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Effect of residual extensibility of polyester filament yarn on low-stress mechanical properties of fabric

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Polyester multifilament yarns having residual extensibility 6.31, 12.50, 18.75, 24.20 and 30.21 % have been manufactured with nearly identical filament and yarn linear density. All filaments yarns are then converted to fabric of nearly same areal density. As the residual extensibility of yarn increases, the bending rigidity of corresponding fabric decreases. The coefficient of friction of fabric samples is higher at both too high and too low residual extensibility but it is found least at 18.75% residual extensibility. Too low and too high residual extensibility is not suitable to produce smooth fabric surface and hence fine optimization of residual extensibility is required. The fabric sample consisting of yarns of 18.75 % residual extensibility shows the maximum total hand value of 4.54, which can be considered excellent for ladies thin dress application on 0-5 scale.

Keywords: Bending rigidity, Compression energy, Linearity, Low-stress mechanical properties, Polyester, Residual extensibility, Tensile energy, Total hand value, Trilobal yarn

1 Introduction

The mechanical properties of textile fibres largely influence the mechanical behaviour of all fibrous substrate, wherein they are incorporated. Among various mechanical attributes of fibres like tensile strength, modulus, torsional rigidity, bending rigidity, surface property and extensibility, some may intimately influence the fabric hand behaviour. Textile fibres are available in a wide range of tensile properties, like high tenacity /low extension such as flex, to low tenacity/high extension such as wool fibre.

The invention of trilobal fibre to mimic the silk motivated to engineer the fibres according to product requirement[1]. Fortunately, the polyethylene terephthalate (PET) fibre is one of the extensively used textile fibres due to its availability with wide variety of properties[2]. The degree of molecular chain orientation and residual extensibility of PET filament yarns are strongly interconnected and its inverse relationship is well established[3]. Fully drawn PET filament yarns are produced by stretching and winding the filament yarn on winder at speed of 5000m/min(ref.4), as suggested by Gowd *et al.*[4]

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As the residual extensibility of filament yarns keeps on decreasing, its utility also shifts from apparel applications to industrial, because most of the industrial yarns have very low extensibility with very high tenacity and modulus; kevlar fibre is one of the industrial fibres.

For shirting fabrics, a low modulus fibre is suitable to offer a best comfortable wear. Matsudaira and Matsui[5] believe that PET fibre is still tagged with poor handle fibre from the point of view of low-stress mechanical properties. Drawing is the process which is primarily responsible for alignment of molecular chains and crystallinity development in fibres. As the fibre drawing takes place its residual drawing possibilities suppresses. From handle point of view, the fibre toughness is important parameter[6], which is related with residual extensibility.

In this study, efforts have been made to explore various possibilities to engineer polyester multifilament yarns in order to produce woven fabrics of better hand value. In one of the approaches, PET multifilament yarns have been produced at different spinning speeds by maintaining the denier per filament and total yarn denier constant to achieve varying residual extensibility of the PET multifilament yarns with trilobal cross-sectional shape and finally woven fabric samples for ladies dress materials are produced. The low-stress mechanical properties and hand behaviour are evaluated using Kawabata evaluation system (KES-FB). The sole objective of this study is to understand the influence of residual extensibility of multifilament yarn on fabric handle, which will help to design a filament yarn of optimum residual extensibility.

2 Materials and Methods

2.1 Trilobal Multifilament Yarns of Different Extensibility

Five different trilobal cross-sectional shape PET multi-filament yarns (50/36/0), manufactured at different spinning speeds 5400, 5100, 4800, 4500 and 4200 m/min (sample code T54, T51,T48, T45 and T42 respectively) by keeping the number of filaments (50) , total yarn denier (36 den) and twist (zero or untwisted) constant (i.e. 50/36/0), were used for this study. The corresponding fabric codes used were TF54, TF51, TF48, TF45 and TF42.

2.2 Sizing and Warping

All five yarns were sized using 5% polyvinyl alcohol (PVA) as sizing ingredient and 0.2% antistatic agent at 40 m/min on SS 565 CCI Tech single end sizing machine.

Single supply package SW 550 CCI Tech warping machine was used to complete the warping at 100 m/min.

2.3 Fabric Manufacturing and Wet Processing

Five different fabric samples were woven using five different yarns of varying residual extensibility (6.31, 12.50, 18.75, 24.20 and 30.25 %) under identical conditions with plain weave (60 ends/cm and 48 picks/cm) with fabric sample code TF54, TF51, TF48, TF45 and TF42 respectively. SL8900s CCI Tech single rigid rapier loom has been used to prepare these fabric samples. Fabric samples have been desized and scoured under identical conditions using 3 g/L non-ionic detergent Lisapol N and 1:30 material-to-liquor ratio at 90°C for 90 min. Areal density used were 70, 68, 71, 71 and 72 g/m^2 for TF54, TF51, TF48, TF45 and TF42 fabrics respectively.

2.4 Tensile Behaviour of Multifilament Yarns

In order to evaluate tensile behaviour, multifilament yarn samples were mounted on Instron tensile testing machine (Instron 4200 series) as per ASTM D-3822-01 standards with special jaw to prevent any slippage during loading and taking specimen length 500mm.

2.5 Birefringence

The fibre diameter was measured in micron and phase difference parallel and perpendicular to fibre axis in presence of compensator was taken from table in nanometres on Leica microscope, as shown below:

$$\Delta n = \frac{\text{Phase difference (nm)} \times 6.18}{\text{Fibre diameter in micron} (\mu\mu \times 1000} \qquad \ldots (1)$$

where Δn is the birefringence value of the fibre.

2.6 Crystallinity and Density

The equatorial scans were then recorded with the help of Philips wide angle X-ray diffractometer using the reflection technique from 10º to 35º. The degree of crystallinity is given by the following expression[7]:

$$\text{Crystallinity (\%)} = \frac{Ac}{Ac + Aa} \times 100 \qquad \ldots (2)$$

where Ac is the area under crystalline region; and Aa , the area under amorphous region. Average of four observations was taken as value of crystallinity in each category.

The density of fibres was measured by density gradient column (Devonport, London) comprising a mixture of n-heptane ($\rho = 1.28$ g.cm^{-3}) and carbon tetrachloride ($\rho = 1.48$ g.cm^{-3}) as per ASTM D-1505 standard. An average of 10 readings was recorded.

2.7 Sonic Modulus and Bending Behavior

The sonic modulus was tested by dynamic modulus tester (Model PPM-SR) manufactured by HM Morgon Inc., Norwood Mass, USA according to the test method suggested by the manufacturer with a sound pulse of longitudinal waves at a frequency of 5 KH_z.

Bending behaviour of yarns was tested on Kawabata evaluation system (KES-FB2 pure bending tester) according to the method suggested by KES manufacturer under optional conditions for yarns/films. The yarns were stack on 20cm long window having 1 cm slit for yarn bending.

2.8 Low-stress Mechanical Properties of Fabric Samples

The fabric low-stress mechanical properties, such as tensile, shear, bending, compression, surface roughness and friction were measured on Kawabata fabric evaluation system (KES-FB).

3 Results and Discussion

Extensibility of fibres is an important physical property which plays a crucial role to decide the low-stress mechanical properties and wearing comfort.

3.1 Structure and Tensile Behaviour of Yarn

Tables 1 and 2 show the relationship of residual extensibility of PET multifilament yarn with some structural parameters of PET trilobal filaments.

The modulus and maximum tensile strength follow a trend which can be explained on the basis of fine structure parameters like birefringence and sonic modulus. It may be observed that as the residual extensibility decreases, molecular chains crystallize in the direction of applied stress (fibre axis) as shown in Tables 1 and 2. With the increase in winding speed or decrease in residual extensibility, birefringence values of the fibres are also increased, which is an indication of increase in overall orientation in both amorphous and crystalline regions. This fact is further supported by sonic modulus data.

The bending rigidity and bending hysteresis of all the yarns are found to increase with fall in residual extensibility. This can be explained on the basis of increasing crystallinity and compactness of constituent filaments in terms of density as shown in Table 2.

3.2 Low-stress Mechanical Behaviour of Fabrics

3.2.1 Tensile Behaviour

Extensibility of fabric at low-stress level (EM) gives the tensile strain under strip biaxial extension. Extensibility has a good correlation with fabric handle. The higher the extensibility, the better is the fabric quality from the handle point of view. A high EM value also signifies greater wearing comfort. Fabric extensibility generally increases with increase in areal density. This implies that heavy fabrics might give better handle property, due to their higher extensibility at low-stress deformation. The extensibility (EM) values of fabrics are shown in Table 3. It may be seen from this table that with the increase in residual extensibility in filament yarns from T54 to T42, the corresponding low-stress extensibility (EM) in fabric samples TF54 to TF42 rise is not significant.

The linearity (LT) is the indication of straightness of stress-strain curve. The small value of LT is the indication of higher fabric extensibility in the initial strain range and this gives higher wearing comfort. The fabric TF54 made of yarn T54 shows highest value of LT which is decreasing with increase in residual extensibility. As the residual extensibility increases from filament yarn T54 to T42, the fabric linearity of extension decreases from 0.90 to 0.79 (14%) and tensile energy (WT) decreases by 33%. It may also be seen that the yarns having higher extensibility show loss in linearity in extension, which is indication of higher wearing comfort. The tensile energy (WT) is a measure of toughness, which also reflects the mobility of the garment under deformation. The tensile resiliency which is a measure of tensile elasticity also follows a descending trend with increase in residual extensibility of corresponding filament yarns, as shown in Fig. 1**.** At this point, it can be inferred that the rise in filament residual extensibility is the cause of fall in LT, WT and RT. Optimum residual extensibility should be selected for the requirement of application specific.

3.2.2 Bending Behaviour

The results of bending behaviour of fabrics are shown in Table 3 and Fig. 2. The bending rigidity (B) is a measure of ease with which fabric bends. Basically, the bending rigidity of fabric depends on the bending rigidity of constituent fibre and yarns from which the fabric is manufactured if fabric constructional parameters kept identical. The fabric

Table 1 — Tensile behaviour of un-sized trilobal filament yarns

Sample code	Strain % at max	Modulus, cN/tex	Birefringence × 10^2	Sonic modulus, cN/tex	Tenacity at max, cN/tex
T54	06.31	805.56	15.14	1042.94	24.31
T51	12.50	781.99	14.72	983.59	23.86
T48	18.75	717.19	14.04	910.11	21.95
T45	24.20	612.27	12.81	812.09	20.53
T42	30.21	524.59	10.11	674.44	19.29

Table 2 — Physical characterization of Trilobal multifilament yarns

Sample code	X-ray crystallinity %	Density g/cc	Density crystallinity %	Bending rigidity $\times 10^{-2}$ g.cm^2/yarn	Bending hysteresis $\times 10^{-2}$ gf.cm/yarn
T54	26.03	1. 3795	37.08	1.19	0.20
T51	23.58	1.3785	36.25	1.15	0.19
T48	23.50	1.3715	30.41	1.09	0.17
T45	23.00	1.3690	28.33	0.87	0.14
T42	20.56	1.3680	27.50	0.69	0.10

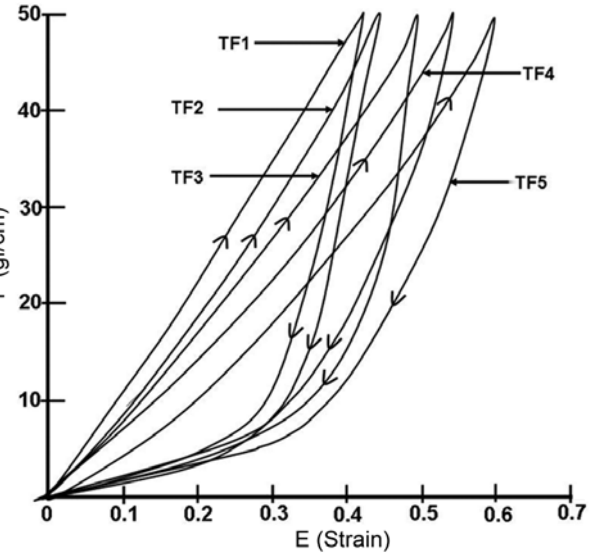

Fig. 1—Tensile behaviour of fabric samples (KES-FB1)

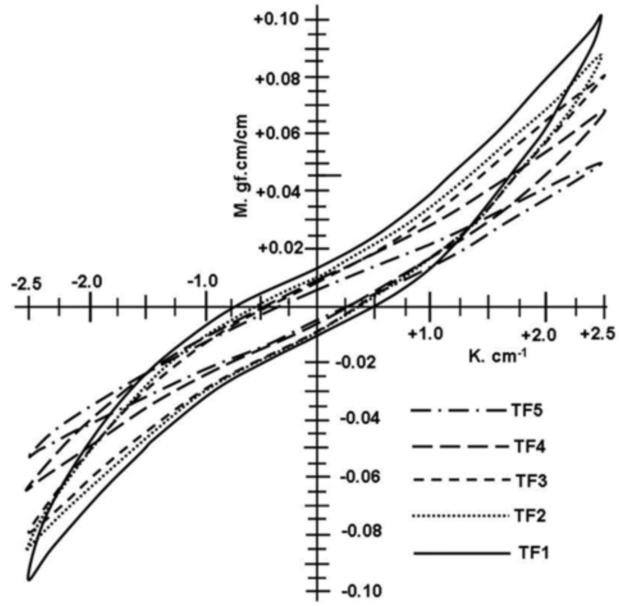

Fig. 2— Bending behaviour of fabric samples

Table 3 — Tensile, bending and shear behaviour of fabric samples

Sample. code	Tensile				Bending		Shear		
	EM	LT	WT	RT	B	2HB	G	2HG	2HG5
TF54	0.42	0.90	3.15	73.89	0.037	0.024	0.773	1.438	3.346
TF51	0.43	0.86	3.05	70.35	0.034	0.021	0.786	1.928	3.758
TF48	0.43	0.85	2.66	69.25	0.033	0.020	0.839	2.293	4.325
TF45	0.44	0.81	2.20	65.27	0.029	0.018	0.414	1.654	3.905
TF42	0.44	0.79	2.10	63.36	0.026	0.018	0.414	1.128	1.678

Table 4 —Surface and compression behaviour of fabric samples

Sample code	Surface properties			Compression properties				
	MIU	MMD	SMD	LC	WC	RC	T	W
TF54	0.119	0.0142	2.59	0.718	0.088	94.85	0.22	6.50
TF51	0.108	0.0131	2.24	0.698	0.090	64.97	0.18	6.25
TF48	0.102	0.0125	1.98	0.628	0.092	63.57	0.18	6.30
TF45	0.107	0.0129	2.23	0.621	0.097	58.82	0.17	6.35
TF42	0.108	0.0138	2.44	0.559	0.104	56.38	0.17	6.05

construction and nature of post weaving treatment given to the fabric are also important factors to influence the bending rigidity of the fabric. It is evident from Tables 3 and 4 that as the residual extensibility of yarn increases from T54 to T42, the bending rigidity of corresponding fabric decreases from TF54 to TF42.

This may be attributed to the fall in crystallinity or rise in amorphous content from T54 to T42 yarns with the corresponding increase in residual extensibility in PET multifilament yarns. The increase in residual extensibility has resulted in fall in overall orientation of molecular chains which is evident from fall in the value of birefringence and sonic modulus (Tables 1 and 2). Similar trend is observed in case of bending hysteresis also as shown in Fig. 2. This can be explained by decreasing trend in sonic and young's modulus by increasing the residual extensibility of filament yarns.

3.2.3 Shear Behaviour

The shear rigidity (G) of a fabric depends on the mobility of cross threads at the intersection point, which again depends on weave, yarn diameter and the surface characteristics of both fibre and yarn. From the point of view of handle, the lower the shear rigidity, the better is the fabric handle. The shear behaviour of fabric samples follows a typical path on which the shear rigidity and shear hysteresis are in increasing order from TF54 to TF48 as shown in Fig. 3.

The fabric samples are treated in water for desizing upto 90 min at 90 ºC. The boiling water shrinkage may be another possible cause along-with residual extensibility for this typical trend. The shear hysteresis (2HG, 2HG5) also follow the similar trend (Fig. 3) as in shear rigidity G (Table 3).

3.2.4 Surface Characteristics

The surface characteristics of a fabric influence the handle, comfort and aesthetic properties of the cloth. The coefficient of friction (MIU) of the fabric surface is a function of fibre properties, yarn structure, fabric geometry and finishing treatment of the fabric. MMD is the mean deviation of the MIU; in other words, it is the measure of variation of MIU. The geometrical roughness of the fabric is represented by SMD. The surface behaviour of fabric samples is mentioned in Table 4. The MIU is higher at both too high and too low residual extensibility but it is least for TF48 and it may be attributed to the fact that too high extensibility possesses extra grip among the filaments and too low extensibility shows insufficient grip among the constituent filaments. The SMD and MMD also show a similar trend from TF54 to TF42. It can be inferred that too low and too high residual extensibility is not suitable to produce smooth fabric surface but optimization of residual extensibility is required.

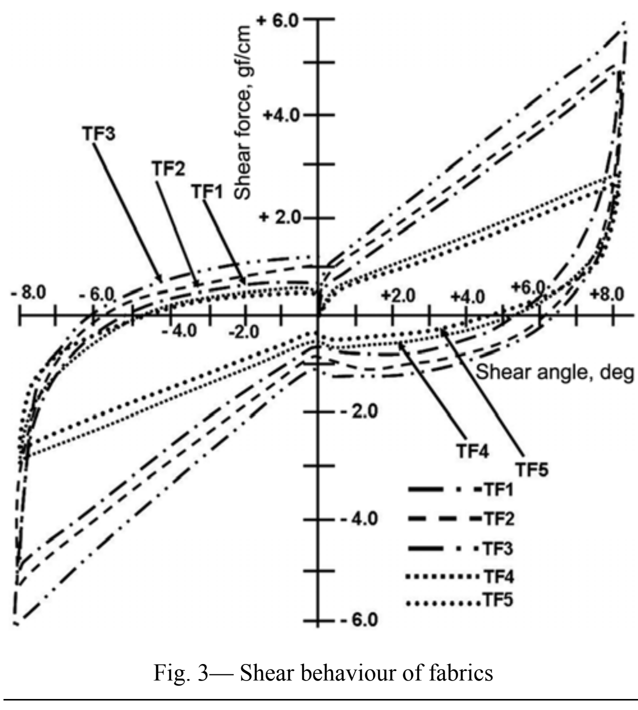

Fig. 3— Shear behaviour of fabrics

3.2.5 Compression Behaviour

The compressibility of a fabric is mainly decided by yarn packing density and yarn spacing in the fabric. During fabric compression, firstly the protruding fibres get compressed in fabric surface, secondly yarns get compressed by movement of constituent fibres and finally the fibres itself get compressed and its cross-sectional shape get changed as described by Matsudaira[8]**.** Compressibility has some intimacy with fabric thickness. The higher the thickness, the higher is the compressibility and it relates with primary hand value like fullness of the fabric.

The higher value of linearity in compression (LC) is the indication of hard feeling in material. The compression behaviour has indicated a relevancy with the filament residual extensibility. The compression behaviour is shown in Table 4.

The linearity in compression (LC) and resiliency of compression (RC) that is elasticity to compression show a decreasing trend with increasing filament yarn residual extensibility. At this stage, it can be inferred that, for high and durable compression the fibre extensibility should be at higher side. The compression energy data indicate that the fabric TF54 made from less extensible filament (T54) has low WC and it increases with the increase in residual extensibility. The TF54 offers the hardest while TF42 has softest feeling among all five studied samples.

3.3 Hand Behaviour of Ladies Thin Dress Material

The hand behaviour of fabric samples for ladies thin dress material is shown in Table 5. The antidrape

Table 5 — Hand behaviour for ladies thin dress material

Sample code	Primary hand value						THV
	Stiffness Y1(koshi)	Antidrape stiffness Y2 (hari)	Fullness Y3 (fukurami)	Crispness Y4 (shari)	Scrrooping feeling Y5 (kishimi)	Flexibility with soft feeling Y6 (shinyakasa)	
TF54	7.08	8.35	2.69	4.25	4.23	3.70	3.90
TF51	7.00	8.06	3.12	3.81	4.15	3.90	3.97
TF48	7.99	8.00	3.25	3.57	1.97	2.18	4.54
TF45	6.91	7.61	3.54	3.32	4.67	4.30	4.33
TF42	6.73	7.14	2.77	3.73	4.75	4.53	4.14

stiffness (Hari) and crispness (shari) show a decreasing trend with rise in residual extensibility of filament yarns. It indicates that the yarn having very low residual extensibility is suitable to offer higher crispy feel in fabric due to its high toughness. The flexibility with soft feeling (shinyakasa) requires further optimization because no clear trend is emerged from limited experimental data. The stiffness of fabric sample shows a mixed trend while fullness of fabric, a complex hand expression which depends basically on fabric thickness, and other mechanical and geometrical aspects of fibre and fabric also show a mixed trend.

The THVs of fabric samples indicate that the optimization of residual extensibility is required. The TF48 fabric shows the maximum THV of 4.54 which is excellent for ladies thin dress application point of view, as shown in Table 5. Both too high and too low residual extensibility have found the lower THV.

4 Conclusion

The residual extensibility of polyester multifilament yarn is an important parameter for fibre manufacturer by which the low-stress mechanical properties can be engineered. In case of ladies thin dress material, 20% extensibility offers highest THV. The following inferences are drawn from this study:

4.1 The bending rigidity and bending hysteresis of yarns having different residual extensibility (T54-T42) increase with decrease in residual extensibility.

4.2 As the residual extensibility of yarn increases, the bending rigidity of corresponding fabric decreases.

4.3 The coefficient of friction (MIU) of fabric samples is higher at both too high and too low residual extensibility but it is least at 18.75% residual extensibility.

4.4 Too low and too high residual extensibility is not suitable to produce smooth fabric surface.

4.5 The fabric sample (TF48) consisting of yarns of 18.75% residual extensibility, shows the maximum THV of 4.54 which can be considered excellent for ladies thin dress application on 0-5 scale. Both too high and too low residual extensibility are found to result lower THV for ladies dress materials.

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