EMPIRICAL MODELLING FOR SOUND ABSORPTION COEFFICIENT OF KENAF FIBRE BY USING RESPONSE SURFACE METHOD

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DEDICATION

"My dearest queen of my heart Captain Hajjah Sofia Adila (Rtd), both princess Amaaniey Sofia and Auuniey Sofia, parent, family, Dr. Saliza bt Abdul Aziz, Dr. Saardin bin Abd Aziz and friends"

This is for all of you

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ABSTRACT

This thesis discusses the use of Box Behnken Design (BBD) approach to plan experiments to find the Sound Absorption Coefficient (SAC) for Kenaf/Polypropylene (PP) and Kenaf/Epoxy sandwich sample with an overall objective of optimising the density ($0.25g/cm^3$ - $0.65g/cm^3$), thickness (10mm - 50mm), pressure (1000kg - 5000kg), and frequency of sound (125Hz - 5000Hz). Based on the literature review, research that identifies the significance of independent variables of sound absorber capability using particular methodology remain scarce. Besides that, there was no research that adopted Design of Experiment (DOE) to be used before experimental work on acoustic areas related to natural fibre, specifically on Kenaf Fibre (KF). All research on identification of SAC was done by analysing previous research, by using calculation and experimental work and analysis. It was found that all research on KF and its sound characteristics such as SAC did not produce any empirical equation which could give benefits to other researchers on their study on the same characteristics. The researcher managed to achieve all the objectives of this research. The first objective of this study is to identify the significance of factors for a mixture of the composition between KF with PP and a mixture of the composition between KF with Epoxy to get the SAC by using the RSM as the DOE. The second objective is to compare the SAC between the simulation result and the experimental result based on the suggested test sample by the RSM and tested in an impedance test tube. The third objective is to develop and compare the empirical equation for the SAC from simulation result and experimental result by using the density, thickness, compression pressure, and frequency as the significant factors. RSM was adopted to validate the output parameters (responses) which were decided by the input process parameters. RSM also quantified the relationship between the variable input parameters and the corresponding output parameters and validated by Analysis of Variance (ANOVA) before experiments on 24 sets of sample that proposed by BBD were performed. Value of R^2, *Adjusted* R^2 and *Predicted* R^2 with >95%, and p-value with <0.005 were referred. RSM estimated the interaction and the linear effects. A regression model was developed and its adequacy was verified to predict the output values at nearly all conditions. The output parameters measured through experiments (actual) were in good match with the predicted values using the model developed by BBD with Average of Residuals value < -0.051235. Using Design-Expert software, 2D and 3D plots were generated and explicitly give an idea of the dominating process of variables over others and the order of dominance (Density, Thickness, Frequency and Pressure). This research is significant because it produced minimum number of experiments, a validated empirical equation model and conducted an optimised test. Therefore, in conclusion, the SAC and Empirical Equation output from the RSM is reliable, valid and compatible with the experimental results having minimum residuals. As such, a mixture of KF with Epoxy ($SAC = 0.2045 - (0.27081 \times Density) + (0.002305 \times Thickness) + (0.00014 \times Frequency) + (0.000009583325 \times Pressure)$) is more reliable as a sound absorber if compared to KF with PP.

ABSTRAK

Tesis ini membincangkan penggunaan pendekatan reka bentuk *Box-Behnken* (BBD) untuk merancang eksperimen bagi mencari *Sound Absorption Coefficient* (SAC) untuk sampel Kenaf/Poly-propylene (PP) dan Kenaf/Epoxy dengan tujuan keseluruhan untuk mengoptimumkan ketumpatan(0.25g/cm^3 - 0.65g/cm^3), ketebalan(10mm - 50mm), tekanan(1000kg - 5000kg), dan frekuensi bunyi(125Hz - 5000Hz). Berdasarkan tinjauan literatur, tidak ada penyelidikan yang mengenal pasti kepentingan pembolehubah bebas dengan keupayaan penyerap bunyi yang menggunakan sebarang metodologi. Selain itu, tidak ada kajian yang menggunakan pendekatan *Design of Experiment* (DOE) sebelum kerja percubaan di kawasan akustik yang berkaitan dengan fiber semulajadi, khususnya Fiber Kenaf (FK). Semua kajian mengenai pengenalpastian SAC dilakukan dengan menganalisis kajian terdahulu, dengan menggunakan pengiraan dan kerja eksperimen serta analisis eksperimen. Didapati bahawa semua kajian mengenai FK dan ciri-ciri bunyi seperti SAC tidak menghasilkan sebarang persamaan empirikal yang akan memberi manfaat kepada penyelidik lain untuk mengkaji ciri-ciri yang sama. Penyelidik berjaya mencapai semua objektif kajian ini. Objektif pertama kajian ini ialah mengenalpasti kepentingan faktor campuran komposisi antara FK/PP dan campuran komposisi antara FK/Epoxy untuk mendapatkan SAC yang optimum dengan menggunakan DOE sebagai *Response Surface Method* (RSM). Objektif kedua ialah perbandingan SAC diantara keputusan simulasi dan eksperimen berdasarkan sampel cadangan daripada RSM dan diuji pada *impedance test tube*. Objektif ketiga ialah menghasilkan dan membandingkan Persamaan Empirikal untuk SAC diantara keputusan simulasi dan eksperimen dengan menggunakan ketumpatan, ketebalan, tekanan mampatan dan frekuensi bunyi sebagai faktor penting. RSM telah digunakan untuk mengesahkan parameter output (respon) yang diputuskan oleh parameter proses input. RSM juga mengukur hubungan antara parameter input pembolehubah dan parameter keluaran yang sepadan dan disahkan melalui *Analysis of Variance* (ANOVA) sebelum eksperimen ke atas 24 set sampel yang dijangkakan BBD dilaksanakan. Nilai R^2, *Adjusted* R^2 dan *Predicted* R^2 dengan >95%, dan *p*-value dengan <0.005 dirujuk. RSM menganggar interaksi dan kesan linear. Model regresi dibangunkan dan keputusan model disahkan bagi menganggarkan hubungan antara parameter input pembolehubah dan parameter keluaran yang sepadan. Keputusan daripada eksperimen yang dilaksanakan adalah selari dengan keputusan yang dijangkakan ketika proses simulasi menggunakan BBD dilakukan dengan nilai *Average of Residuals* < -0.051235. Dengan menggunakan perisian *Design-Expert*, plot 2D dan 3D dihasilkan menggambarkan proses pembolehubah yang mempengaruhi pembolehubah lain dan susunan pembolehubah mengikut julat dominasi (ketumpatan, ketebalan, frekuensi dan tekanan). Kajian ini amat memberikan kebaikan kerana menghasilkan kuantiti sampel eksperimen yang minimum, satu persamaan model empirikal yang disahkan dan menjalankan proses ujikaji yang optimum. Justeru, sebagai rumusan, SAC dan Persamaan Empirikal dihasilkan oleh RSM boleh digunapakai, sah dan berpadanan dengan keputusan eksperimen beserta perbezaan minimum. Campuran FK dan Epoxy ($SAC = 0.2045 - (0.27081 \times Density) + (0.002305 \times Thickness) + (0.00014 \times Frequency) + (0.000009583325 \times Pressure)$) lebih boleh digunapakai sebagai penyerap bunyi jika dibandingkan dengan campuran FK dan PP.

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LIST OF ABBREVIATIONS

AM	-	Algebraic model
BBD	-	Box Behnken Design
CCF	-	Coconut Coir Fibre
CF	-	Coir fibre
DPF	-	Date palm fibre
DOE	-	Design of Experiment
DE	-	Design-Expert
DFAS	-	Digital Frequency Analysis System
GF	-	Glass fibre
ITM	-	Impedance Tube Method
KF	-	Kenaf fibre
MM	-	Mathematical modelling
NF	-	Natural fibre
NAC	-	Noise absorption coefficient
NM	-	Numerical modelling
OPF	-	Oil palm fibre
POMFS	-	Palm Oil Male Flower Spike Fibre
PP	-	Perforated panel
PLB	-	Permeable layer backing
PP	-	Poly-Propylene
RS	-	Reaction surface
RA	-	Regression analysis
RC	-	Retention coefficient
RCs	-	Regression coefficients
RRIM	-	Reinforced reaction injection moulding
RSM	-	Response Surface Method
SM	-	Scientific method
SNR	-	Signal-to-noise ratio
SAC	-	Sound Absorption Coefficient
TLF	-	Tea-leaf-fibre

TP	-	Thermoset polymers
WCC	-	Woven cotton cloth

LIST OF SYMBOLS

±	-	Parameters on each factorial design
0	-	Variables blocked at mean level
^{0}C	-	Celcius
cm	-	Centimetre
E	-	Energy
g	-	Gram
Hz	-	Hertz
kg	-	Kilogram
kHz	-	kiloHertz
m	-	metre
p-value	-	Probability value
R^2	-	R squared
β	-	Beta

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The Response Surface Method (RSM) as explained in this study, is a technique that has been employed in numerous studies to examine relationships (Khuri and Cornell, 1996). RSM founded on a group of statistical and mathematical methods is used for constructing models empirically in whereby the response is affected by a number of variables coupled with its aim to heighten or optimise the response (Montgomery, 2005). Engineering sciences form the most widespread applications using RSM. As such, the main aim of this technique is to achieve the best response. However, if there is greater than one response, other options should be considered, which can optimise more than a single response.

Additionally, where there are problems associated with the design data, the Design of Experiment (DOE) is applied to address these restrictions. The second aim of this study is to investigate the outcome of the response regarding the alterations carried out in a certain way for a design variable. Besides that, the explicit and implicit relationship for the input parameters and its output response in the probabilistic analysis is needed. However, at times, this is challenging, except for simple cases, as even more recognised functional associations are occasionally significantly difficult to be undertaken through conventional probabilistic analysis using the integration method.

Accordingly, for this investigation, the Box Behnken Design (BBD) as the DOE is employed to strategise towards the experiment to attain the Sound Absorption Coefficient (SAC) as dependent variables for Kenaf/Poly-Propylene (PP) and Kenaf/Epoxy sandwich samples. This DOE optimises the independent variables, namely, frequency, compression pressure, thickness and density. The SAC is said to be the volume of absorbed sound energy, and not reflective of a given substance. The SAC is characterised as the proportion for the measure of how much energy is consumed to produce the sound energy. Moreover, it does not have any amount in dimension and is communicated as numbers ranging from 0 to 1.0 (0% to 100% absorption efficiency individually), indicated by α. Besides that, it is said that when the coefficient number is higher, absorption is improved (Fouladi and Nassir, 2013). Although, it should be noted that the coefficient changes with frequency. Further, this BBD also allows obtaining the approximation collaboration plus the linear effects, thereby providing knowledge on the response surface under examination.

Furthermore, BBD provides the highest efficiency for any research having three factors and three levels. The suggested design which is the BBD requires 24 runs or executions of the test before its data is valid for collection purposes and in modelling its final response surface for three independent variables (Long Wu et al., 2012). Advance software, Design-Expert (DE) version 11, was used to manage the test and to randomise the executions. A regression model was then generated whereby its appropriateness was verified to forecast the results in nearly all circumstances. Twenty-four sets of input data were employed to analyse the model in a series of experiments (Long Wu et al., 2012). The parameters obtained from the test were in parallel with the simulation values when using the model. Through using the Design-Expert software, 3D and 2D plotted graphs were created for the RSM that was produced. The plots provided a distinct picture of the process variable which dominated over others and its order in terms of dominance. As such, the plots displayed the trends and their interaction for the variables in the test.

Nevertheless, this research was significant through the multitude of experiments that were performed, the reliability of the empirical model produced and validated and lastly, being further optimised. Figure 1.1 illustrates the flow of the research in a simplified graphical form.

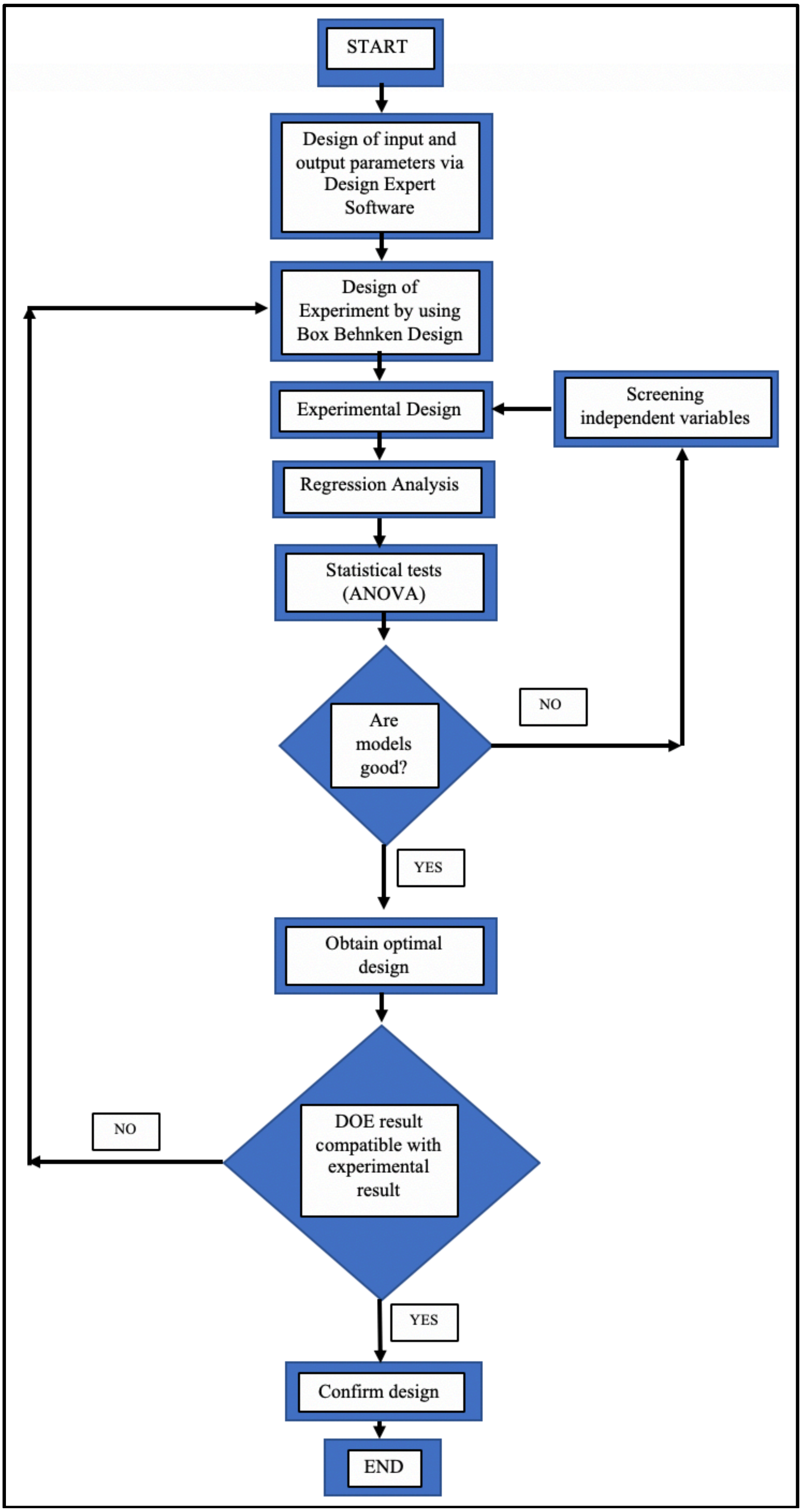

Figure 1.1 Research flow

1.2 Problem Statement

Sound pollution or high levels of sound are a major health concern for humans which can have a significant impact in our daily lives. However, there are various means in reducing the proliferation of sound and impact through the application of sound absorption material. Moreover, to make this material environmentally friendly, a mixture of natural fibre is combined with a polymer to produce the sound absorption material. For the structure of non-woven and polymer materials that are used to adsorb sound, various parameters affect the capability of the fabric or material as an excellent noise absorber (D'Alessandro and Giulio, 2005). In the majority of cases, the outcome of these parameters is tested by manipulating or changing these parameters individually. Although, analysing these parameters individually will not provide complete information since it may neglect the interactive effects of the parameters and in some cases, giving contrasting results from those in other published writings (Yilmaz et al., 2011).

Investigating the impact of absorbing sound for a variety of non-woven materials regarding air permeability, fibre composition, thickness and bonding has been carried out by numerous researchers (Kucuk and Korkmaz, 2012). In previous research, the associated effect of the parameters was not extensively assessed, as only a few parameters were considered at the time stipulated. Moreover, most research examined the effect of various parameters such as the type of fibre, distance of the fabric or material from the receiver, number of layers, source intensity, type of fabric, and actual density to insulate sound for a variety of non-woven punched materials (Sengupta, 2010). Also, in prior studies, there were some factors which were analysed but reported separately. Also, previous research related to acoustic properties was carried out by comparing the calculation with experimental data. No research specifically related to Kenaf fibre (KF) and SAC was found that performed a simulation and experiment data comparison.

Regarding the problem statements of this research, the initial problem statement according to previous studies and researchers in the acoustic area related to natural fibre, specifically KF, was that, no research was found using the DOE approach before the experimental work to identify the significance of dependent variables to independent variables, which represent the SAC in this research. All research in this study to identify the SAC are undertaken through the analysis of previous research, using the calculation, and by performing experimental work and analysis (Al-Rahman et al., 2014; Abdullah et al., 2011; Arenas and Crocker, 2010).

Regarding the second problem statement, the SAC is identified from the experimental work when the frequency is exposed to the sound absorber fabricated with several independent variables. Based on previous studies, the present practice to identify the SAC is by using the conventional method, which is based on experimental data and comparing it to data found in the literature and calculation of the SAC. None of the research in the acoustic area compares the SAC from the experimental data with the simulation data using any type of DOE, RSM, and software (Kucuk and Korkmaz, 2012; Long Wu et al., 2012; Myers et al., 2005).

Finally, for the third problem statement, based on previous research all studies associated with natural fibre and KF, specifically on its sound characteristics such as SAC, have failed to produce any empirical equation (Fouladi and Nassir, 2013). The empirical equation not only offers benefits to the other researchers in enhancing the scope of the study but helps to reduce costs and time.

1.3 Research Question

The research questions for this study are presented as follows:

(a) What type of methodology can determine the importance of certain factors for the composition and mixture between KF with PP and the composition and mixture between KF with Epoxy to obtain the SAC?

(b) How to verify the compatibility of SAC gain from the simulation result and the experimental result tested in an impedance tube.

(c) How to verify and validate the acceptability and compatibility of the empirical equation from the result of the simulation and result from the experiment.

1.4 Research Objectives

Previous studies have led to incorrect or misleading interpretations by examining individual and interactive effects of using different parameters in parallel. RSM, which combines the design of a test, is relatively beneficial in conducting the test to review the effects of multiple variables at the same time (Biles, 1975). The benefits of incorporating this method are seen in the outcome from various parameters. As such, their result can be recognised both qualitatively and quantitatively along with their associated interaction effects. This approach also allows for the projection of the heightened or enhanced area that involves the concurrent consequences of many parameters. The BBD is a tool that is utilised to examine the concurrent effect of various parameters (Long Wu et al., 2012).

Accordingly, the parameters used in the research comprise of the composition density, sample thickness, amount of applied pressure for compressing the sample and the sound frequency applied during the impedance tube test. The BBD comprises three variables which are divided into its level (-1, 0, +1) in conducting the experimental work (Long Wu et al., 2012). The SAC was measured founded on ASTM E2611, ASTM E 1050 and ISO 10534-2, which explains that the standard instrument used for acoustic testing is a horizontal impedance tube, digital frequency analyser and microphone (Rao, 2008). When the sound frequency approaches the material and is incident to it, the sound frequency will be absorbed, reflected, and transmitted. This also depends on the type of material or fabric. Absorbing the incident wave is thought to be the optimal way to mitigate sound propagation.

The research objectives for this research are presented below:

(d) To determine the importance of the factors for the composition and mixture between KF with PP and the composition and mixture between KF with Epoxy to obtain the SAC using the RSM as the DOE.

(e) To compare the SAC between the simulation result and the experimental result based on the suggested test sample by the RSM, tested in an impedance test tube.

(f) To develop and compare the empirical equation for the SAC from the simulation result and experimental result using the density, thickness, compression pressure, and frequency as important factors.

1.5 Research Scope and Limitations

The enhancement method is achieved using the BBD, which is the proposed RSM (Gaitonde, 2008; Borkowski, 1995). In adopting this approach, the software, Design-Expert (Version 11, Stat-Ease Inc., Minneapolis, USA), is employed. Using the BBD, the parameters that constitute the process (i.e. composition density, sample thickness, amount of applied pressure in compressing the sample and sound frequency used during the test) used in fabricating the sample can be further optimised through the least quantity of experiments performed. Also, employing various mathematical and statistical methods for creating, enhancing and enhancing the processes, RSM is fundamentally used in situations in which one or more input variables potentially impact certain measures depicting performance or quality attributes aligned to the applied method or output as suggested by Gaitonde (2008) and Borkowski (1995).

Nevertheless, this research can be used to create a model and utilised as a sound absorber through optimising or enhancing three main parameters namely, the composition density, sample thickness, and pressure applied on the sample which is a combination of the mixture between the KF with PP and KF with Epoxy. From the experimental results, the model was further validated using a different set of input values, as the fourth parameters for sound frequency. Thus, the surface plot was produced to depict the pattern of the SAC, using a certain mix of input parameters. Invariably, this is of benefit in understanding the effect of the parameters associated with the process and the resultant output parameters, which additionally helps to determine the best parameter series regarding the SAC.

Accordingly, this study focuses on comparing the SAC from the simulation result and the SAC from the experimental result. The comparison is used to identify the compatibility of the SAC between both the simulation and experimental results. Based on the findings of this research, a conclusion can then be made for the SAC from the simulation result and whether it is valid or should not be used in future research. Notably, the conclusion is not restricted to this research with selected parameters but all research using BBD as the DOE. Also, at the end of the research, the SAC empirical equation that was generated and compared between the simulation result and the experimental result. This empirical equation can only be used within the range of values of the selected parameters. This study also focused on four parameters established as independent variables, namely density of the composition and mixture between KF with PP and KF with Epoxy only, sample thickness, applied pressure to the sample and the sound frequency transmitted to the sample.

Furthermore, the parameter set as the dependent variable was the SAC. From the four parameters selected, the BBD suggested that 24 samples be fabricated. The list of values for each parameter was randomly generated by the Design Expert application software specifically for BBD as the DOE.

Several limitations were inherent in this study. The pressure applied to the sample for 10 minutes at a temperature of 170 ^{o}C was to melt the PP sheet and to ensure the sample fully absorbed the Epoxy with hardener. After that, the required pressured was applied to the sample for 5 minutes, while the thickness of the sample was measured and held for 24 hours. This period was suggested due to the curing time of the PP sheet after melting and the curing time of the Epoxy with hardener. After the PP and Epoxy were hardened, the sample remained at the selected thickness.

Furthermore, once the sample was cured with the selected density, thickness and applied pressure, the sample was then trimmed into a circle having a diameter of 35 mm which was set due to the size of the impedance tube. Once the sample was placed inside the tube, it was considered that no leaking of noise was evident and all sound frequency transmitted was fully absorbed by the sample.

1.6 Significance of the Study

The findings of this research are expected to contribute towards this field and to assist researchers in investigating the SAC of KF with PP and Epoxy using the empirical equation that was produced from this work. This research was undertaken to compare the validity of the SAC empirical equation between the experimental result and the simulation result. It is anticipated that the approach adopted in this study can also be used by other researchers to investigate the SAC for other types of fibre, using different parameters as independent variables.

Notwithstanding, the RSM will assist researchers in reducing both costs and time spent during the fabrication and experimental work. The savings attributed to both costs and time in this study were based on the number of samples fabricated and according to the number of parameters that were selected. Indeed, if comparing the conventional method with the RSM, the number of samples suggested to be fabricated according to the number of independent variables was less but still produced the same result and output for analysis. Additionally, the SAC empirical equation produced can be used by industry for mass manufacturing of sound absorber material according to user requirements and the surrounding environment. Thus, the optimum composition can be fabricated through mass production and commercialised. Here, a dimension of size 30 cm x 30 cm is suggested for the user in catering for the area that is required to be covered by the sound absorber.

1.7 Organisation of the Study

This study is organised into five chapters that encompass the design, fabrication and analysis of data to achieve the research objectives.

Chapter One: provides an overview and background to the study, the problem statements and the need for new and innovative methods in the acoustic research field. Also presented in this chapter are the research questions, objectives, scope and significance of the research.

Chapter Two: presents a review of previous literature and relevant studies that provide useful information to enable to reader to gain a better appreciation and understanding for undertaking this research study.

Chapter Three: presents and outlines in detail the chosen methodology used for this research.

Chapter Four: presents and describes the data collection process and analysis of the results gained from the fabrication and simulation undertaken according to the methodology presented in Chapter 3.

Chapter Five: presents the overall conclusion to the study and future work recommendations that could be employed to enhance the work of this study.

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