Research Article

Investigation on Modulus of Elasticity of Badminton String by Response Surface Methodology

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Received 17 August 2022; Revised 14 September 2022; Accepted 16 September 2022; Published 26 September 2022

1. Introduction

As enhancing health awareness of the public, sports activities have become an indispensable part of people’s cultural life [1, 2]. Badminton is an indoor sport, which is favored by the public [3], because it not only improves the function of the lungs, but also promotes the metabolism of the human body [4]. According to the statistics of the International Badminton Association, the population engaged in badminton is second only to running. Recently, the population of China’s badminton market is more than three hundred million, and there are about one billion people in the world [5].

In the badminton sports, the performance of badminton string, especially the modulus of elasticity (MOE), is the key to determine the hitting effect, and it is the ratio of stress and strain of the badminton string in the elastic deformation stage [6]. At present, the most common badminton string in the market is made of nylon (polyamide, PA) with multilayer weaving technology, and its structure can be divided into core, outer, and coating from inside to outside [7]. Nylon (polyamide, PA) is a kind of plastic made of polyamide resin, and its properties are sensitive to the external environment, such as humidity, temperature and so on [8, 9].

According to the literature review, the material properties of nylon used for harp strings were investigated by Nicolas and Jim [10], they found that MOE is sensitive to changes in testing frequency and stress, and their functional fits were also determined, which are proposed to be adopted in automated tuning systems of harp strings. Wang et. al [11] explored the structure and impact strength of nylon when toughened by POE-g-MAH, they showed that the impacting strength of nylon is positively related with the content of POE-g-MAH, but the flexural strength and the tensile are negatively correlated with the content of POE-g-MAH. In the related research, a series of nylon reinforced modification experiments were carried out by Steinert et al. [12], it indicated that the carbon nanotubes can be used to improve the mechanical of nylon. Garner et al [13] explored the influence of composition on the mechanical properties of nylon 6/2 copolymer, and they demonstrated that both the moduli and the tensile strengths rapidly decreased with the increase of laurolactam content, and the crystallinity has a negative effect on the improvement of impact strength. Based on related research, it can be obtained that MOE is an important index to evaluate the elasticity of materials, and it is mainly affected by external temperature, humidity, force and other factors [14, 15].
In the badminton sports, the elasticity of badminton string is an important parameter to evaluate the hitting ability of a racket [16]. According to the literature review, most studies focus on the changes in MOE of badminton strings at different temperatures. However, badminton string is mainly composed of nylon, which is sensitive to external humidity and tensile rate [17, 18]. Therefore, it is necessary to comprehensively explore the influence of external temperature, humidity, and tensile rate.

In this work, a series of tensile experiments were carried out, and special attention was given to the changes in MOE of badminton string at different external conditions. A regression model was developed to analyze the relationship between the MOE and processing parameters, including temperature, humidity, and tensile rate, and this work is proposed to provide a theoretical basis to broaden the application of nylon in badminton sports.

2. Materials and Methods

2.1. Experimental Material. In this work, as shown in Figure 1, commercial badminton strings with a constant diameter 0.7 mm were used, they were made of made of nylon and manufactured by Li-Ning Badminton Technology Development Co., Ltd (Fujian, China). The dynamic changes in stress and strain were detected by a universal mechanical testing machine (CMT-4000, Shenzhen Xinsansi material testing Co., Ltd, Guangdong, China) at different humidity and temperature by using a constant temperature and constant humidity box (KMHW-15, Keming environmental Instrument Industry Co., Ltd, Guangdong, China), and the MOE was acquired by the ratio of the stress and strain as given in (1) [19].

\[
\text{MOE} = \frac{\sigma}{\epsilon}, \quad (1)
\]

where \(\sigma\) stands for the stress, and \(\epsilon\) represents the strain of badminton strings.

2.2. Experimental Design. Response surface methodology (RSM) [20] was adopted in this work, which was used to develop a mathematical model and determine the effect of processing parameters and their interactions on the MOE. Table 1 is the experimental design obtained by Design-Expert software (Version 12, Stat-Ease Inc., USA) [21]. The dependent variable of MOE was approximated by a non-linear mathematical model as listed in (2) [22], it was applied to analyze the relationship between variables (temperature, humidity, and tensile rate) and dependent variable (MOE).

\[
\text{MOE} = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i<j}^{k} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2, \quad (2)
\]

where \(\beta_0\) represents the fixed term, \(\beta_i\) and \(\beta_{ij}\) stand for the coefficients of the linear and the quadratic terms, respectively, \(\beta_{ii}\) represents the interacting term and \(X_i\) is the variable of temperature, humidity, and tensile rate.

3. Results and Discussion

3.1. RSM Model of MOE for Badminton String. According to the obtained data in Table 1, the response surface model of the MOE in MPa for badminton string was developed as shown infid3:

\[
\begin{align*}
\text{MOE} &= 1.81 - 0.0175T - 0.10625H \\
&\quad + 0.02875S - 0.0325TH - 0.0175TS \\
&\quad - 0.045HS - 0.0275T^2 - 0.005H^2 + 0.048S^2,
\end{align*}
\]

where \(T\) stands for the processing temperature in °C, \(H\) is the processing humidity HR in %, and \(S\) represents the tensile rate in mm/min.

Table 2 shows the fitting results of the MOE model, it can be found that the determination of coefficients \(R^2\) and Adjust-\(R^2\) are equal to 0.960 and 0.908, respectively, they are all close to 1, which indicates that the model fits well. Stand deviation (Std. Dev.) is the experimental standard deviation, it can reflect the degree of dispersion of a data set. Coefficient of variation (C.V.%) means the ratio of the standard deviation of the original data to the mean of the original data [23, 24]. In this work, Std. Dev. and C.V.% are equal to 0.027 and 1.490, respectively, their values are very low, which proved the feasibility of the MOE model. Furthermore, Figure 2 plots the values of predicted and actual MOE, the actual and predicted MOE values are very closed, and no singular point was found in Figure 2. Hence, the developed model can be used to predict the changes in MOE and selection of optimal conditions for badminton strings with the greatest MOE.
3.2. Influence of Processing Parameters on the MOE.
Figure 3 shows the influence trend MOE of badminton string at different temperature, humidity, and tensile rate. It can be obtained that the MOE of badminton string had a lower trend with the increase of temperature, this change was mainly caused by the main components of nylon fiber for the badminton string, i.e., bond length and bond angle between polymer skeleton and carbon atom have great impact on the MOE of nylon, the rise of temperature makes the bond length and angle between the molecules change. For the elastic deformation stage of polymer, the decrease of macroscopic properties was the reason leading to the decrease of MOE with the increase of temperature. This phenomenon is consistent with the results obtained by the Cohen et al. [25] who explored the effect of temperature on the MOE of nylon coil actuators. They all showed that the MOE of nylon declines with the increase of temperature.

Furthermore, it can be found that the MOE of badminton string decreased with the increase of humidity. Badminton string used in this work is made of nylon, nylon is a linear crystalline polymer containing the amide group on the main chain of the molecule, which is formed by condensation polymerization of lactam. Due to the uniform distribution of amino compounds on its molecular chain, nylon is sensitive to humidity. Based on the related work about nylon-based composite [26], the moisture had great impact on the fiber/matrix interface, and the adhesion between printed filaments. Thus, the increase of humidity led to the decline of the MOE of badminton string. Finally, with the increase of the tensile rate, the MOE of badminton string decreased first and then increased. As shown in Figure 1, in order to improve the service life of the thread, the badminton string was manufactured by weaving. Different tensile rates have different effects on the destruction of the weaving structure. Thus, the MOE of badminton string increased first and then decreased with increase of tensile rate.

3.3. Analysis of Variance for MOE. In this work, analysis of variance (ANOVA) was used to explore the contribution of variation from different sources to the total variation through analysis. The ANOVA result of MOE is given in Table 3, and the influence degree of each processing parameter on the dependent variable of MOE can be obtained.
A significance level of 5 percent (\( \alpha = 0.05 \)) was adopted. The 
p-value of the model is 0.0004, it is lower than 0.05, it  
indicates that the model is significant and can be further  
analyzed. Among the terms of the model, the 
\( p \)-values of \( H \), \( S \), \( TH \), \( HS \), and \( S^2 \) are  
< 0.0001, 0.0198, 0.0473, 0.0127, and 0.0190, respectively,  
they are all lower than 0.05. Thus, the variable of \( H \) and \( S \),  
two-level interaction effects of \( TH \) and \( HS \), and quadratic term of \( S^2 \)  
have significant influence on  
the MOE. This result was proved by Liou [27], his work also  
determined that the humidity has significant effect on the  
MOE of nylon. Meanwhile, the \( p \)-values of \( T \), \( TS \), \( T^2 \), and \( H^2 \)  
are equal to 0.1101, 0.2369, 0.0755, and 0.7158, respectively,  
they are all higher than 0.05. Hence, the variable of \( T \), two-
level interaction effects of \( TS \), and quadratic terms of \( T^2 \) and \( H \)  
have insignificant contribution to the MOE.

As also given in Table 3, the percentage of source sum of  
squares to total sum of squares, namely, % Cont.; it shows  
the influence degree of the three influencing factors on the  
MOE, the % Cont values of \( T \), \( H \), and \( S \) are equal to 1.88,  
69.23, and 5.09, respectively, i.e., \( H > S > T \). Therefore,  
humidity (\( H \)) has the greatest influence on the MOE of bad-  
minton string, followed by tensile rate (\( S \)) and temperature  
(\( T \)).

Furthermore, the % Cont values of \( TH \), \( TS \), and \( HS \)  
are equal to 3.25, 0.94, and 6.23, respectively, i.e., \( HS > TH > TS \).  
Therefore, the interaction item of humidity and tensile rate  
(\( HS \)) has the most significant contrition to the MOE model,  
followed by temperature and humidity (\( TH \)), and temperature  
and tensile rate (\( TS \)). Finally, the % Cont values of \( T^2 \), \( H^2 \),  
and \( S^2 \) are equal to 2.44, 0.08, and 0.52, respectively, i.e.,

Table 3: ANOVA result of MOE.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>% cont.</th>
<th>F-value</th>
<th>p-value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>0.12</td>
<td>9</td>
<td>0.014</td>
<td>92.31</td>
<td>18.59</td>
<td>0.0004</td>
<td>*</td>
</tr>
<tr>
<td>( T )</td>
<td>2.450E-003</td>
<td>1</td>
<td>2.450E-003</td>
<td>1.88</td>
<td>3.35</td>
<td>0.1101</td>
<td>—</td>
</tr>
<tr>
<td>( H )</td>
<td>0.090</td>
<td>1</td>
<td>0.090</td>
<td>69.23</td>
<td>123.35</td>
<td>&lt;0.0001</td>
<td>*</td>
</tr>
<tr>
<td>( S )</td>
<td>6.613E-003</td>
<td>1</td>
<td>6.613E-003</td>
<td>5.09</td>
<td>9.03</td>
<td>0.0198</td>
<td>*</td>
</tr>
<tr>
<td>( TH )</td>
<td>4.225E-003</td>
<td>1</td>
<td>4.225E-003</td>
<td>3.25</td>
<td>5.77</td>
<td>0.0473</td>
<td>*</td>
</tr>
<tr>
<td>( TS )</td>
<td>1.225E-003</td>
<td>1</td>
<td>1.225E-003</td>
<td>0.94</td>
<td>1.67</td>
<td>0.2369</td>
<td>—</td>
</tr>
<tr>
<td>( HS )</td>
<td>8.100E-003</td>
<td>1</td>
<td>8.100E-003</td>
<td>6.23</td>
<td>11.06</td>
<td>0.0127</td>
<td>*</td>
</tr>
<tr>
<td>( T^2 )</td>
<td>3.184E-003</td>
<td>1</td>
<td>3.184E-003</td>
<td>2.44</td>
<td>4.35</td>
<td>0.0755</td>
<td>—</td>
</tr>
<tr>
<td>( H^2 )</td>
<td>1.053E-004</td>
<td>1</td>
<td>1.053E-004</td>
<td>0.08</td>
<td>0.14</td>
<td>0.7158</td>
<td>—</td>
</tr>
<tr>
<td>( S^2 )</td>
<td>6.737E-003</td>
<td>1</td>
<td>6.737E-003</td>
<td>0.52</td>
<td>9.20</td>
<td>0.0190</td>
<td>*</td>
</tr>
<tr>
<td>Residual</td>
<td>5.125E-003</td>
<td>7</td>
<td>7.321E-004</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Cor total</td>
<td>0.13</td>
<td>16</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 4: 3D surface profile displaying the effect of processing parameters on MOE: (a) temperature and humidity; (b) temperature and  
stretching rate; (c) humidity and stretching rate.
Thus, the quadratic term of $T^2$ has the greatest impact on the MOE model, followed by $S^2$ and $H^2$.

Note: *: significant, $p$-value < 0.05; /: insignificant, $p$-value < 0.05; df: degrees of freedom; % Cont: percentage of source sum of squares to total sum of squares.

Figure 4 is the 3D contour diagram of the MOE model; the contour density can vividly display the influence degree of each interaction term on the MOE. Combined with the analysis of ANOVA in Table 3, the interaction item of TH has a significant influence on the MOE, in which humidity H plays a major role; the interaction item of TS has an insignificant influence on the MOE, in which tensile rate S plays a major role; the interaction item of HS has a significant influence on the MOE, in which humidity H plays a major role.

3.4. Prediction and Validation. Based on the results in the section of 3.1, the developed RSM model can be used to predict the MOE of badminton string and optimization of performance at different processing conditions. In badminton, MOE is the main factor affecting the elasticity of badminton string [28]. Therefore, the processing parameters are optimized with the highest MOE value as the goal. The predicted optimal results are shown in Figure 5 and Figure 6, it can be found that the factors corresponding to the optimal MOE were 2.021 predicted by the MOE model with the temperature of 10.7°C, the humidity of 0.19%, and the tensile rate of 59.98 mm/min, respectively. In order to verify the reliability of model prediction, validation tests were carried out to obtain model prediction errors, and the results are shown in Table 4. Under the optimal processing conditions with the temperature of 10.7°C, the humidity of 0.19%, and the tensile rate of 59.98 mm/min, the predicted and actual values of MOE were equal to 2.021 MPa and 2.158 MPa, respectively, and the error of those two values was only −6.77% within the acceptable range. Thus, the developed RSM model can be adopted to predict the changes in MOE and selection of optimal conditions for badminton strings with the highest MOE. Meanwhile, the best use environment in terms of the greatest MOE for nylon badminton strings...
are as follows: 10.7°C temperature, 0.19% humidity, and 59.98 mm/min tensile rate.

4. Conclusions

In order to improve the properties of nylon badminton string, the changes in MOE of badminton string at the different processing conditions of temperature, humidity, and tensile rate, were in focus by using RSM. The main conclusions are as follows:

1. MOE of nylon badminton string showed decreasing trends with the increase of temperature and humidity, while the MOE decreased first and then increased with the increase of tensile rate.
2. Processing parameters of humidity and tensile rate had significant contribution to the changes in MOE, and temperature had insignificant influence on the MOE. Furthermore, humidity has the greatest influence on the MOE of badminton string, followed by tensile rate and temperature.
3. A response surface model for the MOE of badminton string with a good fitting degree was developed, which can be used for MOE prediction and optimization of processing parameters. In this model, the significant terms included: variables of H and S, two-level interaction effects of TH and HS, and quadratic term of S^2.
4. For the sake of higher MOE of badminton string, the optimal processing conditions were determined, where the temperature is 10.7°C, the humidity is 0.19%, and the tensile rate is 59.98 mm/min.
5. In this work, main attention was only given to the MOE of badminton string. However, there are also many other evaluation indicators for the performance of badminton string, which need to be further analyzed, such as tensile strength, fatigue strength, wear resistance and so on.

Data Availability

All data are available within the manuscript.

Consent

Not applicable.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


