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Elastic recovery of elastomeric-polyester-based staple yarns and filaments

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In this study, a new type of elastomeric fibre based on elastomeric polyester, i.e., poly (butylene terephthalate)-block-(tetramethylene oxide) is used as poly (ether-ester)1, and poly (ether-ester)2 obtained by melt spinning poly (ether-ester)1 with poly (butylene terephthalate). These elastomeric staple fibres are then spun into elastomeric yarns using ring and compact spinning systems. The spun yarns exhibit varying levels of elastic recovery at different fixed elongation levels, depending on the blend ratio. Additionally, filament yarns, including partially oriented yarn, fully drawn yarn and poly (ether-ester) polyester-based filament yarns, are tested using the same fixed extensions for comparison. The elastic recovery obtained is greater than 95% in nearly all cases, meeting the acceptable level for elastomeric yarn production. Other important functional elastic recovery parameters, such as permanent set, immediate elastic recovery, and delayed elastic recovery, are also determined. This study confirms that these elastomeric yarns offer a promising new material for the textile and fashion markets.

Keywords: Compact spin, Elastic recovery, PEE-cotton yarn, Permanent set, Ring spin

1 Introduction

Elastic fabrics are becoming increasingly popular in the fashion industry, available in various specifications to suit multiple applications, such as sportswear, knitted garments, underwear, swimwear, and denim. Fit, comfort, fabric feel, and elastic recovery after body movement are critical in these applications[1]. Comfort and fabric recovery in denim materials, as well as trendy fit, are determined by several factors, including fabric weight, weave type, and so on[2], as well as the number of stretchy fibres and twist multiplier in the blended yarn. It is widely acknowledged that the quality of the feed product directly impacts the quality of the textile materials. Continuous research is carried out to improve the chances of obtaining the desired features. Combining fibres with different inherent physical and mechanical properties allows leveraging the advantages of all the positive effects of fibres in the blend. Spandex (Lycra) fibres are frequently blended with cotton and synthetic fibres to create elastomeric yarns suited to various applications[3,4]. The ability of elastic fibres, yarns, and fabrics to retain their original dimensions with minimal permanent change or without rupture is one of their mechanical properties. Elastic recovery is the name given to this mechanical property. The elastic recovery of materials can be expressed using parameters such as IER (immediate elastic recovery), DER (delayed elastic recovery) and PS (permanent set). IER is a parameter which refers to a textile material's ability to immediately recover its dimensions after deformation when the applied load is removed. The straightening and/or stretching of fibres in the yarn structure is associated with the occurrence of immediate elastic recovery in yarns. DER is the ability of a material to recover from deformation over time. It is a time-dependent recovery. PS is the amount of deformation from which the material cannot recover. The loading limit of a given fibre is critical because a permanent set that occurs when loading exceeds a certain level of force or number of cycles is just as important as material breakage[5]. The effects of various production and testing parameters have been studied[6-8]. Blended elastomeric yarns are almost always made by using elastomeric filaments as the core and various other fibres as the sheath[1,9].

This study determines the elastic recovery and related parameters for novel yarns spun from poly (ether ester) staple fibres developed by the Research and Development Center of Fibre Materials, Chengdu Textile College, Chengdu, China. The study examines

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blended yarns of these fibres with cotton and polyethylene terephthalate (PET) by conventional ring spinning and compact spinning. Additionally, poly (ether-ester) (PEE(D)) yarns, partially oriented yarn (POY) and fully drawn yarns (FDY) are manufactured and tested. The findings reveal emerging new opportunities for developing novel textile fibres and yarns using conventional and new technologies, contributing positively to advancements in material science and technology worldwide.

2 Materials and Methods

2.1 Materials

2.1.1 Production of Elastomeric Fibres

PEE1 is a yarn spun from a new elastomeric poly (ether-ester) (PEE) fibre, produced by melt spinning of block-copolymer poly (butylene terephthalate)-block- (tetramethylene oxide) chips supplied by First Fibre Co. Limited, China. The fibre's thermoplastic elastomer structure included an 80/20 weight ratio of poly (butylene terephthalate) (PBT) as the hard segment and poly(oxytetramethylene) (POTM) as the soft segment.

PEE2 is a yarn spun from a blend of polymer chips, combining poly (butylene terephthalate) (PBT) from Jiangsu Yi Zhen Co. with PEE1 through melt spinning, yielding a fibre with a rubber-like elasticity.

Both PEE1 and PEE2 staple fibres were produced by melt spinning, following the fabrication and technological parameters in accordance with Haile *et al.*[10]. The acceptable quality cotton and PET staple fibres to produce blended yarns were procured from the commodity market.

2.1.2 Production of Filament Yarns (POY1, POY2, FDY1, FDY2 and PEE(D))

Filament yarns were produced using melt spinning at Guangdong Synthetic Fibre Research Institute Co., Ltd. Poly (ether ester) slices with trade name (3F), given by First Fibre Co. Limited, China, is used to produce filament yarns. The spinning temperatures were set at 225-235 °C, with screw temperatures controlled across four zones: 200 °C, 215 ° C, 228 °C, and 230 °C. The box temperature was maintained at 235 °C, and the winding speed was 3550 m/min for both POY and FDY. The POY was drawn 1.5 - 1.6 times.

The PEE production followed specific conditions: slice drying at 150°C for 10 h; vacuum degree: 0.092 MPa; melt temperature in melt spinning: 240°C; tank temperature: 245°C; assembly pressure: 7 MPa and spinning speed: 1100 m/min. Drawing conditions included a second water bath at 60°C, steam stretching and heat preservation temperature of 90°C, a crimp count of 10/cm, and a drawing ratio of 3.91.

2.1.3 Production of Staple Yarns

To produce pure PEE, PEE/PET, and PEE/COT staple yarns, a complete ring spinning line was used, including FB218 carding machine, FA387 drawing frame, A450C roving frame, FA506 ring spinning frame, and JT598 compact spinning machines. The exception was PEE2/PET 50/50, which was spun using a ring frame. Card sliver with a weight of 23.0 g/5 m was used. The roller speed was 300 rpm, the top roller pressure was 392 N, 294 N, and 392 N, and the draft ratio was 6. The twist factor of Roving was 52.9, and sliver weight was 5.0 g/10 m. Break and total draft multiples on the ring frame were set to 34.2 and 1.23, respectively. The EMI4/0 traveller was chosen to minimize hairiness. A self-made laboratory-scale compact spinning machine was used with process parameters similar to ring spinning.

In the winding process, an ESPERO-M winder equipped with an electronic yarn clearer was used to prevent yarn defects. The machine ran at a moderate speed to avoid excessive end breaks, producing medium-sized packages.

In total, eleven elastic staple yarns were produced, with different blend ratios and linear densities (Fig. 1).

2.2 Test Methods

2.2.1 Elastic Recovery Test

This test was carried out using the YG065C yarn strength testing machine (Shandong Laizhou Electronic Instrument Co., Ltd.). The test conditions were as follows: the clamping length for staple yarns was 250 mm and 500 mm for filament yarns. The extension rates were set at 20, 40, 50, 60, 100, 150, and 200 mm/min, corresponding to fixed elongations of 2%, 4%, 5%, 6%, 10%, 15%, and 20%, respectively. Room temperature and humidity were kept at 20°C and 65%, respectively, with a residence time of 3 min for each cycle. Six cycles of stretching and relaxing were performed on the yarn, and the

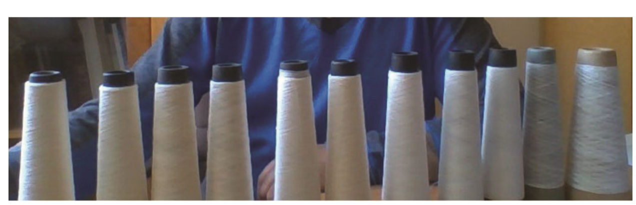

Fig. 1 — Elastomeric staple yarn samples

average result was derived from ten tests. Pretensions were adjusted based on ASTM D1774-79 standards.

The maximum elongation remains constant, and its value was pre-set to the abovementioned values. The pretention Fs, fixed elongation value, fixed elongation residence time t1 (60 s), and recovery time t2 (120 s) were predetermined prior to testing. The clamp dropped at the start of the test to stretch the yarn sample to the pre-set elongation value before returning to the original clamping length. This process repeated across six cycles, and curve AB was traced. The specimen was loaded for 60 s at point B_1 during the final cycle stretch. The internal stress relaxation load of the yarn sample gradually decreased at this point until it reached point C. The load gradually decreased below the pretension line as the lower gripper rose to its original position, the tensile curve went from C to 0 line, and the corresponding point D on the curve was obtained, giving the corresponding elongation L_1. When the lower gripper rose, the yarn relaxed and remained for 120 s. Finally, the bottom gripper descended until it reached the predetermined elongation level. At point E, the curve crossed the Fs line, and the corresponding elongation was L_2. The lower grip then rose to complete the elastic recovery test. Figure 2 depicts the elastic recovery behaviour of yarn during loading and unloading. The elastic recovery parameters were calculated based on the obtained L_1 and L_2. All three parameters were calculated using the total extension.

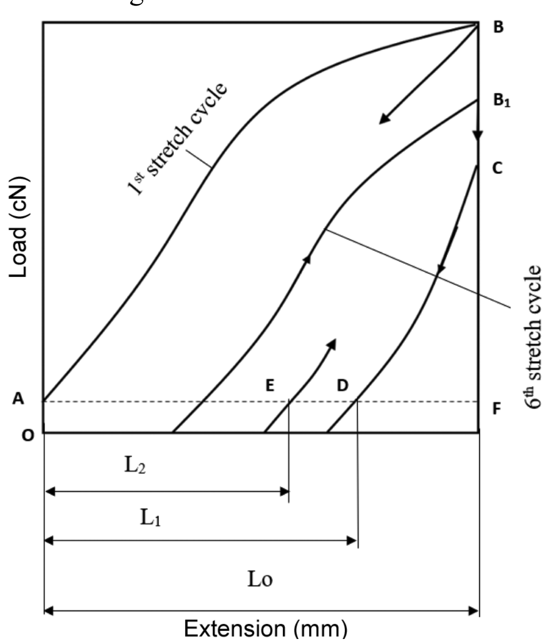

Fig. 2 — Cyclic loading and unloading diagram for measuring elastic recovery

The elastic recovery parameters were calculated using the following equations:

Immediate elastic recovery (%) =

$$\frac{L_0 - L_1}{L_0} X100 = \frac{DF}{AF} X100 \quad \dots (1)$$

Delayed elastic recovery (%) =

$$\frac{L_1 - L_2}{L_0} X100 = \frac{ED}{AF} X100 \quad \dots (2)$$

Permanent set (%) = $\frac{L_2}{L_0} X100 = \frac{AE}{AF} X100$ … (3)

2.2.2 Measurement of Twist

The yarn under consideration was twisted in the "Z" direction, with the twist level calculated according to the ASTM D 1423 standard. The twist was measured using the YG155A twist tester machine, which operated on the "untwisting and then twisting" principle with a load of 20 **cN** and a gauge length of 50 cm. Twists per meter (TPM) were calculated, and ten tests were conducted to determine the average, minimum, maximum, and standard deviation values.

2.2.3 Yarn Unevenness Test

The YG136 yarn evenness tester from Shaanxi Changeling Textile Electromechanical Technology Co., Ltd. was used to assess yarn uniformity. The testing range was 100%, the testing speed was 400 m/min, and the testing time was 1 min 0 s. The results of three tests on each yarn were averaged.

3 Results and Discussion

3.1 Elastomeric Fibres and Filament Yarns

The elastomeric fibres PEE1 and PEE2 are successfully produced and their mechanical and technological properties are found to be satisfactory for further processing. The key properties of these fibres are given in Table 1.

Table 1 reveals that both PEE1 and PEE2, cut to the same staple length of 39.1 mm, have high elastic recovery (>98%) and high elongation at break of 104% and 65%, respectively. Differences in values demonstrate the effect of PBT content in the blend during PEE2 melt spinning. Their elastic modulus of 0.6 cN/dtex and 1.0 cN/dtex, as well as other mechanical properties, make these fibres suitable for conventional processing technologies such as ring spinning. When PET and cotton fibres are blended with high elongation and lower modulus PEE fibres, their low elongation at break and high modulus significantly affect elastic recovery parameters.

Table 1 — Properties of used fibres

Fibre type	Fineness dtex	Staple length mm	Tenacity cN/dtex	Elastic modulus cN/dtex	Elongation at break, %	Elastic recovery at 10% elongation, %
PEE1	1.56	39.1	0.6	0.6	104	> 98
PEE2	2.03	39.1	3.20	1.0	65	> 98
PET	1.56	38	4.94	110	14	>50
Cotton	1.46[1]	30	2.4-2.6	71	5.5	-

[1]*This value is converted from the micronaire value (3.85) measured experimentally*

Table 2 — Elastic filament yarns properties

Filament yarn	Linear density, dtex	Breaking elongation, %	Tenacity, cN/dtex	Modulus, cN/dtex	Number of single filaments
PEE(D)	169	18.84	0.86	9.05	60
POY 1	266.67	62.2	0.81	8.9	48
POY 2	266.67	69.2	0.83	9.2	48
FDY 1	192.22	28.54	1.2	1.3	48
FDY 2	192.22	17.89	1.2	1.3	48

Table 3 — Mechanical properties of elastic staple yarns

Yarn type	Breaking elongation, %	Tenacity, cN/tex	Modulus, cN/dtex	Linear density, tex
PEE1	25.0±5.4	9.6±0.3	2.7±0.6	22.5
PEE2[1]	22.2± 1.5	13.1±0.3	8.5±0.9	22.4
PEE1/PET 60/40	13.3±4.7	6.57±0.5	20.4±2.6	20.0
PEE1/PET 20/80	10.4±0.6	16.0±1.7	21.6±2.4	28.0
PEE2/PET 50/50[1]	13.2±1.3	19.1±2.0	4.8±0.8	17.0
PEE1/COT 20/80	5.58±0.38	16.0±1.2	28.0±1.1	19.0
PEE1/COT 35/65	4.42±0.41	11.6±1.1	23.5±2.7	19.0
PEE1/COT 50/50	5.23±0.57	13.5±1.3	23.5±2.9	14.0
PEE1/COT 55/45	18.8±0.8	7.37±0.9	11.0 ±1.4	20.1
PEE1/COT 65/35	25.68±0.14	7.18± 1.2	10.8± 1.1	19.0
PEE1/COT 80/20	28.6±2.9	7.07±0.9	7.6±1.2	20.0
PET	14.87±0.74	22.0± 1.5	27.9± 1.5	55.5
COTTON[2]	7.06± 0.69	18.4± 1.2	36.8± 0.8	29.2

[1]*This was produced through ring spinning, while the others were produced through compact spinning.*
[2]*The data on cotton yarn was taken from*[11]

Table 2 shows the mechanical properties of continuous filaments PEE(D), POY, and FDY. The breaking elongation of partially oriented filaments POY1 and POY2 is much greater than fully drawn filaments (FDY1, FDY2, PEE(D)). FDY 2 has the lowest breaking elongation at 17.89%. FDY filaments have the same tenacity of 1.2 cN/dtex, which is slightly higher than PEE(D) and POY (0.81-0.83 cN/dtex) and a low modulus (1.3 cN/dtex) compared to POY and PEE(D) (9.05 cN/dtex). This indicates that fully drawn filament yarns have higher strength, modulus, and lower elongation than partially drawn ones.

3.2 Elastic Staple Yarns

PEE1 and PEE2 fibres are blended with cotton and PET fibres, followed by an evaluation of their mechanical and technological properties, shown in Tables 3 and 4.

Table 3 shows that the blend ratio significantly affects the mechanical properties of blended elastic staple yarns. The percentage of unevenness is determined by the yarn structure, twist, fibre properties in the blend, and production conditions. In this case, the difference in mechanical properties due to twist and unevenness is regarded as minor.

Table 4 — Average twist and unevenness of elastic staple yarns

Yarns	Average twist (TPM)	Average CV %	Average Um %
PEE1	664	18.21	15.32
PEE2[1]	729	18.42	14.28
PEE1/PET 60/40	869	17.95	13.94
PEE1/PET 20/80	546	17.76	12.86
PEE2/PET 50/50[1]	452	18.18	14.4
PEE1/COT 20/80	896	17.09	13.21
PEE1/COT 35/65	881	21.99	16.35
PEE1/COT 50/50	859	29.53	22.25
PEE1/COT 55/45	922	26.18	20.15
PEE1/COT 65/35	911	24.84	18.78
PEE1/COT 80/20	905	25.63	16.75

Increasing PEE1 or PEE2 content increases breaking elongation while increasing cotton and PET content raises tenacity and modulus. For example, PEE1/PET 60/40 and PEE1/PET 20/80 have breaking elongation 13.3±4.7% and 10.4±0.6%, tenacity of 6.57±0.5 and 16.0±1.7 cN/dtex, and modulus of 20.4±2.6 and 21.6±2.4 cN/dtex, respectively. Similarly, PEE1/COT 80/20 and PEE1/COT 20/80 have breaking elongation of 28.6±2.9 and 5.58±0.38%, tenacity values of 7.07±0.9 cN/dtex and 16.0±1.2 cN/dtex, and modulus values of 7.6+1.2 cN/dtex and 28.0±1.1 cN/dtex, respectively.

The average twist and unevenness of staple yarns are shown in Table 4. Twist and unevenness levels significantly impact yarn quality in general, and mechanical properties, particularly elastic behavior[12,13]. As the twist level increases, the elastic recovery behaviour of the yarn deteriorates. The optimized twist level is maintained to achieve maximum elastic recovery[14]. The yarn's unevenness is represented as the average coefficient of variation of mass (CV%) and average unevenness (Um%). CV% is a mass variation metric. It is calculated by dividing the average mass variation by the standard deviation of mass variation. A higher CV value indicates that the yarn is more irregular. U% is the average value of all deviations from the mean expressed as a percentage of the overall mean. This is referred to as U% by the Uster company. PEE1/COT 50/50, in this case, shows the highest average CV of 29.53 % and average Um of 22.25 % compared to all other yarns. Various factors influence the degree of unevenness, including the material, manufacturing method, fibre type, and so on. For the given blended yarns linear density and material composition, the obtained values are acceptable[15].

3.3 Elastic Recovery

Figure 3 indicates high elastic recovery across all elastic staple yarns, which decreases with the increase in cotton and PET content. When the fixed extension level is increased to 20%, PEE 1 staple yarn, and PEE(D) filament yarn, recover by 98.88% and 98.17%, respectively [(Fig. 3 (a)]. Even though PEE/Cotton blends and POY multifilament yarns have lower elastic recovery at higher extensions, the obtained elastic recovery is satisfactory. At 20% elongation, POY1 and PEE1/COT 65/35 demonstrated 82.54% and 90.24% elastic recovery, respectively [(Fig. 3 (a)].

Coarse cottons recover from stress less elastically than fine cottons due to their low modulus. Cotton has nearly variety-independent elastic recovery from a given strain. Cotton has no yield point (or, more precisely, no tension or strain). Elastic recovery gradually approaches 0.3. In comparison to other fibres, cotton recovery is minimal. Even minor strains cause significant residual deformation[15]. The elastic recovery response of the current yarns is influenced by the nature of the raw materials in the blend.

Elastic recovery of yarns with relatively lower breaking elongation is tested at fixed extension rates of 2%, 4%, and 6%. Figure 3(b) shows that, except PEE2/PET 50/50, which exhibits higher elastic recovery (98.73, 98.69, 98.64) at 2, 4, and 6% extension, all cotton and PET blend samples exhibit nearly identical behaviour when the fixed extension rate is changed. PEE2/PET 50/50 exhibits no discernible difference in response to an increase in extension rate of 2% to 6%. Maximum elastic recovery of 96.12% for PEE1/COT 20/80 at 2%, 93.29% for PEE1/COT 50/50 at 4%, and 90.92 for

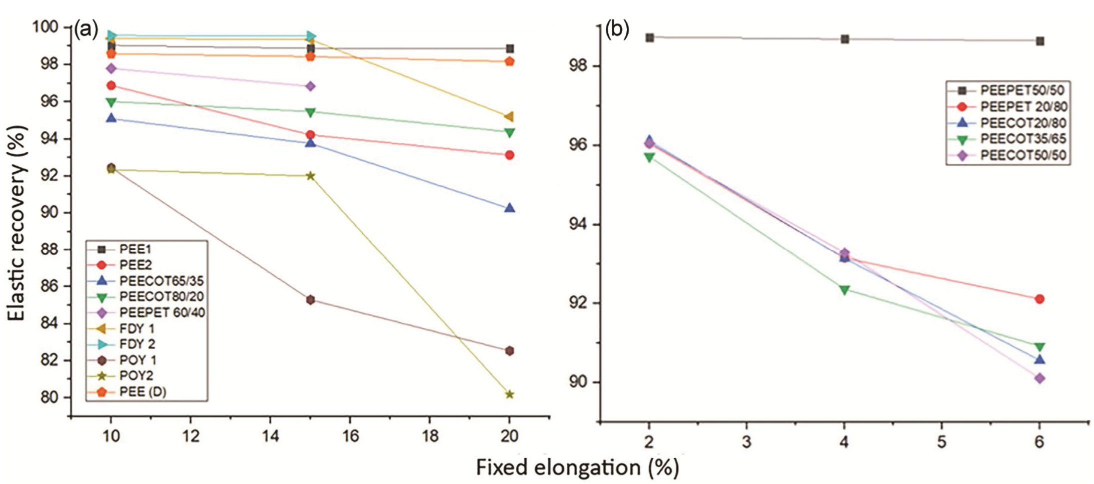

Fig. 3 — Elastic recovery at fixed elongation of (a) 5%, 10%, 15% & 20% and (b) 2 %, 4 % & 6 %

PEE1/COT 35/65 at 6% fixed extensions are recorded. The study shows these yarns' suitability for textile products requiring high elastic recovery. Figures 3(a) and (b) clearly show the elastic recovery behaviour of the under-researched yarns.

3.3.1 Permanent Set

One of the most important elastic recovery parameters is permanent deformation. Several factors, including fibre type, yarn construction, applied force, stress duration, and environmental conditions, influence the degree of permanent deformation. It can result in dimensional changes, a decrease in strength, or a change in the appearance of the fabric in textiles[15]. The results of six cyclic loading-unloading cycles on two groups of yarns, high and comparatively low elongation yarns, are shown in Figs 4 (a) and (b). In comparison to POY1 and POY2 yarns, which have the higher permanent set (17.46 and 19.82) at 20% elongation, FDY1 and PEE(D) multifilament yarns have the lowest results (4.8 and 1.48) at 20% extension, especially as the extension rate increases. Fig. 4 (a) shows that PEE1 outperformed staple yarns by 1.12%. Fig. 4 (b) shows similar results for yarns with short extensibility, except for PEE2/PET 50/50, which had the lowest permanent set at 6% elongation of 1.36%. PEE1/COT50/50 produced a permanent set of 9.89% at a fixed extension of 6%. These findings aid textile technologists in selecting appropriate yarns for various end uses.

3.3.2 Immediate Elastic Recovery

The ability of a yarn to regain its original elasticity is influenced by factors such as fibre type, yarn architecture, tension, and finishing procedures. Yarns with higher elasticity and better elastic recovery properties tend to recover faster. Immediate elastic recovery improves at 15% elongation, reaching around 92%. As illustrated in Figs 5 (a) and (b) PEE1 responds steadily as the extension rate increases.

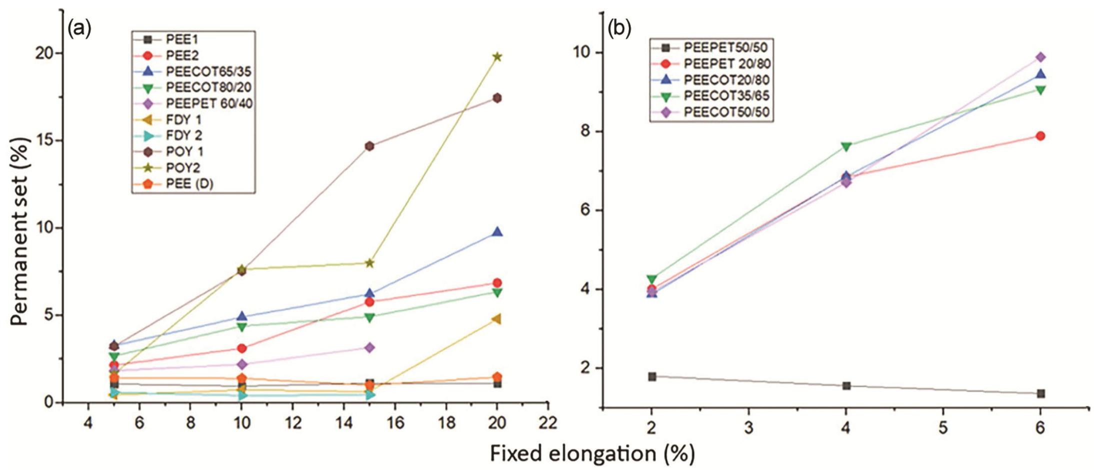

Fig. 4 — Permanent set at fixed elongation of (a) 5%, 10 %, 15% & 20% and (b) 2%, 4% & 6%

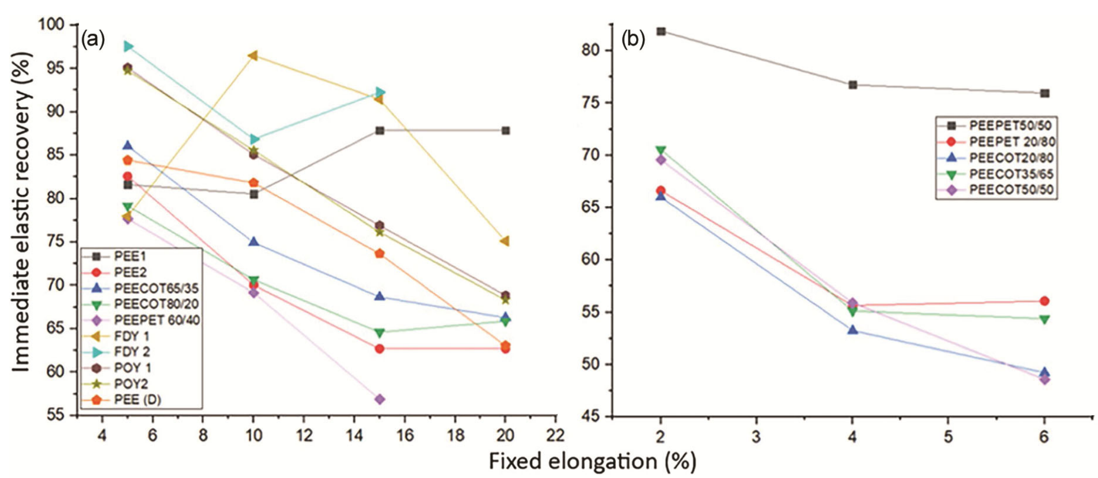

Fig. 5 — Immediate elastic recovery at fixed elongation of (a) 5%, 10%, 15% & 20% and (b) 2 %, 4 % & 6%

Other yarns show a similar pattern, with rapid elastic recovery decreasing as the fixed elongation increases. At 2%, 4%, and 6% elongation, PEE2/PET 50/50 shows relatively higher responses of 81.88%, 76.75%, and 75.96%, respectively, while others demonstrate similar but lower values. For PEE1/COT 50/50, the recovery percentages are 69.56%, 55.91%, and 48.58% at 2%, 4%, and 6% elongation, respectively. One of the reasons could be the lower elasticity of the cotton fibres in the blend.

3.3.3 Delayed Elastic Recovery

The ability of a textile to recover from deformation over time is referred to as delayed elastic recovery. DER is hampered because it takes time for displaced fibres to receive energy from nearby fibres and return to their original positions. Many polymers, including elastomers, have viscoelastic properties and DER. Rubber, for example, is a well-known viscoelastic material that deforms under stress and gradually returns to its original shape. In this study, the PEE fibre used in staple blended yarns demonstrates efforts to improve raw materials with enhanced elastic properties[15,16]. The test results for this elastic phenomenon are shown in Figs 6 (a) and (b).

PEE yarns and blends exhibit greater DER than FDY and POY multifilament yarns. The fact that PEE1 has a delayed elastic recovery decrease at 15% and 20% elongation warrants further investigation. The results suggest that the degree of fixed elongation influences the recovery process.

3.4 Analysis of Variance (ANOVA)

ANOVA was performed to compare the elastic properties among the manufactured yarn samples. All samples showed a statistically significant difference. Table 5 presents the ANOVA for the sample yarns at 5% elongation. However, based on the data shown in the tables and figures above, it is evident that some yarns showed less difference than others in each elastic recovery characteristic. Figure 2 illustrates the elastic recovery of PEE1 and PEE2. Factors for this can be numerous and must be thoroughly investigated in the future; nonetheless, the blending ratios and type of fibres

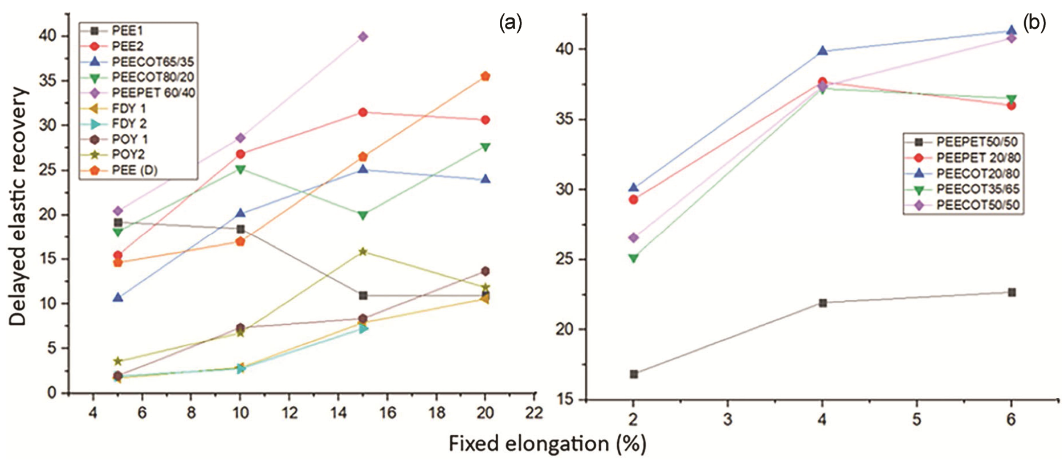

Fig. 6 — Delayed elastic recovery at fixed elongation of (a) 5%, 10%, 15% & 20% and (b) 2%, 4% & 6%

Table 5 — ANOVA for various elastic recovery parameters

Parameters		Sum of squares	df	Mean square	F	Sig.
Immediate elastic recovery, %	Between Groups	16486.574	10	1648.657	50.028	.000
	Within Groups	3262.545	99	32.955		
	Total	19749.118	109			
Permanent deformation, %	Between Groups	16010.375	10	1601.037	167.485	.000
	Within Groups	946.369	99	9.559		
	Total	16956.744	109			
Delayed elastic recovery, %	Between Groups	2480.722	10	248.072	12.690	.000
	Within Groups	1935.252	99	19.548		
	Total	4415.974	109			
Elastic recovery, %	Between Groups	16010.375	10	1601.037	167.485	.000
	Within Groups	946.369	99	9.559		
	Total	16956.744	109			

blended with PEE1 and PEE2 remain among the most significant factors.

4 Conclusion

Elastic yarns have become indispensable in the textile industry, particularly for apparel and sportswear. Elasticity and elastic recovery are essential for clothing comfort or to meet product-specific needs. To achieve these properties, high elastic yarns must be incorporated into the fabric structure. In this study, a new type of elastomeric fibre based on elastomeric polyester, i.e., poly (butylene terephthalate)-block-(tetramethylene oxide), is developed as PEE1 and as PEE2 obtained by melt spinning PEE1 with PBT. Extensive tests investigated the elastic recovery behaviour of elastomeric yarns made from staple fibres and their blends. The results show that most yarns exhibit an elastic recovery of 95% or more. When the tensile strain reaches 10% for the various elastic fibre yarns, the elastic recovery increases to over 95% and continues to exceed 90% when the tensile strain reaches 20%. This high elastic recovery, lacking in many common yarns, provides a solid foundation for future textile innovations and fashion development.

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