Recent Developments in the Evaluation Technology of Fiber and Textiles: Toward the Engineered Design of Textile Performance

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ABSTRACT: The engineered design and manufacturing of high-quality fabrics have been targets of textile technology in this century; however, this has not yet been achieved. There are two reasons for this. One is that a method for the objective evaluation of the primary performance of fabric as clothing material was not established until recently; second, the complex mechanical behavior of the textile fabrics consisting of a fiber assembly has not yet been solved theoretically. The primary performance has been evaluated subjectively by fabric hand judgment. Recent achievement in the objective evaluation technology for fabric hand and other performances of fabric has enabled us to move toward the engineered design of fabric quality. After a brief introduction of the objective method, the "ideal fabric" project, which we are now conducting, is introduced. This project aims at the development of an engineered design of high-quality suiting with applying the objective evaluation technology. For future development in engineered design technology, we need basic research on the mechanics of textile structures, and on fiber itself. Fibers are the basic material of textiles. The details of fiber property are required for the advanced research of textile mechanics. Recent progress in the single-fiber measurement technology, we call it "micromeasurement," is introduced. Finally, the textile technology in the 21st century is forecasted. © 2002 John Wiley & Sons, Inc. J Appl Polym Sci 83: 687–702, 2002

Key words: evaluation technology; fiber micromeasurement; fabric hand, ideal fabrics; engineered design of textile

TEXTILE TECHNOLOGY: ITS PRESENT STATUS

A woven structure is a simple structure. Two sets of threads, the warp and the weft, are interlaced and form a cloth. For many years, this simple structure has been used as clothing material. This woven structure is still one of the basic structures used for clothing material today. Although the structure of the weave is simple, the design of the fabric's primary performance as a clothing material is not so simple. There are two reasons for this. One is that a method for the objective evaluation of the primary performance of fabric was not established until recently; second, the complex mechanical behavior of the textile fabrics

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consisting of a fiber assembly has not yet been solved theoretically. In addition, the property of fiber itself is still not explained sufficiently for textile design. The engineered design of the primary performance of clothing material is still a target of textile technology.

THE PRIMARY PERFORMANCE OF CLOTHING MATERIAL

The basic function of clothing is the protection of the human body from the environment. However, consumers seek a higher quality, that is, comfort clothing, after the protective function is satisfied to some extent. This quality of clothing is the primary concern of the consumer, and the mechanical properties of fabric are closely related to this quality. Clothing materials such as apparel fabrics are typical "human interactive materials"[1,2] that are used near the body and there is a strong interaction between material properties and human preference. Such materials must conform to human preferences, and this fabric performance is the first thing evaluated by consumers. The evaluation of the primary quality, however, is not easy, and has been evaluated by means of a subjective method, called hand evaluation. This method has been used even in modern textile factories. This is the reason that the textile industry has depended on the experience of skilled hands for the quality design of their final products. The engineered design and manufacturing of high-quality fabrics have been targets of textile technology for many years; however, this has not yet been achieved.

THE ENGINEERED DESIGN OF FABRIC QUALITY IS A GOAL FOR TEXTILE TECHNOLOGY DEVELOPMENT

For the engineered design of fabric quality, we need the three fundamentals of technology:

1. Theories for designing fabric mechanical properties
2. Objective evaluation technology of fabric hand and other fabric properties relating to the fabric primary quality
3. Explanation of the finer details of fiber properties for the advanced design of fabric performance.

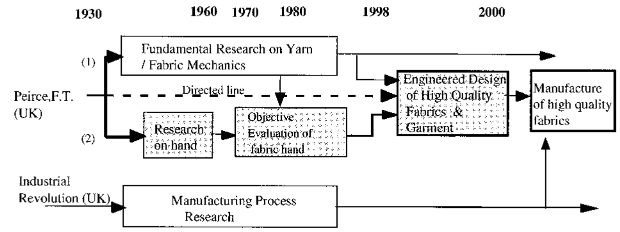


Figure 1 A history chart of the textile technology in this century.

Figure 1 shows a map of the progress made in textile technology in this century and the direction in the near future.[3] After the industrial revolution, the textile industry began large-scale production of textiles. In the beginning of this century, the textile industry was already aware of the lack of engineered design methods for their products. In 1930, in his article in the *Journal of the Textile Institute,* Peirce[4] (UK) clearly directed the engineered manufacturing of high-quality textiles and pointed out the importance of investigation of the first two items listed above for engineered design. Since then, textile mechanics gradually became one of the main research fields in textile technology along with the research of textile processing and machinery (see Fig. 1).

The research on fabric objective evaluation, however, was delayed, although many textile researchers have taken an interest in it. A main target of this research was to explain fabric hand property. The research on fabric hand, however, could not become a main research field in the textile technology because of the complex structure of hand judgment, and was misunderstood that it was not scientific research. As such, it took time to evaluate an approach to fabric hand. In the initial stage of hand research, the main investigation focused on explaining what the fabric hand is. There were several pioneering works in this research. Lundgren[5] accumulated many expressions which were used in the hand judgment of apparel fabrics; Go[6] discussed an approach to fabric hand. On the basis of this research and other pioneering work on fabric hand, we gradually directed our research target to the objective evaluation of fabric hand.

THE DEVELOPMENT OF THE OBJECTIVE METHOD FOR EVALUATING FABRIC HAND

In 1970, Kawabata and Niwa organized a research committee, the Hand Evaluation and

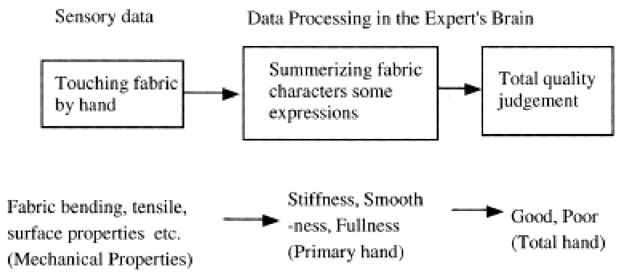


Figure 2 Hand evaluation by the experts in worsted textile mills.

Table II Grading of the Feeling Intensity for Primary Hand

HV	Feeling Intensity
10	Very strong
9	
. . .	
5	Average
. . .	
1	Very weak
0	No feeling

Standardization Committee (HESC), in Japan.[7] The committee worked toward the standardization of subjective hand evaluation methods which were used by the experts in textile mills, and also toward the development of an objective evaluation system. About 10 hand evaluation experts were invited to join the committee. These experts belonged to worsted textile and finishing mills. The details of the committee's development have already been published in some journals,[1,2,7,8] and presented herein is a summary of how to objectively evaluate fabric hand and other important performance factors of fabric.

The Primary Hand and Hand Value (HV)

Figure 2 shows how the experts in worsted mills evaluate fabric hand and the fabric quality with a subjective method.[8] First, the experts catch the fabric characteristics that are closely related with fabric performance of suiting, such as stiffness and smoothness. Three hand expressions for winter/autumn suiting, and four for midsummer suiting (for tropical climate suit) were selected, as shown in Table I, as the important hand expressions for fabric property that are commonly used among the experts.

For each of these important hand expressions, the exact meaning was standardized, and their intensities are graded by number 1 (feel very weak) to 10 (feel very strong), as shown in Table II. These hand properties were termed primary hand, and the grading number was HV.

Total Hand Value (THV)

The total hand is also a hand expression of fabric which expresses quality of fabric; that is, it is an overall hand expressing good hand or poor hand, and judged based on the primary hand of fabric. This total hand was also standardized following the standardization of the primary hand by the grading numbers 1 (poor) to 5 (excellent), as shown in Table III.

We can now express fabric hand with the numerical expressions, as shown in Table IV. This system is a semiobjective evaluation system. The hand values of a fabric are evaluated by comparing the fabric with the standard samples. Although the evaluation is still a subjective method, the evaluation is made on the basis of the standard. This reduced individual differences of evaluation even among experts. In addition, fabric hand is expressed by a set of HVs and the THV numerically; this enabled us to step to the next stage, that is, the construction of the objective evaluation system.

Table I The Primary Hands-Expressing Fabric Characteristics

For Winter and Autumn Suiting	For Midsummer Suiting
Stiffness (Koshi)	Stiffness (Koshi)
Smoothness (Numeri)	Crispness (Shari)
Fullness (Fukurami)	Fullness (Fukurami)
	Anti-drape (Hari)

Table III The Total Hand Value as Fabric Quality Number

THV	Grading
5	Excellent
4	Good
3	Average
2	Fair
1	Poor

Table IV An Example of the Hand Property of a Fabric

THV	4.2
HV	
Stiffness	5.2
Smoothness	6.8
Fullness	6.5

Fabric sample: #112 worsted suiting for winter use.

The Objective Evaluation of Fabric Hand

The Objective Evaluation System

To connect these hand properties with fabric design, an objective evaluation system of hand properties is needed instead of the subjective method. The objective system shown in Figure 3 was planned in 1970 and realized around 1973. Applying this system, the HVs and THVs can be derived from the mechanical properties of fabric. Measuring instruments for the fabric mechanical and surface properties were also developed in parallel to the survey of the subjective evaluation and was applied to the development of the objective evaluation system. This instrument was later called the KESF system and commercialized. Now the second generation of this instrument is appearing (Fig. 4), in which the operation of the instrument is fully automated. This measuring system provides not only HV and THV, but also the suit

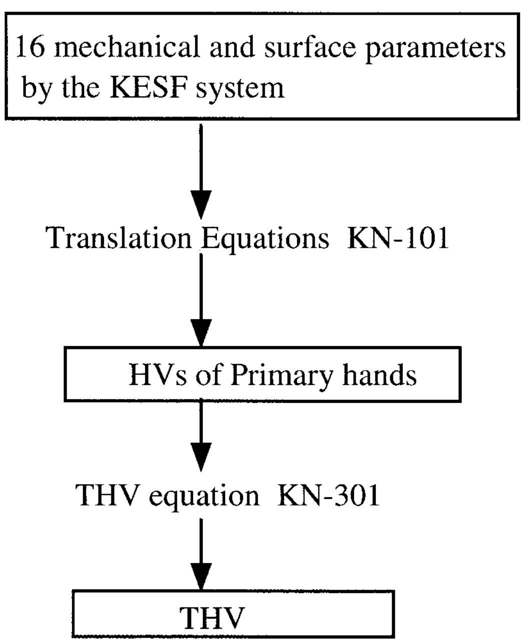


Figure 3 The objective system for hand evaluation.

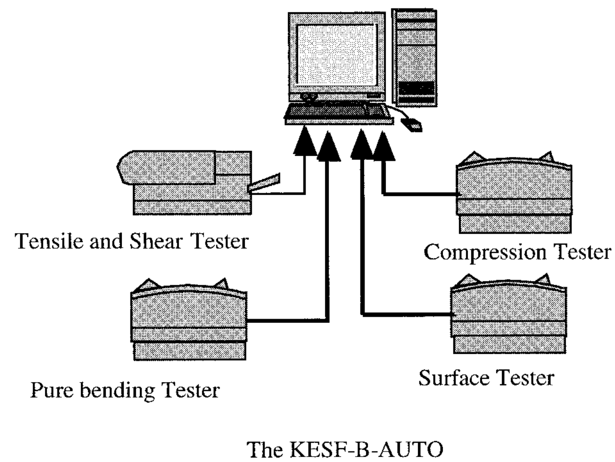


Figure 4 The Configuration of the KESF-B-AUTO model.

appearance prediction value, total appearance value (TAV), which is shown in the next section.

The Parameters Representing the Mechanical and Surface Properties of Fabric

For details of the mechanical and surface properties, refer to previous articles.[1,2,7,8] In Table V, the meaning of the parameters are outlined. The tensile, bending, and surface properties are measured in both warp and weft directions and these parameters in the two directions are identified by 1 and 2, respectively; for example, EM1, EM2. For the HV evaluation, the mean value of these two directional values are applied for each parameter.

These parameters are also applied to other fabric performance predictions and, in these cases, the two directional values are applied separately in general. The parameters are defined so that these parameters represent the mechanical properties relating to fabric hand as precisely as possible. All mechanical properties are measured with the basic deformation modes of fabric, not with complex deformations. This enables us to proceed to the next important stage of research, that is, the fabric quality design with controlled fabric mechanical properties.

TOTAL APPEARANCE VALUE (TAV)

THV and HV are based on the traditional evaluations of fabric hand, which have been used by many experts in textile mills. Suit manufacturing, however, had been a private business of tai-

Table V The Mechanical and Surface Parameters Applied to the Objective Evaluation of Fabric Hand Values and the Prediction of Other Fabric Performance

Property	Parameters	Relation with the Wearing Performance of Fabric
Tensile	*LT*	Linearity in extension. A higher value causes a stiff feeling.
	WT	Tensile energy. A lower value causes hard extension.
	RT	Resilience. A lower value causes inelastic behavior.
	EM	Tensile strain, and gives extensibility. The desired value in the warp direction is 4–5%, in the weft direction, greater than 10%.
Bending	*B*	Bending stiffness. A larger value makes fabric stiff.
	2*HB*	Bending hysteresis. A larger value causes inelastic behavior in bending.
Shearing	*G*	Shear rigidity. A larger value makes fabric stiff and paper-like.
	2*HG*	Shear hysteresis. A larger value causes inelastic behavior in shearing.
	2*HG*5	Shear hysteresis at 5° shear angle. A larger value causes inelastic property in shearing and wrinkle problems.
Compression	*LC*	Linearity in compression. A higher value causes a hard feeling in compression.
	WC	Compression energy. A lower value causes a hard feeling in compression.
	RC	Resilience. A lower value causes inelastic compression property.
Surface	*MIU*	Mean frictional coefficient. Too high and too low values yield unusual surface feeling.
	MMD	Surface frictional roughness. A higher value causes roughness.
	SMD	Surface geometrical roughness. Too high and too low values make unusual feeling of surface.
	T	Fabric thickness.
	W	Fabric weight per unit area.

loring craftsmen for many years. Tailoring became an industry around 1970 and line production of suits began. New tailoring engineers emerged at that time; however, they had no traditional evaluation method of fabric properties relating to prediction of suits. The engineers met with many difficult problems on the production line. With the cooperation of apparel engineers, first, we tried to apply the mechanical parameters as shown in Table V to tailoring process control[9] and also attempted to connect these parameters with suit appearance, that is, making-up of suit. The prediction value is the TAV and the equations for deriving the TAV have been investigated with the cooperation of apparel engineers and university researchers.[8] The TAV is graded as shown in Table VI.

The TAV predicts the quality of appearance of the suit made from a fabric before tailoring based on fabric mechanical parameter measurements, and consists of three components, as shown in Table VII. The formability component is the component related to the curved line of suit, including the formability performance of fabric. The elastic component is also related to the beautiful silhouette of suit which results from the fabric elastic properties, mainly the bending property. The drape component is also related to suit in regard to the drape of the fabric. The TAV is derived from these three component values using equations.

Table VI TAV, the Prediction Value for Making-Up Performance of Suiting

TAV	Grading
5	Excellent
4	Good
3	Average
2	Fair
1	Poor

Table VII The Three Components of TAV

Components	Grading
Formability	Same grading as that for TAV in Table VI for each component.
Elastic potential	
Drape	

Figure 5 shows the derivation process of the three components and TAV.

THE CRITERIA FOR PREDICTING MECHANICAL COMFORT

Fabric mechanical properties are closely related to elements of the tailoring operation, such as creating smooth three-dimensional curve of suit using overfeed technique. In parallel to the development of the objective evaluation system of fabric hand, apparel engineers in the HESC were also interested in the application of the mechanical parameters to tailoring process control to eliminate the problems caused by the difficult mechanical properties of fabric.[9] They clearly indicated a range of the mechanical parameters for the noncontrolled tailoring (noncontrol zone), as shown in Figure 6. When the parameters are

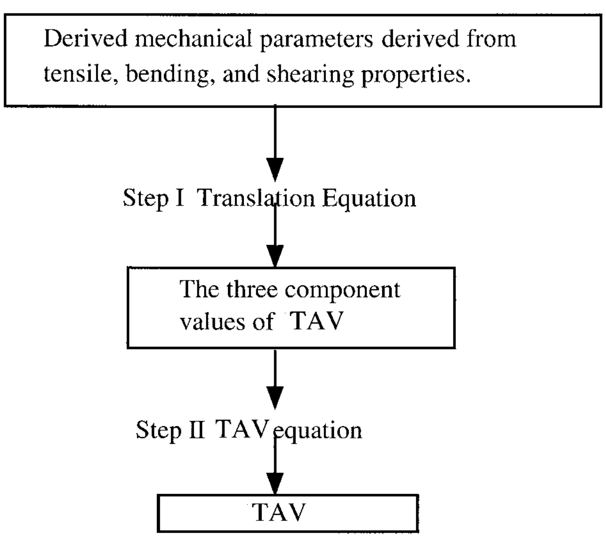


Figure 5 Derivation of the TAV. There are no subjective methods for predicting the TAV; only this objective method is available for obtaining the TAV. As shown below, TAV > 4 is the condition for ideal fabrics.

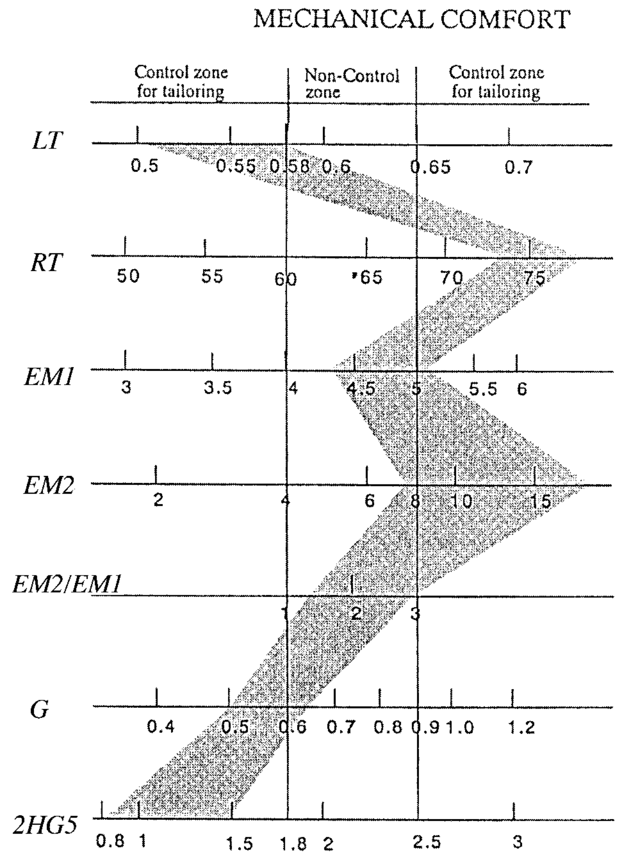


Figure 6 The mechanical comfort zone is indicated by the shaded zone. The central zone is the noncontrol zone and the comfort zone does not coincide with the noncontrol zone. This suggests that good fabric is not necessarily easy for tailoring.

within this zone, the tailoring processing does not require any special control. If some of the mechanical parameters fall outside of this zone, a necessary control in tailoring operation must be taken.

We termed this chart "control chart." During the application of this control chart to tailoring process control, the tailoring engineers again found that there is a zone in which the parameters of good suiting fall. "Good" means that the suit made from these good fabrics make a suit mechanically comfortable for wearing and also make a beautiful silhouette. The shaded zone in Figure 6 shows the mechanical comfort zone, where tensile, shearing properties are applied. As seen in Figure 6, this good zone is not necessarily coincident with the noncontrol zone. This means that the tailoring of good suiting is difficult and a suitable control is needed on the production line of tailoring. This finding of the good zone supple-

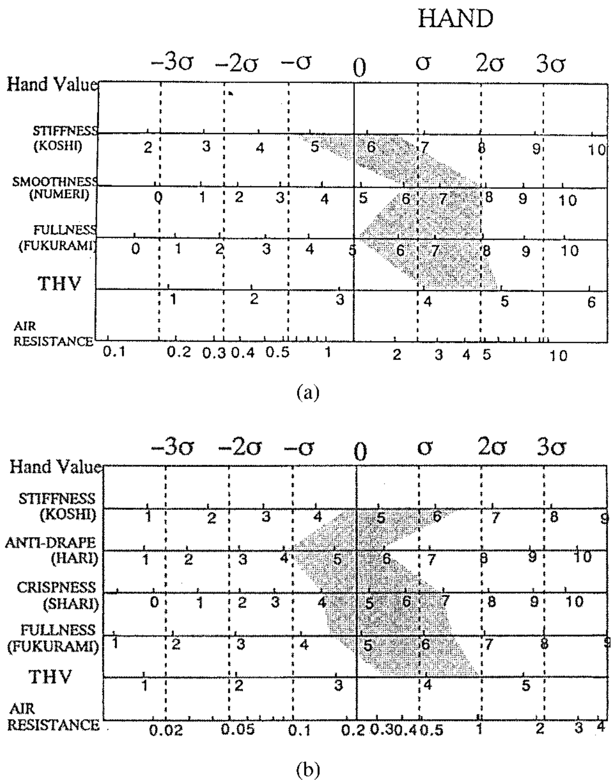


Figure 7 (a) The hand chart for winter/autumn men's suiting. The high-quality zone is shown by a snake zone. (b) The hand chart for midsummer men's suiting. The high-quality zone is shown by the shaded zone.

ments the evaluation of fabric quality from tailoring engineers' experience.

THE HAND CHART AND THE APPEARANCE CHART

To overlook the fabric hand property and suit appearance prediction, the hand charts shown in Figures 7 and 8, respectively, are convenient. The shaded zone is the good zone in which high-quality fabrics usually fall in. These charts are frequently used in both research and process control.

THE CHART OVERLOOKING THE TOTAL PERFORMANCE OF A SUITING

For evaluating the performance of a suiting, the overlooking chart is convenient, as shown in Figure 9. This chart aggregates the following fabric properties: 1. mechanical parameters; 2. fabric hand; 3. suit appearance prediction; and 4. mechanical comfort.

The KESF AUTO system outputs this chart after the measurement of a fabric and provides all information about the performance of fabric. This is the result of the development of the objective evaluation system which we have conducted since 1965. We are now moving the investigation toward the engineered design of fabric design to realize ideal fabrics for suits. Similar technology is, of course, applicable to other categories of fabrics.

TOWARD THE ENGINEERED DESIGN OF FABRIC QUALITY[10,11]

The properties of good fabrics for suits have been clarified by the objective method. These properties are clearly shown based on the mechanical data of fabric. The target for the fabric design and manufacturing is now becoming clear. We are now proceeding with trials to create a guideline for manufacturing ideal fabrics for suit. Ideal fabrics are fabrics that satisfy the following three conditions: 1. good hand (high THV); 2. good appearance of suit (high TAV); and 3. satisfy the

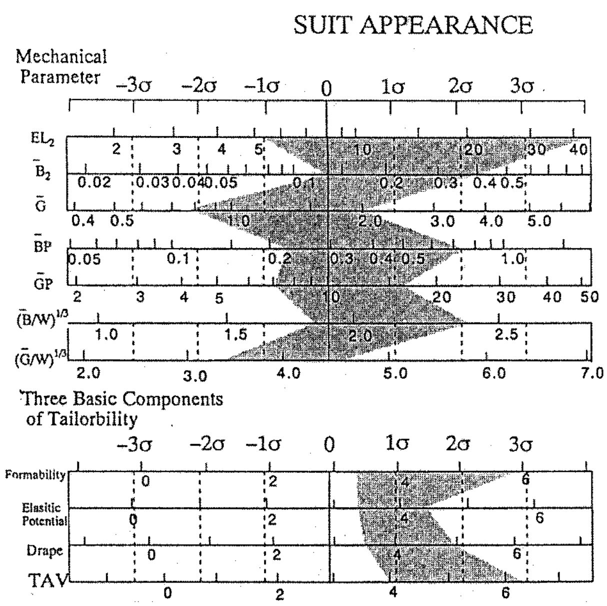


Figure 8 The suit appearance prediction chart. The top chart shows the derived mechanical parameters[2] and the bottom shows the three components of TAV and the TAV. This chart is applied regardless of fabric season.

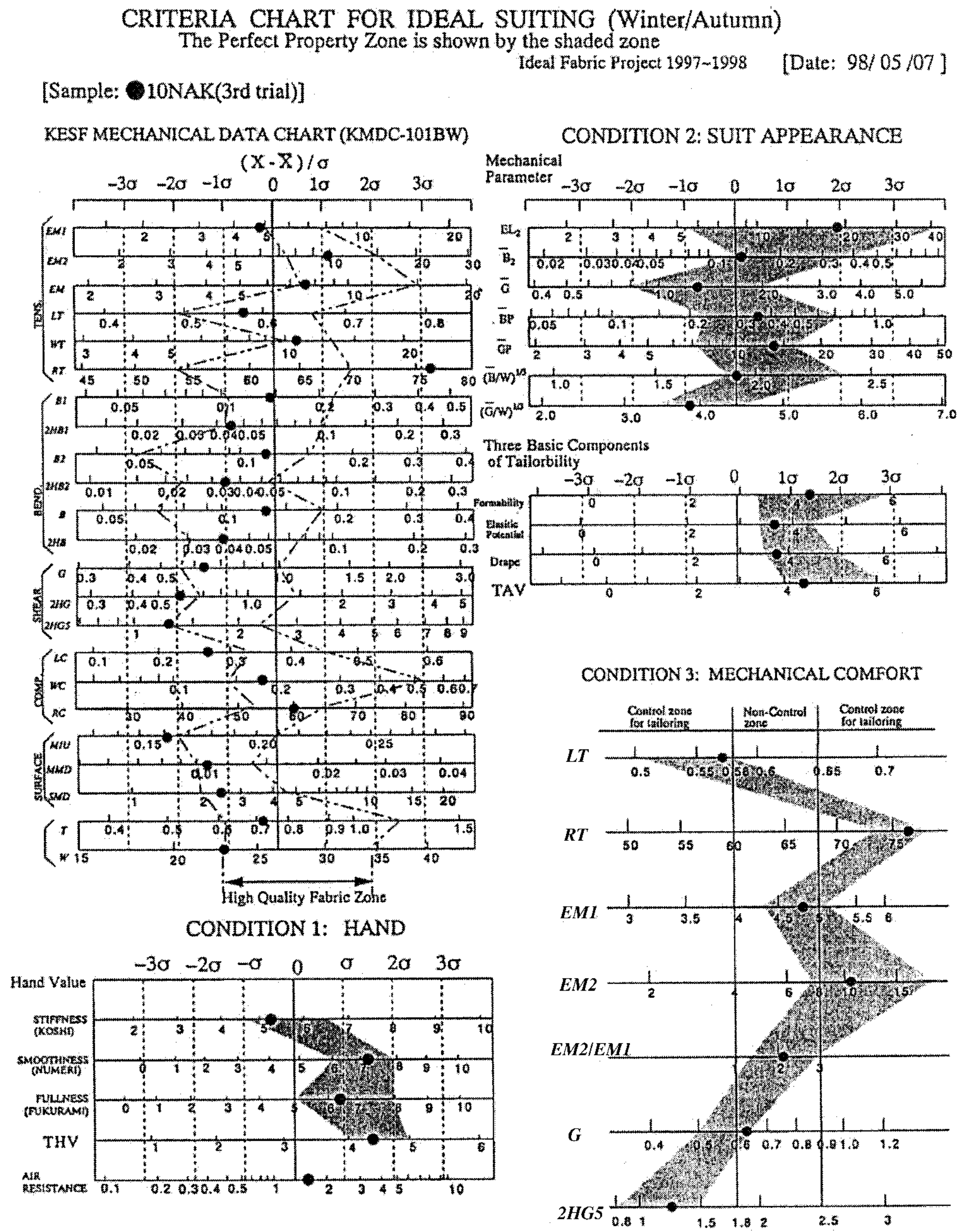


Figure 9 The chart overlooking the total performance of a suiting. An example of a suiting (100% worsted) is shown. This fabric has been developed applying the objective evaluation technology as one of "ideal fabric."

mechanical comfort conditions (shaded zone on control chart).

Table VIII(a) shows the criteria for ideal fabric, which we have proposed on the basis of data analysis. When the fabric properties satisfy these conditions, we call the fabric "perfect," or "ideal." The conditions for mechanical comfort are shown in Figure 6 by a shaded zone. As a reference, the ranges for the high-quality fabrics are shown in Table VIII(b) and also by shaded zones in Figures 7 and 8.

IDEAL FABRIC MANUFACTURING TRIAL[11]

To make a guideline for manufacturing ideal fabrics, I have organized the Ideal Fabric Project for manufacturing ideal fabrics in 1996 in collaboration with universities and industries in our country. This project has been supported by the Japanese scientific fund. The system of development is shown in Figure 10. A fabric is selected for the base fabric. This fabric is not yet ideal fabric; however, it has a good property that can be im-

Table VIII(a) The Criteria for the Ideal Fabric

	Type of Suiting		Remarks
	Winter–Autumn	Midsummer	
1. THV	THV $\geqq 4.0$	THV $\geqq 3.5$	THV: 1 (poor)–5 (excellent)
2. TAV	TAV $\geqq 4.0$	TAV $\geqq 4.0$	TAV: 1 (poor)–5 (excellent)
3. Mechanical comfort (inside the snake zone)	$0.58 \geqq LT \geqq 0.50$	$0.60 \geqq LT \geqq 0.50$	LT: average of LT_1 and LT_2
	$78 \geqq RT \geqq 73$	$78 \geqq RT \geqq 73$	RT: average of RT_1 and RT_2
	$5.1 \geqq EM_1 \geqq 4.3$	$5.1 \geqq EM_1 \geqq 4.3$	
	$18 \geqq EM_2 \geqq 7.5$	$18 \geqq EM_2 \geqq 7.5$	
	$3.0 \geqq EM_2/EM_1 \geqq 1.3$	$3.0 \geqq EM_2/EM_1 \geqq 1.3$	
	$0.65 \geqq G \geqq 0.50$	$0.65 \geqq G \geqq 0.50$	
	$1.5 \geqq 2HG5 \geqq 0.8$	$1.5 \geqq 2HG5 \geqq 0.8$	

Suffix 1, warp direction; 2, weft direction

proved by a weave-design change in the trimming level to bring the fabric to ideal. The process of the improvement is as follows:

1. Find a base fabric of which property may be improved by a weave-design change in the trimming level to bring the fabric to ideal.
2. Weave design is made for the improvement on the basis of the analysis of objective measurement of the fabric. In many cases, we have to seek yarns suitable for the weft or warp, and then, in some cases, seek fibers to get the suitable yarns. We need cooperation with fiber producers.
3. Based on the design of weave, the THV, TAV, and other performances of the fabric are predicted based on the objective evaluation. The design is repeated until the ideal fabric property is predicted.
4. Then weaving and finishing begin. It is important to measure and inspect the fabric property in the finishing process at least once.

This procedure is not for all fabrics. The purpose of this trial is to obtain a guideline for manufacturing ideal fabrics. When we have the guidelines for several types of fabrics, then we may modify the weave design within a narrow range near the guideline.

Tables IX–XI show an example of the development of the ideal fabric. The base fabric W5 was first chosen. This fabric is a good hand fabric and we considered that the W5 could be improved by a weave-design change of trimming level to bring

Table VIII(b) The Range of Properties of High-Quality Suiting (for Reference)

Property	Parameter	Range	
		Winter–Autumn	Midsummer
1. Primary HV	Stiffness (Koshi)	$4.5 \leqq \text{HV} \leqq 6.5$	$4.5 \leqq \text{HV} \leqq 6.5$
	Smoothness (Numeri)	$6 \leqq \text{HV} \leqq 8$	—
	Fullness (Fukurami)	$5 \leqq \text{HV} \leqq 8$	$4.5 \leqq \text{HV} \leqq 6.5$
	Crispness (Shari)	—	$4 \leqq \text{HV} \leqq 7$
	Anti-drape (Hari)	—	$4 \leqq \text{HV} \geqq 6$
2. Primary appearance value (components of TAV)	Formability component	$\geqq 3.3$	$\geqq 3.3$
	Elastic potential component	$\geqq 3.3$	$\geqq 3.3$
	Drape component	$\geqq 3.5$	$\geqq 3.3$
3. Air permeability	Air resistance R KPa $\cdot$ s/m	$\geqq 1$	$\leqq 1$ (0.02–0.2: very permeable)

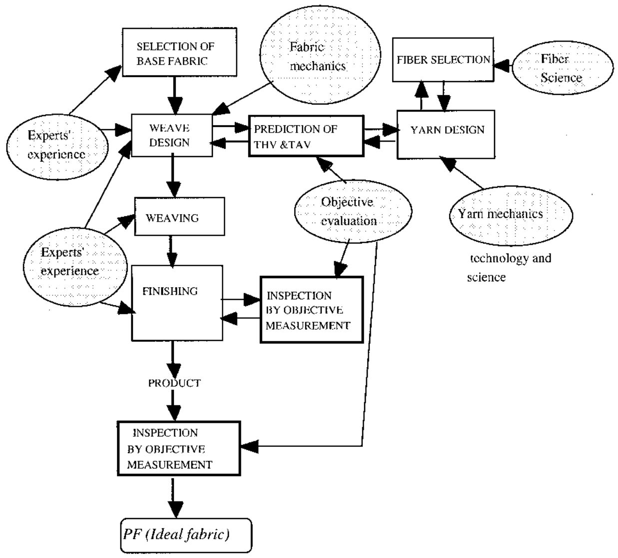


Figure 10 Development of the ideal fabrics under the cooperation of university and industry.

the fabric to the ideal fabric. A main problem in the property of this original fabric W5 is its very low TAV, as seen in Table IX. The reason for this low TAV was investigated on the basis of the data analysis of this fabric, with careful inspection of the properties shown in the appearance prediction chart. We decided to increase the bending stiffness of the fabric by increasing fiber diameter. An anxious problem in this design change was the drop of fabric THV caused by the use of coarser fiber diameter.

The first trial was an inspection of this problem. The design change was made carefully and it was confirmed that good finishing could cover the drop of THV. The second trial was directed to realizing the ideal fabric. Table X shows the new design (identified by sample 10), prediction of the properties of sample 10, and the result of the experimental trial (10N). Sample 10NR is a refinished sample of 10N.

As seen in Table X, the ideal fabrics were obtained from the second trial fabrics. Only the mechanical comfort (MC) condition was not satisfied for the minor reason that the extensibility of warp direction was a little larger than the range of ideal value. 10NR is perfectly the ideal fabric. This is indicated in Table X by the PF mark.

The third trial was conducted following the results of the second trial. One purpose of this trial was to confirm the reproducibility of the 10N fabric, and another was to mend the extensibility in warp direction with finishing. As seen in Table XI, the perfect fabric was obtained. This property is also shown in Figure 8.

Figure 11 shows the properties of those W5-original, W5-mild changes (the first trial); 10N (the second trial) and 10NAK (the third trial) are plotted. It is clearly shown that the ideal fabric was realized. The 10NAK falls perfectly in the good zones.

We are planning that a fair organization certifies "ideal fabric" and stamps the certification as shown in Figure 12 on the fabric for customers such as tailoring companies and consumers.

TOWARD ENGINEERING DESIGN AND MANUFACTURING OF FABRICS

We are just in the beginning stage of the engineered design of fabric quality. As shown from our experience of the ideal fabric trials, which was introduced herein, the future of the engineered

Table IX Properties of the Base Fabric W5

No.	Trial	Warp	Weft	$n1$	$n2$	W
0-0	W5-original	2/91S (17.3 μm 100%)	2/91S (17.3 μm 100%)	92	86	18.0

EM-1	EM-2	B-1	B-2	$2HB$-1	$2HB$-2	Koshi (Stiffness)	Numeri (Smoothness)	Fukurami (Fullness)
5.38	10.5	0.0798	0.0553	0.0243	0.0150	3.64	6.54	5.30

THV	TAV	MC	PF
3.68	1.76		

Table X The Second Trial

No.	Trial	Warp	Weft	$n1$	$n2$	W
10	W5-10 design and prediction	2/60S (20.3 μm 100%)	2/56S (20.3 μm 50%, 21.5 μm 50%)	74	71.5	22.9
10N	Experimental result	2/60S (20.3 μm 100%)	2/56S (20.3 μm 50%, 21.5 μm 50%)*	74	71.5	21.5
10N-R	Experimental result (refinished)	2/60S (20.3 μm 100%)	2/56S (20.3 μm 50%, 21.5 μm 50%)*	74	71.5	22.7

EM-1	EM-2	B-1	B-2	$2HB$-1	$2HB$-2	Koshi (Stiffness)	Numeri (Smoothness)	Fukurami (Fullness)
5.38	12.00	0.128	0.119	0.0342	0.0284	5.67	7.06	4.79
5.85	8.21	0.116	0.121	0.0338	0.0349	5.32	6.70	5.00
4.78	8.79	0.135	0.111	0.0396	0.0326	5.20	6.90	5.80

THV	TAV	MC	PF
4.30	4.21	PF-a	PF
4.07	4.03	PF-a	PF
4.24	4.03	PF	PF

A new design for W5 (sample no. 10) and the prediction of property, and experimental results (no. 10N and 10N-R, where -R is the sample that was refinished).

MC, mechanical comfort; PF, perfect, ideal fabric.

design and manufacturing of apparel fabrics is promising.

The same "ideal" technology is applicable to the design of other fabrics such as women's garment fabrics. One problem in this application is, however, a lack of reliable evaluations of the fabric quality for the women's fabric even by the subjective method. We are continuing the survey of the quality evaluation for women's fabrics. Although the examples of the application introduced was only worsted fabrics, the criteria are applicable to all men's suiting regardless of fiber kind, that is, wool, synthetic fiber, or their blends. Recent investigations also

Table XI The Third Trial for Reproducibility and Some Trimming for Improvement, Design 10NA (PF-Mark, Perfect)

No.	Trial	Warp	Weft	$n1$	$n2$	W
10NA	W5-10 design and prediction	2/60S (20.3 μm 100%)	2/56S (20.3 μm 50%, 21.5 μm 50%)	74	72	22.8
10NA KA	W5-10NA experimental result	2/60S (20.3 μm 100%)	2/56S (20.3 μm 50%, 21.5 μm 50%)	74	72	22.8

EM-1	EM-2	B-1	B-2	$2HB$-1	$2HB$-2	Koshi (Stiffness)	Numeri (Smoothness)	Fukurami (Fullness)
4.5	10.0	0.135	0.112	0.0396	0.0329	5.22	6.90	5.80
4.79	10.1	0.143	0.116	0.0460	0.0350	5.19	7.08	6.34

THV	TAV	MC	PF
4.24	4.14	PF	PF
4.36	4.30	PF	PF

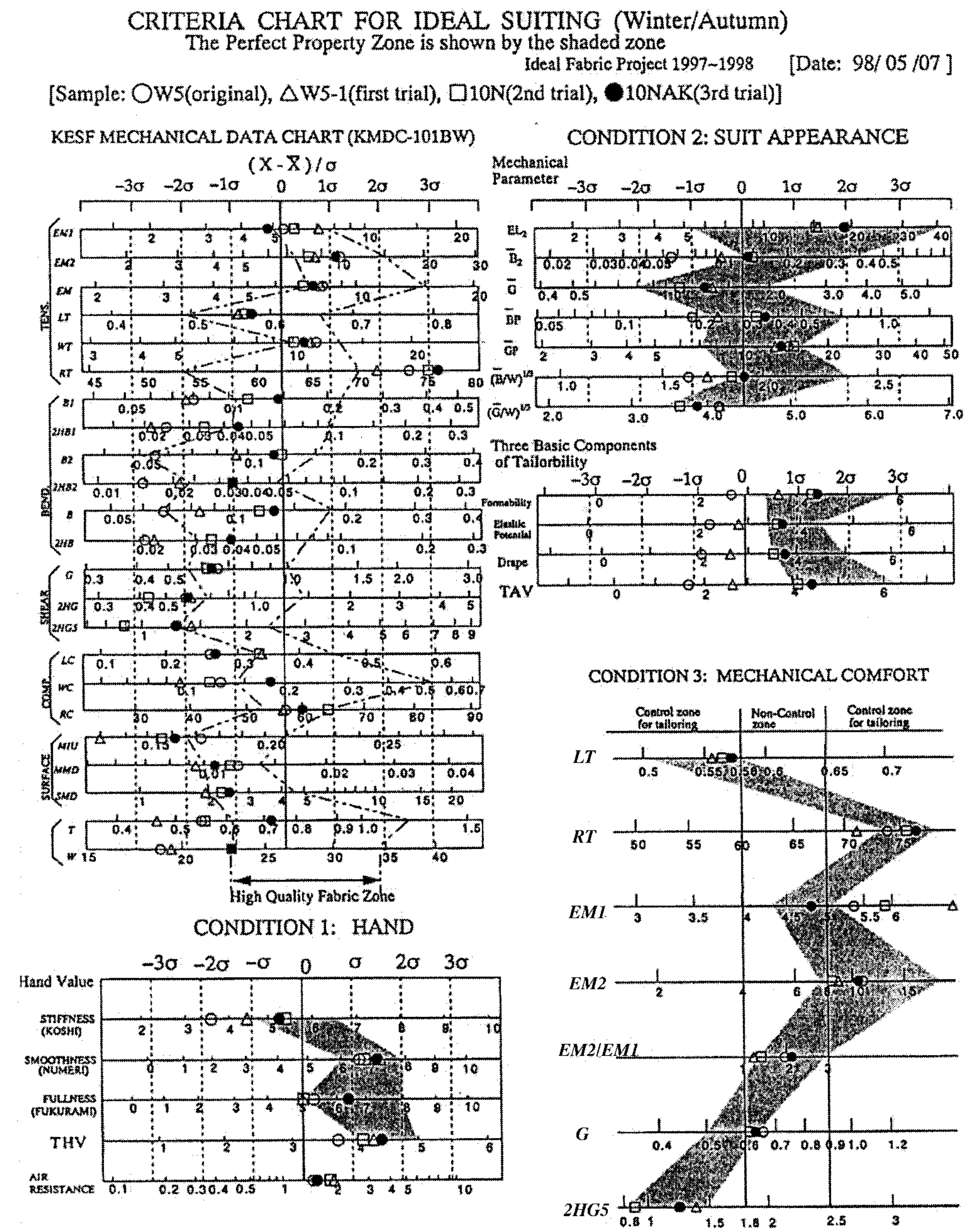


Figure 11 The improvement of original W5 by the first, second, and third trials are shown. The property is gradually improved. The final fabric is the Perfect Fabric (Ideal fabric).

show that the evaluation criteria which we used here can be applicable to women's suiting with high accuracy.

The engineered design and manufacturing technology will provide high-quality fabrics with reasonable price for consumers. Fibers are valuable resources, not only natural fibers but also synthetic fibers. We need to produce apparel fabrics carefully so that only high-quality fabrics are manufactured. This also saves energy for production. This is a clear direction for the textile industry in the 21st century.

ADVANCED STUDY OF FIBER PROPERTIES

Fibers are the basic material of textiles. The details of fiber property are required for the advanced research of textile mechanics. Because of the strong orientation of chain molecules and microstructure of fibers along the longitudinal direction, fibers have strong anisotropy in their mechanical property. Figure 13 explains the mechanical parameters of fiber. The five parameters shown in the figure are the mechanical parameters describing the fiber property. Even if we assume that the fiber is a linear elastic body, we need to use these five constant parameters as the material properties of the fiber. We have had little data on these parameters for commercial fibers with the exception of longitudinal extension modulus.

When the fibers are applied to technical textiles, especially to composite reinforcement, we need full data of the anisotropy in mechanical property of the fiber. For apparel textiles, the design of textiles will become more precise. Following this, we have to know details of fiber properties. We have already met with insufficient information about fiber properties. For example:

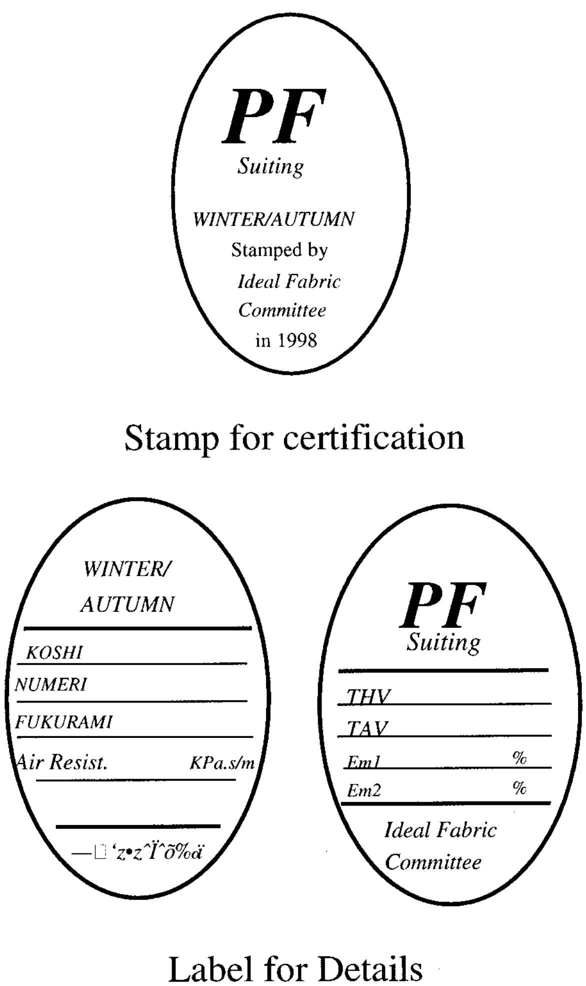


Figure 12 "Perfect" mark example, which guarantees the fabric quality and shows basic characteristics of the fabric.

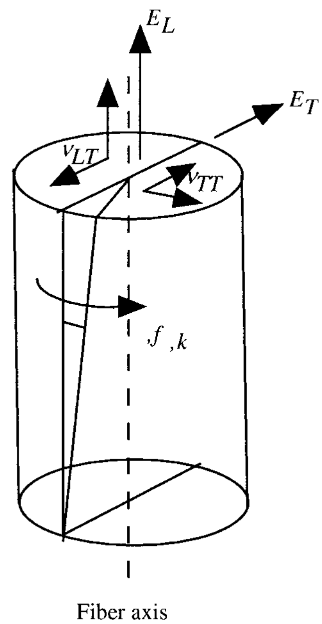


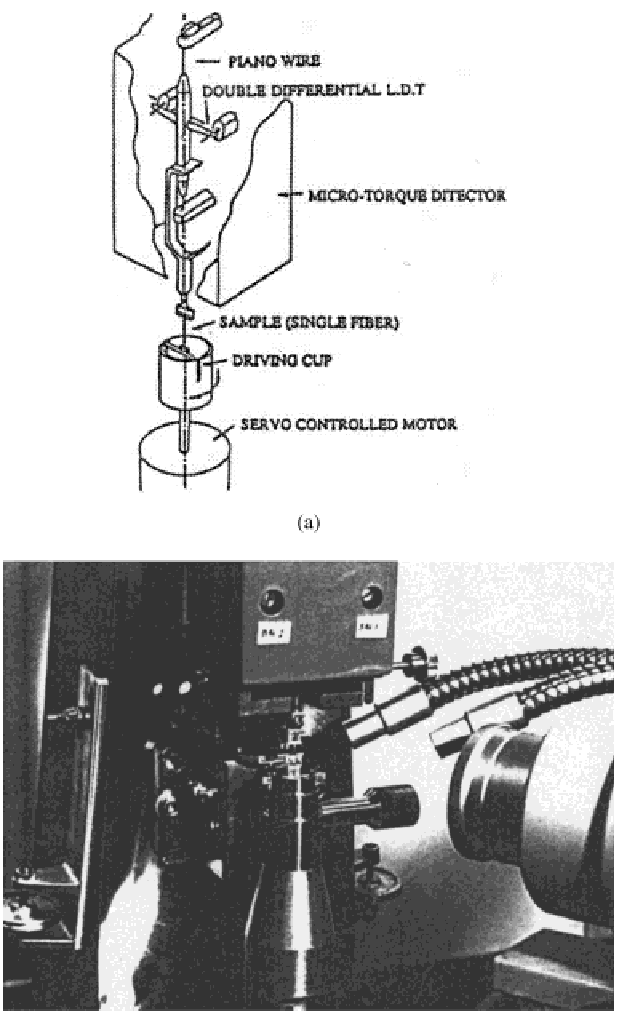
Figure 13 Mechanical parameters of fiber property.

1. Details about the contact problem of two fibers (related to frictional properties such as behavior of hysteresis of fabric tensile force): E_T is necessary
2. The tensile property of yarn and fabric in the low-load region: G_T is important.
3. The effect of moisture on textiles: the information about the effect of moisture on G_L, E_T has not yet been explained, but is probably different from that of E_L.
4. Are there any particular differences between commercial fibers in these properties, 1–3?

We now need such details of fiber properties for the advanced design and engineered design of textiles.

DEVELOPMENT OF THE "MICRO-MEASUREMENT" SYSTEM

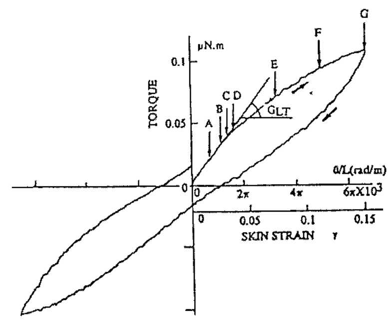
For the investigation of details of fiber properties, a single fiber measurement is necessary. The single fiber measurement is, however, attended with practical difficulties because of the micrometer order of fiber size. Because of the importance of fiber property, some researchers have been interested in the difficult measurement. Pinnok et al.[12] measured E_T in 1966, not for fine diameter fiber, but for filament-like fibers. Later, in 1974, Phoenix and Skelton[13] measured E_T of some commercial fibers. The measurement of G_L has been tried by other researchers, and an instrument for measuring G_L has been commercialized, although this instrument did not become popular because of complicated operation and accuracy problems. Anandjiwala and Goswami[14] reported fiber/yarn fatigue interaction, and measured the torsion fatigue property of single fiber by using his own instrument. His report pointed out the importance of fiber property for solving textile processing problems. Poisson's ratios, ν_{LT} and ν_{TT} are not yet clearly understood. In the past 100, only



(a)

(b)

Figure 14 (a) Principle of the torsion tester.[15,16,20] (b) Appearance of the torsion tester.[15,16,20]



Symbol	Shear strain
A	0.015
B	0.025
C	0.031
D	0.037
E	0.075
F	0.112
G	0.154

Figure 15 One cycle of the torque–torsion angle curve of Kevlar 49® fiber. The arrows indicate the strain amplitude of the repeated cycle testing.[20]

tensile modulus and other tensile properties of fiber have been explained. The data of other properties of fibers are, however, not sufficient for the advanced research of textiles that will be important in the next century. We have many commercial fibers now. We need the database of mechanical property details of these fibers. Also, the database should explain the relation between the mechanical parameters and the micro-structures of fiber.

Kawabata also initiated his new research project on the measurement of fine mechanical properties of fiber using a single-fiber measurement technique,[15–20] which we call "micro-measurement." This system consists of five testers:

1. Precise extension tester of single fiber with very small mechanical noise
2. Transverse compression tester for single fiber

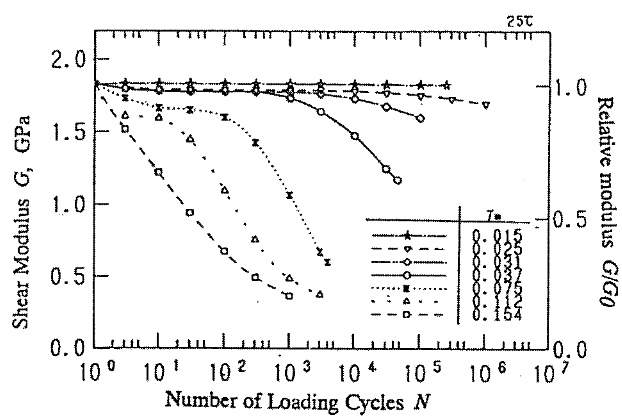


Figure 16 Reduction of G_L with increasing numbers of repeated torsion for different strain amplitudes. Sample is Kevlar 49 fiber.[20]

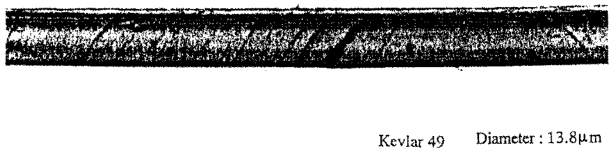


Figure 17 The fiber appearance after repeated torsion cycles.

3. Torsion tester of single fiber with ultrahigh sensitivity torque detector
4. Poisson's ratio tester for ν_{LT}
5. Axial compression tester of single fiber or a micro-composite specimen consisting of a fiber bundle.

ν_{TT} is measured using the micro-composite specimen. This system was completed around 1990 and we are expanding our database. Figure 14 shows the torsion tester for single-fiber measurement.[15,16,20] The highest sensitivity range of torque is now $0-0.05\ \mu\text{N}\cdot\text{m}$. This tester has a function of applying repeated torsion, and torsion-fatigue testing has been done for many kinds of fibers. Figure 15 is the one-cycle torque-torsion curve of Kevlar® 49 single fiber. Repeated cycle torsion was applied at several torsion angles, shown by the arrow on the curve. Figure 16 is the reduction of G_L with increasing numbers of torsion cycles.[20] It is clearly shown that G_L is decreased with increasing numbers of cycles and there is a rule of strain amplitude–number of cycle equivalent principle, similar to the temperature–time equivalent principle observed in the viscoelasticity of polymer solids. Figure 17 shows the fiber appearance after repeated torsion.

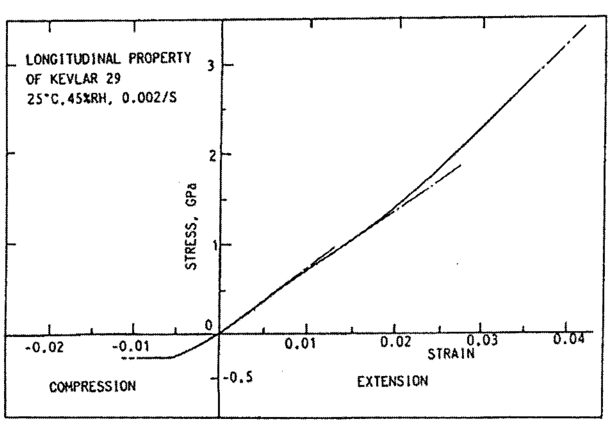


Figure 18 A complete longitudinal stress–strain relation of Kevlar 49 fiber over the longitudinal extension–compression range.[19]

Table XII All Parameters of Kevlar 29 and Anisotropy in Strength (or Yielding Stress)

Mechanical Parameters of Kevlar 29 Under 25°C and 45% RH

E_L (GPa)	
Tensile	79.8 (initial strain zone, strain < 0.005)
	69.5 (at strain 0.02%)
	98.4 (near breaking strain zone, strain ≃ 0.038)
Compression	60.0 (at strain −0.001)
	45.0 (at strain −0.002)
	12.0 (at strain −0.004)
E_T (GPa)	2.59
G_{LT} (GPa)	2.17
ν_{LT}	0.63
ν_{TT}	0.43

Strength of Kevlar 29 Under 25°C, 45% RH

		Stress (GPa)	Strain
Longitudinal	Tensile (GPa)	2.55	0.037
	Compression (GPa)	0.31 (yielding)[a]	0.007
Transverse	Compression (GPa)	0.056 (yielding)[b]	0.091
Longitudinal shear		0.101 (yielding)[c]	0.047

[a] Maximum stress.
[b] See Figure.
[c] ΔD/initial D; D, fiber diameter.

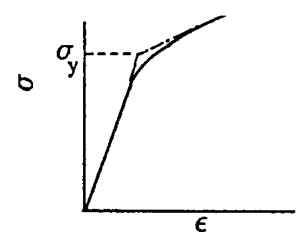


Figure 18 shows a complete longitudinal stress–strain relation of Kevlar49® fiber over the axial extension–compression range. As seen from this figure, the axial compression yielding stress is much weaker than the extension strength. Table XII shows all parameters of Kevlar 49 and anisotropy in strength (or yielding stress).[19]

The advanced design of textiles is becoming important not only for apparel but also industrial textiles. There is a rapid expansion in the application of textiles for industrial use. The precise properties of fibers are also needed for the ad-

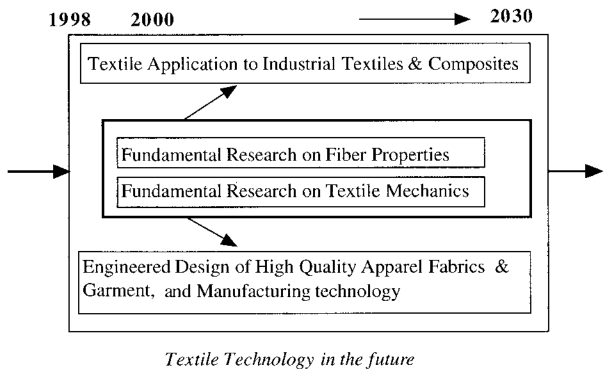


Figure 19 The prediction map of textile research for 30 years in the next century.

vanced design of industrial textiles and fiber-reinforced composite materials. The database of all fibers is strongly needed for the future development of textiles.

DIRECTION FOR THE NEXT DECADE

Figure 19 is the prediction map of the textile research in the next century. Living standards will continue to rise. The engineered manufacturing of high-quality clothing and clothing materials is an absolute necessity for the future of textile industries. As already mentioned, fibers are valuable natural resources, even synthetic fibers. We have to use them carefully, so that we do not produce poor textiles, but only high-quality textiles of reasonable price. This also saves much energy. The only solution for this issue is the engineered design and engineered manufacturing of textiles.

In addition to this trend, another new engineering application for textiles is the industrial use of textiles. The use of fibrous composite materials is now rapidly expanding as they become the next generation of materials. Both of these engineering applications depend on the advanced theories of textile mechanics and on the deep understanding of fiber properties. Figure 19 is a forecasting of the structure of textile technology in the 21st century. Textile technology must be reconstructed and we must push basic research toward more advanced research levels.

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