Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 03, June, 2025
Website: usajournals.org

APPROXIMATION OF THE DEPENDENCE OF STATIC EXTRACTION FORCE OF SILK FROM COCOON SHELL ON TIME AND TEMPERATURE

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Abstract:
This article investigates the static extraction of silk from the cocoon shell, focusing on the force required for silk release, the influence of time, and variations in temperature during silk reeling. Our research examines key stages of cocoon preparation for reeling, including the softening of sericin to reduce its adhesive strength, increasing the cocoon's weight by filling it with water, and locating the continuous silk filament's end. During the reeling process, cocoons are submerged in water, and a certain level of resistance force is needed to counterbalance the silk's tension. A secondary aim of the cocoon preparation process is to increase the weight of the cocoons, which is achieved by saturating their inner cavity with water.

Keywords: Cocoon, silk filament, sericin, silk reeling, cocoon preparation, static and dynamic extraction forces.

Introduction

Silk reeling is the reverse of the winding process and is carried out from the outermost layer toward the inner part of the cocoon. However, unlike winding, the reeling process involves overcoming the adhesiveness of the silk filament attached to the cocoon shell. The adhesion force of the silk to the shell is considerable, averaging 1.52 ± 0.04 cN. To reel silk from a dry cocoon shell in air, a force ranging from 0.73 to 3 cN is required, making it possible to reel the silk in dry conditions. This method is mainly used for laboratory analysis.

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However, reeling under such conditions can only be performed at a very low speed—approximately 0.366 meters per minute.

Materials and methods

In industrial settings, cocoons are reeled at speeds of 120 m/min or higher. This is made possible by a significant reduction in the adhesive strength of sericin, which is achieved by softening it through steaming in water. Consequently, the first objective of the cocoon preparation process for reeling is to soften the sericin to weaken its adhesion. However, this alone is not sufficient. Since cocoons are immersed in water during the reeling process, a force is required to counteract the filament's tensile force. The second objective of cocoon preparation is to increase the cocoon's weight, which is accomplished by filling its internal cavity with water.

Thus, the preparation of cocoons for reeling involves softening the sericin, reducing its adhesive force, increasing the cocoon's weight by saturating it with water, and locating the end of the continuous silk filament.

The main goal of this process is to perform these steps with minimal cost while preserving the maximum amount of silk in the shell for raw silk production.

In silk reeling, adhesion is defined as the force P_n required to separate the filament from the cocoon shell in a direction perpendicular to the plane where the reeled loop is situated. This force, called the static extraction force, acts at the point where the silk exits the shell and is numerically equal to the adhesive force C, but directed oppositely.

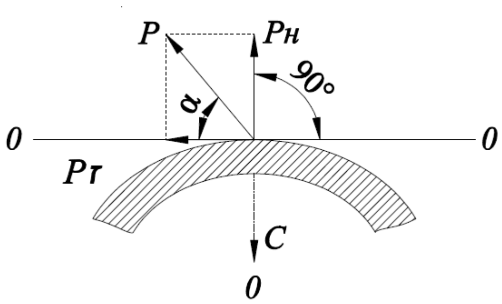

Fig. 1. Diagram of the relationship between adhesion strength and the force applied during the threading process

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Here:
P is the force applied to the filament and acting in the direction of its motion (tensile force of the reeled silk),
Pn is the normal component of the force P,
C is the adhesive (bonding) force, equal in magnitude but directed oppositely,
P is the tangential component of the force P, which tends to slide along the adhesion plane within the cocoon shell,
α is the detachment angle of the filament from the shell,
00 is the plane in which the emerging silk filament is located.
From the diagram, the force Pn separating the filament from the shell is equal to the product of the hypotenuse P and the *sin* of the opposite angle α, i.e.:

$$P_{н} = Psin\alpha \quad (1)$$

On the other hand, according to the definition of $P_{н} = C$, we get:

$$P_{H} = C = Psin\alpha \quad (2)$$

Therefore:

$$P = P_{H} / sin\alpha = C / sin\alpha \quad (3)$$

When α = 90°, the direction of motion coincides with the direction of filament removal from the cocoon shell. In this case, sin α = 1, and $P_n = C = P$, while $P_t = 0$, meaning the filament tension is at its minimum.
When α = 0°, the filament's motion aligns with the plane of adhesion. Here, sin α = 0, and P = C / 0 = ∞. This implies that when α = 0, the force applied along the axis of the filament at a certain critical inclination angle k exceeds the adhesion force on the loop surface within the shell, causing the filament to break rather than be reeled [1].
From the above, it follows that in order to reduce filament breakage, the following conditions must be met:
- The normal force P_n must be less than the breaking strength of the silk filament;
- The filament's detachment angle α must be greater than the critical angle, in which case $P > P_p$, where P_p is the breaking force.

This can be achieved by selecting appropriate cocoon processing regimes.

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The extraction of silk from the cocoon shell is influenced by both static and dynamic forces. The static force required for filament extraction is determined using a quadrant balance.

For this purpose, the end of the silk filament under investigation is attached to the hook of the quadrant pointer, which is then positioned horizontally. The test cocoon is placed in a beaker of water heated to 40–45 °C. Afterward, the quadrant arm is gradually lowered until it stops. As the arm exerts pulling tension, the filament is drawn out from the cocoon, and this tension balances the force holding the filament within the shell. At equilibrium, filament movement stops. In this condition, the quadrant pointer's reading is taken as the static extraction force of the filament, which is considered equal to the adhesive strength of the sericin binding the filament within the shell.

Typically, in order to utilize experimental results in practice, the relationship between input parameters and experimental outcomes is approximated using a polynomial expression. The degree of adequacy of this approximation is determined through statistical analysis. Initially, the presence of a correlation is confirmed, and this correlation is expressed in the form of a regression equation [2].

To construct a regression equation, the following steps must be taken:

a) Derive an empirical regression equation;

b) Evaluate the significance of the regression equation at a given confidence level;

c) Assess the strength of the correlation between variables using the empirical correlation ratio and the coefficient of determination.

For correlation analysis, it is advisable to adopt the following nonlinear equation:

$$y_x = b_0 x + b_1 x^2 + b_2 x^3 \qquad (4)$$

The coefficients are determined by the method of least square deviation in the equation b_0, b_1 and b_2. Accordingly, the following functional $S = \sum_{i=1}^{n}(y_i - y_x)^2 = \sum_{i=1}^{n}(y_i - b_0 x_i - b_1 x^2{}_i - b_2 x_i^3)$ conditions for achieving a minimum of

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$\frac{\partial S}{\partial b_0}=0$, $\frac{\partial S}{\partial b_1}=0$, $\frac{\partial S}{\partial b_2}=0$ using b_0, b_1 and b_2 to find the coefficients, we obtain a system of equations

$$\begin{aligned} b_0S_2+b_1S_3+b_2S_4&=Z_2\\ b_0S_3+b_1S_4+b_2S_5&=Z_3\\ b_0S_4+b_1S_5+b_2S_6&=Z_4 \end{aligned} \tag{5}$$

Here

$$S_2=\sum_{i=1}^{n}x^2{}_i,\ \ S_3=\sum_{i=1}^{n}x_i^3$$

$$S_4=\sum_{i=1}^{n}x^4{}_i,\ \ S_5=\sum_{i=1}^{n}x_i^5,$$

$$S_6=\sum_{i=1}^{n}x_i^6$$

$$Z_2=\sum_{i=1}^{n}x_iy_i,$$

$$Z_3=\sum_{i=1}^{n}x_i^2y_i$$

$$Z_4=\sum_{i=1}^{n}x_i^3y_i$$

We assess the significance of the resulting link based on the recommendations in [4,5]. We use this statistic $F=\frac{s_R^2}{s_e^2}=\frac{Q_R(n-m)}{Q_e(m-1)}$ (4) determine the value and use it to calculate the Fisher-Snedekor criterion $F_{\alpha;k_1;k_2}$ we compare with

Here

$\alpha=0.05$ $k_1=m-1$, $k_2=n-m$

n - number of observations,

m - the number of parameters to be evaluated in the regression equation for a quadratic function $m=3$;

$$Q=\sum_{i=1}^{n}(y_i-\overline{y})^2$$

$$Q_e=\sum_{i=1}^{10}(y_{x_i}-y_i)^2$$

$$Q_R=Q-Q_e$$

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Here $y_i(i=1..10)$-average assessment of experts (in points), $\bar{y}=\frac{\sum_{i=1}^{10} y_i}{n}=\frac{Z_1}{n}$ - their arithmetic mean value,

y_{x_i} - (2) evaluation the values in $x=x_i$: $y_{x_i}=y_x(x_i)$

In the next stage $F=\frac{s_R^2}{s_e^2}=\frac{Q_R(n-m)}{Q_e(m-1)}$ the value of the statistic is compared with the value n of the Fisher-Snedekor criterion in the table. F_{α,k_1,k_2}

For the case under consideration, m=3, n=6. If the inequality holds, the regression equation is appropriate according to the criterion, otherwise the above regression relationship does not exist. From this formula, the density $F > F_{0.05;2;2}$ coefficient (adequacy) is determined.

$R_{yx}=R=\sqrt{1-Q_e/Q}$ and this quantity is called the coefficient of determination. If the coefficient changes in this intervals $0 < R < 0.5$, $0.5 < R < 0.8$, $0.8 < R < 1$, it determines the level of connections as low, medium, and high, respectively [3].

Table 1. Static yield strength of yarn from medium-caliber cocoons as a function of temperature and time

Time, min	Temperature, °C							
	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
	Static output force, cN							
1	2.08	1.95	1.78	1.20	1.10	0.65	0.30	0.28
3	1.97	1.84	1.68	1.15	1.02	0.58	0.21	0.22
5	1.93	1.70	1.50	1.10	0.95	0.50	0.20	0.20
1	2.10	1.99	1.80	1.25	1.10	0.68	0.30	0.30
3	2.00	1.90	1.71	1.20	1.00	0.60	0.25	0.24
5	1.96	1.76	1.54	1.18	0.91	0.51	0.20	0.20

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By Fergana region

1) Approximate yarn yield strength from cocoons treated (steamed) for 1 min

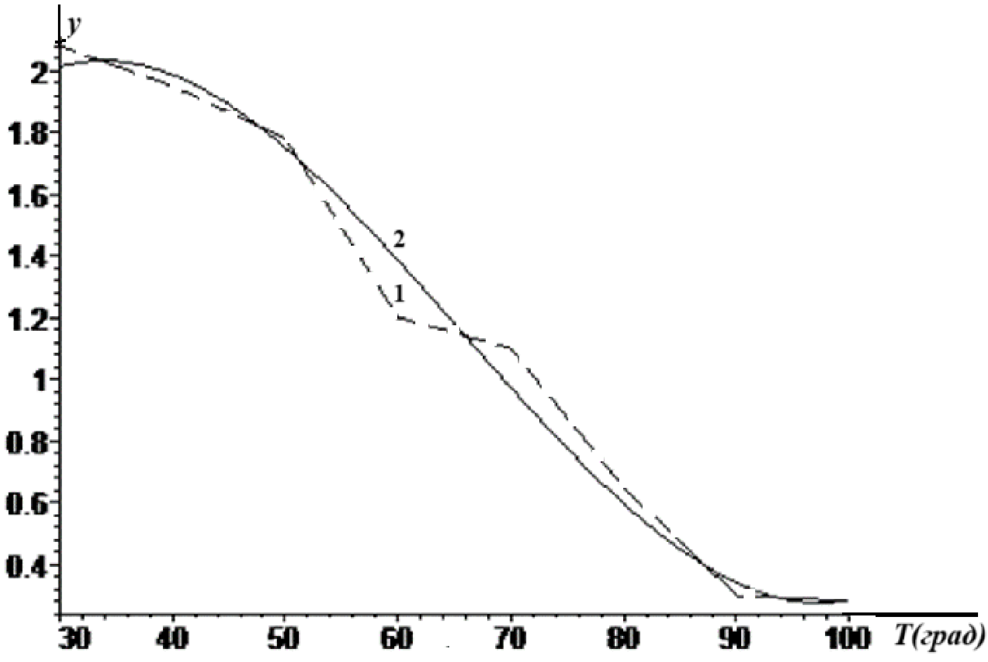

Figure 1. Experimental (1) and approximation (2) curves for the output force y(cN) at t=1 min

The approximation line is $y=0,14x-0,003x^2+0,00014x^3$. The adequacy of the approximation lines was assessed according to the Fisher-Snedekor criterion. In this case, Q_e=0,06; Q_R=3,57, and the statistic in formula (1) is equal to F=145,36. At the values $\alpha = 0.05, m = 4, n = 7$ given in the table, $F_{0.05,2,2} = 8.65$, and the condition $F > F_{0.05;2;2}$ is fulfilled, and the coefficient of determination (adequacy) according to the criterion is equal to R=0.99 [6].

2) for 3 minutesApproximate yarn yield strength from treated (steamed) cocoons

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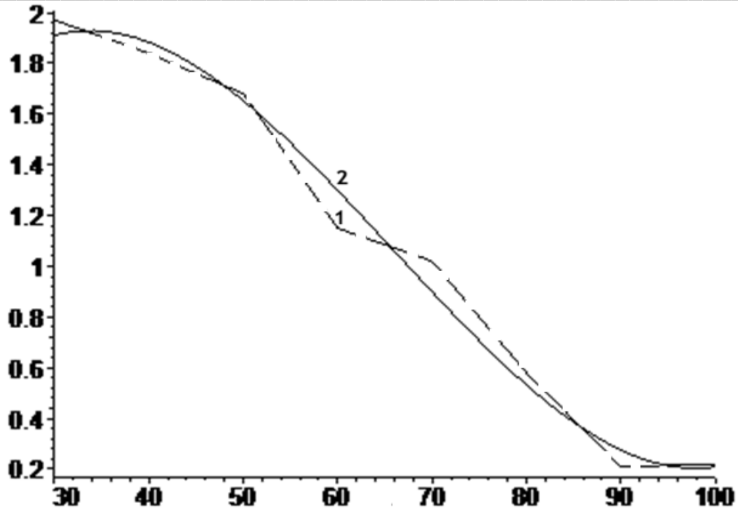

Figure 1. Experimental (1) and approximation (2) curves for the output force y(cN) t = 3 min

The approximation line is $y=0,13x-0,0026x^2+0,00002x^3$. The adequacy of the approximation lines was assessed according to the Fisher-Snedekor criterion. In this case, Q_e=0,04; Q_R=3,44, and the statistic in formula (1) is equal to F=173,22. At the values $\alpha = 0.05, m = 4, n = 7$ given in the table, $F_{0.05,2,2} = 8.65$, and the condition $F > F_{0.05;2;2}$ is fulfilled, and the coefficient of determination (adequacy) according to the criterion is equal to R=0.99 [6].

3) for 5 minutesApproximate yarn yield strength from treated (steamed) cocoons

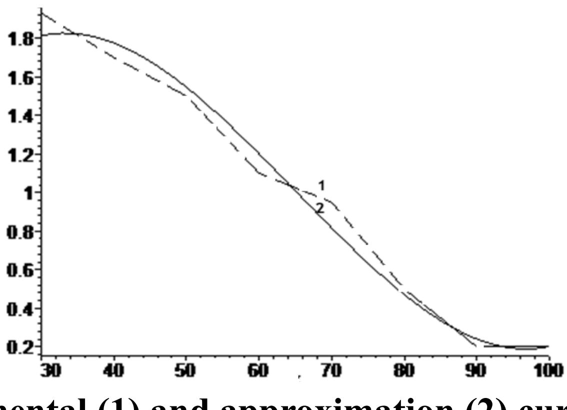

Figure 2. Experimental (1) and approximation (2) curves for the output force y(cN) t = 5 min

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The approximation line is $y=0,12x-0,0025x^2+0,000012x^3$. The adequacy of the approximation lines was assessed according to the Fisher-Snedekor criterion. In this case, Q_e=0,05; Q_R=3,09, and the statistic in formula (1) is equal to F=148,93. At the values $\alpha = 0.05, m = 4, n = 7$ given in the table, $F_{0.05,2,2} = 8.65$ and the condition $F > F_{0.05;2;2}$ is fulfilled, and the coefficient of determination (adequacy) according to the criterion is equal to R=0.99 [6].

1) Approximate yarn yield strength from cocoons treated (steamed) for 1 min

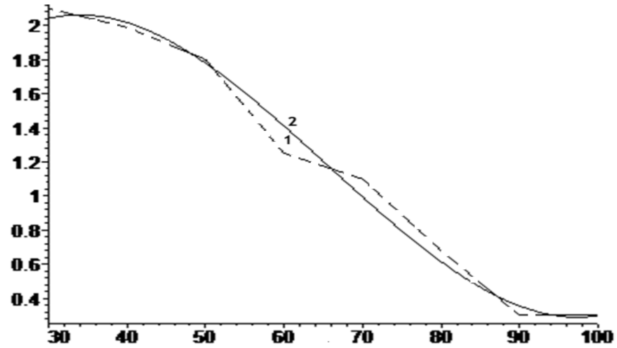

Figure 3. Experimental (1) and approximation (2) curves for the output force y(cN) $t = 1$ min

The approximation line is $y=0,13x-0,0027x^2+0,000013x^3$. The adequacy of the approximation lines was assessed according to the Fisher-Snedekor criterion. In this case, Qe=0.05; QR=3.65, and the statistic in formula (1) is equal to F=187.46. At the values $\alpha = 0.05, m = 4, n = 7$ given in the table, $F_{0.05,2,2} = 8.65$, and the condition $F > F_{0.05;2;2}$ is fulfilled, and the coefficient of determination (adequacy) according to the criterion is equal to R=0.99 [6].

2) Approximate yarn yield strength from cocoons treated (steamed) for 3 min

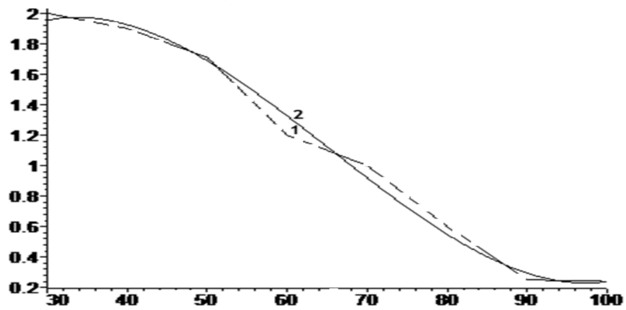

Figure 4. Experimental (1) and approximation (2) curves for the output force y(cN) $t = 3$ min

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The approximation line is $y=0,13x-0,0026x^2+0,000013x^3$. The adequacy of the approximation lines was assessed according to the Fisher-Snedekor criterion. In this case, Qe=0.03; QR=3.52, and the statistic in formula (1) is equal to F=291.90. At the values $\alpha = 0.05, m = 4, n = 7$ given in the table, $F_{0.05,2,2} = 8.65$, the condition $F > F_{0.05;2;2}$ is met, and the coefficient of determination (adequacy) according to the criterion is equal to R=0.99.

3) Approximate yarn yield strength from cocoons treated (steamed) for 5 min

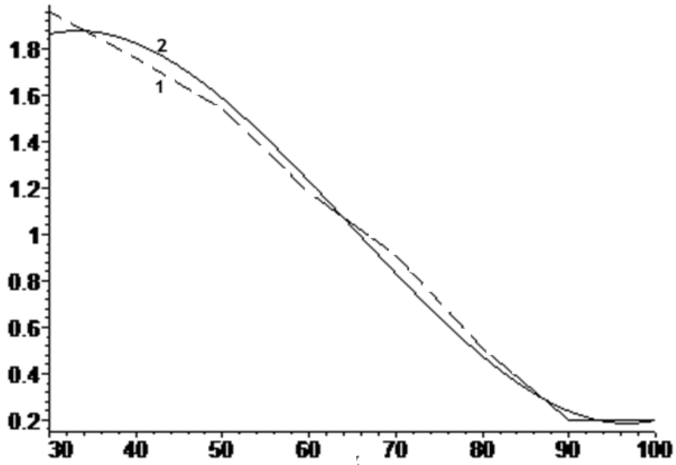

Figure 5. Experimental (1) and approximation (2) curves for the output force y(cN) $t = 5$ min

The approximation line is $y=0,12x-0,0026x^2+0,000013x^3$. The adequacy of the approximation lines was assessed according to the Fisher-Snedekor criterion. In this case, Q_e=0,03; Q_R=3,32, and the statistic in formula (1) is equal to F=291.90. At the values of $\alpha = 0.05, m = 4, n = 7$ given in the table, $F_{0.05,2,2} = 8.65$, the condition $F > F_{0.05;2;2}$ is fulfilled, and the coefficient of determination (adequacy) according to the criterion is equal to R=0.99[7.].

Conclusion

The amino acid composition of local cocoons was 25% hydrophilic amino acids in cocoons grown in relatively warm regions, and 20% in cocoons grown in relatively cold regions. The amount of raw silk produced was 35% and 30%,

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
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respectively. The effect of time and temperature on the shedding of cocoons grown in different regions was studied, and it was found that the best result was obtained for cocoons grown in both regions by processing for 3-5 minutes at a temperature of 100 °C. The most optimal option for dissolving sericin in the cocoon was also found to be 3-5 minutes and a temperature of 100 °C.

Cocoons grown in a relatively cold environment achieved 97.3% water saturation when the steaming temperature was 100°C and the water filling temperature was 71°C. Cocoons grown in a relatively warm environment achieved 97.4% water saturation when the steaming temperature was 100°C and the water filling temperature was 69°C.

A device for determining the quality of cocoon washing was created based on the determination of the kinetics of sericin dissolution. A program that determines the quality of cocoon steaming determines the color produced by the biuret reaction of the cocoon shell. It determines the time of color development within a unit of time. It allows determining the quality of steaming and washing based on the color produced and the time of its development. The main task of the proposed method is to take a 0.1 g sample from the cocoons brought to the process of preparing cocoons for washing, put it in a glass container, and pour 1% (NaOH) and 0.1% ($CuSO_4$) solutions on it. As a result, a consistent color development is observed depending on the dissolution of sericin in the cocoon. Based on the difference between the colors and the speed of color development, the quality of cocoon washing is transmitted to the computer and analyzed.

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