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REVIEW

Mechanical Behavior of Silk Fabric with Different Fiber Diameters Using a Non-contact Laser sensor

Kenichi NAKAJIMA[1]* and Mikihiko MIURA[2]

[1] Transgenic Silkworm Research Unit, Genetically Modified Research Center, National Institute of Agrobiological Sciences (Tsukuba, Ibaraki 305–8634, Japan)
[2] Faculty of Textile Science and Technology, Shinshu University (Ueda, Nagano 386–8567, Japan)

Abstract

In this study, the development of a laser-sensor-based, non-contact size control system for reeling thin raw silk is described. Thin raw silk cannot be reeled with current automatic reeling machines because they yield unusual silk fabrics. The effectiveness of the developed system was confirmed by a comparison of the properties of raw silk obtained from the developed system with that obtained from a conventional silk reeling machine. Next, for thin and thick raw silk, which are thinner than 10 d (denier, 1 denier = 1 gram per 9,000 meters) and thicker than 100 d, respectively, the influence of raw silk size and twist number on the characteristics of the obtained twisted yarn was examined. The results showed that the thread properties are strongly influenced by the twist number. Furthermore, the fiber number influenced the fiber structure, depending on the raw silk size. The bending characteristic of a 100 d silk was shown to be particularly good among the degummed silk. It was also shown that silk with lower bending strength and greater bending recovery can be crafted using thicker raw silk. In addition, thin and thick fabrics were woven using thin and thick raw silk respectively and the texture of each fabric was measured using the JIS test fabric silk as a control. The *Hakugin* fabric was found to be soft because the value of its "KOSHI" (stiffness) and "HARI" (anti-drape stiffness) was low and that of its "SHINAYAKASA" (flexibility) was high. Furthermore, the level of significance for the main and combinational effects for the "softness" and "luster" categories was 1%, that for the combinational effect for the "smoothness" category was 1%, and that for the main effect for the "likability" category was 1% respectively.

Discipline: Sericulture
Additional key words: physical properties, process management, raw silk, size control, twisting properties

Introduction

The Japanese silk industry had been flourishing until a few decades ago, but its subsequent decline has left it struggling to survive. Current cocoon production has decreased to 230 t, just 0.2% of the peak of 1968, due to the aging sericulture work force and a slump in raw silk prices. Raw silk consumption has also declined to approximately 25.8% of its peak in 1972 to the present level of 31,656 t[3]. Japan, however, remains a major silk consumer, and quality silk is still highly valued by the Japanese. Kimonos and other types of silk clothing account for the majority of silk consumption in Japan. However, "differentiation" and "hand" are the two most popular words in today's Japanese silk industry, as many consumers are demanding materials that differ from conventional silk.

In Japan, various attempts have been made to address this demand, one of which involved the use of thin and thick raw silk, thinner than 10 d and thicker than 100 d, respectively, the scope of which goes beyond the conventional 21–42 d range. Accordingly, new silkworms spinning thin or thick filaments have been bred[12]. Thin cocoon filaments in particular have the potential to yield thin raw silk with fewer size deviations[8], which can be used to produce high quality fabrics of uniform thickness[2]. The development of new silk materials using thin and thick raw silk is also underway[10]. Under these circumstances, an investigation into the fundamental characteristics of the twisted yarn produced from thin and

*Corresponding author: e-mail kenchi@affrc.go.jp
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thick raw silk seems warranted, which will hopefully spawn new potential applications for silk yarn.

Materials and methods

1. Development of a laser sensor-based size control unit to produce high-quality thin silk

We used cocoons made by a breed of *Bombyx mori* silkworms *Hakugin* with average cocoon filament size of 1.15 d.

We placed a laser sensor (LX2-02; Keyence, wavelength: 780nm, optical axis width: 5 mm) in the upper part of the croisure of a simple reeling machine (homemade), and measured the width of the raw silk passing under the laser light during reeling. Fig. 1 shows the size control unit built for this application, comprising a laser sensor unit (LX2-V10, Keyence), an A/D conversion unit (KV-AD40, Keyence), a CPU unit (KV-700, Keyence), a PC, and an upper- and lower limit warning lamp. The measurements are digitally recorded by the PC, which facilitates size control of the same. We set guides on the top and bottom of the laser-sensor-based control unit to boost measurement stability and also devised a way to reduce contact with the thread[4]. The sampling speed of this system was 12,500 samples/s, but we set it to 2 times/s considering the processing capacity of the PC. A normal automatic reeling machine, has a search capacity of once every 2 s, though shorter times are also possible. The data are recorded by the PC in plain text format, whereupon various forms of analysis are possible using Microsoft Excel. In addition, an electrical signal is output when the limit value is exceeded, as determined by the upper and lower limit level set for the raw silk width, in which case each lamp can be turned on.

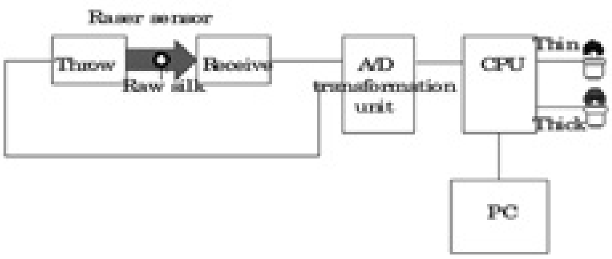


Fig. 1. Outline of the laser-sensor-based size control system
Laser sensor (LX2-V10, Keyence), A/D transformation unit (KV-AD40, Keyence), CPU unit (KV-700, Keyence), PC (NEC, OS: Windows XP).

In addition, we measured the raw silk size when reeling 10 d raw silk on a simple reeling machine (homemade; reeling speed, 50 m/min) and on an automatic reeling machine for cocoon testing (CT2; Nissan; reeling speed, 150 m/min). Furthermore, we rewound the reeled raw silk, measured the raw silk width when rewinding with this system, and then compared both data sets. We also made a 50 m sizing skein, measured the raw silk size, and then compared the actual and measured values. Table 1 shows the five different measurements taken.

2. Effects of size and twist number on the characteristics of silk twisted yarn

We used cocoons with an average filament size of 2.89 d, produced by a strain of *Bombyx mori* silkworms called *Shunrei* × *Shogetsu*, which is commonly reared in Japan.

(1) Raw silk

After cooking the cocoons, four different sizes of raw silk — 10, 27, 42, and 100 d — were reeled using an automatic reeling machine for cocoon testing at a rate of 150 m/min. We improved the reeling machine during production because thin (10 d) and thick (100 d) raw silk were outside the certified range of the automatic reeling machine. For 10 d raw silk, the thread guide pulley position was adjusted to fit the thin raw silk, and the size detector was modified with a custom-made part. While reeling 100 d raw silk, the reeling tension increased significantly to the point of interrupting the process. We placed a 100 g weight on the reeling machine sensor lever to resolve this problem[5].

In addition, we measured the tensile strength, elongation, and Young's modulus of the 10, 27, 42, and 100 d

Table 1. Five different measurements and their identification numbers

Measurement identification number	Method of reeling	Detail of measurements
A0	10 denier raw silk produced using a laser-sensor-based unit installed in a homemade reeling machine	Raw silk width recorded during reeling
A1		Raw silk width measured with a laser-sensor-based system
A2		Size computed based on 50 m raw silk
B1	10 denier raw silk produced using an automatic reeling machine with conventional size detectors	Raw silk width measured with a laser-sensor-based system
B2		Size computed based on 50 m raw silk

raw silk fibers using a tensile testing machine (RT-100, Orientec). In this experiment, we used a sample length of 10 cm and repeated the measurements 50 times.

(2) Twisting yarn

Using a doubling and twisting machine (KF-5 32, Suga), we used each raw silk size to produce 200 d twisted yarn with twist numbers of 100, 200, 500, and 1,000 T/m.

We conducted the same investigations for degummed twisted yarn. Degumming was performed with 0.5% Na_2CO_3 for 20 minutes at 97°C.

Furthermore, we measured the tensile strength, elongation, and Young's modulus for each sample before and after degumming the twisted yarn, using a tensile testing machine. In this experiment, we used a sample length of 10 cm and repeated the measurements 50 times.

We also examined the bending rigidity and hysteresis of the yarn using an automatic pure bending tester (KES-FB2, Kato Tech.). We measured these values ten times on yarn specimens that were 1 cm in length.

3. Analysis of a sensory test with thin and thick fabric and a comparison of the KES hand value

We made a thin fabric (C) from 10 d raw silk that was reeled using thin filaments from *Hakugin* cocoons and a thick fabric (D) made from 100 d raw silk that was reeled using thick filaments from *Ariake* cocoons. We washed both fabrics in water after degumming using a degumming liquid (0.04% Clewat K, 0.3% Marseille soap, 0.03% Na_2CO_3, 0.3% Na_2SiO_3, 0.05% Scoreroll, and 0.05% $Na_2S_2O_4$) for 2 h at 95°C. We also used the Japanese Industrial Standard silk fabric (E, JIS L 0803) as a reference.

(1) Sensory test

We made a 10-cm-square sample to compare the three kinds of fabrics: C, D and E. Because there were three sets, with combinations used to compare two pieces of three kinds of textiles, and with 100 subjects chosen for the three groups, we received a total of 300 evaluations[9].

We offered a five-category rating scale — "very good," "fairly good," "same level," "fairly bad," and "very bad" — to be applied to the two fabrics for the criteria of *softness*, *plumpness*, *warmth*, *smoothness*, *luster*, and *likability*[6].

This was followed by a statistical analysis using Scheffe's method of pair comparison.

(2) Kawabata Evaluation System (KES) hand value

We measured the hand value of the three kinds of fabrics — C, D and E — using a KES automatic tester (KES-FB, Kato Tech.).

Results and discussion

1. Development of a laser- sensor-based size control unit to produce high-quality thin silk

Fig. 2 shows the raw silk width data (A0), which was measured when this system reeled the raw silk, and the raw silk width data (A1) for when it was rewound and remeasured.

We found that approximately 43.3% of the cocoon filament swelled with water upon reeling, because the mean raw silk width measured during reeling was 47.9 μm, and the mean raw silk width rewound and remeasured was 33.4 μm.

In addition, when both were compared, they displayed similar behavior in terms of the tendency for change in the raw silk width. Fig. 3 shows a graph of the chronological order of the raw silk width data, which was measured by this system when reeling the raw silk (A0) and the raw silk size obtained from the sizing skein. It was considered that we could assume the raw silk size by measuring the raw silk width when reeling the raw silk, because both measurements showed the same tendency.

To check on this, we therefore constructed Fig. 4, which shows a scatter diagram of the measured and actu-

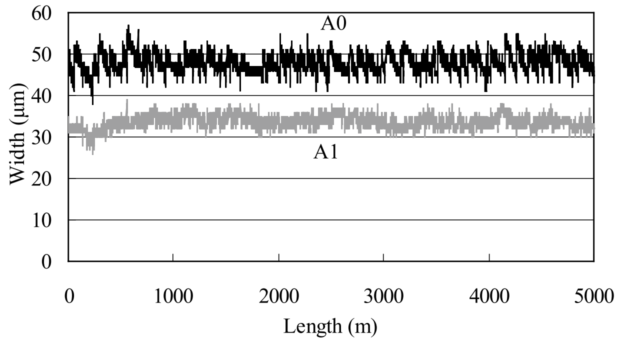


Fig. 2. Two different series of raw silk width, A0 and A1, as measured by the laser-sensor-based system

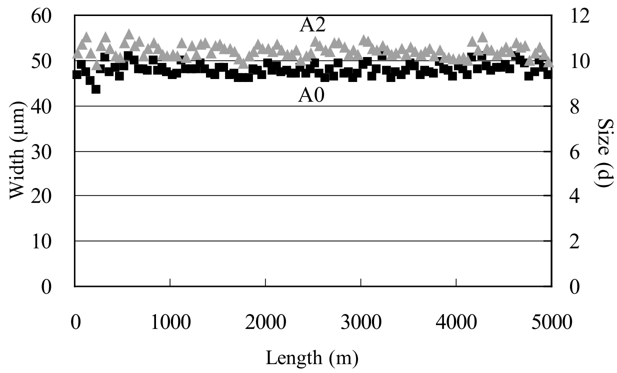


Fig. 3. Series of widths measured by laser-sensor-based system, A0, and series of raw silk size, A2

al values (A0 and A2). As a result of applying a straight line to these data using the least-square method, the expression of relations was as follows:

Raw silk size (A2)
= 4.135 + 0.132 × (Raw silk width A0)

In addition, the coefficient of correlation was 0.63, and the determination of the decision coefficient of the straight line was 0.4. Based on these results we then understood that we could assume the approximate raw silk size by measuring the raw silk width. Fig. 5 shows a frequency distribution map of the raw silk size. Using this system, the size was distributed at a rate of 91%, from 10 to 11 d, with a variation index of 0.03. In addition, it was distributed at a rate of 90%, from 13.5 to 16 d, as determined by the size detector method, with a variation index of 0.05. From these results, we understood that the raw silk size control was effective in this system.

2. Effects of size and twist number on the characteristics of silk twisted yarn

The mean and standard deviations of the tensile strength, elongation, and Young's modulus of the four different sizes of raw silk are shown in Table 2. The tensile strength has tended to decline and the elongation become imperceptibly small if the filament size becomes adversely thick to date[7]. In addition, the Young's modulus also showed a tendency to decline.

For non-degummed and degummed twisted yarn, the tensile strength increased slightly but concomitantly with an increasing twist number up to 500 T/m, while the mean tensile strength and elongation values differed significantly between the thin and thick silk sizes. The mean tensile strength and elongation for each combination of raw silk size and twist number are shown in Fig. 6. At 1000 T/m, no significant difference was found among the four different raw silk sizes for non-degummed twist yarn.

As can be seen in Fig. 6 (b), unlike the case of the other raw silk sizes, the elongation decreased remarkably in the 1000 T/m twisted yarn composed of 10 d raw silk, which is apparently due to an increase in the helical angle of the twisted yarn, which had a tighter structure depending on the increased twist number of the raw silk[6]. We therefore observed the twisted yarn under a microscope, comparing it with 100 d raw silk to note the helix angle. The microscopic images are presented in Fig. 7.

Table 3 shows the ANOVA results for the tensile strength, elongation, and Young's modulus of the 200 d degummed twisted yarn, produced using four different sizes of raw silk. The size of the raw silk used in creating the twisted yarn had a key effect on the tensile strength,

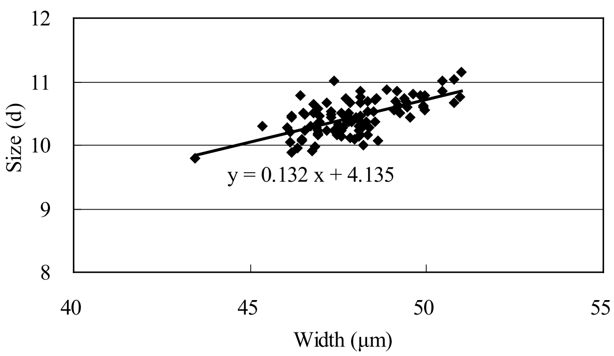


Fig. 4. Scatter diagram of measurements, A0 and A2, and least-squares line

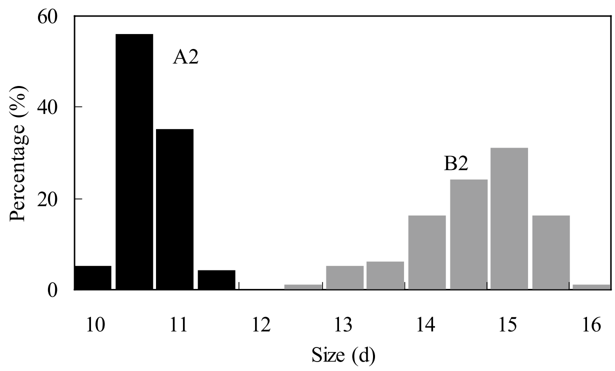


Fig. 5. Size distribution for two types of raw silk, A2 and B2

Table 2. Mean and standard deviations of tensile strength, elongation, and Young's modulus of four different sizes of raw silk

Raw silk size	Tensile strength		Elongation		Young's modulus	
	(Pa)	Sd*	(%)	Sd*	(MP a)	Sd*
10 d	3,549	151.2	22.3	1.4	0.116	0.005
27 d	3,474	190.4	23.8	1.7	0.107	0.004
42 d	3,406	196.6	24.6	1.4	0.104	0.005
100 d	3,233	133.4	24.6	1.4	0.099	0.006

* Standard deviation.

elongation and Young's modulus, while the twist number and its interaction with the size of the raw silk were also highly significant factors for all three physical properties.

Fig. 8 shows the variations for bending rigidity and hysteresis. For twisted yarn, the bending rigidity rose with increasing twist number, as shown in Fig. 8 (a). It also rose as the raw silk size increased for twist numbers from 100 to 200 T/m. The values of the bending rigidity for 1000 T/m, however, showed a reverse order of those for 100 T/m.

The rate at which the bending rigidity increased relative to 100 d raw silk was smaller than for the other silk types. The improved bending rigidity and hysteresis values for smaller sizes of raw silk up to 500 T/m seem attributable to the smaller second moment of the yarn section, which, in turn, is due to the more numerous filaments[11].

The bending rigidity and hysteresis of the degummed twisted yarn were less than those of the non-degummed yarn, although they rose with increasing twist number.

Conversely, the ANOVA results for bending rigidity and hysteresis are shown in Table 4. In contrast to the results for non-degummed twisted yarn, no significant difference was found for hysteresis relative to either raw silk size or its interaction with the twist number. This lack of difference might be attributable to gaps generated within the twisted yarn by the removal of sericin, which decreases the size effect of the raw silk. The influence of the twist number on the twisting properties was extremely strong.

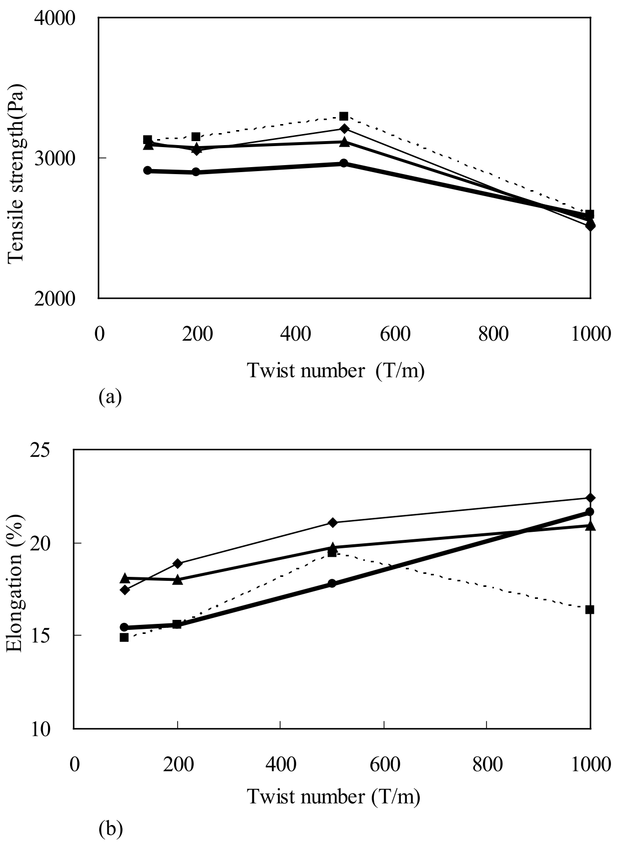


Fig. 6. Effect of twist number on tensile strength: (a) elongation, (b) in raw silk yarn prepared with different sizes of raw silk

Each point is presented as the mean value of 50 measurements. Closed symbols: squares, diamonds, triangles and circles represent 10, 27, 42, and 100 d, respectively.

3. Analysis of sensory test with thin and thick fabric and a comparison of the KES hand value

(1) Sensory test

The results of a sensory test that employed human touch on the three fabrics showed significant differences among the fabrics in terms of *softness*, *smoothness*, *luster*, and *likability* and indicated that thin fabrics are preferable. In addition, differences in the sensory level based on the sex and age of participants were also confirmed, hence these factors influenced the generation of results (see Table 5). Overall, the results showed that consumers prefer fabrics that are soft and smooth, and also have luster.

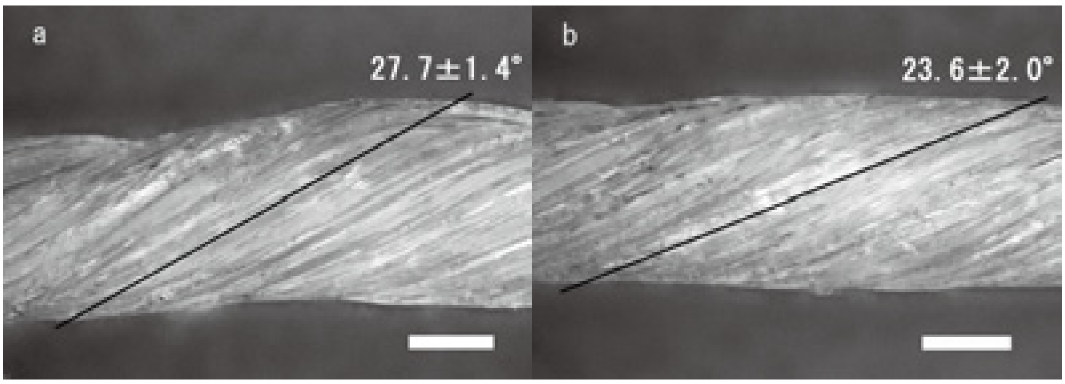
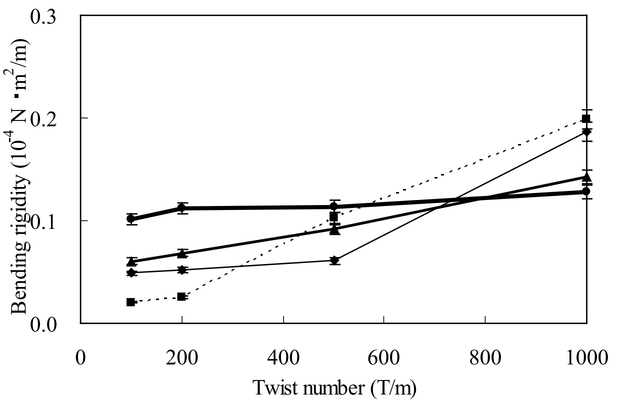


Fig. 7. Microscopic views of 200 d non-degummed twisted yarn with a twist number of 1000, made from (a) 10 d raw silk, and (b) 100 d raw silk Scale bar = 100μm

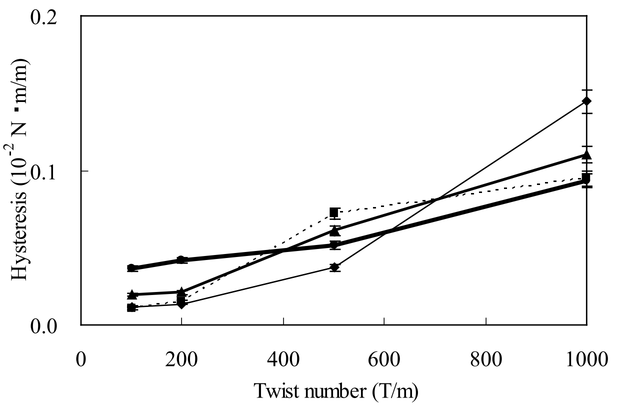
Table 3. ANOVA results showing three physical properties for 200d degummed twisted yarn

Factor		Tensile strength	Elongation	Young's modulus
F Value	Raw silk size (A)	763.2	291.7	166.2
	Twist number (B)	836.4	705.8	2,522.9
	A×B	79.9	37.5	16.8
Significant	Raw silk size (A)	**	**	**
	Twist number (B)	**	**	**
	A×B	**	**	**

Level of significance: 1%, **; 5%, *



(a)



(b)

Fig. 8. Effect of twist number on bending rigidity (a) and hysteresis (b) in non-degummed twisted yarn prepared with different thicknesses of raw silk

Each point is presented as the mean value of 10 measurements. Closed symbols: squares, diamonds, triangles and circles represent 10, 27, 42, and 100 d, respectively.

(2) KES hand value

Table 6 shows how the KES hand value showed the mean of the basic dynamics property value for all three types of fabrics. This figure was calculated thinly-made for the 201LDY women's upper garments category that we measured using the KES–FB system[1].

In response to pulling, based on the LT, WT, and EM values, we understood that fabric D could be easily lengthened, and its positive recovery performance was also shown, because of the large RT value. In addition, we understood that fabric D was hard to bend due to its large B value, and had a poor recovery performance due to its large 2HB value.

We understood that fabric E was hard to shear from its G value, and that its recovery performance was poor due to its large 2HG and 2HG5 values.

We understood that fabric D had the lowest degree of fluency, based on a comparison of the surface values of each fabric.

Next, Fig. 9 shows a comparison of the properties of each fabric. As can be understood from this, fabric C was soft because its "KOSHI" and "HARI" were low and its "SHINAYAKASA" was high.

In addition, we understood that fabric D was hard because its "KOSHI", "HARI" and "KISHIMI" were high and its "SHINAYAKASA" was low.

Fabric E, conversely, shows a value that is between those of the two fabrics.

Conclusion

In this study, raw material cocoons were chosen and the raw silk production method used to construct silk fabrics with characteristics suitable for making thin and anti-wrinkle silk fabrics was examined. In addition, the influence of the conditions of thread processing on the thread properties was examined. Fabrics were also woven using thin and thick raw silk, whereupon their texture was evaluated using a sensory test and KES hand values.

A system for controlling the size of wet raw silk threads using a laser sensor was developed. With this sensor, thin raw silk threads with intended size of 10 d were made, after which their properties were evaluated. The size of this raw silk was compared with that of the silk made using a conventional size detector, and the new laser sensor system was found to be more effective, with

Table 4. ANOVA results showing bending rigidity and hysteresis of degummed twisted yarn

Factor		Bending rigidity	Hysteresis
F Value	Raw silk size (A)	6	0.8
	Twist number (B)	398.4	145.4
	A×B	2.5	0.4
Significant	Raw silk size (A)	**	
	Twist number (B)	**	**
	A×B	**	

Level of significance: 1%, **; 5%, *

Table 5. Correlative line with a marking result of the sensory test and sex and generation distinction

(C- D)

Average	Softness 2.40	Plumply -0.08	Warmth 0.02	Smoothness 0.06	Luster 1.24	Likability 0.66	Sex 1.67	Generation 30.60
Softness								
Plumply	0.241 *							
Warmth	0.027	0.354 **						
Smoothness	0.025	0.089	-0.128					
Luster	0.144	-0.052	-0.031	0.180				
Likability	0.322 **	0.350 **	0.367 **	0.056	0.163			
Sex	0.168	0.156	0.302 **	-0.166	-0.150	0.169		
Generation	0.106	0.092	0.154	-0.079	-0.254 **	0.007	0.052	

(D- E)

Average	Softness 1.72	Plumply 0.60	Warmth 0.66	Smoothness 2.44	Luster 1.82	Likability 0.90	Sex 1.66	Generation 29.40
Softness								
Plumply	0.392 **							
Warmth	0.060	0.584 **						
Smoothness	0.604 **	0.221 *	-0.003					
Luster	0.203 *	-0.041	-0.283 **	0.408 **				
Likability	0.534 **	0.225 *	-0.018	0.584 **	0.390 **			
Sex	0.156	-0.036	-0.158	0.210 *	0.515 **	0.274 **		
Generation	-0.510 **	-0.122	0.023	-0.335 **	-0.240 *	-0.419 **	-0.213 *	

(C- E)

Average	Softness 1.72	Plumply 0.60	Warmth 0.66	Smoothness 2.44	Luster 1.82	Likability 0.90	Sex 1.66	Generation 29.40
Softness								
Plumply	0.184							
Warmth	0.390 **	0.170						
Smoothness	0.215 *	-0.083	0.369 **					
Luster	-0.172	-0.092	0.046	0.422 **				
Likability	0.430 **	0.161	0.434 **	0.242 *	-0.084			
Sex	-0.031	0.085	-0.060	-0.112	-0.073	0.115		
Generation	-0.117	-0.139	-0.007	0.043	0.138	-0.058	-0.157	

Level of significance: 1%, **; 5%, *

Table 6. Comparison of basic dynamics property values (Average)

			C	D	E
TENSILE	EM	%	5.20	7.56	3.17
	LT	-	0.712	0.611	0.661
	WT	gf・cm/cm^2	7.70	11.55	5.28
	RT	%	48.96	60.61	60.76
BENDING	B	gf・cm^2 /cm	0.0203	0.0539	0.0419
	2HB	gf・cm/cm	0.0089	0.0152	0.0160
SHEAR	G	gf/cm・deg	0.06	0.03	0.11
	2HG	gf/cm	0.02	0.00	0.05
	2HG5	gf/cm	0.50	0.10	0.99
SURFACE	MIU	-	0.242	0.254	0.243
	MMD	-	0.0108	0.0246	0.0099
	SMD	μm	2.918	4.440	4.150
COMPRESSION	LC	-	0.548	0.360	0.213
	WC	gf・cm/cm^2	0.630	0.081	0.025
	RC	%	69.84	72.84	72.00
THICKNESS	T	mm	0.183	0.310	0.164
WEIGHT	W	mg/ cm^2	2.6500	7.8750	5.8250

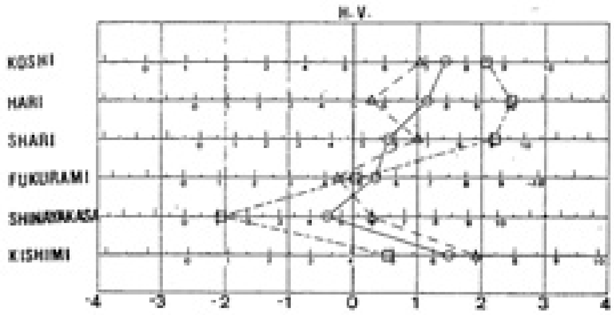


Fig. 9. Comparison of KES hand values. Triangles, squares, and circles represent C, D, and E, respectively

Using a fabric texture measurement system (KES-FB, Kato Tech.), we measured the texture of three types of fabrics of C, D, and E.

a smaller size deviation in the raw silk.

In addition, the physical and twisting properties of various types of raw and degummed silk threads were compared by varying the size and twist number. The results suggest that for the twisted degummed silk threads, the flexural properties were significantly better in the 100 d group, in which the twist number was particularly high, indicating that thick raw silk threads allow the production of silk with superior flexural properties.

Conversely, thin fabrics were made using the thin-filament silkworm race *Hakugin* and thick fabrics were made using the thick-filament silkworm race *Ariake*. A sensory test was conducted on these fabrics and the results were compared with the texture properties of the fabrics as determined by the KES. The sensory test results showed significant differences in four criteria: *softness*, *smoothness*, *luster*, and *likability*. In addition, differences in sensory values emerged between genders and among the age groups of the participants.

With regard to texture, the *Hakugin* fabrics had lower "KOSHI" and "HARI" values, and a higher "SHINAYAKASA" value, which indicates that the *Hakugin* fabrics were softer. These results suggest that it is desirable to make thin fabrics using the thin-filament type of cocoon.

Although KES is a measurement method originally intended for wool fabrics, it was employed in this study because it is also commonly applied to evaluate the characteristics of silk fabrics.

To specifically evaluate the impact of the properties of silk thread on cloth characteristics, further study is necessary, which will investigate the impact of slight changes in weaving conditions during the silk cloth manufacturing process.

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