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Comparative Study of the Characteristics of Knitted Fabrics Produced from Recycled Fibres Employing the Chauvenet Criterion, Factorial Design and Statistical Analysis

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Abstract
The raw material of a fabric has a substantial influence on its functional aspect. However, the fabrics used for clothing manufacture should offer comfort, protection, ease of maintenance, durability and aesthetics. This study aims to compare the properties of knitted fabrics made of recycled polyester by employing the Chauvenet criterion, factorial design and statistical analysis to determine which raw material composition provides more functionality to the final product. Knitted fabrics (jersey fabrics with statistically equal weights) made of two types of yarns, namely 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton, were tested. For the finished fabrics, the following tests were performed: weight, pilling, burst pressure, elasticity and elongation, moisture absorption, and dimensional change. The response surface graphics were analysed to determine the optimum regulation value for the knitting machine to manufacture fabrics with statistically equal weights. The best results were obtained with knitted fabrics produced with 80%-polyester/20%-recycled-polyester yarns.

Key words: *Chauvenet criterion, knitted fabrics, recycled polyester, statistical studies, sustainable fibre.*

RESEARCH & DEVELOPMENT

Introduction

The world economy has undergone considerable changes, where formerly restricted markets are now open and involve global competition. However, consumers now require more specified and sophisticated products, resulting in greater market segmentation. Many factors have contributed to the intensification of competitiveness, such as globalisation, new technologies, demand for high quality products and others. The competitiveness issue has been increased in recent decades to ensure survival in this environment. Companies must offer better and differentiated products. These challenging situations raise the level of business intelligence, unfold and multiply manufacturing operations, and finally involve other production chains, which results in the generation of more and better skilled jobs. In this way, a challenging environment is the condition for sustainable development [1].

In parallel, the search for sustainable lifestyles is becoming a more important goal of the world in the present and for future generations. According to Sachs [2], " sustainability in the time of human civilization will depend on its ability to submit itself to the precepts of ecological prudence and make good use of nature". Considering fashion, the production of new products for clothing according to sustainable principles is a challenge. Fashion is ephemeral due to the short life cycles of the majority of products associated with consumerism. This type of product conception is a challenge also for the textile sector because of large waste generation from their polluting processes. Therefore to attend this new consumer demand, textile companies are gradually using raw materials from systems less harmful to the environment, such as the organic production of fibres or textile recycling, as a form of differentiation and fashion appeal. The relationship between sustainability and textile must consider three main points: production, user and disposal [3].

A promising possibility is the production of fibres made from recycled PET (polyethylene terephthalate). The term polyester is used for polymeric materials that contain ester groups in the macromolecular chain [4]. Although many types of polymers have been developed, only the crystalline ones with a melting point between 220 °C to 280 °C allow for the production of textile fibres [5]. The application of recycled fibre in the textile industry to manufacture fabrics for various end products has been growing each year.

Recycled polyester fibre

Polyester is a polymer compound of monomers bonded via ester linkages [6], for which the recycling process is a way to reduce wastes of this raw material [7]. Recycled polyester fibre is obtained from the recycling of synthetic packaging materials, and can be blended with cotton, linen and viscose to improve the lightness, softness and comfort of fabric [8].

Generally the recycling process can be performed in two ways:

i) Depolymerisation: a chemical recycling process where the molecular structure of the polyester is broken, removing all stains and impurities, and is then returned to the original raw material form;
ii) Mechanical: a process where post-industrial and/or post-consumer waste is melted and reshaped into its original form. This process is more efficient than the chemical method because it requires less energy [9].

Table 1. Comparison between virgin and recycled polyester processes [10].

Process comparison	
Virgin polyester	**Recycled polyester**
Crude oil well head	Process eliminated
Crude oil refinery	
Naphta	
Xylenes	
Paraxylene	
Terephthalic acid & mono ethylene glycol	
Polymerization	Chip production
Extrusion	Extrusion
Texturing	Texturing

Table 1 compares virgin and recycled polyester processes [10].

Materials and methods

The methodology of this research is divided into three stages: choice of material, experimental planning and trials.

Materials

The materials used in the elaboration of this research were divided into two groups:

i) Spun yarns of recycled-polyester/cotton (50/50) 19.7×1 tex;

ii) Filament yarns of recycled-polyester/polyester (80/20): 167f68 dtex.

Each raw material generated a knitted fabric manufactured on L. Degoisey single circular knitting machines, 95.25 mm in diameter (3 ¾ inches), with 236 20 gauge needles and a positive feeding system. The knitted fabrics were finished in a single bath, using a laboratory winch to ensure the same finishing conditions.

Methods

Completely random 2^2 factorial designs were set, and for each raw material and each machine regulation, a replication was made. The order of execution of the regulations as well as their replications were determined by lottery [18, 19].

Control Factors

In a positive feeding system, the length of the loop is a fundamental parameter of quality control and fabric dimensions. Therefore the machine regulation parameters that can influence the fabric dimensional characteristics are:

- Positive feeding speed (Factor A);
- Input tension of the yarn (Factor B).

To determine the minimum and maximum speeds of positive feeding (P.F.S.), the superior and inferior limits of the acceptable coverage factor of each raw material was used, and the machine rotation was set at 200 r.p.m.

The maximum and minimum height levels of the stitch cams were determined by setting the them at the lowest level possible (most opened point) and verifying the input tension of the yarn at that position (highest level of tension). Next the cams were set at the highest level (most closed position) and the tension value was verified at that position (lowest tension value).

Experimental values of control factors

i) Yarns with 80%-polyester/20%-recycled-polyester (***Figure 1***)
Factor A: Positive feeding speed – 140 m/min
Factor B: Stitch Cam height – 5 cN

ii) Yarns with 50%-recycled-polyester/50%-cotton (***Figure 2***)
Factor A: Positive Feeding Speed – 146 m/min
Factor B: Stitch Cam Height – 5 cN.

Analysis of the results

To verify the presence of abnormal results in the samples tested, the Chauvenet criterion was employed. The significance of the experimental results was verified through analysis of variance (ANOVA), with a confidence interval of 95% ($p = 0.05$), and determination of the optimal regulation of the machine was performed through analysis of the response surface.

Response surface graphs

To determine optimum regulation values of circular machines and hence produce single jersey fabrics with statistically equal weights, response surface graphs were plotted (***Figures 1*** and ***2***) with data (weight in relation to positive feeding speed - factor A and input tension of the yarn - factor B) from the production process of fabrics made from 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton, respectively.

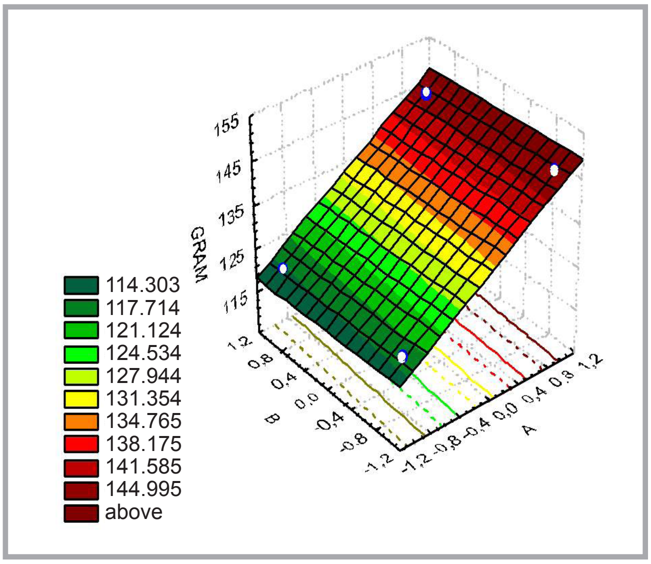

Figure 1. *Response surface graphic of weight (g/m²) in relation to normalised positive feeding speed (A) and normalised input tension of the yarn (B) for knitted fabrics made of 80%-polyester/20%-recycled polyester fibres.*

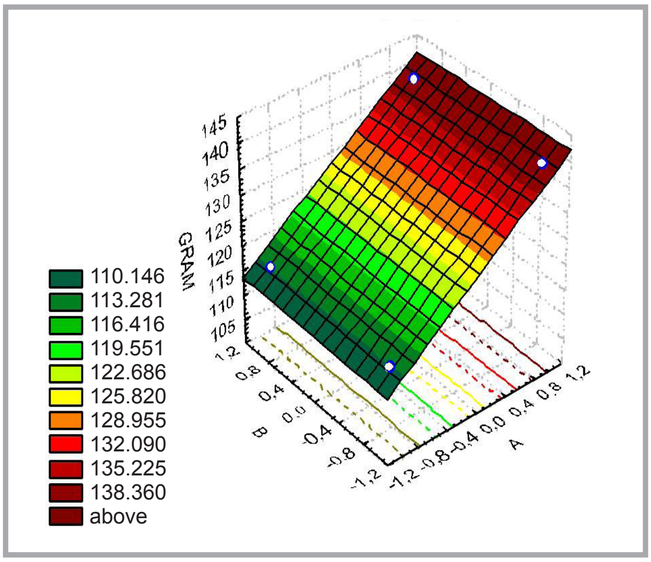

Figure 2. *Response surface graphic of weight (g/m²) in relation to normalised positive feeding speed (A) and normalised input tension of the yarn (B) for knitted fabrics made of 50% recycled-polyester/50%-cotton fibres.*

Trials

The following trials were conducted on the finished fabrics:

i) Determination of weight (ASTM D 3776 – 96): preparation of five test objects, weighed using an analytical balance, and subsequent calculation of the weight in grams per square meter [11, 12];

ii) Tendency for pilling formation (ASTM D 4970 – 05): one-hundred cycle trial, realised on a Martindale device (SDL Atlas, USA), and comparison with photographic patterns [13];

iii) Determination of the burst pressure (ASTM D 3786 – 01): implementation of five trials on Mullen tester (USA) equipment for measuring the value of pressure exerted over the test objects to the instant of rupture [14];

iv) Determination of elasticity and elongation (JIS L 1018 – 02): preparation of five test objects cut in the wale direction of the knitted fabrics, and five cut in the course direction for application of a 2.94 N/cm load during a period of one minute, with an initial distance of 7.0 cm (W) [15];

v) Determination of moisture absorption by capillarity (JIS 1907 – 02): preparation of five test objects for water contact during a period of ten minutes and determination of the height in mm [16];

vi) Determination of dimensional alteration (NBR 10320 – 88); because of the use of a small diameter circular knitting machine, the preparation of the test object was modified from 38 × 38 cm and the marking of three measurements of 25 cm to 21 × 16 cm, 7 cm markings in the transversal direction and 5 cm in the longitudinal direction [17].

Statistical studies

Chauvenet criterion: **conditioning of the experimental values**

This procedure specifies that a result must be rejected if the probability of obtaining the standard deviation relative to it is less than 1/(2n), where n is the sample size [20].

The criterion consists of calculating the ratio of the standard deviation *DR* for each component y_i of the sample, as shown in ***Equation 1***; subsequently, it is compared with a standard rate DR_0, obtained in ***Table 2***, where:

$$DR = \frac{y_i - \bar{y}}{S} \quad (1)$$

Component y_i will be rejected if $|DR| > DR_0$ or maintained if $|DR| \leq DR_0$. If component y_i is rejected, it will be removed from the sequence, and then the values are recalculated. This procedure can be applied once to remove questionable results [21].

Analysis of variance by hypothesis testing

Analysis of variance was performed by hypothesis testing, as described in ***Equations 2*** and ***3*** to verify whether the characteristics of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester are equal or different from the other ones with 50%-recycled-polyester/50%-cotton. ***Equation 4*** shows the ratio calculation *F* and ***Equation 5*** the rejection region of hypothesis H_0.

Hypothesis testing of the variances:

$$H_0 : \sigma_1^2 = \sigma_2^2 \quad (2)$$

$$H_1 : \sigma_1^2 \neq \sigma_2^2 \quad (3)$$

Test statistic: $$F_0 = \frac{S_1^2}{S_2^2} \quad (4)$$

Rejection region of H_0:

$$F_0 > F_{\alpha/2, n_1-1, n_2-1}, \text{ or if}$$
$$F_0 < F_{1-(\alpha/2)\, n_1-1, n_2-1} \quad (5)$$

Confidence interval (1 - α) = 95%

Thus,

$$H_0 \text{ is true } \therefore \sigma_1 = \sigma_2$$

The population variances, though unknown, are equal to:

$$\sigma_1^2 = \sigma_2^2 = \sigma$$

Difference between the two means

This analysis was performed to verify whether the mean values of the fabrics of different conditions produced are equal or different. These types of planning results are obtained from experiments performed in a random way, without an exact definition of the influence variable or its analysis limits.

Equations 6 and ***7*** show hypothesis testing for the difference between the two means using t-distribution.

Table 2. *Values of DR_0 in function of n [23].*

Number of measures (n)	Standard rate, DR_0
2	1.15
3	1.38
4	1.54
5	1.65
7	1.80
10	1.96
15	2.13
25	2.33
50	2.57
100	2.81
300	3.14
500	3.29

Hypotheses:

$$H_0 : \mu_1 = \mu_2 \quad (6)$$

$$H_1 : \mu_1 \neq \mu_2 \quad (7)$$

Equation 8 shows the statistical test.

$$t_0 = \frac{\bar{y}_1 - \bar{y}_2}{Sp\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (8)$$

The ***Equation 9*** shows the calculation of estimates of the population variance.

$$Sp = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \quad (9)$$

Equation 10 shows the rejection region of H0, and ***Equation 11*** the degrees of freedom.

$$|t_0| > t_{\sigma/2, \upsilon} \quad (10)$$

$$\upsilon = n_1 + n_2 - 2 \quad (11)$$

Thus,

$$H_0 \text{ is true } \therefore \mu_1 = \mu_2$$

Results and discussion

Experimental values of the physical tests of weight, pilling, burst pressure, elasticity and elongation, moisture absorption and dimensional change of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton are presented in ***Tables 3, 4*** and ***5***.

Comparing the results presented in ***Table 5***, the fabrics made with yarns of 80%-polyester/20%-recycled-polyester (grade 5) have a lower tendency than those produced with yarns of 50%-recycled-polyester/50%-cotton (grade 2-3).

The Chauvenet criterion was used to verify the presence of unusual results in the series from tests performed on both types of fabrics produced. In this way, ***Tables 8*** and ***9*** present values of the ra-

Table 3. *Weight (ASTM D 3776 – 96) [11], burst pressure (ASTM D 3786-01) [11] and moisture absorption (JIS 1907 - 02)[18] of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton.*

Fabrics	Tests	Weight, g/m²	Burst pressure, kPa	Transversal moisture absorption, cm	Longitudinal moisture absorption, cm
80%-polyester/20%-recycled-polyester	SP1	171.90	900.00	12.30	14.10
	SP2	174.20	860.00	12.70	14.30
	SP3	168.60	850.00	13.20	14.80
	SP4	170.60	880.00	13.00	13.90
	SP5	167.70	900.00	13.50	14.60
	Average	170.60	878.00	12.94	14.34
	Standard deviation	2.60	22.80	0.46	0.36
50%-recycled-polyester/50%-cotton	SP1	163.30	650.00	1.10	1.70
	SP2	161.10	580.00	1.30	1.00
	SP3	155.00	530.00	1.40	1.40
	SP4	154.50	590.00	1.40	1.50
	SP5	158.80	560.00	1.70	1.50
	Average	158.54	582.00	1.38	1.42
	Standard deviation	3.81	44.38	0.22	0.26

Table 4. *Elasticity and elongation (JIS L 1018-02) [15] of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton.*

Fabrics	Tests	Transversal elasticity, %	Longitudinal elasticity, %	Transversal elongation, %	Longitudinal elongation, %
80%-polyester/20%-recycled-polyester	SP1	93.75	83.33	80.76	46.75
	SP2	91.64	93.55	81.54	40.79
	SP3	87.50	87.10	83.16	40.26
	SP4	91.30	90.91	79.74	42.31
	SP5	91.38	91.67	82.34	48.00
	Average	91.11	89.31	81.51	43.62
	Standard deviation	2.26	4.09	1.33	3.54
50%-recycled polyester/50%-cotton	SP1	77.42	76.39	86.75	39.24
	SP2	74.07	76.92	79.27	33.33
	SP3	82.14	76.39	88.89	35.00
	SP4	75.00	82.19	86.90	41.02
	SP5	74.41	72.86	87.50	36.70
	Average	76.61	76.95	85.86	37.06
	Standard deviation	3.36	3.35	3.78	3.11

Table 5. *Pilling (ASTM D 4970– 05) [13] and dimensional change (NBR 10320-88)[19] of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton.*

Fabrics	Tests	Transversal dimensional change, %	Longitudinal dimensional change, %	Pilling
80%-polyester/20%-recycled-polyester	SP1	0.54	1.98	5
	SP2	0.00	0.00	5
	SP3	0.55	1.94	5
	SP4	*/*	*/*	5
	Average	0.36	1.31	5
	Standard deviation	0.31	1.13	*/*
50%-recycled-polyester/50%-cotton	SP1	1.12	0.00	2-3
	SP2	1.68	0.98	2-3
	SP3	1.12	0.98	2-3
	SP4	*/*	*/*	2-3
	Average	1.31	0.65	2-3
	Standard deviation	0.32	0.57	*/*

tio of standard deviation (DR_{Max} and DR_{Min}) and the standard rate (DR_0) of 80%-polyester/20%-recycled-polyester fabrics.

In a similar way, ***Tables 10*** and ***11*** present values of the ratio of the standard deviation (DR_{Max} and DR_{Min}) and standard rate (DR_0) of 50%-recycled polyester/50%-cotton fabrics.

Applying the Chauvenet criterion to the values presented in ***Tables 6*** and ***7***, the conclusion was that no experimental value should be rejected because all of the calculations resulted in $DR_0 > |DR|$.

Tables 8 and ***9*** present the average, standard deviation, number of test samples, and values of t_0 and $t_{\alpha/2;v}$ to define the rejection area of hypothesis H_0, referring to the characteristics of weight, elongation and elasticity of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and those with yarns of 50%-recycled-polyester/50%-cotton. Hypothesis H_0 is true for all of the characteristics tested. In this way, the weight, horizontal and vertical elongation, and horizontal and vertical elasticity are statistically equal for the confidence interval of 95%.

Tables 10 and ***11*** present the average, standard deviation, number of samples tested, and values of t_0 and $t_{\alpha/2;v}$ to define the rejection area of hypothesis H_0, referring to the characteristics of burst pressure, moisture absorption by capillarity and dimensional change of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton. Hypothesis H_0 is true for the following characteristics: burst pressure and horizontal and vertical dimensional change. The burst pressure and longitudinal dimensional change are statistically equal for a confidence interval of 95%. For transversal and longitudinal moisture absorption by capillarity and for longitudinal dimensional change, H_0 is false, that is, they are significantly different. Thus 80%-polyester/20%-recycled-polyester fabrics are more resistant, have less dimensional change and absorb moisture better by capillarity than 50%-recycled-polyester/50%-cotton fabrics.

***Table 6.** Values of the ratio of standard deviation (DR_{Max} and DR_{Min}), and standard rate (DR_0) of 80%-polyester/20%-recycled-polyester and 50%-recycle-polyester/50%-cotton fabrics.*

Fabrics	Parameter	Weight, g/m²	Elongation, %		Elasticity, %	
			Horizontal	Vertical	Horizontal	Vertical
80%-polyester/20%-recycled polyester	DR_{Max}	1.39	1.24	1.39	1.17	1.04
	DR_{Min}	-1.11	-1.33	-1.11	-0.88	-1.46
	DR_0	1.65	1.65	1.65	1.65	1.65
50%-recycled polyester/50%-cotton	DR_{Max}	1.25	0.80	1.27	1.64	1.56
	DR_{Min}	-1.06	-1.74	-1.20	-0.76	-1.22
	DR_0	1.65	1.65	1.65	1.65	1.65

***Table 7.** Values of the ratio of standard deviation (DR_{Max} and DR_{Min}), and standard rate (DR_0) of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton fabrics.*

Fabrics	Parameter	Burst pressure, kPa	Moisture absorption, cm		Dimensional change, %	
			Transversal	Longitudinal	Transversal	Longitudinal
80%-polyester/20%-recycled polyester	DR_{Max}	0.96	1.22	1.28	0.61	0.59
	DR_{Min}	-1.23	-1.39	-1.10	-1.16	-1.16
	DR_0	1.65	1.65	1.65	1.38	1.38
50%-recycled polyester/50%-cotton	DR_{Max}	1.53	1.45	1.07	1.15	0.59
	DR_{Min}	-1.17	-0.36	-1.61	-0.59	-1.16
	DR_0	1.65	1.65	1.65	1.38	1.38

***Table 8.** Mean values (y_1), standard deviation (s_1), and number of test samples (n_1) of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%cotton.*

Fabric	Parameter	Weight, g/m²	Elongation, %		Elasticity, %	
			horizontal	vertical	horizontal	vertical
80%-polyester/20%-recycled-polyester	y_1	170.60	81.51	43.62	91.11	89.31
	s_1	2.60	1.33	3.54	2.26	4.09
	n_1	5	5	5	5	5
50%-recycled-polyester/50%-cotton	y_2	158.54	85.86	37.06	76.61	76.95
	s_2	3.81	3.78	3.11	3.36	3.35
	n_2	5	5	5	5	5

***Table 9.** Values of t_0 and $t_{\alpha/2;\nu}$ to define the rejection area of hypothesis H_0.*

Parameter	Weight, g/m²	Elongation, %		Elasticity, %	
		horizontal	vertical	horizontal	vertical
t_0	1.76	-1.53	0.60	2.78	0.85
$t_{\alpha/2,n1+n2-2}$	2.31	2.31	2.31	2.31	2.31

***Table 10.** Mean values (y), standard deviation (s), and number of test samples (n) of fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton.*

Fabric	Parameter	Burst pressure, kPa	Moisture absorption, cm		Dimensional change, %	
			horizontal	vertical	horizontal	vertical
80%-polyester/20%-recycled-polyester	y_1	878.00	12.94	14.34	0.36	1.31
	s_1	22.80	0.46	0.36	0.31	1.13
	n_1	5	5	5	5	5
50%-recycled-polyester/50%-cotton	y_1	582.00	1.38	1.42	1.31	0.65
	S_2	44.38	0.22	0.26	0.32	0.57
	n_2	5	5	5	5	5

***Table 11.** Values of t_0 and $t_{\alpha/2;\nu}$ to define the rejection area of hypothesis H_0.*

Parameter	Burst pressure, kPa	Moisture absorption, cm		Dimensional change, %	
		horizontal	vertical	horizontal	vertical
t_0	0.48	66.39	116.98	19.51	1.21
$t_{\alpha/2,n1+n2-2}$	2.31	2.31	2.31	2.78	2.78

Summary and conclusions

In the present study, characteristics associated with aesthetics, durability and ease of maintenance were analysed. The following physical tests were performed on finished fabrics produced with yarns of 80%-polyester/20%-recycled-polyester and 50%-recycled-polyester/50%-cotton: weight, burst pressure, pilling formation, dimensional stability, capillarity water absorption, and elasticity and elongation determination.

The experimental values show that the raw materials selected are suitable for clothing manufacture for all of the characteristics analyzed. However, the fabrics made with yarns of 80%-polyester/20%-recycled-polyester have a lower tendency than those produced with yarns of 50%-recycled-polyester/50%-cotton. In addition, 80%-polyester/20%-recycled-polyester fabrics are more resistant, have less dimensional change and absorb moisture better by capillarity than 50%-recycled-polyester/50%-cotton fabrics. In this way, 80%-polyester/20%-recycled-polyester fabrics could offer better aspect, maintenance and durability in comparison with 50%-recycled-polyester/50%-cotton.

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