Optimization of Acoustical Properties Polyurethane (PU) Wood Fibres Foam Composites

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Abstract. In this study, an optimization approach was proposed to improve acoustical behaviours of PU foams. The important parameters of PU foams: content of the combination of renewable monomer and epoxy as polyol, methylene diphenyl diisocyanate (MDI) as crosslinker. Their effects on sound absorption coefficient of PU foams were studied by using Taguchi methods. In addition, wood fibres were incorporated into PU foams as fillers to improve the acoustical properties of PU foams. Three controlled factors: the monomers, wood fibres and sample thickness with three levels for each factor were chosen and Taguchi method based on orthogonal array L9 (3³) was employed to conduct the experiments. Based on the results of Taguchi’s orthogonal array L9 (3³), signal-to noise (S/N) analysis was used and developed to determine an optimal formulation of PU wood fibres foam composites. The results showed that the noise reduction coefficient (NRC) had showed an increased value from 0.4850 to 0.5550 positively improved the acoustic property and the best combination values of variables were monomer mixture of 25 gram, filler ratio of 3% wt and sample thickness of 30mm.

1. Introduction
Recently, sound absorbing materials constitutes one of the major requirements for human comfort and economical nowadays which required in modern technologies environment. The improvement of controlling noise by sound absorption contributes a great opportunity for acoustic attenuation method of various porous materials. Sound absorbing materials are classified on the ability of the material to absorb as much as sound wave and reflect as minimal as it could and at the same time transmit more of the waves [1]. Porous materials are excellent for sound absorption and good heat insulator. Its open pores permit confined airflow via the material thus absorbing sound and additionally preventing efficient heat exchange. Rus et al., [2] studied the porous materials with uniform and non-uniform pore structure gives different result in sound absorption coefficient at different frequency level. Flexible polyurethane foams (PU foams) with high porosity have been extensively used as noise control materials in many applications in industry due to effective sound absorption, light weight, excellent viscoelasticity and acoustic absorption properties [3,4].

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The acoustic panels that are made from natural fibres are less hazardous to human health and eco-friendly than those made from common synthetic fibres. Hence, a rising concern for human health and safety issues has urged manufacturers and engineers to inquire alternative materials from natural fibres as a replacement for synthetic fibres. Natural fibres are essentially completely biodegradable and modern technical developments have made natural fibre processing more economical and environmentally friendly.

Many researchers [5-9] have examined and researched the suitability, competitiveness, and capabilities of natural fibres embedded in polymeric matrices. The researchers concentrated on the effect of the fibre surface modifications as well as manufacturing processes in improving fibre or polymer compatibility. On the other hand, some researchers studied and compared between different natural fibre composites and their stability in various applications [10]. Therefore, the effective sound absorption of any natural fibre polymer composite material can be achieved when it has a more tortuous path, higher surface area, higher flow resistivity, and low porosity within it at the optimal range.

Since, the issue of environmental and sustainability with climate change has become a major consideration in the development of new materials in the world, the wood fiber waste is the best filler to be used. Wood fiber is structural materials in plants and the most abundant biomass in earth. The use of wood fibers as fillers in polymeric composites show advantages as they are inexpensive, derive from renewable resources, present lower density than mineral fibers, undergo little damage during process and their disposal causes minor ecological impact [11].

Design of experiments (DoE) is a systematic approach to engineering problem-solving that applies principles and techniques at the data collection stage. Study by P. Muray et al., [12] highlighted the benefits of using DoE optimization during the development of new synthetic methodology. In other words, DoE method is used to find the cause and effect relationships which is significant to manage inputs and optimize the output prior going into production [13,14]. Meanwhile, Taguchi method is a broadly accepted method of DoE which has proven in producing high-quality products at subsequently low cost [15]. It provides a simple, efficient and systematic approach to estimate the effects of several variables separately, simultaneously or as combinations [16, 17]. Therefore, in this study, Taguchi method based on orthogonal arrays (OA) is a structured with an organized method has been applied to perform the present experiments and the sound absorption of PU foam composites was studied.

2. Methodology
2.1. Materials
Renewable bio-epoxy from the waste cooking oil were prepare at E1 Sustainable Polymer Engineering (AMMC), UTHM, Malaysia which comprises the acid-catalyst ring opening of the epoxides to form polyols [18]. Flexible polyol (Aura 2104 H3) and flexible MDI (diphenylmethane 4,4-diisocyanate) were purchased from Sykt Saintifik Bersatu (M) Sdn Bhd. Table 1 shows the materials used for preparation of PU foams. The wood dusts were obtained from Tukang Kayu A.Hamid Sdn Bhd, furniture industry from Batu Pahat, Johor. With the size of wood fibers, 900-1200 μm, 3 different percentages has been selected which is 1 wt%, 3 wt% and 5 wt%. Figure 1 shows the photographs of (a) wood fibres and (b) the size of wood fibres under microscopy.

| Materials            | Content of each materials (gram) |
|----------------------|----------------------------------|
| Flexible polyol      | 25, 15, 5                        |
| Renewable Bio-epoxy  | 5, 15, 25                        |
| MDI                  | 15                               |
| Wood Fibres          | 0.45, 1.35, 2.25                  |
2.2. Synthesis of PU foam composites
Firstly, flexible polyols were mixed with renewable bio-epoxy were prepared in the plastic container. Subsequently, wood fibres with (1%, 3% and 5%) of matrix weights ratios were added to the mixture and mixed for 5 minutes. Afterward, croslinker, MDI was added to the wood fibres/polyols mixture and vigorously stirred for 15 seconds. Finally, the mixture was left at room temperature to expand and cure for 24 hours. Upon curing, the samples were removed from the plastic container and were cut using knife and cylindrical shape of Teflon mold. Cylindrical samples with a diameter of 100 mm were used for the low frequency range (100–2000 Hz) and samples with 28 mm diameter were used for the high frequency range (200–6000 Hz). All the samples had a thickness of 10mm, 20mm and 30mm.

2.3. Experimental Design
The effects of process parameters in the formulation of PU foam composites and the optimum combination for acoustic properties of PU foam composites were studied by using Taguchi approach. The experiments were conducted with three controllable 3-level factors and one objective. Table 2 shows three controlled factors, i.e., the polyl and renewable bio-epoxy mixture (i.e., A), the content of wood fibers (i.e., B) and the sample thickness (i.e., C) with three levels for each factor. The orthogonal arrays L9 (33) was chosen and then 9 experimental runs were carried out based on the design matrix shown in Table 3.

In engineering, noise reduction coefficient (NRC) is commonly used as an evaluation parameter to characterize sound absorbing materials. NRC is defined as arithmetic mean of the absorption coefficient at frequencies of 250, 500, 1000 and 2000 Hz, which is defined in the following equation,

\[
\text{NRC} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4}
\]

Thereby, NRC of PU foams was selected as target objective, the higher NRC the better sound absorbing. Upon completion of the nine experimental runs, the corresponding response, sound absorption coefficient tested by acoustical property measurements.

Figure 1. Wood fibers prepared for PU foam composites.
Table 2. Description of factors and their levels for Taguchi experimental design.

| Variables       | Parameter code | Level |
|-----------------|----------------|-------|
| Monomer mixture | A              | 5 15 25 |
| Filler ratio    | B              | 1 3 5  |
| Sample Thickness| C              | 10 20 30 |

Table 3. Orthogonal array L₉(3³) of experimental design.

| Monomer | Filler Ratio | Sample Thickness |
|---------|--------------|------------------|
| 5       | 1            | 10               |
| 5       | 3            | 20               |
| 5       | 5            | 30               |
| 15      | 1            | 20               |
| 15      | 3            | 30               |
| 15      | 5            | 10               |
| 25      | 1            | 30               |
| 25      | 3            | 10               |
| 25      | 5            | 20               |

2.4. Sound Absorption Coefficient

Sound absorption test is performed to investigate the ability of certain material to absorb sound. The sound absorption coefficient was obtained by using a two-microphone impedance tube based on transfer function method in accordance to ASTM E1050-98 international standards (ASTM, 1998) [19]. Cylindrical samples with a diameter of 100 mm were used for the low-frequency range (100–2000 Hz) and samples with 28 mm diameter were used for the high-frequency range (200–5000 Hz). All the samples had a thickness of 10 mm, 20 mm and 30 mm. Figure 2 shows the sample foams used for acoustic test. Figure 3 presents the schematic for sound absorption test (a) low frequency tube test (b) high frequency tube test.

Figure 2. PUs foam (a) thickness of 10mm, 20mm and 30mm (b) diameter of 28 mm (c) diameter of 100 mm.
3. Result and Discussion

3.1. Signal-to-noise (S/N) ratio

Signal-to-noise ratio is used to measure the performance characteristic in Taguchi method, and then the experimental results are transformed to S/N ratio. Generally, there are three types of performance characteristic in the analysis of the S/N ratio, which are the lower the better, the higher the better and the nominal the better, respectively.

1) the lower the better:

\[ \eta = -10 \times \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \]  \hspace{1cm} (2)

2) the higher the better:

\[ \eta = -10 \times \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \]  \hspace{1cm} (3)

3) the nominal the better:

\[ \eta = -10 \times \log \left( \frac{1}{ns} \sum_{i=1}^{n} y_i^2 \right) \]  \hspace{1cm} (4)

where \( \eta \) represents the S/N ratio, \( y_i \) represents a quality measurement, \( n \) represents the total number of the tests, \( s \) represents the standard deviation. The quality characteristic in this study is NRC and the higher NRC is preferred. Therefore, the quality characteristic of the NRC is the higher the better.

3.2. Analysis of the S/N ratio

Based on the results of acoustic performances, the S/N ratio was used to determine the important effect of three parameters. The experiments results were further transferred to S/N ratio. According to the quality characteristic of the results, a higher S/N ratio corresponds to the better quality. The optimal level of three factors is the level with the highest S/N ratio. Table 4 shows the experiment results and corresponding S/N ratio for NRC. The S/N ratio for three levels of three factors for NRC is computed and listed in Table 5; the larger value of S/N ratio corresponds to larger NRC, which means the best sound absorption properties. The order in the Table 5 ranks the influence of the corresponding factors on the results.

The trend of the S/N ratios for three factors at their three designated levels affecting the sound absorption is shown in Figure 4. It is well known that the higher S/N ratio, the better the response for factorial effect. From the Figure 4, it can be clearly seen that the best combination of three factors to

![Figure 3. Schematic of the experimental setup for (a) low frequency (b) high frequency.](image-url)
obtain the maximum NRC value for the S/N ratio is at level 3 of monomer mixture (25g bio-epoxy), level 2 of filler ratio content (3 wt%) and level 3 of sample thickness (30 mm). It can be also seen that the factor C (sample thickness 30 mm) has the most significant effect on the NRC, followed by factor A (monomer mixture) and factor B (filler ratio). So the optimal combination of parameters can be obtained as ‘Monomer 25 - Filler ratio 3 - Sample Thickness 30’ for NRC. The above results revealed that the sample thickness PU foam composites significantly affect the sound absorption coefficient. Therefore, suitable amount of monomer, filler ratio and sample thickness must be determined in order to obtain higher sound absorption of PU foam composites.

From this results, highest thickness of the PUs foam samples, the higher the sound absorption values [14]. Thus, the sound absorption has direct relationship with the thickness of the polymer foams. The increasing in thickness gives better performance of the materials as sound absorber which due to higher interconnected porous structure. This is also shows that the porous structure increased the level of vibration energy in the foam and gives highly versatile acoustic foam [20].

Table 4. Experimental results of NRC and corresponding S/N ratio.

| Run | Factors | Response A | B | C | NRC | S/N Ratio |
|-----|---------|------------|---|---|-----|----------|
| 1   | 5       | 1          | 10|    | 0.12500| -18.0618 |
| 2   | 5       | 3          | 20|    | 0.33250| -9.5642  |
| 3   | 5       | 5          | 30|    | 0.46750| -6.6044  |
| 4   | 15      | 1          | 20|    | 0.37000| -8.6360  |
| 5   | 15      | 3          | 30|    | 0.48500| -6.2852  |
| 6   | 15      | 5          | 10|    | 0.14750| -16.6242 |
| 7   | 25      | 1          | 30|    | 0.46250| -6.6978  |
| 8   | 25      | 3          | 10|    | 0.16975| -15.4038 |
| 9   | 25      | 5          | 20|    | 0.36250| -8.81384 |

Table 5. S/N response for NRC.

| Symbol | Factor       | Level 1  | Level 2  | Level 3  | Max-min | Order |
|--------|--------------|----------|----------|----------|---------|-------|
| A      | Monomer      | -11.410  | -10.515  | -10.305  | 1.105   | 2     |
| B      | Filler ratio | -11.132  | -10.418  | -10.681  | 0.714   | 3     |
| C      | Sample       | -16.697  | -9.005   | -6.529   | 10.167  | 1     |

Figure 4. S/N graph for NRC.
3.3. Confirmation test

The optimum combination is not included in the orthogonal array $L_9(3^3)$, so it was necessary to conduct the confirmation test in order to validate the experimental results. The experiment was conducted making use of the above obtained optimum parameters. The curves for sound absorption coefficient of the material was shown in Figure 5 and compared with the initial sample points. The results showed the acoustic properties are improved effectively. By calculating the data obtained from the confirmation test (Table 6), the NRC of the optimal PU foams was 0.5550 and the highest sound absorption coefficient was up to 0.88. The NRC had showed an increased value from 0.4850 to 0.5550, improving 7.0% compared with Run 5 (Table 4), which showed best absorption properties among 9 runs.

![Figure 5. Curves of sound absorption coefficient for the optimal PU foams.](image)

**Table 6.** The optimum design of formulation after optimization.

| Parameters          | A | B | C | NRC  |
|---------------------|---|---|---|------|
| The optimum design  | 25| 3 | 30| 0.5550 |

4. Conclusion

This study proposed an effective optimization approach to improve the acoustical behaviors of PU foam composites by optimizing the formulation of PU foams. Taguchi method based on the orthogonal array $L_9(3^3)$ was employed to conduct the experiments. Sound absorption coefficient was selected as the objective. To further achieve the optimum formulation of PU foams, three design variables were formulated aiming to simultaneously maximize the sound absorption. Signal-to noise (S/N) analysis was used to determine an optimal formulation of PU foam composites. The results showed that the acoustic properties of PU foam composites can be improved by optimizing the formulation of PU foams and the best combination values of variables were monomer mixture of 25 gram, filler ratio of 3% wt and sample thickness of 30 mm. By performing the confirmation test, the NRC had showed an increased value from 0.4850 to 0.5550 positively improved the acoustic property.
5. References

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