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Optimization of Water Permeability of "Green" Non-Woven Filter Media from Lignocellulosic Fibers Using Taguchi Method

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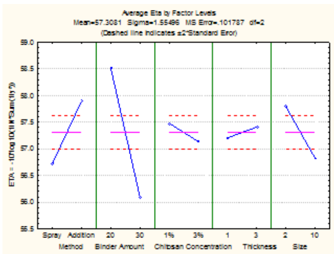
Graphical abstract



Abstract

Water permeability is often used in characterization of the filter media. This paper focuses on the evaluating the effects of the process parameters and design parameters on the permeability of filter media as an output and considered as a response and the prediction of the optimal combination of synthesis parameters with an objective of maximizing the permeability. For this purpose, the Taguchi experimental design technique, analysis of varians (ANOVA), and signal-to noise (S/N) ratio were used. In this study, only eight filter configurations of Taguchi's L_8 orthogonal design were fabricated and tested. As a result from these experiments, the filter configuration satisfying the maximum water permeability value was determined, which show that statistical analysis is a useful method to quantify filter permeability objectively.

Keywords: Permeability; empty fruit bunches; chitosan; Taguchi

1.0 INTRODUCTION

Non-woven filter media are used to separate one or more phases from a moving fluid passing through the media. Most of the currently available filter media in the market are made of synthetic polymers and fibers. Many of these polymers and fibers are petroleum-based and non-biodegradable in nature after disposal. End of life disposal of these non-biodegradable filter media is becoming critical and expensive. Although there are some efforts to recycle and/or reuse the disposed filter media, most of them end up in landfills while some are incinerated, which is expensive and emits environment pollutants. Utilizing of renewable resources in the production of filter media may potential lead to reduction of environmental pollution due to their biodegradability. Environmental consciousness suggests that non-woven filter media should be reusable, have extended life, pollutants capture capabilities, compost ability and /or be recyclable.

Non-woven filter media are widely used in industry as they are flexible, relatively strong, and most importantly, permeable. Non-woven filter media are widely used in treatment processes for removing pollution from air and water for environmental purposes [1-3]. In almost all the applications where a fibrous material is deployed, its permeability is critically important [4]. The permeability of the filter media is the physical parameter that characterizes the degree of resistance to water flow through fibrous fiber. It predicts filter performance during the whole process of filtration [5]. However, natural fibers are irregular in shape and are poorly defined. Furthermore natural fibrous fibers have lumen that does not contribute to the flow of water through it. Natural fibers swell in water due to porous cell wall. Natural fibers collapse and form a ribbon shape structure due to pressure effect. Therefore studying the permeability of natural fiber filter media is rather difficult [6].

Taguchi method is widely employed in various field of science, namely chemistry, engineering, life sciences, agriculture, etc [7-10]. But limited study has been reported for filter media application [11]. Optimization of process parameters is the key step in the Taguchi method in achieving high quality of products without increasing the cost. The Taguchi method applies fractional factorial experimental designs, called orthogonal arrays, to reduce the number of experiments. The selection of a suitable orthogonal array depends on the number of control factors and their levels. An advantage of orthogonal arrays is the relationship among the factors under investigation. The columns are mutually orthogonal where all combinations of factors levels repeated an equal number of times. The balanced experiment permits the effect of one factor under study to be separable from the effects of other factors. Thus, the findings of the experiment are reproducible. In addition, an advantage of orthogonal arrays is their cost efficiency. Although balanced, the design of an orthogonal array does not require that all combinations of all factors be tested. Therefore, the experimental matrix can be smaller without losing any vital information.

Taguchi method is based on several steps as follows; identification of the objective of the experiments, identification of the quality characteristics and selection of design parameters, determination of the number of levels, selection of the appropriate orthogonal array, executive of the experiments based on the arrangement of the orthogonal array, evaluation of the results using signal-to-noise (S/N) ratios, ANOVA, selection of the optimum levels of factors and verification of the optimum process parameters through the confirmation experiment. In this research, the important process parameters affecting the permeability were studied with minimum number of experiments using Taguchi method.

2.0 MATERIAL AND METHODS

Non-woven empty fruit bunches filter media were fabricated by wet lay-up filter making process. In this study, empty fruit bunches were used as main components in non-woven filter media. Chitosan was used as a binder in filter making processes to provide sufficient strength to the body so that the media can be retained in the desired shape without breaking during filtration processes. The study determines the permeability of filters as defined by Darcy's law for a flow of water through a fibrous media. For the permeability experiments, reverse osmosis water will pass through the filter cell at constant flow rate (10 ml per minute) by a pump. P_{in}, P_{out} and volume of collected water will be recorded at every 30 seconds. The permeability experiment for each filter was repeated three times and the average coefficient of the permeability of the filter was calculated.

2.1 Experimental Design Based on Taguchi Method

Taguchi method was used to design the experiments. Taguchi method is one of the optimization techniques that could be applied to optimize the permeability of the synthesized filter media. The objective of this study is to estimate the best synthesis conditions of non-woven filter media based on wet lay-up techniques by using Taguchi experimental design. The main parameters were fabrication methods, amount binder used per mass of fibers, binder concentration, filter thickness and fibers size. This study is focused on evaluating the effects of the process parameters on the permeability of filter media as output and considered as a response and the prediction of the optimal combination of synthesis parameters with an objective of maximizing the permeability. Five influence factors were selected and varied at two levels. In Table 1 the factors A, B, C, D and E are denoted, the fabrication method, amount of binder used per mass of fibers, binder concentration, filter thickness and fiber size. Table 1 also shows the values for the two levels of experimental settings.

The Taguchi method was applied to the experimental data using statistical software "Statistica 7.0". Taguchi proposed a set of orthogonal arrays to standardize fractional factorial design. The total degree of freedom need to be compute in order to select an appropriate orthogonal array. The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the parameters. In this study, an L_8 orthogonal array was used. In a L_8 orthogonal array there are eight parameter levels combinations for each pair of column, and each combination occurs once. The advantage of Taguchi method is the ability to estimate all the main factor effects and all the possible interactions, where all are orthogonal to one another, in a minimum number of experiments. The use of the orthogonal array significantly reduces the number of experimental configurations to be studied. This is why the L_8 orthogonal arrays are used in this work. Table 2 shows that a total of eight experimental combinations in the Taguchi method that have been used in this study.

2.2 Analysis of Experimental Data and Prediction of Performance

The experimental data were processed with "higher-the-better" quality characteristic to determine the optimum conditions for the permeability and to identify individual parameters of significant for permeability of the non-woven filter media. The plot of average response curves, signal-to-noise (S/N), ANOVA have been used for the data analysis. The mean at the optimal condition (optimal value of the response characteristic) is estimated as

$$\mu = \overline{T} + \left(\overline{A_2} - \overline{T}\right) + \left(\overline{B_2} - \overline{T}\right) = \overline{A_2} + \overline{B_2} - \overline{T} \quad (1)$$

where, T is the overall mean of the response, and A_2 and B_2 represent average values of response at the second levels of parameters A and B, respectively.

Table 1 Design factors and their levels of Taguchi method

Design factors	Symbol	Low level (1)	High level (2)
Fabrication method	A	spray	addition
Amount of chitosan solution per 50g of fiber	B	20	30
Binder concentration	C	1	3
Filter thickness	D	1	3
Fiber size	E	2	10

Table 2 Standard L_8 (2^5) orthogonal array used in the Taguchi method

No.	Control factors				
	A	B	C	D	E
1	2	2	1	2	1
2	2	2	1	1	2
3	2	1	2	2	2
4	2	1	2	1	1
5	1	2	2	2	1
6	1	2	2	1	2
7	1	1	1	2	2
8	1	1	1	1	1

3.0 RESULTS AND DISCUSSION

Permeability is a material property that depends strongly on the filter structure. The non-woven filter structure developed in this study is in the form of randomly oriented fibers. For slow flow through fibrous media, permeability is related to pressure drop across the media through the famous law of Darcy. The resistance of a porous media to the flow of water is usually expressed by Darcy's Law.

In this study, the tests were media permeability measurements to water. According to the L8 array designed by Taguchi method, different filter samples were prepared and permeability of each sample was determined. The results of the eight runs using the filter media with different combinations of the five factors are shown in Table 3. Permeability is the responses that observed for the experiment. Each experimental trial was conducted with three replications. STATISTICA Version 7.0 software was used for analyzing the measured response. Table 3 shows the average value of the permeability of the non-woven filter media for each experimental point in (cm/sec) units.

3.1 The Signal-to-Noise (S/N) Ratio Analysis

Taguchi method recommends the use of the loss function to measure the performance characteristic deviation from the desired value. The value of the loss function is further transformed into signal-to-noise (S/N) ratio. The optimum should be determined using the S/N ratio of the results obtained from the experiments designed by orthogonal array technique.

These S/N ratios are meant to be used as measures of the effect of noise amount of variability in the response data and closeness of the average response to target [12].

Therefore, in order to evaluate the influence of each of the selected factors on the response, the signal-to –noise(S/N) ratio for each factor has to be calculated. The signal noise ratio have indicated that the effect on the average responses and the noise were measured by the influence on the deviations from the average responses, which would indicate the sensitiveness of the experiment output to the noise factor. There are three basic S/N ratios, the larger-the-better, the smaller-the-better and the nominal-the-better. In this study, the S/N ratio was chosen according to the criterion the larger-the-better, in order to maximize the response which in this study is permeability. For the larger-the-better characteristic, the S/N increases as the average results increase. Improved consistency or reduced variability between units will again raise the S/N [13]. The S/N ratio for the larger-the better target for the response was calculated as follows:

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (2)$$

where S/N is the larger-the-better signal-to-noise ratio, y_i is the individually measured response value (experimental results) and n is the number of measurements taken in one test run. Because of choosing “the bigger-the-better” algorithm, increasing the S/N ratio is corresponding to increasing the permeability of the produced non-woven filter samples. The S/N ratios for the response are shown in Table 4.

The effect of each process parameter on the S/N ratio at different levels for the response can be separated because the experimental design is orthogonal. The S/N ratio for a single factor can be computed by averaging the value of S/N ratios at different levels. The mean of the S/N ratio at different levels of the process parameters for the response is summarized in Table 5.

Figure 1 shows the average S/N ratio graph for permeability. It can be noticed from this figure that B is the most important factor affecting the responses. The maximum value of response is at highest level of B1. The minimum value of the response is at the lowest level of C2. It can also be seen in the figure that E has a lower relevant effect, while both C and D show the lowest effect among the factors considered here.

Table 3 Experimental results of Taguchi orthogonal array L_8 and the average permeability of the filter media

No.	**A**	**B (g)**	**C (%)**	**D (mm)**	**E (mm)**	**Average Permeability (cm/s)**
1	Addition	30	1	3	2	73.4
2	Addition	30	1	1	10	66.9
3	Addition	20	3	3	10	86.0
4	Addition	20	3	1	2	91.8
5	Spray	30	3	3	2	64.3
6	Spray	30	3	1	10	54.2
7	Spray	20	1	3	10	76.2
8	Spray	20	1	1	2	85.9

Table 4 S/N ratio for responses

No.	**A**	**B (g)**	**C (%)**	**D (mm)**	**E (mm)**	**S/N Ratio (db)**
1	Addition	30	1	3	2	57.25139
2	Addition	30	1	1	10	56.46018
3	Addition	20	3	3	10	58.67738
4	Addition	20	3	1	2	59.20013
5	Spray	30	3	3	2	56.11063
6	Spray	30	3	1	10	54.56188
7	Spray	20	1	3	10	57.59516
8	Spray	20	1	1	2	58.60826

Table 5 Average S/N ratio for each level of the parameters

	S/N ratio	
	Level 1	**Level 2**
Fabrication method	56.71898	57.89727
Amount of chitosan solution per 50g of fiber	58.52023	56.09602
Binder concentration	57.47875	57.14750
Filter thickness	57.20761	57.40864
Fiber size	57.79260	56.82365

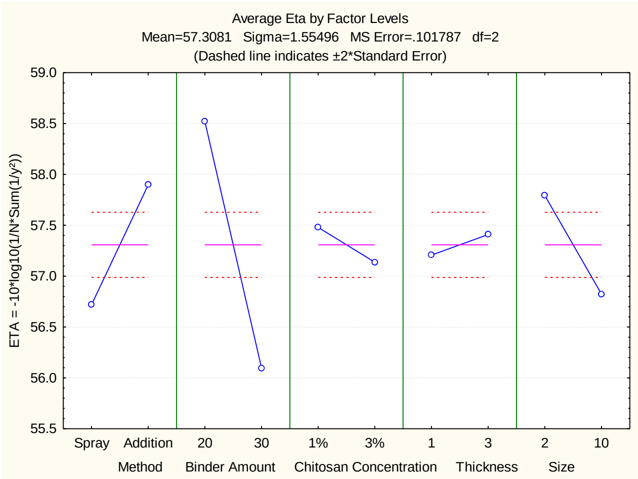


Figure 1 Average S/N ratio graph for permeability

3.2 Analysis of Variance (ANOVA)

The purpose of the ANOVA is to quantitatively investigate which process parameter significantly affects in the permeability. ANOVA was performed for S/N ratios with STATISTICA 7.0 statistical program. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean of the S/N ratio, into contributions by each process parameter and the error. An ANOVA table for S/N ratio was given in Table 6.

Table 6 shows the sum of squares, mean square, F value, residual and also percentage contribution of each factor. The precision of a parameter estimate is based on the number of independent samples of information which can be determined from the degree of freedom. The F value or F-distribution is a probability distribution used to compare variance by examining their ratio. It is a test for comparing model variance with residual variance. When the variances are close to each other, the ratio will be close to one and it is unlikely that any of the factors have a significant effect on the response. The larger their ratio and the more likely that the variance contributed by the model is significantly larger than random error [14]. Table 6 also shows the other adequacy measures R2 for each response. The adequacy measure was close to 1, which is reasonable and indicate adequate models. Percentage contributions of all factors are presented in Figure 2. The order of importance of factors is as follows: amount of binder per fiber > fabrication method > length of the fiber > thickness of filter > chitosan concentration.

The ANOVA indicates that for permeability model, the main effect was the B; the second order effects were A, C, while C and D have a week effect. Therefore, the strong effects and elements to be included into the prediction equation are A2, B1, C1, D2 and E1. The prediction equation in terms of actual factors then becomes:

$$\mu = \bar{T} + (\bar{A}_2 - \bar{T}) + (\bar{B}_1 - \bar{T}) + (\bar{C}_1 - \bar{T}) + (\bar{D}_2 - \bar{T}) + (\bar{E}_1 - \bar{T}) \\ = \bar{A}_2 + \bar{B}_1 + \bar{C}_1 + \bar{D}_2 + \bar{E}_1 - 4\bar{T} \quad (3)$$

Table 6 ANOVA table for the S/N ratio

Source	Sum of square	df	Mean square	F value	p-value prob.>F	
A	2.77671	1	2.77671	27.2796	0.034758	Significant
B	11.75362	1	11.75362	115.472	0.008549	Significant
C	0.23290	1	0.23290	4	0.269528	
D	0.08082	1	0.08082	2.2881	0.466904	
E	1.87774	1	1.8774	0.7940	0.050163	Significant
Residual	0.20357	2	0.10179	18.4477		
R^2=0.9983						

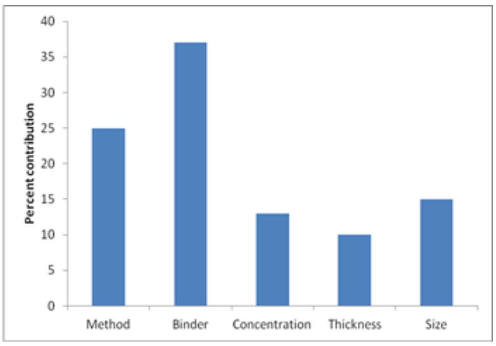


Figure 2 Contribution of control factor on the performance statistic

■4.0 CONCLUSION

Eco-friendly or "green" non-woven filters media was obtained by the combination of biodegradable polymer as the binder and biodegradable natural fibers as raw materials. Since both components are biodegradable, the filter media produced were expected to be biodegradable. A new approach is established using Taguchi method for determination of the optimum permeability of newly developed non-woven filter media. The obvious advantage of using statistical methods is that it is simple to use and understand. It provides a platform to screen all possible factors that can help quantify the uniformity of filter permeability. Therefore, in this investigation, Taguchi method has been used as a statistical tool to measure the permeability of the filter.

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