Doctoral Dissertation (Shinshu University)

Study on development of comfort underwear with polypropylene blended yarn

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Table Content

Chapter 1

Preface

1.1 Background

Recently, consumer interest in functional underwear with high thermal insulation and quick drying is increasing[1]. Since 2005, the Ministry of the Environment has promoted "Cool Biz" and "Warm Biz" as business fashions, as measures against global warming, and functional underwear has been released by various manufacturers. The Great East Japan Earthquake in 2011 increased demand for functional underwear for saving electricity.

Some popular underwear was produced by devising a cross-sectional shape of synthetic fibers that allows both warmth and hydrophobicity, to allow quick drying of sweat[2]. Other popular underwear was produced by blending cellulose with heating by absorption and synthetic fibers with high insulation[3]. Underwear with thermal regulation material[4] is also popular. As functions required for comfortable underwear, good texture, light weight, mobility and moderate thermal sensation without wet feeling and bulkiness were reported by many researchers[5-7]. Although contact characteristics (skin contact feeling), pressure characteristics (clothing pressure), and heat and moisture transport characteristics (clothing microclimate) are factors that affect the comfort of clothing[8], heat and moisture transfer characteristics are the most important factor for underwear from recent trends. Ideal underwear material has fibers that are soft, light, quick-drying and moderately thermally conductive.

Polypropylene fiber (PP) has the characteristics required for comfortable underwear, such as low thermal conductivity, low Young's modulus, hydrophobicity and light weight (Table 1.1). In addition, PP can be manufactured inexpensively, because it is produced in large amounts by special polymerization of propylene in petroleum refining. Furthermore PP has perfect resistance to mold and harmful insects. However, commercialization of PP has not progressed in Japan. PP needs a stabilizer because of its low stability in sunlight. In the 1950s, accidents occurred in which the stabilizer melted and ignited in the dryer because of the low melting point of PP. Since then, PP has not been used as a garment material for safety reasons. So, there is little data on PP as a clothing material, and its use method is unknown. Nowadays, an insoluble stabilizer has been developed and the safety issue has been resolved [9]. The Japan Chemical Fibers Association revised "Polypropylene No Toriatukai Ni Tuite" that defines matters of concern for PP fiber as clothing and bedding applications, so PP and cellulose can be used in combination when safety is demonstrated by an oxidative heat generation test [10]. PP is entering a new phase as a clothing material, so investigation of its use is important.

There have been several studies relating to PP underwear. In a comparison of all PP and all cotton underwear in a cold environment by subjective evaluation and clothing climate measurement with the protocol of exercise to rest and comparing a subjective evaluation and clothing climate measurement, the clothing humidity and the temperature inside the clothes of all PP two-layer underwear were significantly higher than those of all-cotton two-layer underwear. In the back part, the difference between the highest point and the lowest point of the temperature inside the clothes became significantly lower by wearing all PP two-layer underwear [11]. In a comparison of the same samples, all PP two-layer underwear kept the skin temperature higher than 100% cotton two-layer underwear after walking exercise [12, 13]. Regarding mechanical properties of knitted fabric with blended yarn PP and cotton, changing the mixing rate in steps by the same yarn number, blending PP against cotton made the hand value (THV) lower and the total appearance value (TAV) and durability higher [14].

Since PP is hydrophobic, PP underwear should be designed to combine PP and other fiber materials in order to design water transportability required for comfortable underwear. There is no case study on wearing comfort of underwear with polypropylene blended yarn, and investigation on the usage of PP blended yarn is inadequate. There is also no case study regarding autonomic nervous activity and wearing stress evaluation for PP underwear. Psychological and physiological responses to the wearing feel differ due to homeostasis[15], so autonomic nervous activity and wearing stress are also important considerations in designing comfortable underwear.

In the process of developing comfortable underwear, evaluation technology is required for prototyping. There are several studies on comfort evaluation of underwear, such as studies on objective evaluation by Kawabata Evaluation System (KES)[17-19], studies on evaluation by psychological measurement and correlation of wearing feel and fabric property [5,7], studies on evaluation by thermal manikins[20], and studies on evaluation by the relationship between and wearing feel and thermos-physiological parameters such as temperature and humidity inside the clothes and amount of sweating [11-13, 21, 22]. In particular, there are many reports on the heat and moisture transport properties of underwear, so it is considered an important factor of underwear by many researchers. In recent years, development of comfortable underwear has been attempted by capturing the wearing comfort from autonomic nervous activity and wearing stress by physiological indicators [23, 24], but the number of such reports is still small.

Table1.1 Properties of PP fiber[16]

		Staple	Filament	
			Average	Powerful
Strength [g/d]	Dry	4.5～7.5	4.5～7.5	4.5～9.0
	Wet	4.5～7.5	4.5～7.5	4.5～9.0
Wet and Dry Strength Ratio（%）		100	100	100
Loop Tenacity（g/d）		8.0～14.0	8.0～12.0	11.0～14.0
Knot Strength（g/d）		4.0～6.5	4.0～5.5	4.5～6.0
Elasticity（%）	Dry	30～60	25～60	15～25
	Wet	30～60	25～60	15～25
Elastic Recovery of Elongation（%）〔3%〕		90～100		
Apparent Young's Modulus（kg/㎟）		160～450	330～1000	
Moisture Regain（%）	Official	0		
	Standards	0		
Specific Gravity		0.91		

1.2. Purpose and Construction of Thesis

The purpose of this study is to investigate the possibility of developing comfortable underwear using PP. Based on the hypothesis that comfortable underwear can be designed using polypropylene blended yarn, sample underwear was manufactured from the stage of yarn. The effect of blended fiber and blending ratio were investigated from the physical, psychological and physiological aspects.

Fig.1.1 shows the construction of the thesis. Chapter 1 covered the purpose of this study and the thesis.

In Chapter 2, as a step in considering the wearing comfort of underwear, knitted fabrics using polypropylene blended yarn with various fiber materials were manufactured for investigation of the effects of blending fiber material. Material properties of fabrics were evaluated by Kawabata Evaluation System (KES), Japan Industrial Standards (JIS) and BOKEN standard. The possible use of PP fiber as underwear material was examined by comparing the material properties of knitted fabrics of blended fiber materials.

In Chapter 3, a wearing experiment was carried out for representative samples selected from the result of Chapter 2; the physiological and psychological effects of blending fiber material on wearing comfort were examined. The possibility of using PP as underwear material was confirmed by the wearing stress test.

In Chapter 4, in order to examine the balance of PP and blending fiber materials, blended yarns with various blending ratios of PP and cotton were prepared, and knitted fabrics for underwear were prepared using the yarn. Material properties of knitted fabrics were measured by KES, JIS and BOKEN standards in order to estimate a suitable blending ratio.

In Chapter 5, the results of Chapters 2 to 4 were summarized, and a conclusion and future prospects were stated.

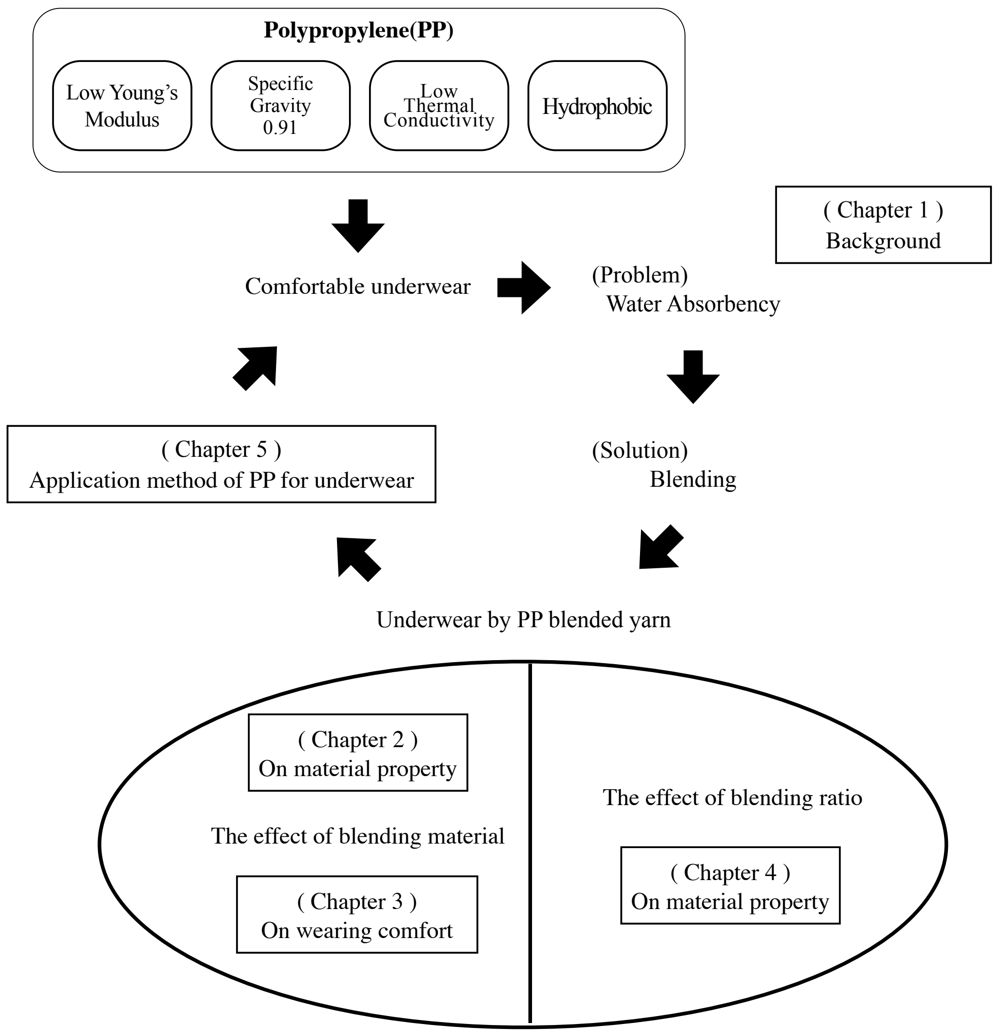

Fig. 1. 1. Constitution of thesis

Chapter 2

The Effect of Blended Fiber Material for Knitted Fabric with Polypropylene Blended Yarn

2.1. Introduction

There is a possibility that useful clothing materials can be made by combining PP with other fiber materials. As mentioned in Chapter 1, blending is one of the methods of combining PP and other fiber materials, and there is no case study verifying the effect of blending various fiber materials with PP. In this chapter, knitted fabric for underwear was prepared using blended yarn of PP and various fiber materials. Material properties of these knitted fabrics were evaluated by Kawabata Evaluation System (KES), Japan Industrial Standards (JIS) and BOKEN standards. The effects of blended fiber material on wearing comfort were investigated based on the material properties. By principal component analysis of the measurement results, information was extracted on the material properties that remarkably changed due to blending various fiber materials with PP. In addition, the samples were classified by cluster analysis of the measurement results of material properties, to consider the degree of influence of the blended fiber material. Based on these methods, the possible use of PP as underwear material was examined.

2.2. Samples

2.2.1 Yarns

Table 2.1 shows eight spun yarns made of a staple unified with the same cotton yarn number with 50s. Six spun yarns were blended yarns of PP and other fiber material.

The other two spun yarns were 100% PP and 100% polyester (PET) for comparison. PET used for blending with PP (hereinafter referred to MCPET) was modified by cross-sectional processing to improve water absorption performance. PET used for comparison with PP (hereinafter referred to as CDPET) was a PET that can be stained at atmospheric pressure with cationic dye. Table 2.2 shows the material properties of the yarns with coefficient of variation (CV%). PP/Ry became the same yarn number as designed, and PP/Wy became thinner than designed. Fig 2.1 shows the side view of yarns magnified by 100 times by electron microscope (KEYENCE VE-9800), and the diameter of the yarn without tension was measured using these images. The diameter was measured 10 times, and the mean was the representative value. Since the yarn was unified with the same cotton yarn number and PP has the

Table 2.1 Material of each yarn

Symbol	Material & Blending Ratio with size of fiber
PPy	Polypropylene100% : 1.0dtex× 38mm
PP/MCPETy	Polypropylene50% : 1.0dtex × 38mm / Polyester50% : 1.4dtex × 38mm
PP/Ry	Polypropylene50% : 1.0dtex × 38mm / Rayon50% : 0.9dtex × 38mm
PP/Ny	Polypropylene50%: 1.0dtex × 38mm / Nylon50% : 1.3dtex × 38mm
CDPETy	Polyester100% : 1.4dtex × 38mm
PP/Cy	Polypropylene50%:1.0dtex × 38mm / Cotton50% : 4.2micronaire × 37mm
PP/Acy	Polypropylene50% 1.0dtex × 38mm / Acrylic50% : 0.9dtex×38mm(5%) 0.9dtex×51mm(45%)
PP/Wy	Polypropylene50% : 1.0dtex × 38mm / Wool50% : 22μm × 1.5inch

lowest specific gravity with 0.91[12], the diameter of PPy was the maximum. The weight per unit length was calculated by the yarn number based on corrected mass. The heaviest was PP/Cy, and the lightest was PP/Wy. In order to consider the influence on yarns of differences in the specific gravity of fiber materials, regardless of the manufacturing error of weight, the apparent density was defined by dividing the weight by the volume, which was calculated by approximating the cross-section of the yarn to a circle. The apparent density of PPy was the lowest because

Table 2.2 Properties of each yarn (CV%)

Symbol	Yarn Number [Ne]	Diameter [μm]	Weight [g/m]	Apparent Density [g/㎤]	Number of Twist [time/inch]	Elastic modulas [N/mm]	Young's modulas [N/㎟]	Irregularity U%
PPy	50.02 (2.50)	245.10 (5.69)	0.01181	0.282	25.85 (4.11)	0.13 (10.5)	2549 (10)	10.97
PP/MCPETy	49.90 (1.90)	200.93 (7.30)	0.01183	0.368	25.59 (2.28)	0.12 (6.4)	3023 (6)	11.08
PP/Ry	50.00 (2.56)	194.34 (7.73)	0.01181	0.359	25.49 (3.10)	0.14 (6.0)	3233 (6)	10.26
PP/Ny	50.70 (1.88)	198.80 (8.51)	0.01165	0.482	26.16 (2.31)	0.11 (7.5)	2433 (7)	12.48
CDPETy	49.90 (1.90)	160.60 (10.6)	0.01179	0.573	24.78 (2.45)	0.07 (7.8)	1706 (6)	14.20
PP/Cy	49.70 (2.24)	165.17 (8.15)	0.01188	0.786	25.44 (4.75)	0.13 (9.0)	3587 (8)	11.58
PP/Acy	49.90 (1.62)	229.02 (15.08)	0.01183	0.520	25.51 (3.42)	0.10 (8.1)	2183 (8)	10.45
PP/Wy	51.20 (1.58)	207.99 (7.21)	0.01153	0.403	25.60 (2.12)	0.11 (10.0)	2633 (9)	18.14

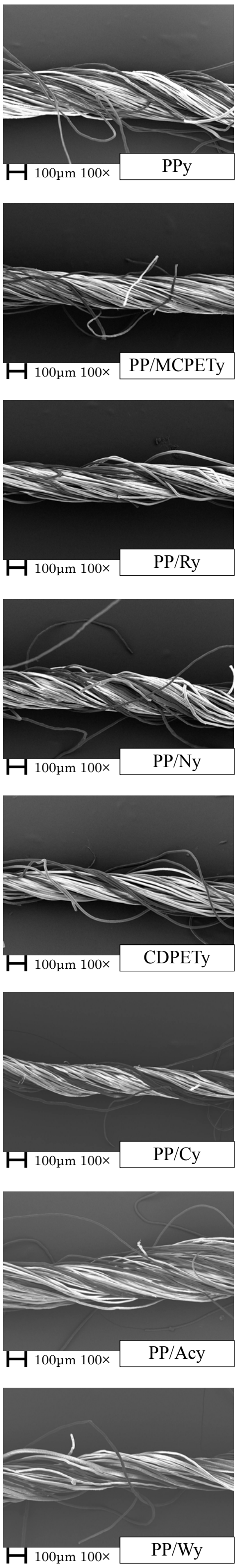

Fig2.1. Side view of yarn

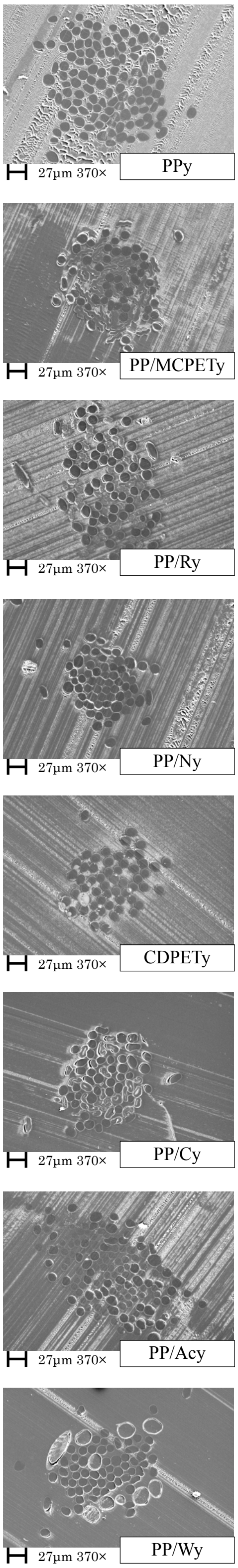

Fig2.2. Cross section of yarn

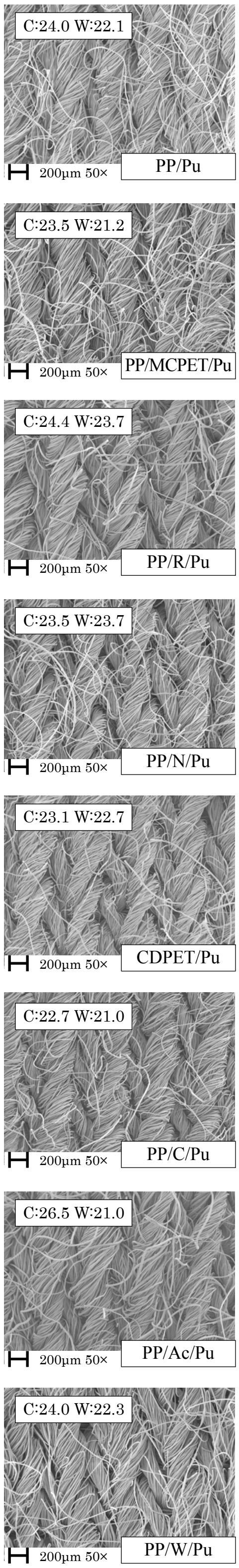

Fig2.3. Side view of fabric with stitch density per 1.27cm C:Course W: Wale

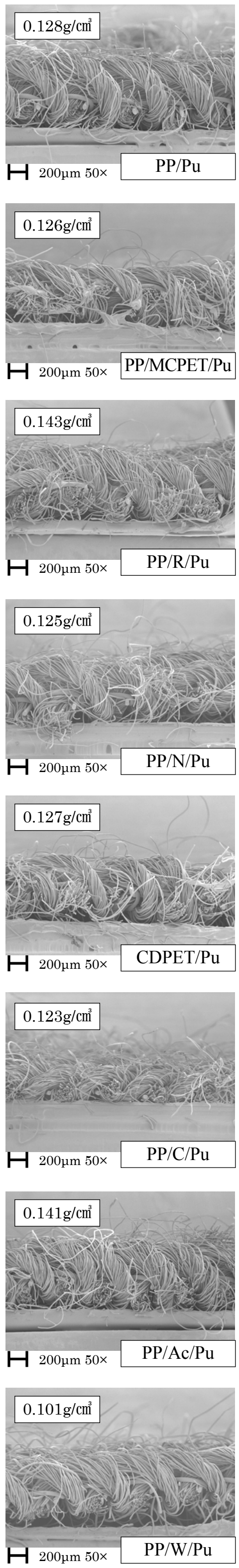

Fig2.4. Cross section of fabric with appearent density

of PP's specific gravity. Fig 2.2 shows the cross-section of yarns at magnification of 370 times by electron microscope (KEYENCE VE-9800). The yarn was embedded in epoxy to preserve its cross-sectional shape, and its surface was exposed by microtome (EMUC6 LEICA). In PPy, the number of fibers is large and the cross-section of the yarn is wide. The number of fibers decreased with blending of various fiber materials. Since PET has a high specific gravity, CDPETy tended to have a smaller number of fibers. The twist coefficient was unified at 3.8. The apparent Young's modulus was measured as resistance of incipient tension of the yarn by JIS (L1095), and elastic modulus was defined by dividing the load by the elongation amount in the first maximum value of change on the Stress-Strain (SS) curve. The number of measurements was 10, and the mean value was taken as the representative value. Because the elastic modulus of PPy was greater than or equal to that of other yarns, the softness of yarn tended to increase with blending. CDPETy was softer than PPy because of the difference of specific gravity. The yarn diameter and the number of fibers of PPy is greater than PET, because PP is lighter than PET. PPy has a lower Young's modulus than PP/MCPETy, PP/Ry and PP/Cy. The yarn evenness was measured at 200[m/s] for 3 minutes. Yarn evenness U% of PP/Wy is the maximum and the fluctuation of yarn diameter was large. The wool fibers were thick and made the yarn unevenness large in the image of the cross-section of yarn.

2.2.2 Fabrics

Table 2.3 shows the eight types of knitted fabrics made of the yarns shown in Table 2.1. The knitting structure was unified to plain knitting to make it easy to observe the difference of blended fiber materials. Twenty denier polyurethane (Pu) was interknit during manufacturing with a blending ratio of 9%. Six knitted fabrics blending PP with various fiber materials were used as samples to examine the effect of blending fiber material. PP/Pu and CDPET/Pu were samples for comparison. Fig. 2.3 shows the side view of fabrics at a magnification of 50 times by electronic microscope (KEYENCE VE-9800), and stitch density was noted. There was no remarkable difference of stitch density between PP/Pu and other samples, and it was suggested that the effects of blended fiber materials should be examined regarding aspects other than the knitting structure. Fig 2.4 shows the cross-section of fabrics at a magnification of 50 times by electronic microscope (KEYENCE VE-9800),

Table 2.3 Material of each fabric

Symbol	Material & Blending Ratio	Note
PP/Pu	Polypropylene91% / Polyurethane9%	Structure：Plain knitting Diameter of circular knitting machine：30” Number of needle：2640 Gauge：28
PP/MCPET/Pu	Polypropylene46% / Polyester45% / Polyurethane9%	
PP/R/Pu	Polypropylene46% / Rayon45% / Polyurethane9%	
PP/N/Pu	Polypropylene46% / Nylon45% / Polyurethane9%	
CDPET/Pu	Polyester91% / Polyurethane9%	
PP/C/Pu	Polypropylene46% / Cotton45% / Polyurethane9%	
PP/Ac/Pu	Polypropylene46% / Acrylic45% / Polyurethane9%	
PP/W/Pu	Polypropylene46% / Wool45% / Polyurethane9%	

and apparent density obtained by dividing the weight by thickness with 0.5gf/cm^2 was noted. PP/Pu was thick, the gaps between its yarns were small and its fibers were agglomerated. In CDPET/Pu, the gaps between yarns were large, and irregularities were observed on the surface. These observations suggested that the yarn diameter influenced the fabric material properties

2.3. Experiment

Material properties of all samples were evaluated by KES, JIS and BOKEN standards. Table 2.4 shows the measurement items. The measured material properties were basic mechanical properties related to the assumed deformation by wearing or handing, weight and thickness, heat, and water and air transport property. For each measurement item, five test pieces were cut from each samples and measured, and the mean was used as a representative value. The size of test pieces for KES was 20 cm × 20 cm, and for other measurement items, the provisions of each method were followed.

Regarding mechanical properties, tensile, shear, bending, compression and surface properties were measured by KES-FB system (Kato Tech) [25]. For tensile properties, tensile rigidity (LT), tensile energy (WT), tensile recoverability (RT) and maximum elongation rate (EMT) were measured. Since the elongation was too large for high-sensitivity condition, the wale direction was measured with a maximum load of 30 gf/cm and tensile speed of 2 mm/s, and the course direction was

Table 2.4 Measurement items of material property

Blocked Property	Symbol	Property	unit	Reference & Conditions of measurement
Tensile	LT	Tensile rigidity	-	KES-FB1 (Wale) Maximun load : 30[gf/cm] Tensile velocity : 2[mm/s] (Course) Maximun load : 12.5[gf/cm] Tensile velocity : 5[mm/s] Condition : 20°C65%RH
	WT	Tensile energy	gf・cm/cm²	
	RT	Tensile recoverability	%	
	EMT	Maximun elongation rate	%	
Shear	G	Shear rigidity	gf/(cm・deg)	KES-FB1 Standard measurement conditions Constant tension : 10[gf/cm] Maximum shear angle : ±8° Condition : 20°C65%RH
	2HG	Elastic for minutes shear	gf / cm	
Bending	B	Bending rigidity	gf・cm²/cm	KES-FB2 Standard measurement conditions Maximum curvature : 2.5/cm Condition : 20°C65%RH
	2HB	Bending recoverability	gf・cm/cm	
Compression	LC	Compressional linearity	-	KES-FB3 High sens measurement conditions Rate of compression : 150[s/mm] Maximum pressure : 10[gf/cm²]
	WC	Compressional energy	gf・cm/cm²	
	RC	Compressional recoverability	%	
Surface	MIU	Mean frictional coefficient	-	KES-FB4 Standard measurement conditions Contact force of MIU and MMD : 50gf Contact force of SMD : 10gf Tension of specimen : 20gf/cm
	MMD	Fluctuation of mean frictional coefficient	-	
	SMD	Surface roughness	micron	
Weight & Thickness	W	Weight of fabric per 1m²	g / m²	Weight by electronic balance Thickness by KES-FB3 Condition : 20°C65%RH
	T	Thickness of fabric with 0.5gf / cm²	mm	
Heat transport property	q-max	Peak heat flux	W/cm²	KES-F7 Thermo-Lab Source of heat : 30°C ΔT : 10°C Air velocity of Qd : 0.3m/s
	K'	Thermal conductance	W/(m²・°C)	
	Qd	Heat retention properties	%	
Air permeability	R	Ventilation resistance	KPa・s / m	KES-F8 Speed : 2 SEMS:M
Water transport	MR	Moisture regain	%	MC : JIS L 1096 WA : JIS L 1096 A-2 Byreck SAQD : BOKEN(BQE A 028) MET : BOKEN(BQE A 035)
	WA	Water absorbing property	cm	
	MV	Moisture vapor permeability	g/m²・h	
	SAQD	Sweat absorption and quick drying	%	
	MET	Moisture exothermicity	°C	

measured with a maximum load of 12.5 gf/cm and tensile speed of 5 mm/s. For shear properties, shear rigidity (G) and elastic for minutes shear (2HG) were measured with standard measurement conditions. As for bending properties, bending rigidity (B) and bending recoverability (2HB) were measured in standard conditions. As for compression properties, compressional linearity (LC), compressional energy (WC) and compressional recoverability (RC) in standard measurement conditions were measured. For surface properties, mean friction coefficient (MIU), fluctuation of mean friction coefficient (MMD) and surface roughness (SMD) were measured in standard measurement conditions. The thickness (T) was measured with 0.5 gf/cm^2. Weight (W) is mass per unit area.

For air permeability, ventilation resistance (R) was measured by KES-F8 (Kato Tech Co., Ltd.)[26]. For heat transport properties, q-max, thermal conductance (K') and heat retention performance (Qd) were measured by KES-F7 Thermo Lab (Kato Tech Co., Ltd.). As for water transport properties, moisture regain (MR) (L1096), water absorption (WA) (L1907 Byreck) and moisture vapor permeability (MV) (L1099A-2) were measured by JIS [28-30]. Sweat absorption and quick drying (SAQD) (transpiration (Ⅱ) test - BQE A 028) and moisture exothermicity (MET) (BQE A 035) were measured by BOKEN standard [31] [32]. In SAQD, the transpiration rate after 20 minutes was taken as the representative value. The measurement environment, except for MV and MET was 20 °C, 65% RH. MV was measured at 40 °C, 50% RH. MET was the temperature change when the environment was changed from 20 °C, 40% RH to 20 °C, 90% RH.

The wale and the course direction were separately measured for tensile, shear, bending, surface property and WA. For measurement items that can be measured on both sides of fabric, the back side which directly contacts the skin while worn was measured.

2.4. Results and Discussion

2.4.1 Material Property Evaluation

In all measurement items relating to the deformability of the basic mechanical property that can be measured separately in the wale and course direction, the variation of data tended to be greater in the course direction than in the wale direction. As a representative example, Figure 2.5 shows the results for shear rigidity (G), and figure. 2.6 shows the elasticity for minute shear (2HG). For the measurement items that can be measured the wale and the course direction separately, the data in the wale direction with small variation was taken as the representative value.

For each measurement item, the effect of blended fiber material was examined by comparing PP/Pu and other samples, and the difference between PP and CDPET was examined by comparing PP/Pu and CDPET/Pu. Because a significant difference with 1% level was found in all measurement items by ANOVA, the difference between PP/Pu and other samples was tested by multiple comparisons with Dunnett's test.

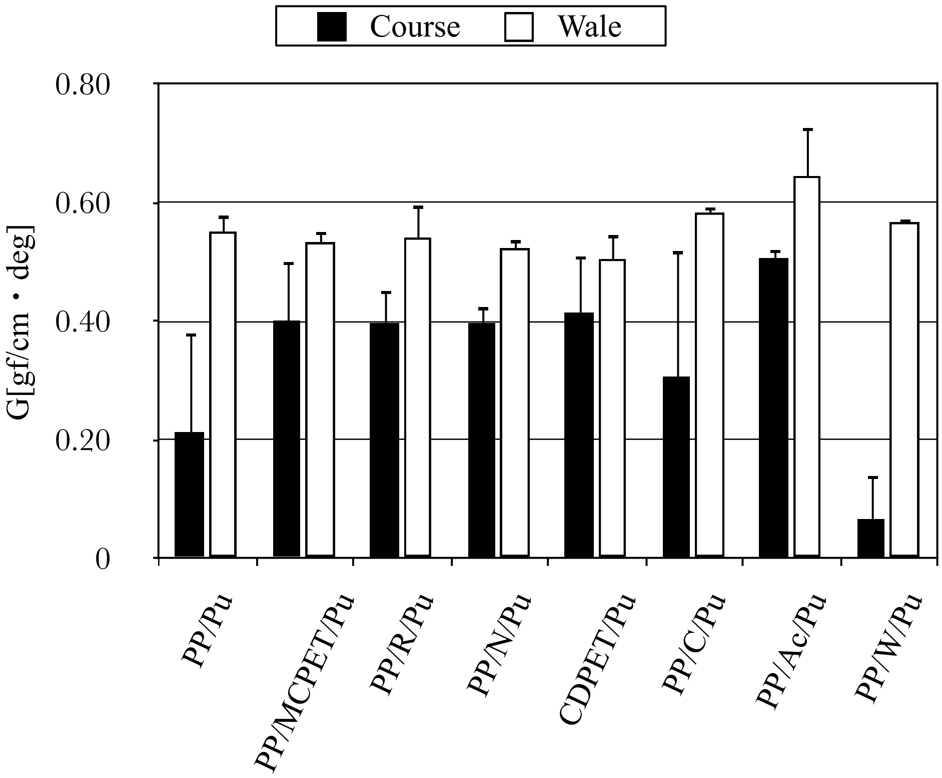

Fig2.5. Results of shear rigidity by KES-FB1

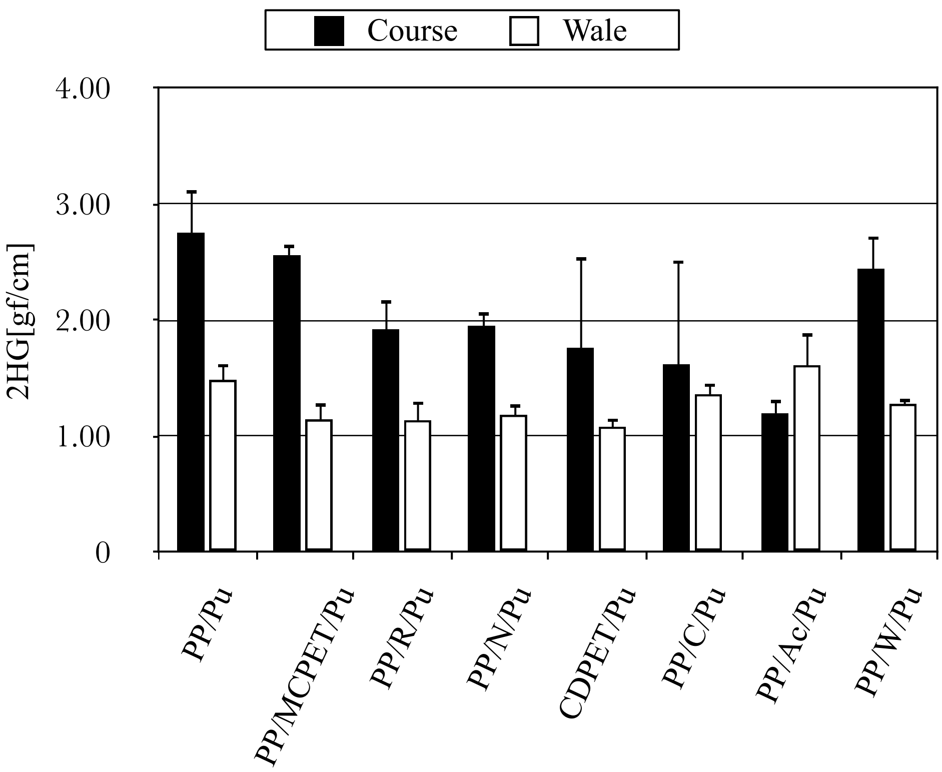

Fig2.6. Results of elasticity for minutes shear by KES-FB1

Ekuseru-Toukei 2010 (Social Survey Research Information Co., Ltd.) was used for statistical analysis. The values in each table are the mean values, and the brackets shows the standard deviations (SD). Each property will be described in turn.

A. Basic Mechanical Property

(a) Tensile

Table 2.5 shows the results of tensile property. LT showed significant differences, with a 1% level between PP/Pu and all the samples except PP/N/Pu. LT became smaller

Table 2.5 Result of tensile properties of each fabric （SD）

Sample	Tensile			
	LT	WT[gf・㎝/㎠]	RT[%]	EMT[%]
PP/Pu	1.00 (0.03)	4.86 (0.13)	66.24 (0.95)	32.45 (1.15)
PP/MCPET/Pu	0.97 * (0.02)	5.72 ** (0.12)	71.06 ** (0.72)	39.43 ** (0.88)
PP/R/Pu	0.95 ** (0.02)	5.60 ** (0.17)	74.55 ** (0.83)	39.29 ** (1.75)
PP/N/Pu	0.98 (0.00)	5.22 ** (0.09)	68.61 ** (0.95)	35.45 ** (0.56)
CDPET/Pu	0.88 ** (0.01)	5.65 ** (0.08)	79.26 ** (0.46)	42.82 ** (0.07)
PP/C/Pu	0.93 ** (0.01)	5.12 ** (0.08)	69.94 ** (0.75)	36.82 ** (0.67)
PP/Ac/Pu	0.93 ** (0.01)	4.85 (0.01)	74.83 ** (0.90)	34.61 ** (0.42)
PP/W/Pu	0.95 ** (0.02)	5.30 ** (0.06)	75.94 ** (0.57)	37.36 ** (0.50)

Significant difference with PP/Pu ：＊＊ $p<0.01$, ＊ $p<0.05$

by blending. WT showed significant differences with a 1% level between PP/Pu and all the samples except PP/Ac/Pu. WT became greater by blending. RT showed significant differences with a 1% level between PP/Pu and all the other samples. By blending, WT became greater and tensile recoverability increased. EMT showed significant differences with a 1% level between PP/Pu and all the other samples. EMT has the same tendency as WT. By blending, EMT became greater and elongation became larger. The reason was considered to be that the yarn diameter and number of fibers of PPy were higher than that of the others due to unifying the yarns with the same cotton yarn number. In a comparison between PP/Pu and CDPET/Pu, PP/Pu was greater in LT, and smaller in WT, RT and EMT. Although PET’s Young's modulus of fiber is higher than PP [33], PP/Pu was less likely to elongate than CDPET/Pu. The reason was considered to be that the yarn’s elastic modulus of CDPETy was smaller than that of PPy. The number of fibers and the yarn diameter of CDPETy is smaller than that of PPy due to PET’s heavy specific gravity, so it was assumed that yarn’s elastic modulus of CDPETy was smaller than PPy, and CDPETy was softer than PPy. As the elastic modulus of yarn was smaller, the fabric tended to elongate easily, so it was considered that the tensile property of the yarn is reflected in the tensile property of the fabrics.

(b) Shear

Table 2.6 shows the measurement results of shear property. G showed significant differences with a 1% level between PP/Pu and PP/Ac/Pu. G became greater by blending acrylic. 2HG showed significant differences with a 1% level between PP/Pu and PP/MCPET/Pu, PP/R/Pu, CDPET/Pu, and with a 5% level between PP/Pu and PP/R/Pu, PP/W/Pu. 2HG tended to decrease by blending, and shear recoverability was improved by blending. The shear recoverability of PP/Pu was lower than CDPET/Pu. Since the number of fibers tended to decrease by blending, it was considered that energy loss due to friction accompanying deformation was decreased and recoverability was improved.

Table 2.6 Result of shearing properties of each fabric （SD）

Sample	Shearing	
	G[gf/cm・deg]	2HG[gf / cm]
PP/Pu	0.55 (0.03)	1.48 (0.14)
PP/MCPET/Pu	0.53 (0.02)	1.14 ** (0.15)
PP/R/Pu	0.54 (0.06)	1.13 ** (0.18)
PP/N/Pu	0.52 (0.02)	1.18 * (0.10)
CDPET/Pu	0.50 (0.04)	1.08 ** (0.08)
PP/C/Pu	0.58 (0.01)	1.36 (0.09)
PP/Ac/Pu	0.64 ** (0.08)	1.61 (0.28)
PP/W/Pu	0.57 (0.01)	1.27 (0.06)

Significant difference with PP/Pu ：＊＊ $p<0.01$, ＊ $p<0.05$

（c） Bending

Table 2.7 shows the measurement results of bending property. B showed significant differences with a 1% level between PP/Pu and all other samples. The value of PP/Pu was the maximum, and the bending rigidity was decreased by blending. 2HB also showed significant differences with a 1% level between PP/Pu and all other samples. Bending recoverability was increased by blending. As with the shear property, there

Table 2.7 Result of bending properties of each fabric （SD）

Sample	Bending	
	B[gf・cm]	2HB[gf / cm]
PP/Pu	0.0175 (0.0020)	0.0358 (0.0063)
PP/MCPET/Pu	0.0095 ** (0.0026)	0.0242 ** (0.0037)
PP/R/Pu	0.0064 ** (0.0015)	0.0108 ** (0.0021)
PP/N/Pu	0.0098 ** (0.0012)	0.0197 ** (0.0029)
CDPET/Pu	0.0030 ** (0.0010)	0.0096 ** (0.0033)
PP/C/Pu	0.0094 ** (0.0005)	0.0120 ** (0.0033)
PP/Ac/Pu	0.0114 ** (0.0007)	0.0145 ** (0.0013)
PP/W/Pu	0.0102 ** (0.0004)	0.0121 ** (0.006)

Significant difference with PP/Pu ：＊＊ p<0.01, ＊ p<0.05

was a possibility that recoverability was affected by decreasing the number of fibers due to blending. CDPET/Pu has lower bending rigidity than PP/Pu, and its recoverability was higher than that of PP/Pu.

(d) Compression

Table 2.8 shows the measurement results of compression property. LC showed significant differences with a 1% level between PP/Pu and CDPET/Pu, PP/C/Pu and PP/W/Pu. LC was decreased by blending cotton or wool. LC of CDPET/Pu was

Table 2.8 Result of compression properties of each fabric (SD)

Sample	Compression		
	LC	WC[gf / cm]	RC[%]
PP/Pu	0.354 (0.010)	0.418 (0.015)	41.59 (1.58)
PP/MCPET/Pu	0.366 (0.010)	0.414 (0.016)	39.57 (0.70)
PP/R/Pu	0.356 (0.009)	0.385 (0.014)	38.84 ** (0.69)
PP/N/Pu	0.345 (0.011)	0.442 (0.029)	36.52 ** (1.18)
CDPET/Pu	0.321 ** (0.011)	0.451 (0.014)	38.86 ** (1.15)
PP/C/Pu	0.416 ** (0.014)	0.364 ** (0.004)	39.50 (1.43)
PP/Ac/Pu	0.337 (0.011)	0.344 ** (0.004)	42.30 (1.78)
PP/W/Pu	0.394 ** (0.010)	0.601 ** (0.040)	40.86 (0.86)

Significant difference with PP/Pu ：＊＊ p<0.01, ＊ p<0.05

lower than that of PP/Pu. WC had significant differences with a 1% level between PP/Pu and PP/C/Pu, PP/Ac/Pu, PP/W/Pu. Fabric became difficult to compress by blending cotton or acrylic, and easy to compress by blending wool. In a comparison between PP and CDPET, CDPET/Pu was more difficult to compress than PP/Pu. RC had significant differences with a 1% level between PP/Pu and PP/R, PP/N/Pu and CDPET/Pu. Compression recoverability was decreased by blending rayon or nylon. CDPET/Pu had lower compression recoverability than PP/Pu.

(e) Surface

Table 2.9 shows the measurement results of surface property. MIU showed significant differences with a 1% level between PP/Pu and PP/MCPET/Pu, PP/N/Pu, CDPET/Pu and PP/W/Pu, with a 5% level between PP/Pu and PP/C/Pu. MMD showed significant differences with a 1% level between PP/Pu and CDPET/Pu and PP/W/Pu. CDPET/Pu was higher than PP/Pu, and MMD became greater by blending wool. SMD showed significant differences with a 1% level between PP/Pu and CDPET/Pu, PP/C/Pu and PP/Ac/Pu. SMD became greater by blending cotton or acrylic. SMD of CDPET/Pu was higher than that of PP/Pu. All of MIU, MMD and SMD were different between PP/Pu and CDPET/Pu. Based on figures 2.3 and 2.4, the reason for the difference of MMD and SMD between PP/Pu and CDPET/Pu was considered to be the thin diameter of CDPETy, making the fabric sparse to increase surface roughness and the deviation of friction. Thus, it was considered that the difference of specific gravity influenced the surface property.

Table 2.9 Result of surface properties of each fabric （SD）

Sample	Surface		
	MIU	MMD	SMD[micron]
PP/Pu	0.109 (0.001)	0.028 (0.007)	2.571 (0.496)
PP/MCPET/Pu	0.120 ** (0.001)	0.031 (0.002)	2.515 (0.548)
PP/R/Pu	0.104 (0.009)	0.032 (0.003)	3.328 (0.520)
PP/N/Pu	0.091 ** (0.003)	0.022 (0.003)	2.345 (0.209)
CDPET/Pu	0.124 ** (0.005)	0.093 ** (0.015)	4.700 ** (0.702)
PP/C/Pu	0.098 * (0.005)	0.034 (0.007)	3.803 ** (0.509)
PP/Ac/Pu	0.101 (0.004)	0.036 (0.008)	4.200 ** (0.592)
PP/W/Pu	0.133 ** (0.007)	0.047 ** (0.005)	3.176 (0.318)

Significant difference with PP/Pu ：＊＊ p<0.01, ＊ p<0.05

(f) Weight and Thickness

Table 2.10 shows the measurement results of weight and thickness. Weight showed significant differences with a 1% level between PP/Pu and PP/R/Pu and PP/C/Pu, and with a 5% level between PP/Pu and CDPET/Pu and PP/W/Pu. Thickness showed significant differences with a 1% level between PP/Pu and PP/R/Pu and PP/C/Pu, and with a 5% level between PP/Pu and CDPET/Pu and PP/W/Pu.

Table 2.10 Results of weight & thinckness (SD)

Sample	Weight & Thickness	
	W[g/m²]	T[mm]
PP/Pu	162.9 (0.5)	1.275 (0.040)
PP/MCPET/Pu	150.1 (1.1)	1.188 (0.028)
PP/R/Pu	166.9 ** (9.6)	1.163 ** (0.018)
PP/N/Pu	154.1 (1.7)	1.235 (0.027)
CDPET/Pu	149.3 * (2.5)	1.176 * (0.020)
PP/C/Pu	138.0 ** (1.6)	1.122 ** (0.039)
PP/Ac/Pu	169.7 (0.6)	1.203 (0.048)
PP/W/Pu	149.7 * (1.2)	1.365 * (0.114)

Significant difference with PP/Pu ：＊＊ $p<0.01$, ＊ $p<0.05$

B. Heat, Water and Air Transport Property

(a) Air Transport Property

Table 2.11 shows the measurement result of ventilation resistance (R). R showed significant differences with a 1% level between PP/Pu and all other samples except PP/R/Pu. The reason was considered to be that the vacant space inside fabric was increased due to decreasing the number of fibers and the yarn diameter by blending.

Table 2.11 Results of ventilation resistance（SD）

Sample	Ventilation resistance R[Kpa・s/m]
PP/Pu	0.158 (0.004)
PP/MCPET/Pu	0.132 ** (0.004)
PP/R/Pu	0.160 (0.010)
PP/N/Pu	0.124 ** (0.011)
CDPET/Pu	0.060 ** (0.000)
PP/C/Pu	0.102 ** (0.008)
PP/Ac/Pu	0.206 ** (0.011)
PP/W/Pu	0.086 ** (0.005)

Significant difference with PP/Pu ：＊＊ p<0.01, ＊ p<0.05

(b) Heat transport property

Table 2.12 shows the measurement results of heat transport property. The q-max showed significant differences with a 1% level between PP/Pu and PP/R/Pu, CDPET/Pu, PP/C/Pu, PP/Ac/Pu and PP/W/Pu. The value of q-max became greater by blending rayon or cotton or acrylic, and lower by blending wool. CDPET/Pu's q-max was lower than that of PP/Pu. Heat conductance (K') showed significant

Table 2.12 Results of heat transport property (SD)

Sample	Heat transport property		
	q-max[W/cm²]	K'[W/(m²・°C)]	Qd[%]
PP/Pu	0.072 (0.001)	57.40 (1.09)	34.1 (1.8)
PP/MCPET/Pu	0.071 (0.002)	60.08 ** (0.57)	29.3 ** (0.9)
PP/R/Pu	0.082 ** (0.001)	69.18 ** (1.73)	29.9 ** (0.5)
PP/N/Pu	0.073 (0.002)	62.95 ** (0.87)	27.9 ** (0.7)
CDPET/Pu	0.067 ** (0.001)	55.58 (0.91)	29.2 ** (1.0)
PP/C/Pu	0.076 ** (0.002)	69.76 ** (1.22)	20.9 ** (0.6)
PP/Ac/Pu	0.078 ** (0.001)	61.97 ** (1.15)	31.0 ** (0.9)
PP/W/Pu	0.062 ** (0.001)	43.64 ** (1.48)	27.1 ** (5.8)

Significant difference with PP/Pu : ＊＊ $p<0.01$, ＊ $p<0.05$

differences with a 1% level between PP/Pu and all other samples except CDPET/Pu, and with 5% between PP/Pu and CDPET/Pu. Heat retention performance (Qd) showed significant differences with a 1% level between PP/Pu and all other samples, and decreased by blending. The reason was considered to be from effects of decreasing R due to decreasing the number of fibers and yarn diameter, and enhancement of thermal conductivity by blending fiber material with high thermal conductivity. CDPET/Pu had a lower Qd than PP/Pu.

（c） Water Transport Property

Table 2.13 shows the measurement results of water transport property. Moisture vapor permeability (MV) showed a significant difference with 1% level between PP/Pu and CDPET/Pu. This difference seems to be caused by fabric porosity difference due to specific gravity difference between PP and PET. Water absorbing property (WA) showed significant differences with a 1% level between PP/Pu and PP/MCPET/Pu, PP/R/Pu, PP/Ac/Pu and PP/W/Pu. Water absorbency was improved by blending MCPET or acrylic, and worsened by blending rayon or wool. Water absorption and quick drying (SAQD) had significant differences with a 1% level between PP/Pu and PP/MCPET/Pu and CDPET/Pu, and with a 5% level between PP/Pu and PP/Ac/Pu. SAQD was improved by blending MCPET or acrylic. CDPET/Pu had higher SAQD than PP/Pu. Moisture regain (MR) showed significant differences with a 1% level between PP/Pu and PP/R/Pu, PP/C/Pu and PP/W/Pu, and with a 5% level between PP/Pu and PP/MCPET/Pu and CDPET/Pu. Since the official regain of PP is 0%[16], MR tended to increase by blending various fiber materials. Moisture exothermic (MET) showed significant differences with a 1% level between PP/Pu and PP/R/Pu, PP/C/Pu and PP/W/Pu. The difference between PP/Pu and CDPET/Pu was confirmed for ventilation resistance (R), q-max, heat conductance (K'), insulation rate (Qd), moisture vapor permeability (MV), water absorption and quick drying (SAQD) and moisture regain (MR). These differences may have been caused by decreasing the yarn diameter and the number of fibers, by specific gravity difference, and by the effects of surface treatment for hydrophilization on CDPET.

Table 2.13 Results of water transport property（SD）

Sample	Water transport property				
	MV[g/㎡・h]	WA[cm]	SAQD[%]	MR[%]	MET[°C]
PP/Pu	157.8 (5.0)	8.8 (0.3)	13.7 (3.2)	0.1 (0.2)	2.0 (0.4)
PP/MCPET/Pu	164.5 (4.7)	9.7 ** (0.2)	20.0 ** (2.0)	0.6 * (0.3)	1.9 (0.3)
PP/R/Pu	157.2 (2.6)	8.2 ** (0.2)	12.1 (3.5)	3.5 ** (0.3)	3.6 ** (0.2)
PP/N/Pu	158.1 (7.6)	8.8 (0.2)	15.8 (3.1)	1.2 ** (0.2)	2.0 (0.3)
CDPET/Pu	181.4 ** (7.4)	8.9 (0.2)	28.6 ** (3.8)	0.6 * (0.1)	2.1 (0.1)
PP/C/Pu	157.5 (8.2)	8.6 (0.1)	15.4 (3.8)	2.1 ** (0.2)	3.2 ** (0.3)
PP/Ac/Pu	154.6 (5.9)	10.4 ** (0.1)	19.5 * (1.8)	0.1 (0.1)	2.1 (0.2)
PP/W/Pu	161.7 (9.8)	8.3 ** (0.1)	11.8 (3.0)	4.0 ** (0.2)	2.9 ** (0.4)

Significant difference with PP/Pu ：＊＊ p<0.01, ＊ p<0.05

2.4.2 Feature Extraction by Principal Component Analysis

In order to specify material properties greatly changed by blending various fiber materials against PP, principal component analysis was carried out on Z-scores calculated for all measurement items of material properties. The function “prcomp” on statistical software R was used for the analysis. Table 2.4 shows the results by principal components analysis. Since the cumulative contribution ratio of the eigenvalues was 85.9% up to the 4th principal component, the 1st principal component to the 4th principal component were used for the discussion.

The 1st principal component was considered to reflect the amount of space inside fabric because the principal component score increased as the moisture vapor permeability (MV) became higher and the ventilation resistance (R) became lower. Increasing fabric space due to decrease in yarn diameter by blending was considered to be the reason MMD is a positive contribution. Tensile property such as RT, EMT and WT, and bending property such as B also contributed greatly. Decreasing the yarn diameter and number of fibers by blending were considered to affect mechanical property because PP has the lowest specific gravity. The 1st principal component summarized the effects of decreasing yarn diameter and number of fibers by blending due to difference of specific gravity.

The 2nd principal component was considered to reflect the heat transportability. The principal component score increases as K' and q-max became higher, thickness became thicker, and compression energy (WC) became lower. Heat transport property and compression property were summarized from the same components,

Table 2.14 Results by primary component analysis

Item	PC1	PC2	PC3	PC4
EMT	0.312	0.094	0.006	0.064
MMD	0.283	0.021	-0.192	-0.102
WT	0.257	0.012	0.071	0.214
MV	0.290	-0.028	-0.188	0.108
LT	-0.258	-0.197	0.080	0.231
R	-0.274	0.149	-0.100	-0.046
B	-0.292	-0.184	-0.048	-0.023
K’	-0.097	0.381	0.167	0.161
q-max	-0.153	0.366	0.148	0.038
MIU	0.198	-0.269	-0.119	-0.144
WC	0.138	-0.397	0.042	-0.088
T	-0.046	-0.417	-0.063	-0.126
LC	-0.035	-0.099	0.352	-0.194
MET	0.049	0.089	0.373	-0.217
MR	0.093	-0.123	0.350	-0.206
W	-0.166	0.057	-0.191	-0.034
SAQD	0.191	0.166	-0.310	0.096
Qd	-0.106	-0.099	-0.319	0.127
WA	-0.104	0.156	-0.321	-0.048
2HB	-0.217	-0.180	-0.131	0.264
RT	0.254	0.067	-0.119	-0.256
2HG	-0.252	0.032	-0.131	-0.302
SMD	0.168	0.241	-0.139	-0.316
RC	-0.131	-0.065	-0.203	-0.379
G	-0.183	0.120	-0.050	-0.418
Standard Deviation	2.979	2.190	2.137	1.802
Contribution	35.5	19.2	18.3	13.0
Cumulative Contribution Ratio	35.5	54.7	72.9	85.9

because both properties could be affected by space inside the fabric. MIU could reflect the surface shape of fabric, so heat transport property and MIU could be summarized from the same components. Heat transportability was greatly changed by blending various fiber materials.

The 3rd principal component was considered to reflect the inverse property of PP added by blending. The principal component score increased as moisture exothermic (MET) and moisture regain (MC) became greater, and heat retention performance (Qd), sweat absorption and quick drying (SAQD) and water absorption (WA) became lower. PP is the lightest fiber material with low thermal conductivity, and the yarns were unified with the same cotton yarn number, so Qd cloud be considered as becoming lower by increasing space inside fabric due to decreasing the yarn diameter and the number of fibers as a result of blending. Since the official regain of PP is 0%, MET and MC were increased by blending. The effects by the difference of specific gravity and heat and water transport property were summarized in this principal component. The contribution of weight was negative since PP/Pu was relatively heavy.

The 4th principal component was greatly contributed to by measurement items relating to recoverability such as RT, 2HB, 2HG and RC, and the principal component score tended to become higher with increasing recoverability. As mentioned above, it was considered that recoverability was improved by decreasing the number of fibers due to blending. SMD was a negative contribution because of its value increased with blending due to decreasing the yarn diameter, since the yarns were unified with the same cotton yarn number. The reason of SMD's contribution was considered that the yarn diameter and the number of fibers changed simultaneously by blending. This primary component seem to reflect the specific gravity difference.

The effect of blending various fiber materials for PP was confirmed in the four aspects of mechanical recoverability, heat transportability, specific gravity and water transport property. It was considered that the decreasing the number of fibers affected the recoverability by blending. In the case of unifying with the same cotton yarn number, the effect of specific gravity appeared on the yarn diameter and the number of fibers, and heat and water transport properties, such as R, MV and Qd, were affected by the difference of specific gravity. Water transport properties were changed by combining PP with other various fiber materials due to PP's hydrophobicity.

2.4.3 Classification of samples by cluster analysis

Samples were classified by cluster analysis with Ward's method for Z-scores of all measurement items, and the extent of change in material property was considered by comparison with PP/Pu as the criterion. The function "hclust" of statistical software R was used for the analysis. Table 2.15 shows the cluster creation history. Fig. 2.7 shows the dendrogram.

Cluster 1 was composed of PP/MCPET/Pu and PP/N/Pu. These two samples have the most similar properties among the eight samples. Cluster 2 was composed of PP/R/Pu and PP/C/Pu. It is considered that both samples classified into the same

Table 2.15 Creating history of cluster

STEP	Component		Symbol
STEP1	PP/MCPET/Pu	PP/N/Pu	① Cluster1
STEP2	PP/R/Pu	PP/C/Pu	② Cluster2
STEP3	PP/Pu	Cluster1	③ Cluster3
STEP4	Cluster1	PP/Ac/Pu	④ Cluster4
STEP5	Cluster2	PP/W/Pu	⑤ Cluster5
STEP6	Cluster4	Cluster5	⑥ Cluster6
STEP7	Cluster6	CDPET/Pu	⑦ Cluster7

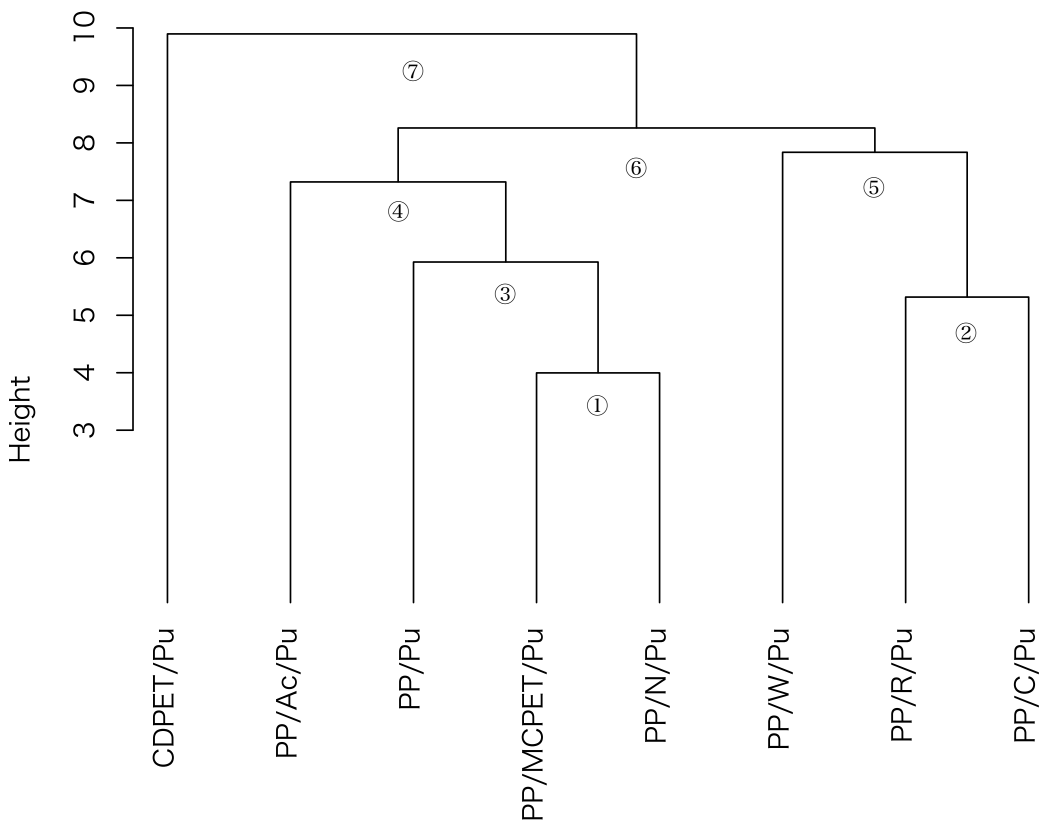

Fig.2.7 Dendrogram by cluster analysis

cluster because their water transport properties are similar due to containing cellulose. Because PP is the lightest fiber material and is hydrophobic, the property of PP/Pu was far from those of samples blended with cellulose. Cluster 3 was composed of PP/Pu and Cluster 1. By blending MCPET, water transport property was changed, but the other properties were not changed greatly. The property of PP/N/Pu was close to that of PP/Pu. Cluster 4 was composed of PP/Ac/Pu and Cluster 3. The property of PP/Ac/Pu was close to that of PP/Pu, but it was relatively far from the sample blended with modified cross-section polyester (PP/MCPET/Pu) or nylon (PP/N/Pu). Because the diameter of PP/Acy was thicker than that of PP/MCPETy or PP/Ny, the reason for the distance difference was considered to be that the property of knitted fabric had differences in mechanical properties and air permeability. Cluster 5 was composed of PP/W/Pu and Cluster 2. This cluster included samples blended with fiber material with a higher moisture regain and heavier specific gravity than PP. Since the official regain of PP is 0% and the specific gravity of PP is the lightest, Cluster 5 was far from PP/Pu. Because of wool fiber's low thermal conductivity and surface shape, the property of PP/W/Pu was far from that of PP/R/Pu and PP/C/Pu. Cluster 6 was composed of Cluster 4 and Cluster 5, and all samples in Cluster 6 contained PP. CDPET/Pu was isolated and its property was the farthest from the PP/Pu. It was considered that the distance between PP/Pu and CDPET/Pu was caused by the difference in yarn diameter and number of fibers due to specific gravity difference between PP and PET, and water transport property difference was due to the surface treatment for hydrophilization on CDPET.

2.5. Summary

In this chapter, the effect of blended fiber materials on wearing comfort of PP underwear was investigated by material property evaluation of basic mechanical property and heat and water transport property. In basic mechanical properties, the effect of the number of fibers on recoverability, and the effect of specific gravity difference were observed. Since the specific gravity of PP (0.91) is the lightest, in case of unifying with same cotton yarn number, the number of fibers and the yarn diameter with all PP was higher, and these tended to decrease by blending. Recoverability also increased by blending. Since PP is hydrophobic and the its official regain is 0%, the effect of blended material was remarkable on water absorption, water absorption and quick drying and moisture regain. Water transportability could be designed by blending modified cross-section polyester and acrylic against the hydrophobic PP. Based on the principal component analysis, the effects on yarn diameter due to the specific gravity difference, the effects on heat and water transportability and the effect on recoverability due to difference of the number of fibers were extracted. The characteristic of PP is the lightest specific gravity, low thermal conductivity and hydrophobicity. In relation to these characteristic, the property of knitted fabric greatly changed depending on the type of blending material. There was an influence of intrinsic properties of PP such as specific gravity, hydrophobicity and low thermal conductivity. In case of manufacturing knitted fabric using PP blended yarn with other various fiber materials unifying same cotton yarn number, it was considered that PP had the effect of decreasing apparent density, thermal conductivity and recoverability.

As a result of classification of samples by cluster analysis, the material property was greatly changed by blending wool or cellulose such as cotton and rayon, and PP's characteristics were not impaired comparatively by blending modified cross-section polyester, nylon or acrylic. The property of PP/MCPET/Pu was close to that of PP/Pu despite its water transportability, so PP/MCPET/Pu was considered as a fabric for underwear that possessed heat retaining performance, softness and water transportability. PP/Ac/Pu was similar to PP/MCPET/Pu. PP/N/Pu was also similar to PP/MCPET/Pu and PP/Ac/Pu, but its water transportability was slightly lower. PP/C/Pu and PP/R/Pu have a high moisture exothermic and a high thermal conductivity due to obtain cellulose, and these fabrics were considered as underwear material that had softness and slightly higher water transportability compared with PP/Pu. Although PP/W/Pu had lower thermal conductivity and higher moisture exothermic as compared with PP/Pu, its was a knitted fabric for underwear with lower water transportability and bad texture due to surface roughness.

From the above, PP/MCPET/Pu, PP/C/Pu and PP/W/Pu were selected as representative samples for experiment in Chapter 3.

Chapter 3

Evaluation of Thermal Wearing Comfort of Underwear Made of Polypropylene Blended Yarn

3.1. Introduction

In Chapter 2, as a result of investigating the effect of blending various fiber materials against PP by material property evaluation, the space between the yarns increased due to the specific gravity difference, and recoverability increased due to decreasing the number of fiber, and the heat and water transport property was greatly changed by blending due to PP's low thermal conductivity and hydrophobicity. Since humans release about 630g moisture per day from the skin as insensible transpiration [34], heat and water transport property of fabric is important for designing comfort underwear. Conventionally hydrophilic materials such as cotton have been considered suitable for underwear, but there is a possibility that the hydrophilic cause cold sweat by retaining water after absorbing because water have a thermal conductivity about 25 times of air [35] . Since PP doesn't adsorb moisture because of its hydrophobicity and its thermal conductivity is low, so there is a possibility of developing underwear that is difficult to remain moisture in fabric for preventing cold sweat by combining PP with hydrophilic fiber or water-absorbing and quick-drying fiber [36]. In this chapter, the effects of blending hydrophilic fibers or a water-absorbing and quick-drying fiber on PP was investigated by wearing experiments from the view points of psychological and physiological.

As mentioned in Chapter 1, wearing comfort evaluation of underwear was mainly investigated by correspondence between material property of clothing material and human subjective value. In this chapter, physiological wearing comfort evaluation was attempted by measuring autonomic nervous activity in addition to subjective value. The experiments in this chapter were conducted with the approval of "Research Ethical Review Committee on Shinshu University". Before the experiment, subjects informed the research contents, the right to suspend and the protection of personal information, then agreed in writing.

3.2. Experiment

3.2.1 Samples

In Chapter 2, knitted fabrics made of PP blended yarn with various materials such as polyester, cotton and wool, and these fabric were classified by cluster analysis on material properties. Based on these results, as shown in Table 3.1, three knitted fabrics which blended with fiber having different water transport property from PP such as water absorption and hygroscopicity, were selected as representative samples to prepare underwear sample for wearing experiments. The sample underwear were long sleeve crew neck T-shirts made of these three fabrics. The yarn of all samples was unified with the same cotton yarn number of 50s. The structure was plain knitting. Polyurethane was interknit at 9% in all samples. Fig. 3.1 shows the side view of yarn used for underwear samples with the diameter. Fig. 3.2 shows the cross-section of yarn used for underwear samples. Fig. 3.3 shows the side view of fabric used for underwear samples with stitch density per 1.27 cm. Fig. 3.4 shows the cross-section of fabric used for underwear samples with apparent density dividing weight by thickness. PP/MCPET/Pu was a combination of PP and modified cross-section polyester (hereinafter MCPET). MCPET was a water-absorbing and quick-drying fiber which had the function of moving moisture on the fiber surface without adsorbing inside the fiber, by increasing the capillary action because of modified cross-section processing on hydrophobic fiber. PP/MCPET/Pu had high water absorption performance because MCPET's fibers aggregated to be in contact with each other on the cross-section of the yarn. PP/C/Pu was a combination of PP and cotton. Cotton adsorbs moisture by hydrophilicity and stores moisture inside the lumen. Since PP/ C/Pu had the thinnest yarn diameter, the thickness of fabric was also the thinnest. PP/W/Pu is a combination of PP and wool. Wool had conflicting properties because of oil in the scale and moisture absorption in the cortex. Because the wool fiber was thicker than the PP fiber in the cross-section of the yarn, the gap between the fibers became larger, and the thickness of the fabric became larger, and the density became smaller. Table 3.2 shows the heat and moisture transport

Table 3.1 Fabrics prepared for wearing experiments

Symbol	Material & Mixing Rate	Note
PP/MCPET/Pu	Polypropylene46% / Polyester45% / Polyurethane9%	Structure：Flat knitting Diameter of knitting machine：30” Number of needle：2640 Gauge：28
PP/C/Pu	Polypropylene46% / Cotton45% / Polyurethane9%	
PP/W/Pu	Polypropylene46% / Wool45% / Polyurethane9%	

Table 3.2 Material properties of fabrics

Reference	Property		PP/MCPET/Pu Mean / CV%	PP/C/Pu Mean / CV%	PP/W/Pu Mean / CV%
KES-F7 Thermo-lab	Heat retention performance[%] (Air velocity : 0.3m/s)		29.3 / 5.4	20.9 / 3.1	27.1 / 5.8
	Thermal conductance [W/(㎡・K)]		60.08 / 0.9	69.76 / 1.7	43.64 / 1.5
	q-max [W/㎠]		0.071 / 2.5	0.079 / 2.1	0.062 / 1.9
KES-F8	Ventilation resistance [KPa・s/m]		0.13 / 3.4	0.10 / 8.2	0.09 / 6.4
BOKEN BQE A028	Sweat absorption and quick drying [%]		20.0 / 10.2	15.4 / 13.7	11.8 / 25.5
JIS L1096	Moisture regain [%]		0.6 / 47.0	2.1 / 11.8	4.0 / 5.4
JIS L1099 A-2	Moisture vapor permeability [g / ㎡ · h]		165 / 2.9	157 / 5.2	162 / 6.1
JIS L 1907	Water absorption[cm]	wale	10.6 / 1.4	8.3 / 1.4	9.3 / 2.2
		course	9.7 / 1.6	8.6 / 1.0	8.3 / 1.6
KES-FB3	LC		0.354 / 2.8	0.416 / 3.4	0.394 / 2.5
	WC [gf/cm]		0.414 / 3.9	0.364 / 1.2	0.601 / 6.7
	RC [%]		39.57 / 1.8	39.50 / 3.6	40.86 / 0.9
KES-FB4	MIU	wale	0.343 / 0.8	0.325 / 5.5	0.386 / 5.3
		course	0.362 / 3.0	0.292 / 2.8	0.405 / 1.2
	MMD	wale	0.77 / 5.5	0.87 / 21.4	1.05 / 10.2
		course	0.95 / 9.5	0.99 / 17.2	1.39 / 12.1
	SMD [micron]	wale	2.64 / 21.8	2.77 / 13.4	2.48 / 10.0
		course	2.48 / 27.9	3.95 / 8.8	3.28 / 8.7
/	Thickness with 0.5gf/㎠ [mm]		1.188 / 2.4	1.122 / 3.5	1.365 / 8.4
	Weight[g/㎡]		150.1 / 0.8	138.0 / 1.2	149.7 / 0.8

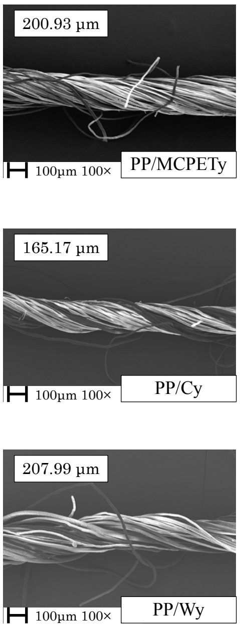

Fig.3.1 Side view of yarn with diameter

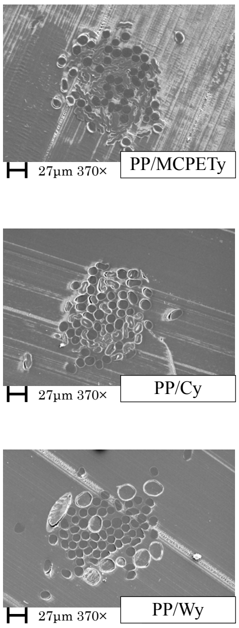

Fig.3.2 Cross-section of yarn

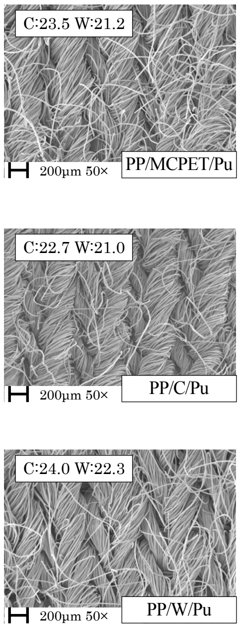

Fig.3.3 Side view of fabric with stitch density per 1.27cm C:Course W: Wale

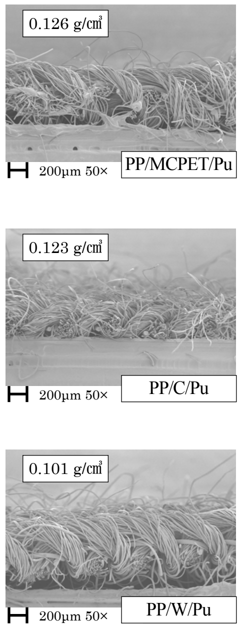

Fig.3.4 Cross-section of fabric with apparent density

property, compression property and surface property as material properties of each sample. Three elements of clothing comfort are microclimate, texture and clothing pressure [8]. It was assumed that the difference in material properties affects microclimate and texture because the sample's garment size was unified in this experiment. Five specimens were cut out and measured for each sample, and the mean value was calculated. The data on the back side of fabric that directly contacts the skin when worn was measured. PP/MCPET/Pu had high heat-retention performance, high water transportability due to high water absorption, high water absorption and quick drying performance, softness for compression due to low LC, and good texture due to low SMD and MMD. Because PP/C/Pu was a fabric with relatively low heat retention performance, high heat conductance and high q-max.

PP/W/Pu had high heat retaining property due to its high heat-retention performance, low thermal conductance and low q-max, but its water transportability was inferior due to low water absorbing and quick drying property, and surface property was poor due to high MIU and MMD. Because heat retention performance was measured at wind velocity of 0.3 m/s and ventilation resistance of PP/W/Pu was lower than that of PP/MCPET/Pu, it is considered that the tendency of thermal conductance and heat retention performance was not matched between PP/MCPET/Pu and PP/W/Pu.

3.2.2 Experimental Method

In order to evaluate the wearing comfort of sample underwear considering autonomic nerve activity, psychophysiological response was measured while the underwear was worn. As physiological responses, electrocardiogram, respiration, periphery blood flow, mean skin temperature and mean humidity inside the clothes were measured. Psychological responses were measured by the semantic differential method (SD method) and ranking method as sensory evaluation. In order to consider the presence or absence of perspiration, the two processes of body cooling were observed in this experiment, one was after moving from a comfortable environment to a chilly environment, and another was after exercise (Fig. 3.5).

Subjects entered a room at 24 °C to adjust body temperature, and rested for 15 minutes. After attaching the electrodes for electrocardiogram and the temperature and humidity sensors to the skin, subjects wore a sample and entered the artificial weather room at 20 °C, 65% RH. After entering the room, the electrocardiogram electrodes were connected to the amplifier with a lead wire, and a breathing sensor and a blood flow sensor were attached, and the experiment was started. It took 5 minutes from wearing a sample to starting the experiment. Subjects rested for 20 minutes immediately after entering the room, and exercised with an ergometer (STB-3200 manufactured by Nihon Kohden) from 20 minutes to 30 minutes after entering the room, and after that rested for 30 minutes. The load of exercise ranged from a heart rate increase of 20% to 30% compared with the resting state. The time taken for measurement of electrocardiogram, respiration and peripheral blood was 2 minutes, and the measurement was taken twice every 10 minutes from 8 minutes after the start of the experiment, and measured 3 times every 10 minutes from 8 minutes after the end of the exercise (5 times in total). In order to prevent noise entering the data, subjects were instructed not to move during data measurement.

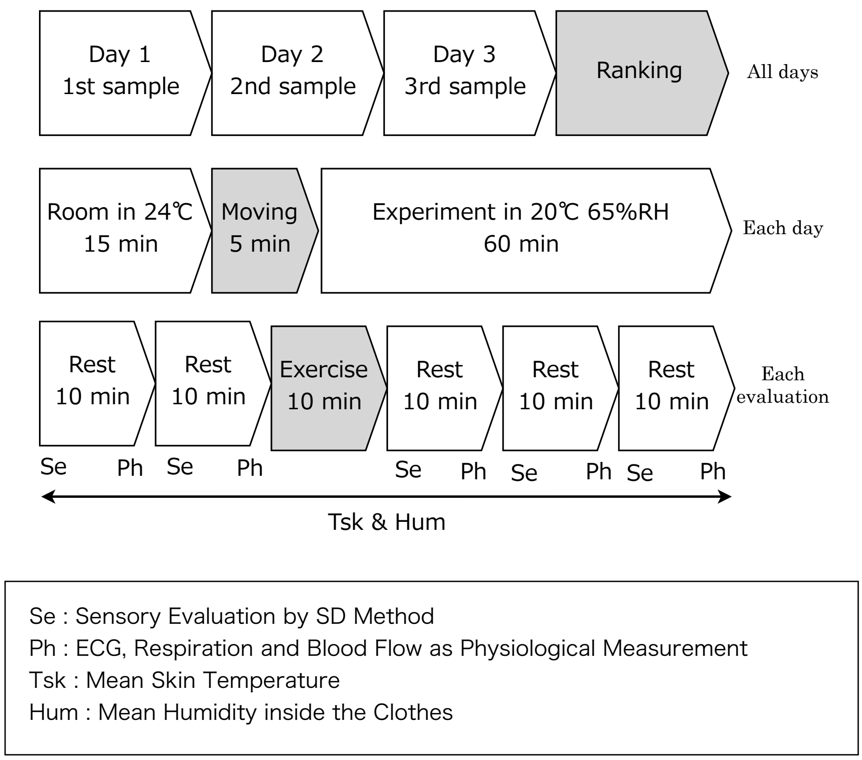

Fig. 3.5 Protocol of experiments

The electrocardiogram was signalized by the bipolar chest lead and amplified by an amplifier ECG100C (BIOPAC Systems, Inc.). Respiration was signalized by thermistor TDS 2002A (BIOPAC Systems, Inc.) attached under the nose, and the signal was amplified by an amplifier SKT100C (BIOPAC Systems, Inc.). Peripheral blood flow was signalized by a laser Doppler blood flow probe TDS146 (BIOPAC Systems, Inc.) attached on second fingertip of left index finger, and the signal was amplified by an amplifier LDF100C (BIOPAC Systems, Inc.). These signals were synchronized by MP150 (BIOPAC Systems, Inc.) and recorded on a computer with a sampling frequency of 2000 Hz.

A thermometer/hygrometer (Hygroclone, manufactured by KN Laboratories, Inc.) was used for measuring the mean skin temperature and the mean humidity inside the clothes. The mean skin temperature (Tsk) was calculated by the following formula according to Ramanathan's 4 point method [34].

$$\mathbf{Tsk = 0.3\ (Tchest + Taarm) + 0.2\ (Tfemolal + Tcalf)}$$

Tchest: Chest skin temperature　Taarm: Upper Arm skin temperature

Tfemoral: Femoral skin temperature　Tcalf: Calf skin temperature

The mean humidity inside the clothes is the mean value of the measurement results of 5 points shown in Fig. 3.6, and the value was converted to absolute humidity using Tetens equation. Mean skin temperature and mean humidity inside the clothes were recorded at 1 minute intervals from the beginning to the end of experiment.

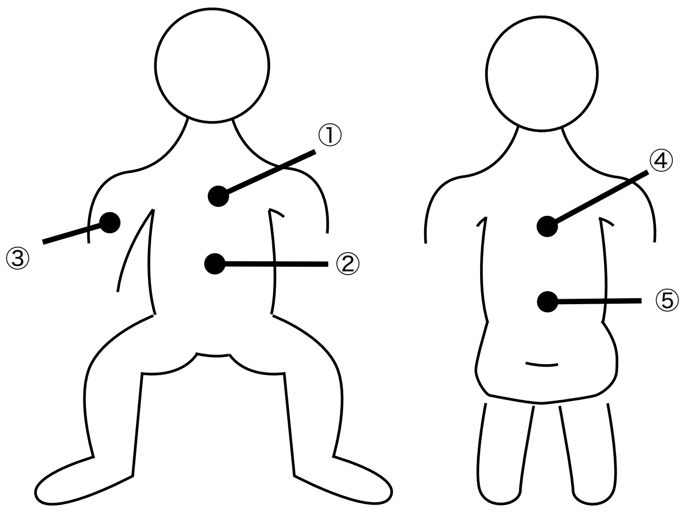

Fig.3.6 Measurement points of humidity inside the clothes

Table 3.3 Terms used for SD method

Comfortable⇔Uncomfortable	快適⇔不快
Cool⇔Warm Refreshing⇔Hot Dump⇔Dry Well-ventilated⇔Poorly-ventilated	冷たい⇔温かい 涼しい⇔暑い べたつき感のある⇔サラッと感のある むれる⇔むれない
Good texture⇔Poor texture Rough ⇔Smooth Soft⇔Hard Restrictive⇔Not restrictive Thin⇔Thick Heavy⇔Light	肌触りの良い⇔肌触りの悪い ざらざら⇔なめらか やわらかい⇔かたい 拘束感のある⇔ない 薄い⇔厚い 重い⇔軽い

Table 3.3 shows the term pair used for the sensory test by SD method. These terms were chosen to cover the sense concerning wearing comfort. The evaluation scale

was seven steps (extremely ~ very ~ slightly ~ neither ~ slightly ~ very ~ extremely) and the evaluation was quantified by giving a score of -3 to +3. The sensory test by SD method was carried out five times in total, immediately after the beginning of the experiment, 10 minutes after the beginning of the experiment, immediately after exercise, 10 minutes after exercise and 20 minutes after exercise. Sensory evaluation by ranking method was carried out after the experiment was completed for all samples and subjects changed private clothes. In ranking method, subjects asked "If you wear these samples as underwear, which one is better? Please rank them in the order you want to wear them" for evaluation of overall wearing comfort. The results were quantified by scores of 1 to 3 in order of good evaluation.

Subjects were five healthy male college students in their 20s. Because the influence of body shape was considered, subject’s BMI was limited to from 17 to 21. The number of subjects used in this experiment is not sufficient for the discussion of statistically significant difference, but statistical analysis was used to consider the difference within the subjects used in this experiment. Therefore, the statistical analysis in this experiment does not discuss the difference in the population.

The subject's clothing was unified in experimental clothes during the experiment, the upper was a sample long-sleeved T-shirt, and the lower was underwear and sweat pants. The garment size was the same as those normally worn by each subject. Samples were conditioned in an experimental environment with 20 °C, 65% RH for more than 24 hours before the experiment. Considering the circadian rhythm, the experiment time zones were unified for all subjects. The interval between meals and experiments was more than 2 hours. Each subject experimented at a pace of one sample per day, so the whole process of the experiment took 3 days.

3.3. Result and Discussion

3.3.1 Mean Skin Temperature and Mean Humidity inside the Clothes

Figure 3.7 shows the measurement results of mean skin temperature. This is the mean value of four subjects (hereinafter called “effective subjects”) excluding one subject whose mean skin temperature was constant before and after exercise. A two-way factorial analysis of variance was performed on the mean value every 10 minutes

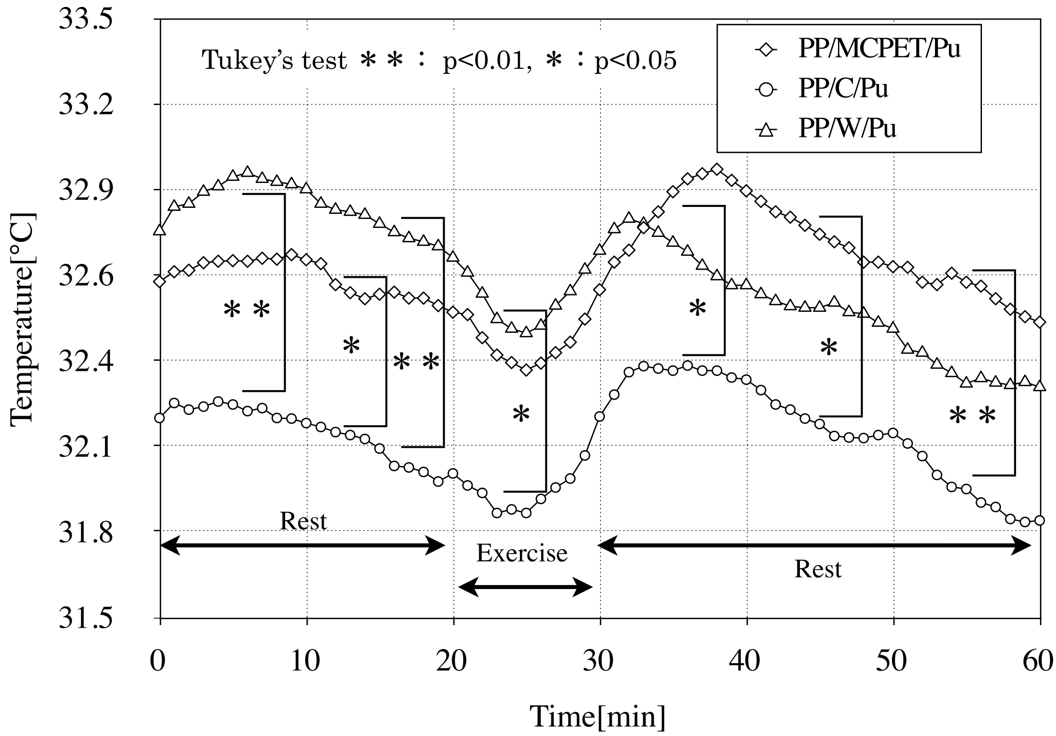

Fig. 3.7 Results of mean skin temperature by Ramanathan method (N=4)

with two factors of sample and lapsed time. The level number of the sample was 3 (PP/MCPET/Pu, PP/C/ Pu and PP/W/Pu), and the level number of lapsed time was 6 (60 minutes divided by 10 minutes). The effect of the sample was significant with a 1% level, the effect of time was significant with a 5% level, and the interaction effect was not significant. As a result of multiple comparison by Tukey's test, there were significant differences between the samples. The mean skin temperature of PP/W/Pu was significantly higher than that of PP/C/Pu from the beginning of the experiment to the end of exercise. The mean skin temperature of PP/MCPET/Pu was significantly higher than that of PP/C/Pu from 10 minutes after the beginning of experiments to 20 minutes after the beginning of experiments. After exercise, PP/MCPET/Pu had higher mean skin temperature than PP/C/Pu. Because there was no significant difference between PP/W/Pu and PP/C/Pu after exercise, the tendency of mean skin temperature changed by exercise. PP/C/Pu had lower mean skin temperature during the whole experiment due to its low heat-retention performance. The temperature difference at time 0 was considered to be caused by the difference of the heat conductance of fabric in the 5 minutes required for attaching sensors, because the initial mean skin temperature was higher with lower heat conductance (K' : PP/W/Pu 43.8[W/(m^2·K)] < PP/MCPET/Pu 60.1[W/(m^2·K)] < PP/C/Pu 69.8[W/(m^2·K)]). Since the experimental condition was without air flow, it was assumed that the initial temperature corresponded to the thermal conductance.

Figure 3.8 shows the results of mean humidity inside the clothes. This is the mean value of three subjects, excluding a subject due to noise out of the four effective subjects. As well as the mean skin temperature, a two-way factorial analysis of variance was performed on the mean value every 10 minutes with two factors of sample and lapsed time. Since the effect of time was significant with a 5% level, the mean humidity inside the clothes was changed by exercise, and the perspiration was assumed to affect skin temperature before and after exercise. Even though there was no significant difference between the samples on a multiple comparison by Tukey's test, the humidity tended to decrease faster with higher water absorption and quick drying property. The humidity increased with exercise and PP/MCPET/Pu showed the largest rise, however the humidity of PP/MCPET/Pu declined faster than that of PP/W/Pu. Since PP/MCPET/Pu had a high water transportability for releasing sweat, it was assumed that PP/MCPET/Pu tended to

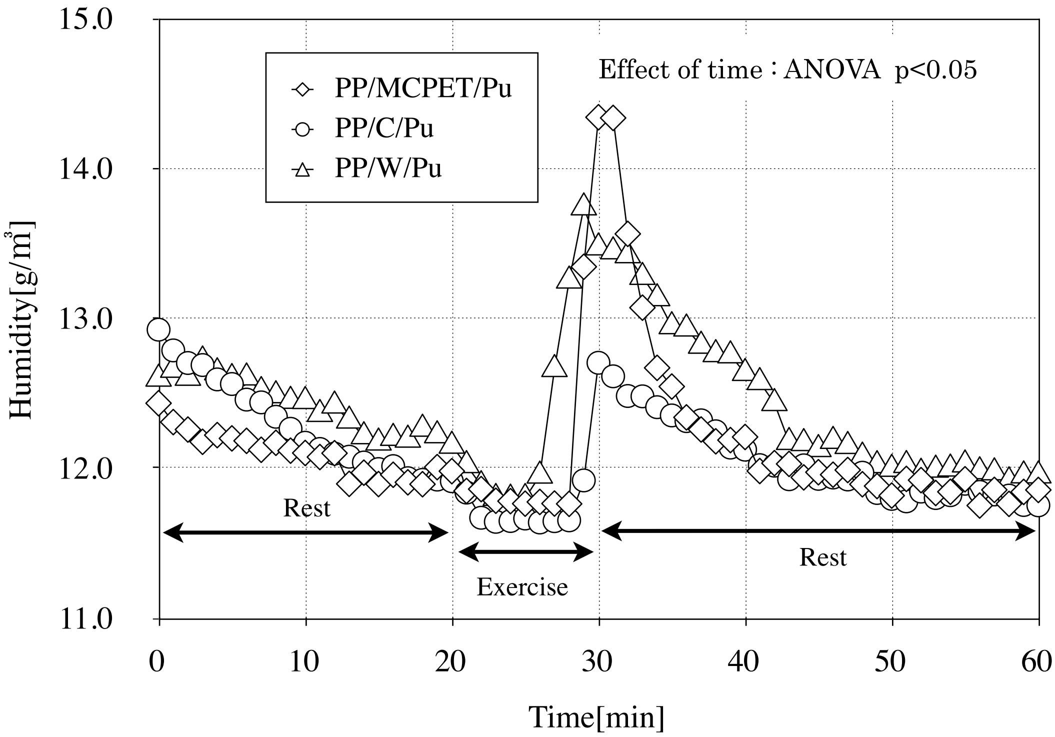

Fig. 3.8 Results of mean humidity inside the clothes（N=3）

have higher mean skin temperature than PP/W/Pu to prevent cooling body after exercise. Because the humidity of PP/C/Pu tended to increase slightly accompanying exercise, it was assumed that the amount of perspiration caused by exercise was small due to low skin temperature based on low heat retention performance of fabric.

3.3.2 Psychological Response Measurement

Table 3.4 shows the results by a two-way factorial analysis of variance performed with two factors of sample and lapsed time on four effective subjects. The level number of the sample was three (PP/MCPET/Pu, PP/C/ Pu and PP/W/Pu) , and the level number of lapsed time was six (immediately after beginning, 10 minutes after beginning, 20 minutes after beginning, immediately after exercise, 10 minutes after exercise, 20 minutes after exercise). The interaction effect was insignificant in all terms. The effect of lapsed time was significant in the terms relating to heat and water transport property such as "Cool ⇔ Warm", "Refreshing ⇔ Hot" and "Well-ventilated ⇔ Poorly-ventilated", and the effect of sample was significant in the terms relating to skin contact feeling such as "Rough ⇔ Smooth". In this experiment, the difference among three samples was captured for clothing microclimate and texture. Both the effect of lapsed time and sample were significant in "Good texture ⇔ Poor texture", and the effect of the sample was significant in “Rough ⇔ Smooth” as terms relating to surface property, and the effect of time was significant in terms relating to heat and water transport property, so it was assumed that both water transport property and surface property affected skin contact feeling. The influence on wearing comfort by blended material with PP was able to be captured from clothing microclimate related to heat and water transport property, and to skin contact feeling relating to surface property. The effect of lapsed time was significant in "Comfortable ⇔ Uncomfortable" as terms relating to the overall wearing comfort, and the effect of lapsed time was significant in terms relating to heat and water transport property, so it was assumed that heat and water transport property greatly affected wearing comfort of underwear with PP blended yarn.

Table 3.4 Results of a two-way factorial analysis of variance for all terms

: ＊＊ $p<0.01$, ＊ $p<0.05$, ＋ $p<0.10$

Terms	Effect of sample	Effect of time	Combined effect
Comfortable⇔Uncomfortable		＊	
Cool⇔Warm		＊	
Refreshing⇔Hot		＊＊	
Dry⇔Damp			
Well-ventilated⇔Poorly-ventilated		＊＊	
Good texture⇔Poor texture	＋	＋	
Rough ⇔Smooth	＊＊		
Soft⇔Hard			
Restrictive⇔Not restrictive			
Heavy⇔Right		＊	
Thin⇔Thick		＋	

Fig. 3.9 shows the time history of the mean scores on "Cool ⇔ Warm" after exercise. Significant differences were examined by multiple comparison with Tukey's test. The scores of PP/MCPET/Pu and PP/W/Pu decreased significantly after exercise, but PP/MCPET/Pu had a positive score and PP/W/Pu had a negative score 20 minutes after exercise. It was assumed that PP/MCPET/Pu felt warmer than PP/W/Pu since PP/MCPET/Pu had higher mean skin temperature after exercise. There was no significant difference with elapsed time on PP/C/Pu, so it was assumed that the difference caused by lapsed time was hard to perceive because of low humidity due to low skin temperature.

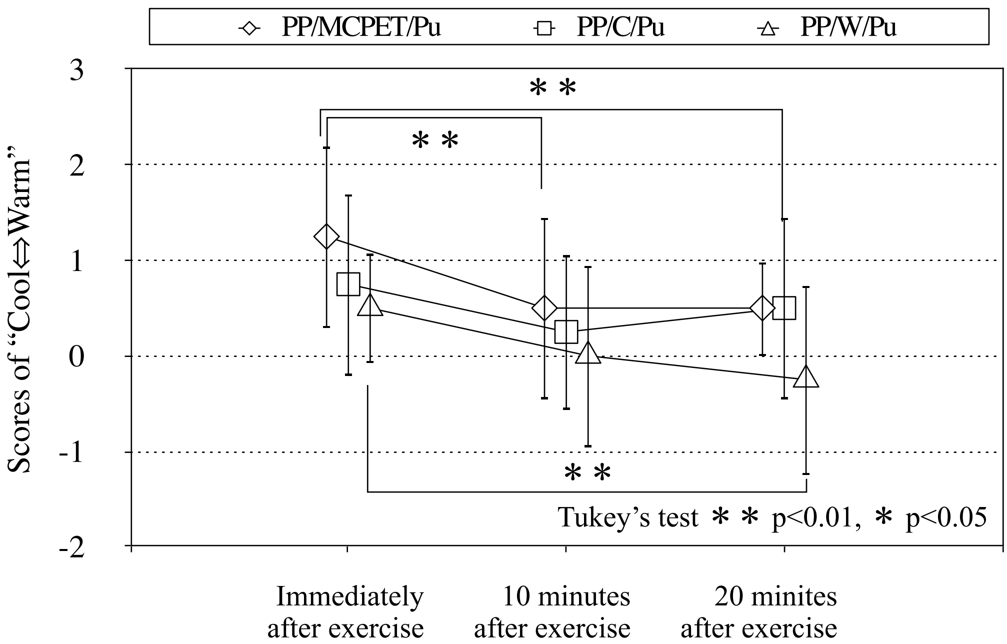

Fig. 3.9 Results of SD method of Cool⇔Warm after exercise（N=4）

Fig. 3.10 shows time history of the mean scores on "Comfortable ⇔ Uncomfortable" after exercise. Significant differences were examined by multiple comparison with Tukey's test. When subjects were wearing PP/MCPET/Pu and PP/C/Pu, discomfort decreased after the exercise. The reason was assumed to be that the humidity inside the clothes decreased quickly due to higher water transportability. For PP/W/Pu, it was assumed that discomfort did not decrease because the humidity inside the clothes decreased slowly. In the case of accompanying perspiration, the water transportability for releasing moisture out of the garment was important, and high water transportability provides warmth and comfort for underwear.

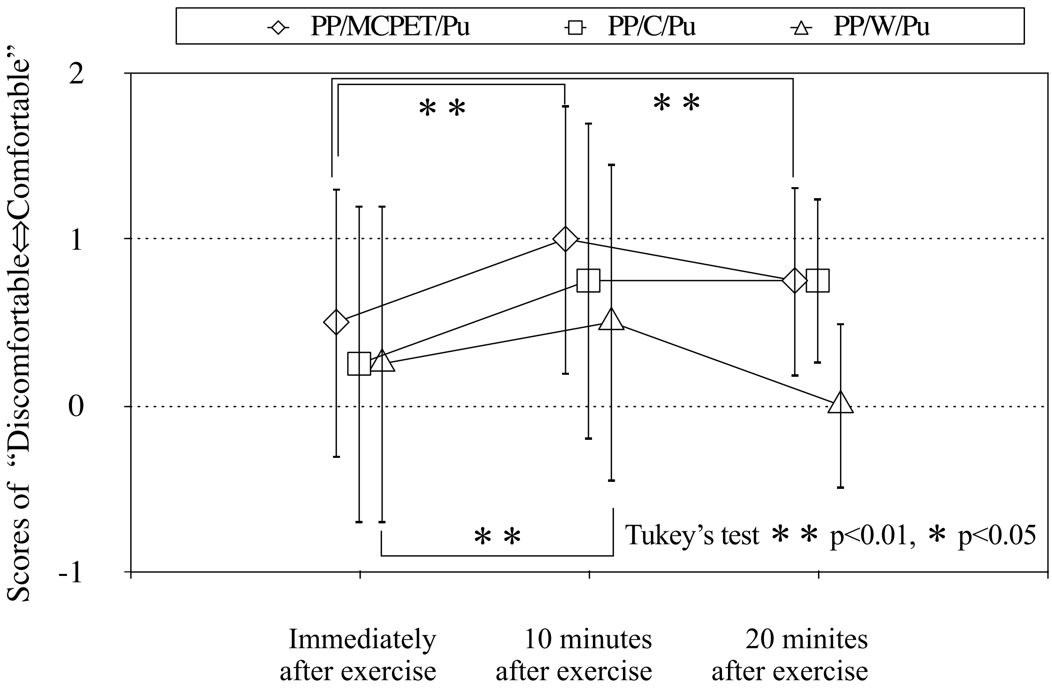

Fig. 3.10 Results of SD method of Comfortable⇔Uncomfortable after exercise（N=4）

Fig. 3.11 shows the time history of the mean scores on “Rough ⇔ Smooth”. Significant differences were examined by multiple comparison with Tukey’s test. The mean scores of PP/MCPET/Pu and PP/C/Pu were significantly higher than that of PP/W/Pu through the experiment, so it was assumed that the difference of surface property caused this sensory difference.

Fig. 3.12 shows the time history of mean scores on “Good texture ⇔ Bad texture”. It was assumed that surface property affected skin contact feeling, because PP/ MCPET/Pu and PP/C/Pu had a better texture than PP/W/Pu through the experiment. PP/MCPET/Pu and PP/W/Pu got worse texture immediately after exercise, and these seemed to be caused by sweating. PP/MCPET/Pu recovered its texture in 10 minutes

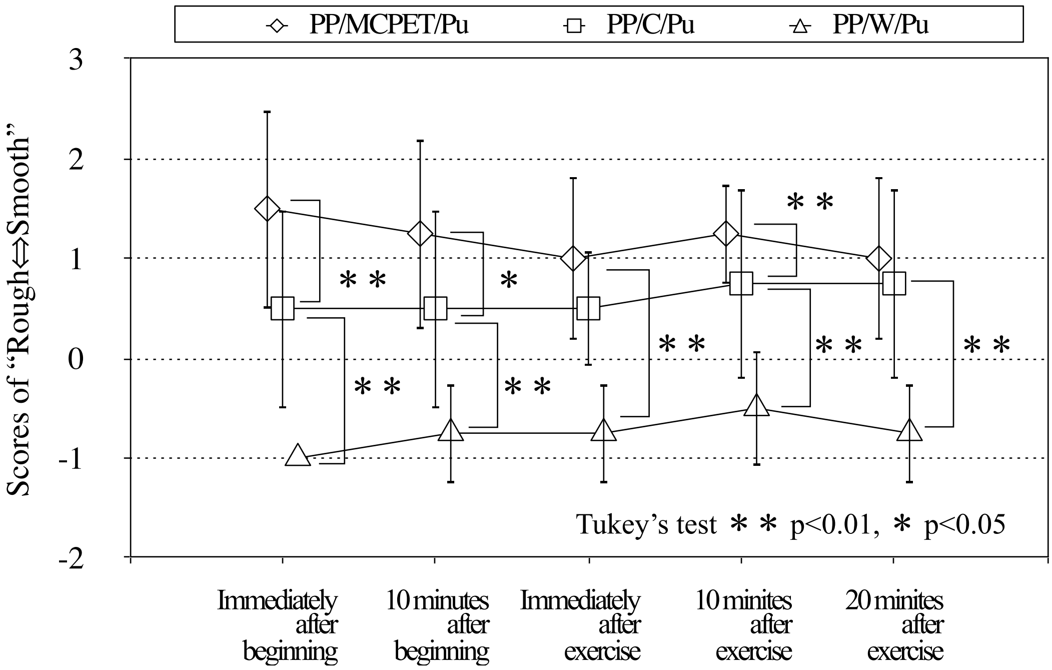

Fig.3. 11 Results of SD method of Rough ⇔ Smooth （N=4）

after exercise, but PP/W/Pu could not recover its texture in 10 minutes after exercise, so the water transportability seemed to affect skin contact feeling. PP/MCPET/Pu is assumed to be comfortable underwear due to its high water transportability, high heat-retention performance and good texture.

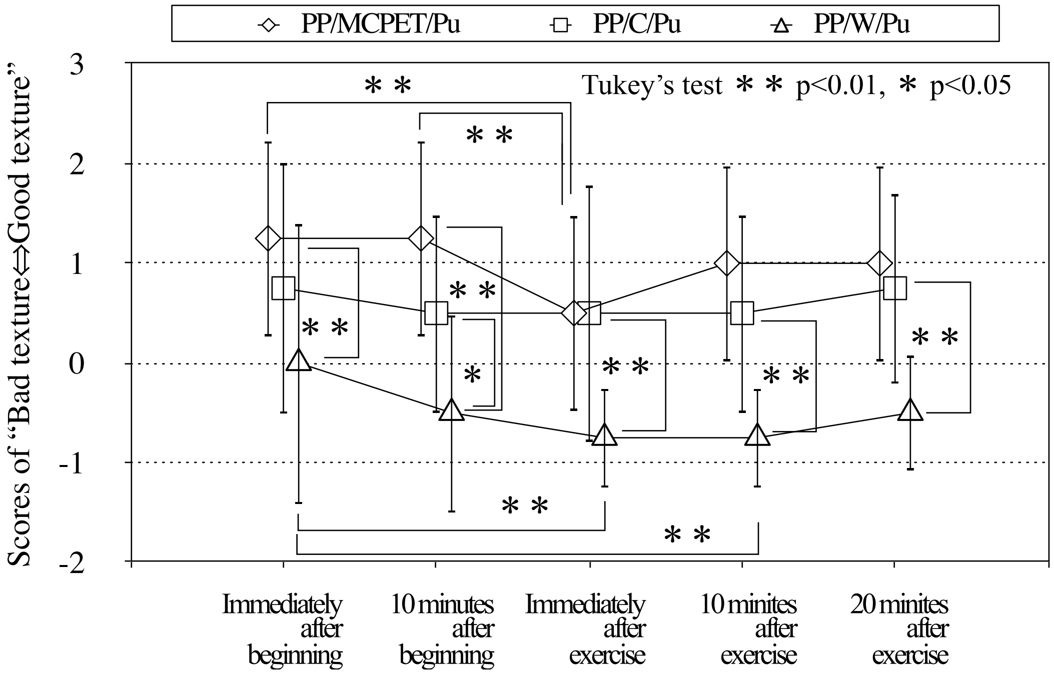

Fig. 3.12 Results of SD method of Good texture ⇔ Bad texture（N=4）

3.3.3 Physiological Response Measurement

Autonomic nervous index LF/HF was calculated from an electrocardiogram to quantify autonomic nerve activity. Time series data of the time between adjacent R waves (R - R interval) was obtained, and spline interpolation was performed. From the FFT analysis on the obtained spline curve, the integration ratio was conducted by dividing the integration of LF (0.04Hz to 0.15 Hz) with the integration of HF

(0.15Hz to 0.40Hz) on power spectrum. MATLAB (Mathworks) was used for the analysis. LH/HF is a sympathetic nerve activity index, with a higher value indicating increasing sympathetic nerve activity. A person who feels stress generates an emergency response [37] that activates the sympathetic nerve system through noradrenaline and adrenaline, and changes occur in the body such as enhancement of cardiac function.

Figure 3.13 shows the results of LF/HF as the average value of the Z scores on four effective subjects. Significant difference was investigated by factorial analysis of variance and multiple comparison with Tukey's test. Significant differences existed in 18 minutes after exercise. LF/HF of PP/MCPET/Pu was lower than that of PP/W/Pu.

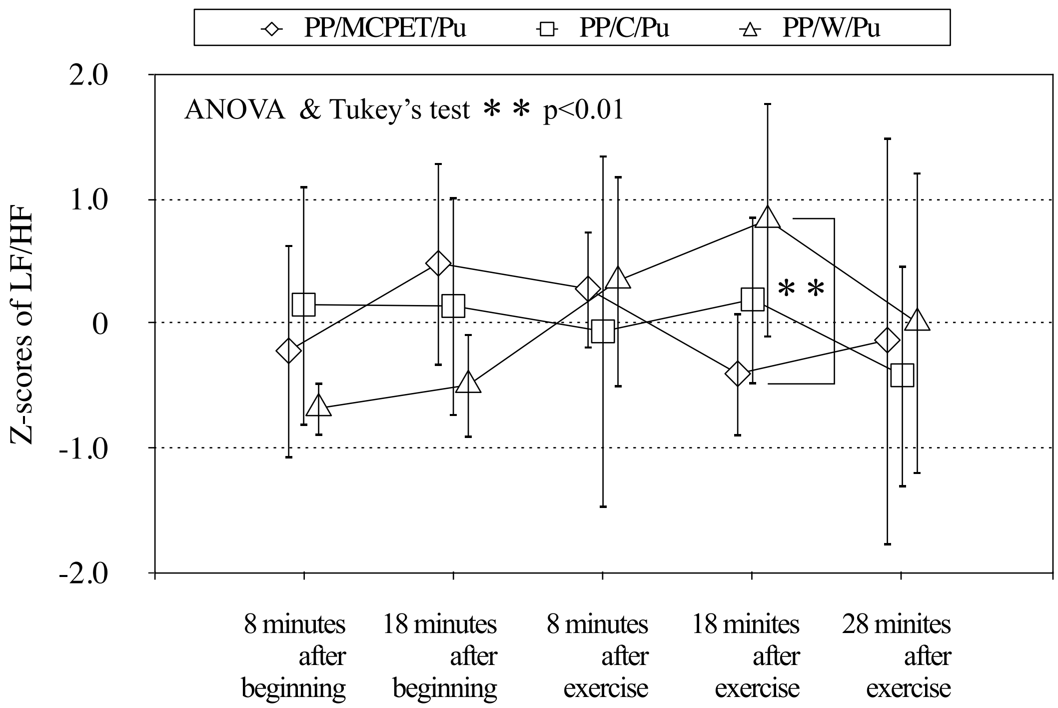

Fig. 3.13 Results of LF/HF by ECG（N=4）

It was suggested that the sympathetic nerve was elevated by wearing PP/W/Pu, and the wearing stress of PP/W/Pu was greater than that of PP/MCPET/Pu. Due to the high water transportability and good texture, the wearing stress of PP/MCPET/Pu was assumed to be smaller than PP/W/Pu. By adding water transportability to a hydrophobic material such as PP by a structural approach such as by blending MCPET, it is possible to design underwear that gives low wearing stress even while the wearer is sweating.

3.4. Summary

The effect of blended fiber material on PP was captured by "clothing climate" and "skin contact feeling". PP/MCPET/Pu had the highest water transportability among the three samples prepared in this chapter, so discomfort decreased quickly after sweating, and its wearing stress is the smallest since the sympathetic nerve activity did not increase. By combining hydrophobic PP and water absorbing and quick drying fiber such as modified cross-section polyester with high heat-retention performance and low moisture regain, underwear that keeps warmth due to releasing sweat quickly was designed. It was possible to develop comfortable underwear by using blended yarn with PP and water-absorbing quick-drying fiber in a suitable blending ratio. Identification of an optimal blending ratio with PP and water-absorbing quick-drying fiber is a future task. The results of this experiment were derived from the difference among the four subjects. In the future, it is necessary to consider the diversity associated with subject's attribution.

Chapter 4

The Effect of Blending Ratio on Knitted Fabric

with Blended Yarn Made

of Polypropylen and Cotton

4.1. Introduction

In chapter 2 and 3, as results of the investigation on knitted fabrics with polypropylene blending yarn, it was found that development of comfortable underwear is possible, despite concerns about sweating, by using blended yarn with PP and water-absorbing quick-drying fiber. Since PP has the lightest specific gravity and low thermal conductivity, warm underwear with high performance can be made by using these characteristic. Although PP's hydrophobicity is excellent regarding quick drying, PP cannot absorb moisture by itself, so it is necessary to combine with water-absorbing and quick drying-fiber fiber or hydrophilic fiber for achieving the sweat performance required for underwear. In this case, the mixing ratio is a problem, but there was no case study to investigate the relationship between the blending ratio and wearing comfort for polypropylene blended yarn. So, the purpose of this chapter is to investigate the effect of blending ratio of polypropylene blended yarn on wearing comfort. Knitted fabrics for underwear were prepared using blended yarn made of PP and cotton with the blending ratio changed stepwise. Since cotton has properties opposite those of PP, it was assumed suitable for investigation of blending ratio with PP. In this chapter, as a first step to investigate the relationship between blending ratio and wearing comfort, material properties were evaluated by Kawabata Evaluation System (KES), Japan Industrial Standards (JIS) and BOKEN standards to examine the effect of blending ratio on basic mechanical properties and heat, moisture and air transport property. The difference was tested between the blending ratios by factorial analysis of variance and multiple comparison for observing the change of material property accompanying the change of blending, and these factors were discussed.

4.2. Samples

4.2.1 Yarns

Table 4.1 shows the blended yarns made of PP and cotton and its blending ratio was changed stepwise at 25% intervals. The fineness of PP was 1.3 dtex and the mean fiber length was 38 mm. The fineness of cotton was 4.2 micronaire and the mean fiber length was 37 mm. Table 4.2 shows the material properties of yarns. While the thickness of yarn was generally unified with cotton yarn number in many experiments, the difference of yarn diameter was considered to affect the material properties of knitted fabric in Chapter 2. Therefore, the yarn number was changed in order to equalize the yarn diameters while considering the specific

Table 4.1 Material of each yarn

Symbol	Material & Blending Ratio with size of staple
C100y	Cotton100%：4.2micronaire × 37mm
P25/C75y	Polypropylene25% : 1.3dtex × 38mm / Cotton75% : 4.2micronaire × 37mm
P50/C50y	Polypropylene50% : 1.3dtex × 38mm / Cotton50% : 4.2micronaire × 37mm
P75/C25y	Polypropylene75% : 1.3dtex × 38mm / Cotton25% : 4.2micronaire × 37mm

gravity difference between PP and cotton. The weight per unit length was calculated by yarn number based on corrected mass. PP75/C25y was the lightest and C100y was the heaviest, because the apparent density decreased by blending PP due to its specific gravity. Fig. 4.1 shows the side view of yarns at magnification of 100 by electron microscope (KEYENCE VE-9800), and the diameter of yarn without tension was measured by the image. The diameter was measured 10 times, and the mean was the representative value. The yarn diameter tended to increase by blending PP. A difference of about 30 μm at the maximum was found in the yarn diameter, and the yarn diameter could not be unified completely. On the side view of the yarns, as the blending ratio of PP increased, fuzzing on the yarn surface decreased, and the fibers were aligned uniformly and smoothly. Fig 4.2 shows the cross-section of yarns at magnification of 270 by electron microscope (KEYENCE VE-9800). The yarn was embedded in epoxy to preserve the cross-sectional shape of yarn, and its

Table 4.2 Properties of each yarn（CV%）

Symbol	Yarn Count	Diameter [μm]	Weight [g/m]	Apparent Density [g/cm³]	Number of Twist [/2.54cm]	Young's modulas [N/mm²]	Elastic recovery % [%]	Irregularity U%
C100y	38.94 (1.59)	175.8 (6.5)	0.0152	0.623	24.55 (2.52)	4981 (16.0)	67 (3.2)	10.12
P25/C75y	44.90 (1.76)	185.3 (9.7)	0.0132	0.484	22.70 (2.82)	3221 (6.0)	87 (2.5)	16.11
P50/C50y	44.40 (1.73)	186.7 (6.2)	0.0133	0.484	25.39 (2.86)	2890 (6.2)	91 (2.0)	14.12
P75/C25y	45.58 (1.82)	203.5 (6.9)	0.0130	0.397	23.30 (3.91)	2708 (8.4)	93 (0.9)	13.39

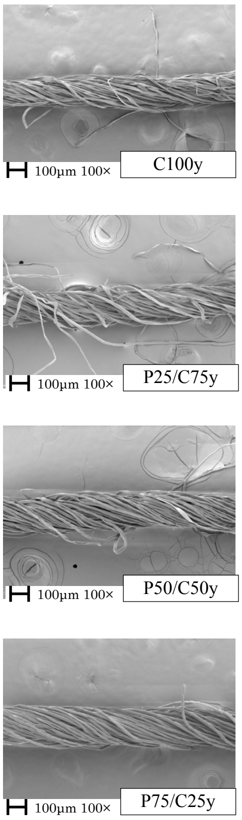

Fig4.1.Side view of yarn

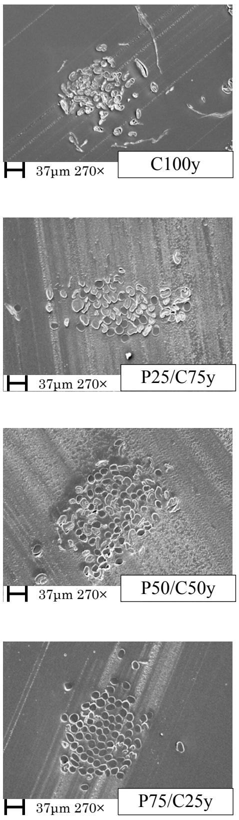

Fig4.2.Cross-Section of Yarn

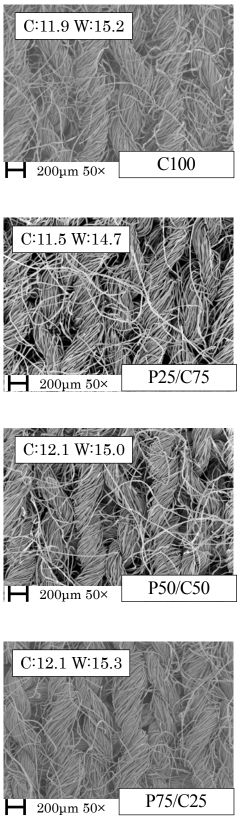

Fig4.3.Side view of fabric with stitch density per 1.27cm C:Course W: Wale

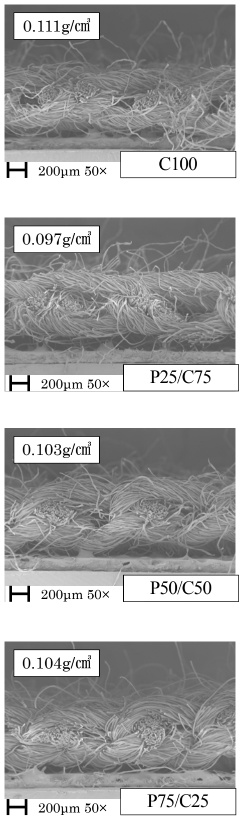

Fig4.4. Cross-section of fabric with density

surface was exposed by microtome (EMUC6 LEICA). Because PP had a circular cross-section compared with cotton fiber, it is considered that fibers are cohered and aligned uniformly with increasing blending ratio of PP. There was bulkiness in P25/C75y and P50/C50y due to gaps between fibers, and the reason was considered to be that the shape of cotton fibers was not linear and the cross-sectional shape of cotton fibers is more diverse than PP. The PP fiber occupied a wide section in the cross-section of P75/C25y because of specific gravity difference between PP (0.91) and cotton (1.54), since the blending ratio is determined by the weight ratio. The number of twists was measured in per inch as the mean value of 10 measurements. The apparent Young's modulus was measured as the resistance of incipient tension of the yarn by JIS (L1095), and its calculation was by dividing the load with elongation amount in the first maximum value of change on the Stress-Strain (SS) curve. The number of measurements was 10, and the mean was the representative value. The apparent Young's modulus increased by blending cotton, so the yarn hardness tended to increase by blending cotton. For recoverability from deformation of yarn, elastic recovery percentage of elongation was measured by JIS (L1095). The number of measurements was 10, and the mean was the representative value. The yarn recoverability tended to increase by blending more PP and less cotton. The yarn unevenness was measured with 200 [m/s] for 3 minutes. The yarn unevenness U% tended to increase by blending more PP.

4.2.2 Fabrics

Table 4.3 shows the knitted fabric prepared using the yarns shown in Table 4.1. Knitting structure was unified with fraise knitting to make it easy to observe the differences in blended fiber material. Fig. 4.3 shows the side view of fabrics at a magnification of 50 by electronic microscope (KEYENCE VE-9800), and stitch density was noted together. There was no remarkable difference of stitch density in a comparison of blending ratios, and it was suggested that the effects of blending ratio should be examined from aspects other than knitting structure. Fig 4.4 shows the cross-section of fabrics at a magnification of 50 by electronic microscope (KEYENCE VE-9800), and apparent density obtained by dividing the weight with thickness with 0.5gf/cm^2 was noted together. By qualitative observation, the unevenness on the surface seemed to become larger by blending more PP, because the bending of yarn become larger for constructing the knit structure due to decreasing Young's modulus of yarn by blending more PP. As the blending ratio of PP increased, the fibers seemed to agglomerate and align uniformly and smoothly on the surface and cross-section of fabrics.

Table.4.3 Specification of fabric

Symbol	Material & Blending Ratio	Note
C100	Cotton100%	Structure：Fraise knitting Diameter of knitting machine：30” Number of needle：1680 Gauge：18
P25/C75	Polypropylene25% / Cotton75%	
P50/C50	Polypropylene50% / Cotton50%	
P75/C25	Polypropylene75% / Cotton25%	

4.3. Experiment

Material properties of all samples were evaluated by KES [25-27], JIS [28,30] and BOKEN standards [31]. Table 4.4 shows the measurement items. The measured material properties were basic mechanical properties related to the assumed deformation by wearing or handling, weight, thickness, air transport property, heat transport property and moisture transport property. Five test pieces were cut from each sample and measured for all items, and the mean value was the representative

Table 4.4 Measurement items of material property

Blocked Property	Symbol	Property	unit	Reference & Conditions of measurement
Tensile	LT	Tensile rigidity	-	KES-FB1 High sens measurement conditions Maximun load : 50[gf/cm] Tensile velocity : 0.1[mm/s] Condition : 20°C65%RH
	WT	Tensile energy	gf・cm/cm^2	
	RT	Tensile recoverability	%	
	EMT	Strain at maximum load	%	
Shear	G	Shear rigidity	gf/(cm・deg)	KES-FB1 Standard measurement conditions Constant tension : 10[gf/cm] Maximum shear angle : ±8° Condition : 20°C65%RH
	2HG	Elastic for minutes shear	gf / cm	
Bending	B	Bending rigidity	gf・cm^2/cm	KES-FB2 Standard measurement conditions Maximum curvature : 2.5/cm Condition : 20°C65%RH
	2HB	Bending recoverability	gf・cm/cm	
Compression	LC	Compressional linearity	-	KES-FB3 High sens measurement conditions Rate of compression : 150[s/mm] Maximum pressure : 10[gf/cm^2]
	WC	Compressional energy	gf・cm/cm^2	
	RC	Compressional recoverability	%	
Surface	MIU	Mean frictional coefficient	-	KES-FB4 Standard measurement conditions Contact force of MIU & MMD : 50gf Contact force of SMD : 10gf Tension of specimen : 20gf/cm
	MMD	Fluctuation of mean frictional coefficient	-	
	SMD	Surface roughness	micron	
Weight & Thickness	W	Weight of fabric per 1m^2	g / m^2	Weight by electronic balance Thickness by KES-FB3 Condition : 20°C65%RH
	T	Thickness of fabric with 0.5gf / cm^2	mm	
Heat transport property	q-max	Peak heat flux	W/cm^2	KES-F7 Thermo-Lab Source of heat : 30°C ΔT : 10°C Air velocity of Qd : 0.3m/s
	K'	Thermal conductance	W/(m^2・°C)	
	Qd	Heat retention properties	%	
Air permeability	R	Ventilation resistance	KPa・s / m	KES-F8 Speed : 2 SEMS:M
Water transport property	MR	Moisture regain	%	MC : JIS L 1096 WA : JIS L 1096 A-2 Byreck SAQD : BOKEN Standards(BQE A 028)
	WA	Water absorption	cm	
	SAQD	Sweat absorption and quick drying	%	

value. The size of test pieces for KES was 20 cm × 20 cm, and for other measurement items, the provisions of each test method were followed. The wale direction and the course direction were separately measured for tensile, shear, bending, surface and water absorption (WA). The measurement environment for all items was 20 °C, 65%RH.

4.4. Results and Discussion

Because significant difference of samples with a 1% level was confirmed in all measurement items except ventilation resistance (R) by factorial analysis of variance (hereinafter called "ANOVA"), the difference between each blending ratio was tested by multiple comparison with Tukey's test. Ekuseru-Toukei 2010 (Social Survey Research Information Co., Ltd.) was used for statistical analysis. Deformability and recoverability of mechanical properties were improved by increasing the blending ratio of PP, so it was assumed that the yarn's apparent Young's modulus and elastic recovery percentage of elongation of the yarn were reflected in the fabric property. Values in each table are mean values, and the brackets show the standard deviation (SD). Each property will be described in turn.

4.4.1 Tensile

Table 4.5 shows the measurement results of tensile properties. LT showed significant differences with a 1% level in the wale and course directions by ANOVA. In the wale direction, there were significant differences with a 1% level for all sample pairs excluding P50/C50 and P75/C25. In the course direction, there were significant differences with a 1% level between C100 and all other samples and between P25/C75 and P75/C25. In both the wale and course directions, LT tended to be lower as the blending ratio of PP was higher and the blending ratio of cotton was lower. WT showed a significant difference with a 1% level in the wale and course directions by ANOVA. In the wale direction, there were significant differences with a 1% level between C100 and P50/C50, P75/C25, between P25/C75 and P50/C50, P75/C25, and between P50/C50 and P75/C25. In the course direction, there were significant differences with a 1% level between C100 and all other samples. WT of wale direction became higher with increasing blending ratio of PP on 25% or more.

Table 4.5 Results of tensile properties of fabrics （SD）

Sample (Cotton : PP)	Tensile							
	LT		WT[gf・㎝/㎠]		RT[%]		EMT[%]	
	Wale	Course	Wale	Course	Wale	Course	Wale	Course
C100 (100 : 0)	0.752 (0.013)	0.776 (0.007)	1.564 (0.120)	5.936 (0.358)	38.004 (2.116)	33.198 (0.745)	8.322 (0.662)	30.622 (1.764)
C75/P25 (75 : 25)	0.703 (0.017)	0.730 (0.026)	1.570 (0.135)	7.776 (0.570)	41.070 (0.865)	34.856 (2.596)	8.930 (0.695)	42.710 (4.145)
C50/P50 (50 : 50)	0.672 (0.015)	0.713 (0.013)	2.026 (0.149)	7.888 (0.430)	42.562 (1.406)	34.990 (1.118)	12.082 (1.176)	44.214 (1.678)
C25/P75 (25 : 75)	0.654 (0.006)	0.684 (0.035)	2.568 (0.235)	7.616 (1.137)	41.892 (0.632)	36.570 (5.518)	15.718 (1.494)	44.342 (4.644)

Significant difference : ＊＊ p<0.01, ＊ p<0.05

WT in the course direction increased by blending PP at 25% or more with cotton. Increasing the blending ratio of PP tended to make fabric easy to elongate. Young's modulus of yarn tended to decrease as the blending ratio of PP increased, so it was assumed that the apparent Young's modulus of yarn was reflected in the fabric property. The mechanism by which the yarn property affects the knitted fabric property is future issue. RT showed significance differences at a 1% level by ANOVA only in the wale direction. There were significant differences with a 1% level between C100 and P50/C50, P75/C25, and with 5% level between C100 and P25/C75. As the blending ratio of PP increased, RT increased and tensile recoverability improved. The elastic recovery percentage of elongation of yarn tended to be higher as the blending ratio of PP was increased, so it was assumed that recoverability of yarn was reflected in fabric property. EMT showed a significant difference with a 1% level in the wale and course directions by ANOVA. In the wale direction, there were significant differences with a 1% level in all sample pairs except C100 and P25/C75. In the course direction, there were significant differences with 1% between C100 and all other samples. In the wale direction, EMT tended to become higher as the blending ratio of PP was increased. In the course direction, EMT increased when the blending ratio of PP was increased to 25% or more. As the blending ratio of PP increased, fabric tended to elongate more easily, and recoverability was increased compared with 100% cotton knitted fabric (C100).

4.4.2 Shear

Table 4.6 shows the measurement results of shear property. G showed a significant difference with 1% level in wale and course direction. In the wale direction, there were significant differences of a 1% level in all sample pairs except between C100 and P25/C75 and between P50/C50 and P75/C25. In the course direction, there were significant differences with a 1% level in all sample pairs except between P50/C50 and P75/C25. In the course direction, G was decreased by blending PP, and became lower as the blending ratio of PP was increased from 25% to 50%. The wale direction was similar to the course direction. 2HG showed a significant difference with

Table 4.6 Results of shear properties of fabrics （SD）

Sample (PP: Cotton)	Shear			
	G [gf/(cm・deg)]		2HG[gf / cm]	
	Wale	Course	Wale	Course
C100 (0 :100)	0.684 (0.0344)	0.734 (0.019)	2.678 (0.1217)	3.3820 (0.1291)
P25/C75 (25:75)	0.540 (0.0158)	0.610 (0.019)	2.156 (0.0666)	2.738 (0.0370)
P50/C50 (50 : 50)	0.468 (0.0045)	0.506 (0.050)	2.138 (0.2316)	2.434 (0.0456)
P75/C25 (75 : 25)	0.474 (0.0055)	0.498 (0.013)	1.988 (0.1230)	2.124 (0.1242)

Significant difference : ＊＊ p<0.01, ＊ p<0.05

a 1% level in both the wale and course directions. In the wale direction, there were significant differences with a 1% level between C100 and all other samples. In the course direction, there were significant differences with a 1% level in all sample pairs except between C100 and P25/C75. In the wale direction, 2HG became lower than that of C100 by blending PP at 25% or more. In the course direction, 2HG became lower than that of C100 by blending PP at 50% or more and decreased as the blending ratio of PP was increased from 25% or more. As the blending ratio of PP increased, deformability and recoverability tended to improve.

4.4.3 Bending

Table 4.7 shows the measurement results of bending property. B showed a significant difference with a 1% level in only the wale direction. There were significant differences with a 1% level in all sample pairs except between P50/C50 and P75/C75. In the wale direction, B was lower than that of C100 by blending PP at 25% or more. As the blending ratio of PP increased, bending rigidity tended to lower. 2HB showed a significant difference with a 1% level only in the wale direction. There were significant differences with a 1% level between C100 and all other samples, and with a 5% level between P25/C75 and P25/C75. In the wale direction, 2HB became lower than that of C100 by blending PP at 25% or more. As the blending ratio of PP became higher, the deformability and recoverability on bending tended to increase as compared with 100% cotton fabric.

Table 4.7 Results of bending properties of fabrics （SD）

Sample (PP: Cotton)	Bending B[gf・㎠/㎝] Wale	Bending B[gf・㎠/㎝] Course	Bending 2HB[gf・㎝/㎝] Wale	Bending 2HB[gf・㎝/㎝] Course
C100	0.087	0.00918	0.110	0.013
(0 :100)	(0.002)	(0.003)	(0.001)	(0.002)
	**		**	
P25/C75	0.056	0.00918	0.072	0.012
(25 : 75)	(0.008)	(0.002)	(0.011)	(0.001)
	**		*	
P50/C50	0.043	0.00926	0.060	0.012
(50 : 50)	(0.002)	(0.002)	(0.005)	(0.001)
	**		*	
P75/C25	0.044	0.00996	0.060	0.013
(75 : 25)	(0.002)	(0.001)	(0.002)	(0.001)

Significant difference : ＊＊ p<0.01, ＊ p<0.05

4.4.4 Compression

Table 4.8 shows the measurement results of compression property. LC showed a significant difference with a 1% level by ANOVA. There were significant differences with a 1% level between P75/C25 and C100, P25/C75, and with a 5% level between P75/C25 and P50/C50. LC decreased by blending PP at 75%. As shown in Fig. 4.2, the cross-section of P75/C25y contained almost all PP fibers with few cotton fibers, and the aggregation state of the fiber was greatly different from other samples, so it could be considered that LC of P75/C25 was different from the others. WC showed a significant difference with a 1% level by ANOVA. There were significant differences with a 1%

level between C100 and all other samples. By blending PP at 25% or more, WC decreased and compression difficulty tended to increase. Referring to the cross-sectional image of the yarn shown in Fig. 4.2, as the blending ratio of PP increased, the bulkiness of the yarn tended to decrease, so it was considered that the WC decreased with a change in the aggregation state of fibers. RC showed a significant difference with a 1% level by ANOVA. There were significant differences with a 1% level between PP75/C25 and P25/C75, P50/C50, and with a 5% level between P75/C25 and C100. P75/C25 was the maximum, and the reason could be considered to be that deformability was decreased due to fiber agglomerationas as the blending ratio of PP

Table 4.8 Results of compression properties of fabrics (SD)

Sample (PP: Cotton)	Compression LC	Compression WC [gf / cm]	Compression RC[%]
C100 (0 :100)	0.568 (0.020)	0.146 (0.003)	39.534 (4.390)
	**	**	*
P25/C75 (25 : 75)	0.569 (0.015)	0.131 (0.008)	34.63 (1.728)
	**	**	**
C50/P50 (50 : 50)	0.555 (0.025)	0.123 (0.006)	34.314 (1.481)
	*	**	**
P75/C25 (75 : 25)	0.514 (0.020)	0.121 (0.006)	48.172 (5.942)

Significant difference : ＊＊ p<0.01, ＊ p<0.05

was increased. As the blending ratio of PP was increased, compression deformability increased in comparison with C100, and compression recoverability became the maximum by blending PP at 75%. The cause was assumed to be the changing fiber agglomeration of cross-section of the yarn.

4.4.5 Surface

Table 4.9 shows the measurement results of surface property. MIU showed a significant difference with a 1% level in the wale and course directions. In the wale direction, there were significant differences with a 1% level in all sample pairs except between P50/C50 and P75/C25. In the course direction, there were significant

Table 4.9 Results of surface properties of fabrics （SD）

Sample (PP: Cotton)	MIU		MMD		SMD[micron]	
	Wale	Course	Wale	Course	Wale	Course
C100 (0 :100)	0.173 (0.004)	0.197 (0.004)	0.007 (0.002)	0.009 (0.001)	4.678 (0.934)	8.932 (1.220)
P25/C75 (25 : 75)	0.187 (0.005)	0.198 (0.004)	0.008 (0.001)	0.009 (0.001)	3.647 (0.733)	9.161 (0.371)
P50/C50 (50 : 50)	0.208 (0.005)	0.218 (0.008)	0.013 (0.003)	0.014 (0.003)	4.351 (0.447)	12.261 (0.685)
P75/C25 (75 : 25)	0.217 (0.007)	0.225 (0.007)	0.020 (0.004)	0.014 (0.002)	4.946 (0.835)	10.585 (0.804)

Significant difference : ＊＊ p<0.01, ＊ p<0.05

differences with a 1% level between C100 and P50/C50 and P75/C25; and between P25/C75 and P50/C50 and P75/C25. In the wale direction, MIU became higher as the blending ratio of PP was increased, in range of 50% or less. The course direction shows the same tendency. As shown in Fig. 4.2, since PP fiber had a circular cross-section and aggregated in the cross-section of a yarn, it was considered that the contact area between the contactor and the fabric increased and the coefficient friction increased by increasing the blending ratio of PP. The influence of contact area was indicated, as reported by B.K. Beherra et al [14]. MMD showed a significant difference with a 1% level in the wale and course directions by ANOVA. In the wale direction, there were significant differences with a 1% level between P75/C25 and all other samples, and with a 5% level between C100 and P50/C50. In the course direction, there were significant differences with a 1% level between C100 and P50/C50 and P75/C25; and between P25/C75 and P50/C50 and P75/C25. In the wale direction, MMD was higher than that of C100 by blending PP at 50% or more, and became higher when the blending ratio of PP was 50% or more. The course direction showed same tendency as the wale direction, and its MMD became higher as the blending ratio of PP was increased from 25% to 50%. As shown in Fig. 4.4, the irregularities of the fabric surface seemed to become larger as the blending ratio of PP was increased. The increase in irregularities seem to be caused by increasing the yarn diameter, decreasing of the bulkiness and by increasing yarn bending, due to a decrease in the apparent Young's modulus. SMD showed a significant difference with a 1% level in only the course direction by ANOVA. In the wale direction, there were significant differences with a 1% level between P50/C50 and C100, P25/C75, and with a 5% level between P75/C25 and C100, P50/C50. In the course direction, SMD was higher compared with C100 by blending PP at 50% or more, and it became higher as the blending ratio of PP was increased from 25% to 50%. The surface tended to be rougher as the blending ratio of PP increased. It was assumed that the aggregation state of the fibers and the apparent Young's modulus of the yarn affected the surface roughness. In blending ratios of PP of 50% or more, the friction coefficient became larger, and the surface roughness increased by blending more PP, in comparison with C100. The sample blending 25% of PP and 75% of cotton had no significant difference in surface properties from sample of 100% cotton.

4.4.6 Weight & Thickness

Table 4.10 shows the measurement of results weight and thickness. Weight (W) showed a significant difference with a 1% level by ANOVA. There were significant differences with a 1% level in all sample pairs except between P50/C50 and P75/C25. C100 was the heaviest due to specific gravity of cotton. Thickness (T) showed a significant difference with a 1% level by ANOVA. There were significance differences with a 1% level between C100 and P25/C75, P50/C50, and between C100 and P75/C25. It is conceivable that C100 is the thickest with 0.5 gf/cm^2 because C100y had bulkiness and smaller yarn bending due to higher Young's modulus.

Table 4.10 Results of thickness & weight of fabrics （SD）

Sample (PP: Cotton)	Thickness & Weight W[g/m²]	T[mm]
C100 (0 :100)	148.7 (2.267)	1.345 (0.016)
	**	**
P25/C75 (25 : 75)	124.85 (2.708)	1.287 (0.008)
	**	**
P50/C50 (50 : 50)	133.15 (1.069)	1.287 (0.014)
	**	*
P75/C25 (75 : 25)	135.65 (2.177)	1.303 (0.031)

Significant difference : ＊＊ p<0.01, ＊ p<0.05

4.4.7 Heat Transport Property

Table 4.11 shows the measurement results of heat transport property. The q-max showed a significant difference with a 1% level by ANOVA. There were significant differences with a 1% level between C100 and all other samples and between P50/C50 and P75/C25, with a 5% level between P25/C75 and P75/C25. The q-max was lower compared with C100 by blending PP at 25% or more, and it became lower as the blending ratio of PP was increased from 50% to 75%, but it showed no change when the blending ratio of PP was increased from 25% to 50%. As shown in Fig. 4.2 and Fig. 4.4, the fibers were agglomerated and the structure changed to conduct heat easily when the blending ratio of PP was increased, and these were assumed to be factors that caused q-max to have no change when the blending ratio of PP was increased from 25% to 50%. There was a possibility that both the material's thermal conductivity and the fabric bulkiness influenced q-max. Heat conductance (K') showed a significant difference with a 1% level by ANOVA. There were significant differences with a 1% level between C100 and all other samples, and between P75/C25 and P50/C50 and P25/C75. K' had the same trend as q-max, and became lower compared with C100 by blending PP at 25% or more, but had no change from increasing the blending ratio of PP from 25% to 50%. Heat retention (Qd) showed a significant difference with a 1% level by ANOVA. There were significant differences with a 1% level in all sample pairs except between P50/C50 and P25/C75. Qd was

Table 4.11 Results of thermal properties of fabrics （SD）

Sample (PP: Cotton)	Thermal		
	q-max [W/cm²]	K' [W/(m² ・K)]	Qd[%]
C100 (0 :100)	0.101 (0.001)	0.00548 (0.000)	24.9 (2.2)
P25/C75 (25 : 75)	0.090 (0.001)	0.00507 (0.000)	35.1 (1.7)
P50/C50 (50 : 50)	0.091 (0.001)	0.00508 (0.000)	34.1 (1.9)
P75/C25 (75 : 25)	0.088 (0.002)	0.00476 (0.000)	39.5 (1.2)

Brackets in the table mark significant differences:
- q-max: C100–P25/C75 **, P25/C75–P75/C25 *, P50/C50–P75/C25 **
- K': C100–P25/C75 **, P25/C75–P75/C25 **, P50/C50–P75/C25 **
- Qd: C100–P25/C75 **, P25/C75–P75/C25 **, P50/C50–P75/C25 **

Significant difference : ＊＊ p<0.01, ＊ p<0.05

higher compared with C100 by blending PP at 25% or more, and it became higher by increasing the blending ratio of PP from 50% to 75%, but had no change from increasing the blending ratio of PP from 25% to 50%. Blending PP with 25% resulted in the same effect as with 50%. Because the influence of fiber agglomeration and fabric bulkiness was the same as q-max and K', there was a possibility that Qd didn't rise linearly as the blending ratio of PP, which has low thermal conductivity, was increasing.

4.4.8 Air Transport Property

Table 4.12 shows the measurement results of air transport property. Ventilation resistance (R) had no significant difference by ANOVA. It was considered that the tendency of thermal conductance (K') and heat retention ratio (Qd) became the same, because there was no difference between samples in R.

Table 4.12 Results of air transport properties of fabrics (SD)

Sample (Cotton : PP)	Air permeability
	R[KPa・s / m]
C100 (100 : 0)	0.038 (0.000)
C75/P25 (75 : 25)	0.035 (0.002)
C50/P50 (50 : 50)	0.036 (0.002)
C25/P75 (25 : 75)	0.033 (0.005)

Significant difference : N.S.

4.4.9 Water Transport Property

Table 4.13 shows the measurement results of water transport property. Water absorbency (WA) showed a significant difference with a 1% level in both the wale and course directions by ANOVA. In the wale direction, there were significant differences with a 1% level in all sample pairs. In the course direction, there were significant differences with a 1% level in all sample pairs except between C100 and P25/C75. In the wale direction, WA became lower compared with C100 by blending PP at 50% or more, but increased by blending PP at 25%. In the wale direction, WA also became lower compared with C100 by blending PP at 50% or

Table 4.13 Results water transport properties of fabrics (SD)

Sample (PP: Cotton)	Water transport			
	WA[cm]		MR[%]	SAQD[%]
	Wale	Course		
C100 (0 :100)	11.16 (0.167)	9.96 (0.195)	4.919 (0.133)	6.4 (4.037)
	**	**	**	**
P25/C75 (25 : 75)	11.84 (0.152)	10.00 (0.255)	3.375 (0.076)	14.0 (3.464)
	**	**	**	
P50/C50 (50 : 50)	9.42 (0.148)	8.64 (0.167)	2.455 (0.097)	15.4 (1.517)
	**	**	**	
P75/C25 (75 : 25)	6.02 (0.449)	5.84 (0.270)	0.971 (0.202)	15.8 (2.168)

Significant difference : ＊＊ p<0.01, ＊ p<0.05

more. Since PP is a hydrophobic material, it was assumed that the WA declined by increasing the blending ratio of PP at 50% or more. Moisture regain (MR) showed a significant difference with a 1% level by ANOVA. There were significant differences in all sample pairs. Since PP's official regain was 0%, the MR became lower with a higher blending ratio of PP. Sweat absorption and quick drying (SAQD) showed significant differences with a 1% level by ANOVA. There were significant differences with a 1% level between C100 and all other samples. The drying speed of fabric depends on the moisture regain, and became faster with lower regain due to longer constant drying rate period [38]. As the official regain of PP is 0%, PP's constant drying rate period was longer than that of cotton, and it was considered that SAQD became higher compared with C100 by blending PP. There was no difference in SAQD by the blending ratio of PP, because the water absorbency decreased as the blending ratio of PP was increased at 50% or more. It is considered that the time required for absorption became shorter with increasing blending ratio of PP in the cycle of water absorbing and releasing. By blending PP at 25% with cotton, moisture transportability was improved without losing cotton's property of water absorbency.

4.5. Summary

The knitted fabrics for underwear were prepared using blended yarn made of PP and cotton with blending ratio changed stepwise, and the material properties of these fabrics were evaluated. As the blending ratio of PP increased, the apparent Young's modulus of the yarn decreased, and the recoverability of yarn increased, and the cohesiveness of the fiber increased. Accordingly, deformability and recoverability of fabric were increased by blending PP. Surface property was worsened by blending PP at 50% or more. Thermal conductivity decreased and heat retention performance increased by blending PP with cotton, but there was no change with increasing the blending ratio of PP from 25% to 50%. Water absorbency decreased by blending PP at 50% or more. Water-absorbing and quick-drying property was improved by blending PP, but there was no difference depending on blending ratio. From the above, an appropriate value was suggested for the blending ratio between PP and cotton, and PP25%-Cotton75% is closed to the value because water transportability and heat retention performance was added without spoiling cotton's characteristic. It was considered that the optimum value can be identified by investigating the blending ratio in the vicinity of PP25%-cotton75%. Although it was considered that material properties of the yarn affected the material properties of the knitted fabric, the elucidation of the mechanism for determining a suitable blending ratio is a future issue.

Chapter 5

Conclusion

The design of comfortable underwear using PP blended yarn was investigated in this thesis. In Chapter 2, the effect of blended fiber materials on knitted fabric using PP blended yarn was investigated by material property evaluation. In blending PP and other various fiber materials with same cotton yarn number, PP tended to encourage lower apparent density, lower thermal conductivity and the lower recoverability. By blending PP and water-absorbing and quick-drying fiber such as MCPET, the knitted fabric could be designed for underwear with high heat-retention performance and high water transportability. The practicality of PP blended yarn was shown.

In Chapter 3, a wearing comfort evaluation by wearing experiments was carried out on underwear using the knitted fabric prepared in Chapter 2. The influence on wearing comfort of blended fiber materials was captured from clothing microclimate relating water transport property and skin contact feeling relating to surface property. The high water transportability quickly reduced discomfort after sweating, and reduced wearing stress, so that it did not encourage sympathetic nerve activity. By combining hydrophobic PP and water absorbing and quick drying fiber, underwear could be designed with low wearing stress due to high heat-retention performance, good texture and high water transportability. PP's property were suitable for underwear, because comfortable underwear could be designed by adding only water-absorbing and quick-drying property on PP's. PP could be effectively utilized as a underwear material, by combining hydrophobic PP and water-absorbing and quick-drying fiber such as modified cross-section polyester due to compensating water transportability.

In Chapter 4, for the purpose of investigating the suitable blending ratio, the knitted fabrics for underwear were prepared using blended yarn made of PP and cotton with blending ratio changed stepwise, and material property of these fabrics were evaluated. The blending ratio with PP25%-Cotton75% was closed to the suitable value because water transportability and heat retention performance was added without spoiling cotton's characteristic. It was considered that the optimal value can be identified by investigating the blending ratio in the vicinity of PP25%-cotton75%. Based on Chapters 2 and 3, even though the underwear design that complements only water absorption for taking the advantage of PP's characteristic is useful, the underwear design in which PP complements the performance of cellulose is also useful. When PP and cellulose were blended, PP decreased thermal conductivity and increased water transportability.

From the above, basic data was gathered for design of comfort underwear with high heat retention, high water transportability and good texture, and the two methods of utilizing PP as underwear materials were found out.

In recent years, it has become common to use a multiple materials in order to design various functions required for underwear. In this study, PP was focused on for developing comfortable underwear. But, based on the results of this study, it seem that an optimal combination method for other various materials also exists. For other materials, it is desirable that optimal solutions be derived from the criteria of human senses/sensibility to increase comfort.

In addition, this study doesn’t mention the diversity associated with the subject's attributes. In order for redevelopment of the Japanese textile industry, it is necessary to satisfy with the needs of individuals in Japan and overseas, so it is desirable to consider the comfort of people with various attributes. I hope this study will help the design of comfortable clothing.

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