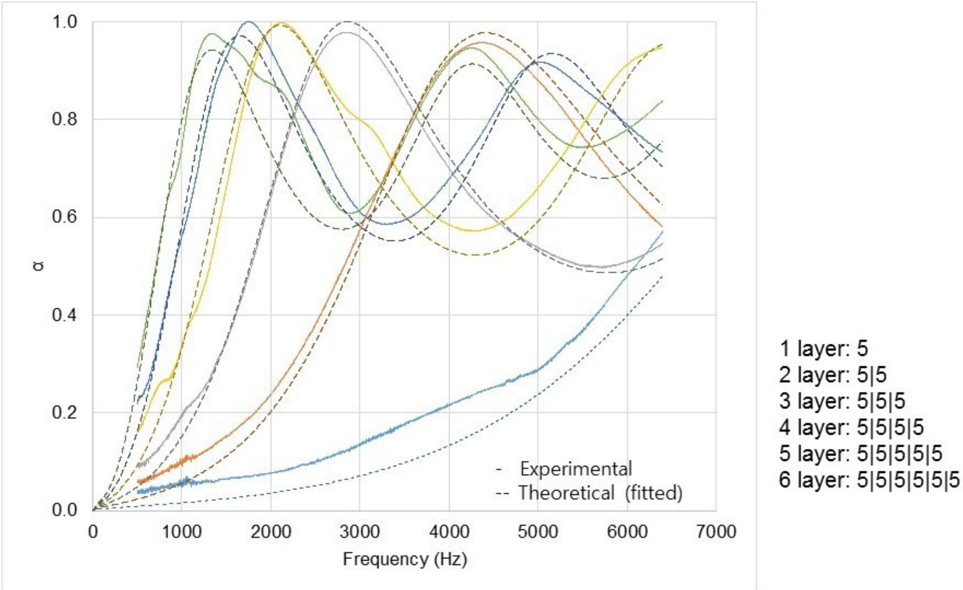


Figure 5: 1-6 layer (1 layer thickness 4mm) multi-layer sound absorbing material prediction and experimental results

3.2 Optimizing sound absorbing performance of two-layer arrangement

First, optimization was performed on the two-layer structure. In the upper graph of Fig. 6, 3 groups of curves correspond to the case of no impregnated case, 3 times GO impregnated case, and 6 times GO impregnated case, respectively. (from bottom to top). As a result of calculating the improvement of the average sound absorption rate, compared to the case without impregnation, 6 times of GO impregnated case exhibited 153% improvement of $\overline{\alpha}$ by calculation , and 148% by experiment.

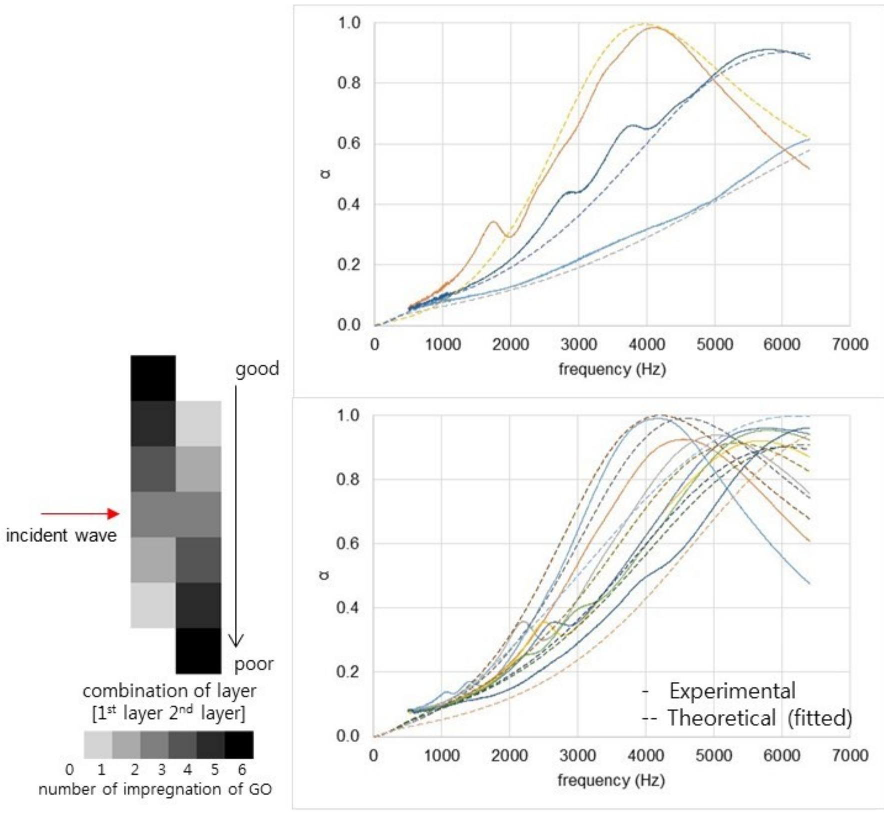


Figure 6: Optimizing sound absorption coefficient by two-layer arrangement

In the lower panel of Fig. 6, the result of fixing the total impregnation amount and optimizing the sound absorption coefficient is shown. In this case, it can be seen that it is advantageous to arrange the sound absorbing material having a high GO impregnation amount in the direction in which sound waves are incident. As a result of examining the improvement of the average sound absorption rate compared to the case of uniformly impregnated, 6|0 combination (6 times impregnation | no impregnation) exhibited 49% improvement of $\overline{\alpha}$ by calculation, and 41% by experiment.

3.3 Optimizing sound absorbing performance of multi-layer arrangement

The optimal structure of the sound absorbing material was examined while increasing the thickness. As a result, it can be seen that in the case of a thin sound absorbing material of about 10 mm, it is advantageous to arrange the sound absorbing material having a high GO impregnation amount in the direction in which sound waves are incident to improve the average sound absorption rate. In the case of a thickness of about 25 mm, it can be seen that it is advantageous to arrange the sound absorbing material having a high GO impregnation amount at two parts of the midpoint of the sound absorbing material and the incident surface. It can be seen that as the thickness approaches 50 mm, it is advantageous to place a sound absorbing material having a high GO impregnation amount on a wall where sound waves are reflected. If the average absorption coefficient derived at the maximum thickness is shown, it can be obtained that the average absorption coefficient is close to 0.9 in a sound absorbing material of about 50 mm.

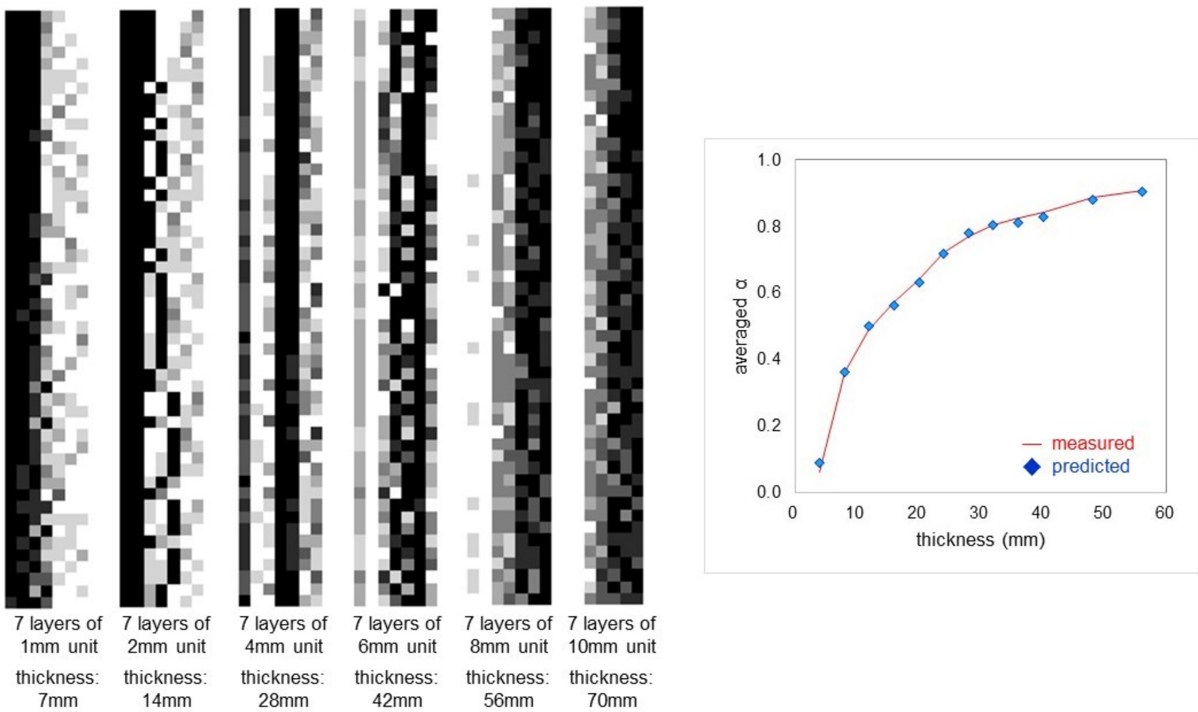


Figure 7: Optimum combinations of layer for maximizing avreage sound absoring coefficient at different thickness (left), maximized average sound absorption coefficient prediction and measurement result (right)

3.4 Summary of improvement of average sound absorption coefficient

The following is a result showing the improvement of the sound absorption coefficient according to the optimal arrangement of the sound absorbing material for each thickness. As the thickness of the layer increases, it can be seen that the improvement amount tends to decrease. In particular, it can be seen that even when the impregnation amount is fixed, the average sound absorption coefficient can be enhanced through an appropriate layer combination.

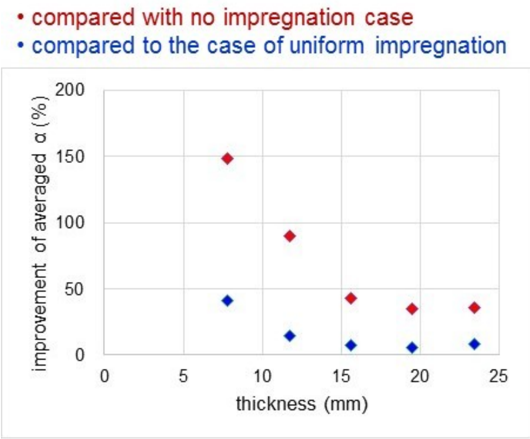


Figure 8: Improvement in average sound absorption coefficient (compared with no impregnation case, compared to the case of uniform impregnation)

3.5 Result on maximizing average sound absorption coefficient

The following shows the sound absorption coefficient curve when the maximum average sound absorption coefficient is derived. The case showing the maximum sound absorption coefficient was shown in combination 0|0|2|2|5|6|6. Here, the thickness of each layer is 8 mm. In addition, similar levels of sound absorption coefficients were also obtained in combinations with similar patterns. The theoretical average sound absorption coefficient calculation result was 0.9074, and the experimental result was 0.9011. In the combination of the same impregnation amount, the combination with the lowest average sound absorption rate was represented by 6|6|6|0|0|3|0, and similar sound absorption characteristics were also found in combinations showing similar patterns. In this case, the average sound absorption coefficient was calculated as 0.6529 and was measured to be 0.7277.

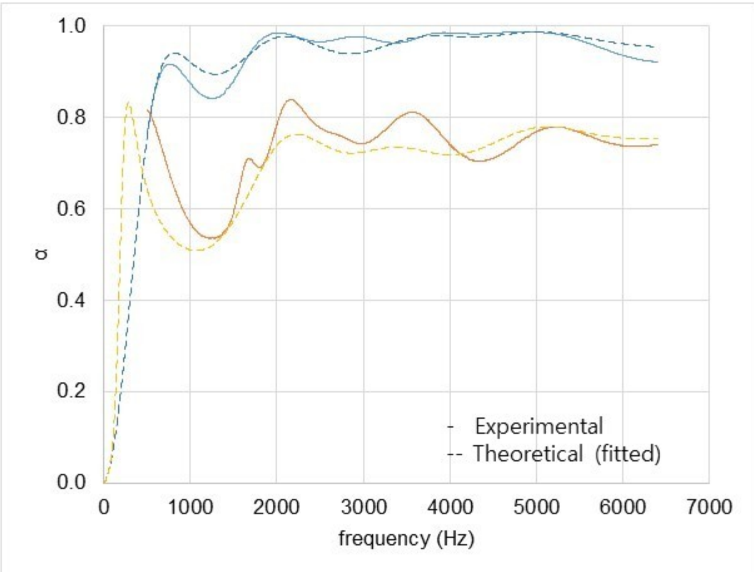


Figure 9: Maximized calculated and measured sound absorption coefficient curves of 7 layers combination (each layer is 8mm, total thickness is 56mm.)

4 Conclusion

A multi-layered layer model is proposed to optimize the sound absorption rate of the sound absorbing material. As a method of maximizing the sound absorption rate by adjusting the GO impregnation amount of each layer is proposed. The procedure for calculating the sound absorption rate using the matrix calculation method is developed based on the theory proposed by Bolton J, Shiau N-M, and Kang Y. Predicted values of sound absorption coefficient are very consistent with the experimental values. As a result of the theoretical calculation of the improvement rate of the sound absorption rate, an improvement of 153% was expected compared to the case without impregnation, and it was measured to be 148%. For uniform impregnation, a 49% improvement was predicted and a 41% improvement was measured. The optimum arrangement of the 56 mm thick sound absorbing material was calculated as 0|0|2|2|5|6|6 and similar patterns. The average sound absorption coefficient was calculated as 0.9074 and measured as 0.9011.

5 Acknowledgements

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