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# Optimization of the Effect of Hydraulic Hot-Pressing-Process Parameters on Tensile Properties of Kapok Fiber Nonwoven Web Based on Taguchi Experimental Design

Muhammad Abdul Mun'aim Mohd Idrus[1,*], Aniq Danish Azli[1], Md Redzuan Zoolfakar[1], Raa Khimi Shuib[2], Abdul Hafidz Yusoff[3], Asmalina Mohamed Saat[1]

[1] Universiti Kuala Lumpur, Malaysian Institute of Marine Engineering Technology, Dataran Industri Teknologi Kejuruteraan Marin, Bandar Teknologi Maritim, Jalan Pantai Remis,32200 Lumut, Perak, Malaysia
[2] Universiti Sains Malaysia, School of Materials & Mineral Resources Engineering, 14300 Nibong Tebal, Pulau Pinang, Malaysia
[3] Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, Kampus Kota, Pengkalan Chepa, 16100 Kota Bharu, Kelantan, Malaysia

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**ABSTRACT**

This paper investigates the effect of temperature on the physical properties of Kapok fiber web formed via the hot-pressing method. The kapok web was prepared using the Ashford drum carder. Test samples were subjected to heat treatment in a hydraulic hot-press under three different temperatures (160, 170, and 180°C), heating durations (5, 7.5, and 10 min), and pressures (500, 750, and 1000 psi). This study was conducted to clarify the tensile properties of kapok fabrics under optimal hot-press-forming process parameters such as temperature, heating time, and pressure; here, the Taguchi L27 orthogonal array experimental design was adopted for the optimization. The surface morphologies and tensile properties of kapok fabrics were investigated. The optimum combination of process factors was obtained through signal-to-noise (S/N) ratio analysis. Furthermore, analysis of variance was employed to determine the importance of the process parameter levels. Moreover, regression analysis was adopted to mathematically model the metamorphism of tensile properties with process parameters. A set of confirmation tests was also conducted, and the results verified the presented models. This study results showed that all three processing factors had significant influences on the tensile strength of the carded nonwoven kapok. The combination of hot-pressing parameters to obtain the optimum tensile strength was obtained as follows: 170°C temperature, 1000 psi pressure, and 10 min heating time.

## 1. Introduction

Kapok fiber (*Ceiba pentandra*) is a renewable resource with a complex structure. It is widely used in daily life because of its excellent performance and favorable cost. Kapok fibers are lightweight, fluffy, and too inelastic to be spun; therefore, they are suitable for stuffing beds, pillows, and cushions [1]. In the last few decades, research interest has moved toward natural fibers such as hemp, sisal,

* *Corresponding author.*
*E-mail address: mamunaim@unikl.edu.my*

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jute, flax, and kapok due to several factors, such as low cost, biodegradability, and application potential [2,3]. These natural fibers are attractive, environment-friendly alternatives to fiberglass as reinforcements in composites. Furthermore, natural fibers are renewable and nonabrasive and exhibit excellent mechanical and physical properties. Their application in composite materials tends to increase because they can save costs and are lightweight. Natural fibers show strength and stiffness comparable with those of fiberglass [4,5]. The strength of natural fiber–reinforced composites is related to the strengths of the components and the fiber–matrix interface [6,7].

Being a potential fiber, raw kapok has been investigated for several applications, including its use as a reinforcement material in the polyester matrix via hybridization with sisal fabrics and glass [7]. Also, kapok fiber has been mixed with thermoplastic cassava starch (TPCS) to improve the water absorption of the TPCS/kapok fiber composite and enhance its stress at maximum load and Young's modulus [8]. The wax layer on the kapok fiber surface endows the fiber with excellent hydrophobic–oleophilic characteristics; thus, this fiber is receiving increasing interest as an oil-absorbing material [9].

Much research has been conducted to study the kapok fiber polymer composite; however, the research on transforming kapok fiber into nonwoven fiber through the drum carder method is very limited. The comparison of kapok fiber with other fibers in the market shows that kapok fiber is a potential fiber for marine applications such as fiberglass boat hull. Among the natural ecological fibers, kapok is the thinnest and lightest and has the highest hollow degree. The fineness of kapok is only half of that of the cotton fiber currently in the market. The structural properties of kapok fiber, including smoothness, antibacterial function, degradability, easy processability, easy ability to tangle, and heat retention, make it more suitable for marine environments. However, Kapok fibers have some weaknesses; they are not well arranged and aligned, making them weak and challenging to use as mat fibers in boat fabrications. This is because the kapok mat density reduces when the fibers are converted into web fabrics. The fiber density is proportional to the fiber mechanical properties. The higher the density of nonwoven fiber fabrics, the better the mechanical properties.

Much effort has been channeled toward building a suitable process for preparing high-density composites or nonwoven fibers. One of the investigated processes is the thermo–hydro–mechanical treatment [10-12]. This process increases the fiber density using heat, moisture, and mechanical compression. The process can improve the mechanical properties of low-density materials and expand the application range of low-density materials without changing their characteristics. The study on the effect of high-temperature heating, specifically above 175°C, on the wood strength and brittleness has yielded various results, because of the different chemical properties and anatomies of the material and the different heating methods [13].

During hot pressing, the thermal energy enhances the fiber plasticity and creates conditions for integrating different bonds; this results in better density and reduces the voids between fibers, thus increasing the fiber strength. Meanwhile, the thermal energy will cause the moisture in the raw board to vaporize [11]. Tanaka and Funaki studied the mechanical properties of heat-treated green composites consisting of rice hull and biodegradable resin. They reported that the heat treatment of rice hull at 600°C improved the composite tensile strength. Nagasaka *et al.,* [14] also studied the mechanical properties of heat-treated Jute fiber and reported that with the increase in the heat-treatment temperature, tensile strength and stiffness decreased due to the occurrence of cracks on the fiber surface.

Li *et al.,* [10] reported that the hot-pressing temperature affected the average density of compressed wood for different surface-layer thicknesses. They used a temperature range of 90°C to 150°C and found that the density was higher when the layer was deeper, and the compressed wood had a uniform density at 180°C. In contrast, at 210°C, the density was lower when the layer was deeper. The current heat-treatment methods are not similar; therefore, the properties of heat-treated fibers may also significantly vary. However, we found that the pressure during heat treatment represents a gap in heat-treatment research for fiber. We believe that heat treatment under certain pressures is very important to produce better mechanical properties. More research to find and optimize the effect of these parameters is needed.

In the current study, raw kapok fiber was modified into nonwoven web fabric. An Ashford drum carder as shown in Figure 1 was used to process raw kapok into web fabrics, which have inferior bonding and strength. The fabrics had low density and too many voids. Thus, it will be challenging to fabricate composites due to the physical and mechanical drawbacks of the fabrics. The web kapok structure may easily break, and its dimension is not consistent.

Thermal heat treatment via hydraulic hot-pressing under pressure for a specific time can be used to improve the strength of kapok nonwoven web. Some of the properties degraded owing to thermal modification, but the dimensional stability and the bonding strength increased without the addition of outside chemicals or binders to the fiber after the carding process. Thus, this research investigated the effects of heat treatment on tensile strength and the parameter optimization to obtain the highest tensile strength of nonwoven kapok.

## 2. Experimental

### *2.1 Materials*

Natural kapok fiber was collected from local sources in Kuala Kangsar, Perak. The kapok fiber properties are presented in Table 1. The Ashford wide (30 cm) drum carder was supplied by Ashford Handicraft Ltd., New Zealand.

**Table 1**
Physical properties of kapok fiber

| Natural fiber | Liner density | Density (g/cm$^3$) | Strength (g/tex) | Elongation at break (%) |
|---|---|---|---|---|
| Raw kapok | 1.17 | 0.97 | 3.7 | 1.7 |

### *2.2 Kapok Fiber Web Production*

A small Ashford wide (30 cm) drum carder as shown in Figure 1 was used for the web formation. Moreover, 100% raw kapok fibers were used, mixed with no other fibers. Each portion weighing 40 g was prepared, and the web was collected from the carding machine, kept in a plastic bag, and placed in an oven at 60°C. The weight of the web produced after carding was about 8 g. The produced samples with 250 mm × 250 mm dimensions all weighed 8 g.

**Fig. 1.** Kapok fiber web produced using Ashford drum carder

### *2.3 Hydraulic Hot-Pressing Process: Experimental Design*

The conditions for the heat-treatment processing of the kapok nonwoven web are presented in Table 2. The web kapok fabric was pressed in a hydraulic hot-press machine under 500, 750, and 1000 psi. The temperature was set at three levels: 160°C, 170°C, and 180°C. Meanwhile, the heating time was set at 5, 7.5, and 10 min. Figure 2 shows the hot-pressing process of the web kapok fabric into the nonwoven fiber. The surface transformation and physical observation were observed and recorded for further analysis.

**Table 2**
Experiment parameters

| | Process parameter | Processing condition levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| A | Temperature (°C) | 160 | 170 | 180 |
| B | Pressure (psi) | 500 | 750 | 1000 |
| C | Time (Min) | 5 | 7.5 | 10 |

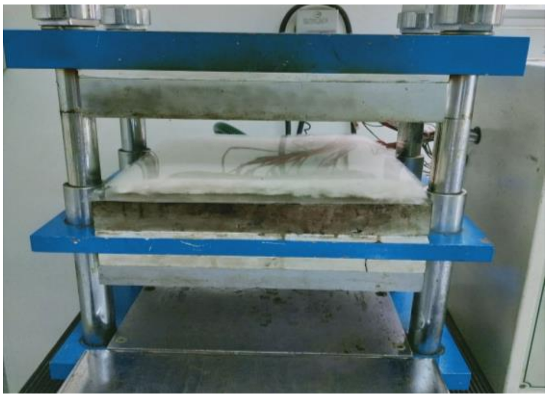


**Fig. 2.** Hydraulic hot-pressing of web kapok into nonwoven mat with higher strength

The design of experiments is a professional tool for modeling and analyzing the impact of control factors for high-quality manufacturing systems on performance output. It is important for selecting the control factors. Based on the literature review on the factors influencing the mechanical properties of nonwoven fiber and polymer [11,15,16], the selected process parameters at three levels were studied using an $L_{27}$ orthogonal array (Table 3). A full factorial experimental design will require at least 27 × 5 = 135 combinations of runs, However, using Taguchi's factorial experiment approach reduces it to only 27 runs, significantly reducing the experimental cost and time. Experimental observations were further transformed into the ratio of mean (signal) to standard deviation (noise), that is, the signal-to-noise (S/N) ratios, which are logarithmic functions of the desired output; the S/N ratios serve as objective functions for optimization, which helps in data analysis and the prediction of optimum results. The standard S/N ratios generally used are as follows: nominal-is-best, lower-the-better, and higher-the-better. In this paper, the characteristic values are selected as "higher-the-better" (Table 2) and are calculated as follows:

S/N ratio $(higher - the - better) \quad = -10\log\frac{1}{n}\,(\Sigma_{i=1}^{n}\frac{1}{y^2}$

where n is the number of observations, and y is the value of the characteristic.

**Table 3**
Experimental design using L27 orthogonal array with experimental results of kapok fabrics tensile strength

| Runs | Variables/factors | | | Response |
|---|---|---|---|---|
| | Temperature (°C) | Time (min) | Pressure (psi) | Tensile strength (MPa) |
| 1 | 160 | 5 | 500 | 22.56 |
| 2 | 160 | 5 | 500 | 22.12 |
| 3 | 160 | 5 | 500 | 22.34 |
| 4 | 160 | 7.5 | 750 | 28.32 |
| 5 | 160 | 7.5 | 750 | 27.95 |
| 6 | 160 | 7.5 | 750 | 28.12 |
| 7 | 160 | 10 | 1000 | 31.38 |
| 8 | 160 | 10 | 1000 | 31.25 |
| 9 | 160 | 10 | 1000 | 31.15 |
| 10 | 170 | 5 | 750 | 33.98 |
| 11 | 170 | 5 | 750 | 33.25 |
| 12 | 170 | 5 | 750 | 33.85 |
| 13 | 170 | 7.5 | 1000 | 36.21 |
| 14 | 170 | 7.5 | 1000 | 36.88 |
| 15 | 170 | 7.5 | 1000 | 35.85 |
| 16 | 170 | 10 | 500 | 37.33 |
| 17 | 170 | 10 | 500 | 37.21 |
| 18 | 170 | 10 | 500 | 37.69 |
| 19 | 180 | 5 | 1000 | 35.23 |
| 20 | 180 | 5 | 1000 | 35.11 |
| 21 | 180 | 5 | 1000 | 36.51 |
| 22 | 180 | 7.5 | 500 | 36.45 |
| 23 | 180 | 7.5 | 500 | 35.85 |
| 24 | 180 | 7.5 | 500 | 36.27 |
| 25 | 180 | 10 | 750 | 34.21 |
| 26 | 180 | 10 | 750 | 35.45 |
| 27 | 180 | 10 | 750 | 34.33 |

*2.4 Morphology Analysis*

Microscopic analysis was performed using a Leica tabletop microscope. Preliminary sample preparation was performed. The samples were characterized via optical microscopy to study the changes in fiber morphology. Several samples were examined to determine and observe the surface changes due to heat treatment. All observations were performed at room temperature.

*2.5 Tensile Test*

Nonwoven kapok fabrics were tensile-tested according to ASTM D 5035-06 on an Instron tensile tester, model 3367. Nonwoven fabric specimens prepared via the raveled strip method (50 mm × 150 mm) were characterized (Figure 3). Tensile tests were performed at a gauge length of 75 mm and a crosshead speed of 10 mm/min. Five specimens were tested to obtain the average tensile properties.

**Fig. 3.** Sample of hot-pressed kapok fiber prepared for tensile test

## 3. Results and Discussion

*3.1 Data Analysis from Table 3: Taguchi Analysis: Tensile Strength (MPa) versus Temperature, Time, and Pressure*

The mean value was used to determine the effect of each process parameter on the tensile strength of nonwoven kapok (Figure 4). From Figure 4(a), the tensile strength increased with an increase in heating temperature from 160°C to 170°C and then decreased with further temperature increase up to 180°C. This result may be due to the thermal degradation of thermally sensitive kapok fiber. Given these results, higher processing temperatures may damage the fiber and decrease its strength. These findings are supported by the burn spot observed at the fiber surface. This burn spot shows that after 170°C, the fiber started to degrade. Other researchers have reported similar effects in which the diminution in the strength properties was due to the thermal degradation rate and loss of substances after heat treatment [13]. For example, hemicellulose, due to its degradation, is lost, as it is less stable to heat than lignin and cellulose, and this is believed to be the main cause of the tensile strength decrease. Figure 4(b) illustrates the effect of the heating time on the tensile strength; the tensile strength increased as the time increased from 5 to 10 min. The maximum tensile strength occurred at a heating time of 10 min. The 10 min heating time yielded the optimum effect for the nonwoven kapok; it enables better integration between fibers, allowing better bonding between them. Figure 4(c) depicts the effect of hydraulic pressure on the tensile strength; the tensile strength increased with the increase in hydraulic pressure from 500 to 1000 psi. Thus, 1000 psiwas the optimum parameter for this process.

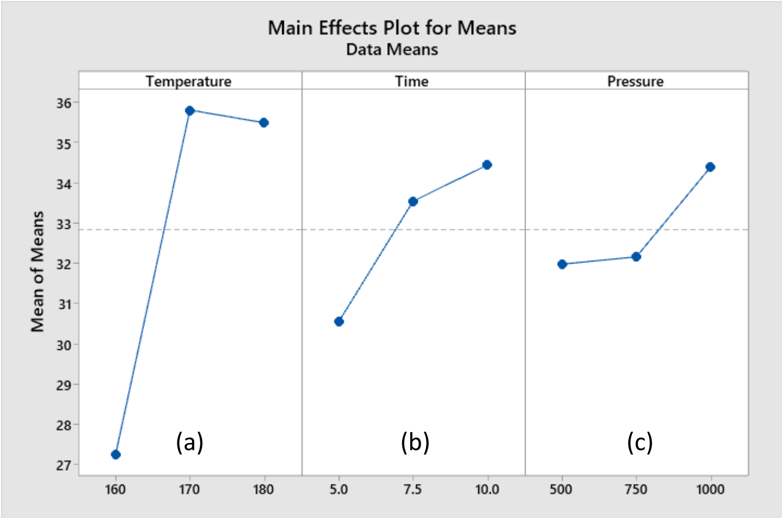



**Fig. 4.** Effect of main process parameters ((a) heating temperature, (b) heating time, (c) hydraulic pressure) on tensile strength

### *3.2 S/N Ratio Analysis*

In this research, S/N ratio analysis was used to determine the optimal parameters to obtain the highest tensile strength (Table 4). The analysis of the results concludes that the largest S/N ratio indicates the optimal processing condition for tensile strength, which is A2B3C3; this optimum level is a combination of 170°C, 10 min, and 1000 psi.

**Table 4**
Response signal-to-noise ratios for tensile strength (larger is better)

| Level | A | B | C |
|---|---|---|---|
| | Temperature (°C) | Time (min) | Pressure (psi) |
| 1 | 28.62 | 29.52 | 29.87 |
| 2 | 31.07 | 30.45 | 30.11 |
| 3 | 31.00 | 30.72 | 30.71 |
| Delta | 2.45 | 1.20 | 0.84 |
| Rank | 1 | 2 | 3 |

### *3.3 Analysis of Variance*

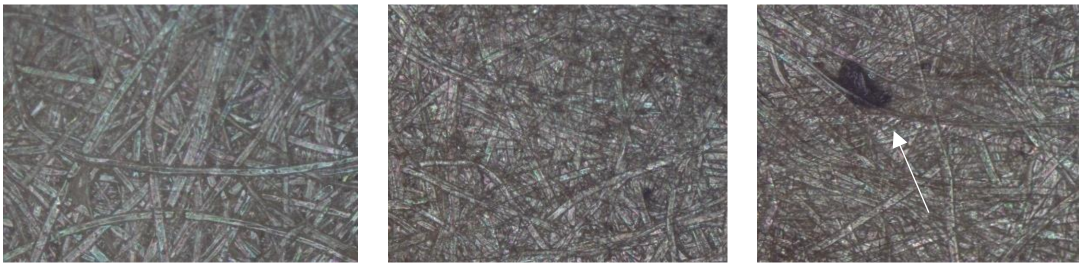
Table 5 presents the results of the analysis of variance (ANOVA). By comparing the percentage contribution of the parameters and the ANOVA results, one can observe that the heating temperature has the greatest influence, since it has the highest F-value and percentage contribution of 95.95%, followed by time (16.85%) and hydraulic pressure (7.34%).

**Table 5**
Analysis of variance results for nonwoven kapok tensile strength (MPa)

| Source | DF | Adj SS | Adj MS | F-Value |
|---|---|---|---|---|
| Temperature | 2 | 424.256 | 212.128 | 95.55 |
| Time | 2 | 74.830 | 37.415 | 16.85 |
| Pressure | 2 | 32.599 | 16.299 | 7.34 |
| Error | 20 | 44.403 | 2.220 | |
| Lack-of-Fit | 2 | 40.907 | 20.454 | 105.32 |
| Pure Error | 18 | 3.496 | 0.194 | |
| Total | 26 | 576.088 | | |

### 3.4 Surface Morphology

Figure 5 shows that with increasing temperature, the kapok fiber mats became darker, and the sample pressed at 180°C had a burn spot. This indicates that the fiber will rapidly degrade as from 180°C and above. These findings corroborate with the reduced tensile strength of the fiber at 180°C. When the fiber is being pulled, the existing burn spot will break due to a weak tensile strength. As shown in Table 4, The heating temperature at 170°C was the optimum for the kapok fiber in this study.



(a) (b) (c)

**Fig. 5.** Surface morphologies (100×) of nonwoven kapok samples hot-pressed at (a) 160°C, (b) 170°C, and (c) 180°C

### 3.5 Confirmation Experiment

The final step is to predict and verify improvements in the observed S/N ratios using the optimal combination level of process parameters. The S/N ratios for the optimal combination of process parameters can be predicted using the following equation:

$$\eta_{opt} = \eta_m + \Sigma_{j-1}^{k} (\eta_j - \eta_m) \quad (1)$$

where $\eta_{opt}$ = predicted S/N ratio, $\eta_m$ = total mean of S/N ratios, $\eta_j$ = mean S/N ratio of optimum levels, k = No. of main design parameters that affect the quality characteristics.

The predicted S/N ratios are compared with the experimentally obtained S/N ratios, and the error associated with each performance measure is presented in Table 6. The experimental results confirm the validity of the Taguchi method for optimizing the hot-press-forming process parameters. The error between the experimental and predicted values is high (17.98%). Therefore, the tensile strength of the nonwoven kapok needs to be improved by applying the Taguchi experimental design.

**Table 6**
Results of the confirmation test

| Performance measure | Optimal process parameter settings | S/N ratio predictive values (dB) | S/N ratio experimental values (dB) | Error (%) |
|---|---|---|---|---|
| Tensile strength | A2B3C3 | 32.0375 | 39.062 | 17.98% |

### 3.6 Regression Analysis

This study attempts to derive mathematical models for estimating the tensile strength of nonwoven kapok, a hydraulic hot-press process parameter, using multiple linear regression analysis. Eq. (2) presents the mathematical models for performance measures.

$$\text{Tensile strength (MPa)} = -46.7 + 0.4123\ \text{Temperature} + 0.779\ \text{Time} + 0.00483\ \text{Pressure} \tag{2}$$

$r^2 = 0.69$

The low equation coefficient ($r^2$) confirms the model weakness and suitability; the calculated constants need to be corrected in the future.

## 4. Conclusions

Nonwoven kapok fibers were experimentally investigated, and heating temperature, pressure, and heating time were obtained as the most important hydraulic hot-pressing parameters that influence the fiber tensile properties. On the one hand, as the natural fibers are thermally sensitive, high processing temperature and long heating time will result in thermal degradation. On the other hand, low processing temperature and short heating time will result in insufficient impregnation and wetting of the fiber, which may cause weaker fabrication of the nonwoven kapok web. The experimental results show that the heating temperature has the most significant effect on the fiber, as it determines the strength of the nonwoven kapok after the carding process. The processing pressure also has a significant impact on tensile strength. A high processing pressure of over 1000 psi and a heating time of over 10 min may damage the kapok fiber and lead to its degradation, resulting in poor tensile strength. The heating temperature, heating time, and pressure are significant for increasing the web kapok tensile strength. Moreover, optimum process parameter combinations are obtained from S/N ratios, and mathematical models for the tensile test of hot-press-formed nonwoven kapok fiber are proposed. From the results, the most important parameter is heating temperature, followed by heating time, and then pressure. Establishing the optimal combination of hot-press-forming parameters is beneficial for future research and application of nonwoven kapok.

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