Investigating the properties of recycled and virgin poly (ethylene terephthalate) textured yarns: Effect of different blending ratios

S. Özbakış[1,2], A. Aydın[1], P. Terzioğlu[2]*

[1]Polyteks Textile Industry Research and Education Co., Bursa, Türkiye
[2]Bursa Technical University, Faculty of Engineering and Natural Sciences, Department of Polymer Materials Engineering, Bursa, Türkiye

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Nowadays, there is a growing interest in the use of recycled polyester in the textile industry, driven largely by the sustainability goals of the European Green Deal. These environmental objectives have encouraged both researchers and manufacturers to develop more eco-friendly alternatives to traditional textile production. Recycling polyester from post-consumer and post-industrial waste offers significant environmental benefits, such as reducing landfill accumulation and lowering carbon emissions. However, challenges still remain, including ensuring the quality of recycled material and its compatibility with existing manufacturing processes. This study focuses on investigating the blending of recycled and virgin poly (ethylene terephthalate) (PET) to produce textured yarns suitable for textile applications. Understanding how blending ratios influence yarn performance is crucial for promoting the use of recycled materials in mainstream textile production. In this research, different blend ratios of recycled to virgin PET—100:0, 0:100, 25:75, 50:50, and 75:25 (% w/w)—were used to produce yarns. The resulting yarns were tested for their mechanical, thermal, and color properties. The results showed that the blending ratio significantly effects the thermal and mechanical properties of the yarns, such as tensile strength and elasticity. However, the dyeability and color characteristics were not significantly impacted by the presence of recycled content. These findings suggest that incorporating recycled PET into yarn production can be achieved without compromising visual or dyeing quality, making it a promising approach for sustainable textile manufacturing.

Keywords: recycled polyester, recycling, sustainable textiles, textile waste, thermal properties, blending ratio

INTRODUCTION

Nowadays, plastics are a complementary part of modern life that has a wide range of applications including packaging, construction, agriculture, and households [1]. They have some specific advantages including low production costs, low density, corrosion resistance, potential in molding in different shapes and sizes [1-5]. Global plastic production has a 3–4% annual growth which raised from 322 Mt in 2015 to 367 Mt in 2020 [6, 7]. Additionally, it is estimated that the plastic production will be tripled in the next 30 years [8, 9]. However, the rapid growth of the plastic production leads to resource depletion and ecological destruction problems because most of the plastics are generally discarded in landfills or incinerated [10, 11]. Therefore, there is an urgent necessity to recycle and reclaim the plastics [12, 13].

Polyethylene terephthalate (PET) is one of the most widely used plastic especially in textile fibers and food packaging (film, bottles, etc.) applications. From the view of sustainable and zero waste society, PET is considered as an alternative feedstock not a waste (Fig. 1). Accordingly, PET is the most widely recycled and reused non-renewable plastic globally [14, 15]. Including the reduction of the energy and related carbon footprint of textile industry which is known as one of the world's biggest polluters [17]. Recently, the raise in both the number of studies on rPET fibers and the quality of the rPET fiber-based textile products also supports the significance of recycling applications and the evaluation of rPET fibers in the textile sector [19].

In this study, yarns were obtained by texturing different ratios (100:0, 0:100, 25:75, 50:50, 75:25) (% w/w) of rPET and virgin PET partially oriented yarns. The properties of the final samples were investigated by using color, mechanical, thermal and structural tests.

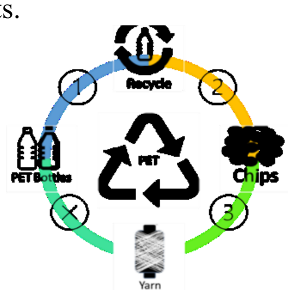

Fig. 1. The cycle of used plastic bottles to become rPET yarn

* To whom all correspondence should be sent:
E-mail: pinar.terzioglu@btu.edu.tr

EXPERIMENTAL

Material

Semi-matte polyester and semi-processed semi-finished polyester chips obtained from INDORAMA Ventures PCL (Thailand) company were used as raw materials. The viscosity of the chips (internal viscosity, IV) is 0.650 dL/g, and the amount of chips per gram is 35 chips/g.

Production of virgin and recycled polyester partially oriented yarn

4 bobbins of partially oriented yarn (POY) and 4 bobbins of rPET POY yarns with the same dtex/filament count feature were produced by melt spinning method using semi-matte polyester and semi- matte rPET chips. Since POY yarns were semi-finished, they are texturized to give the fiber a natural appearance. The operating conditions of the friction texturing machine, used to produce texturized semi-matte POY yarns with different mixing ratios, are shown in Table 1. By texturing POY yarns, 78/72 normal (friction) textured yarns were obtained. Then, POY and rPET POY yarns were 4 times each, rPET POY:virgin polyester POY, in the ratios of 25:75, 50:50, 75:25 % w/w, 4 times rPET POY and 4 times virgin POY, and denier of each is bound to be 300 denier. As a result, 5 pieces of 1 kg 334/288 (dtex/filament number) bobbins were obtained. The yarn samples were named as P1, P2, P3, P4, P5 for 100:0, 0:100, 25:75, 50:50, 5:25 % w/w rPET:PET , respectively (Table 1).

Table 1. Sample codes of yarn samples

Sample code	Blending ratio (rPET: PET)
P1	100:0
P2	0:100
P3	25:75
P4	50:50
P5	5:25

78/72 (dtex/filament count) virgin and recycled semi-matte POY were obtained by melt fiber extraction method using semi-matte polyester and semi-matte rPET chips of filament yarns. The process was carried out at the production unit of Polyteks Textile Industry Research and Education Co. The production speed of rPET semi-dull POY filament yarn is 3000 m/min and the production speed of polyester semi-dull POY filament yarn is 2900 m/min. In the production phase of POY yarns, when the yarn comes out of the nozzle, it comes to the guides and a lubrication process takes place, then it comes to 2 godets and goes around the godets in turn. However, since there is no heating in godets in POY yarn production, the drafting process cannot be fully realized and there is no winding process. The yarn passing through the godets comes first to the centering part and then to the winder, the winder and the last godet are running at the same speed. As a result of these processes, the bobbin winding processes are completed. The obtained values are recorded and the POY yarns are processed into the final product by Polyteks Textile Industry Research and Education Co. The yarns were subjected to texturing process and 334/288 texturized yarns were obtained in the company's own friction texturing machine. The results of texturing tests of 78/72 filament yarns are shown in Table 2. The semi-finished POY yarns and the texturized yarns are shown in Figure 2.

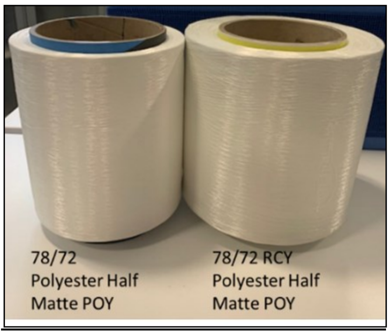

Figure 2. The image of POY yarns

Table 2. Operating conditions of the friction texturing machine

Working conditions of friction texturing machine (AS9-A).	Values
Length (W2) (m/min)	650
Pull (W2/W1)	1.60
Bottom feed (W3)	-3.7
Winding (W4)	-3.2
Winding angle (W5)	32
Disk speed/Yarn speed (W6)	1.80
11 Temperature (°C)	180°C
12 Temperature (°C)	-
Take-up program	55
Oil revolution (rpm)	1.1
Disc combination	1-6-1
Aggregate type	6 mm polyurethane (S-Z-S)
Pressure (bar)	0.3
Type of jet	H.Slide (P203)
Jet zone	Oven
Wx	-2

Bobbin dyeing process

The produced 334/288 (dtex/filament number) textured yarns were sent to Sintas company within the body of Taşdelen Group. Two processes were applied in Sintas company. First, by using a transfer machine, (200 m) 100 g were taken from each of the 5 bobbins, and were turned into a single bobbin (1000 g). The second process is the dyeing process, applied to the resulting bobbin. Bobbin dyeing process was performed in a bobbin dyeing machine from 50°C to 90°C at a speed of 3°C/min, 90°C to 100°C at a speed of 1°C/min, 110°C to 120°C at a speed of 1°C/min, 120°C to 130°C at a speed of 5°C/min and waited for 45 min at the last temperature of 130°C. B.TFBL (1.0 g) was used as a dyestuff. Afterwards, a washing process was started and the dyed bobbin was washed for 20 min at 80°C with the appropriate chemical in a single bath. The last step, the rinsing process, took 20 min at 50°C and the process was completed. The dyed bobbin was divided into 5 equal bobbins by the transfer machine in the twisting unit a speed of 500 m/min and 200 g of yarn was wound on each bobbin at Polyteks company. These coils were correctly numbered according to the order in which they were assembled. Each of the numbered dyed coils was released into the air until they weighed 180 g. Each of the coils given to the air was tested for strength in the STATIMAT brand test device at the laboratory, and then 2 color charts were knitted from each of the coils. Spectrophotometric measurements of the knitted color charts were performed with the X-rite spectrophotometer at the laboratory unit of Polyteks company.

Characterization

- *Characterization of filament yarns.* According to the TS 244 ISO 2060 standard, the weight (yarn number) of the determined length of the yarn was calculated. The tension of 100 m of yarn, which is passed through tension and yarn adjustment guides and tied to the spinning wheel, was determined as 0.051 g/dtex. This process was repeated 5 times for each of the 5 yarn samples. Yarn strength tests were carried out in the STATIMAT brand test device according to the DIN EN ISO 2062 standard. In this device the distance between the clamps is 500 mm, the test speed is 400 mm/min and the pre-tension value is 0.051 g/tex [20, 21]. The results were expressed as mean and coefficient of variation (Table 3).

Table 3. Results of texturing tests of 78/72 filament yarns

Texturation position number	Dtex	Elongation at break (%)	Tenacity (cN/dtex)	Oil
1:3	358.8	21.3±4.4	3.7	1.6
2:2	354.4	23.2±7.7	3.7	1.9
3:1	358.0	21.5±9.4	3.6	1.8

According to the bonding ratios of the POY yarns, they were first sent to the laboratory, their dtex values were measured, then weighed on a precision scale, then oil measurements were made in the Oxford device, and then yarn strength tests were carried out in the STATIMAT brand test device. Afterwards, the bobbins were sent to SİNTAŞ company and were made into a single bobbin (1000 g) in a certain order in the transfer machine (200 m from each bobbin) and then bobbin dyeing was performed. The dyed bobbin was received and separated into 5 different bobbins in order by the transfer machine in the twisting unit of Polyteks.

Yarn strength tests were applied to the 5 bobbins obtained at the laboratory unit with STATIMAT brand test device. Then, the color charts were knitted from each coil and the color charts were measured in CIELAB color space in the X-rite spectrophotometer device. The process steps are described in detail below: In addition, yarn evenness was investigated using an Uster Tester (Uster Technologies, Switzerland) according to the ASTM D1425/1425M.

Characterization of textured yarns

- *Differential scanning calorimetry (DSC).* Thermal analyses of the yarns were carried out in the HITACHI 7020 DSC device according to the ISO 11357-7 standard. Analysis parameters were studied between 30-300°C with 10°C/min temperature increase. The weights of the samples varied between 6-10 mg [22].
- *Characterization of dyed filament yarns.* According to the TS 244 ISO 2060 standard, the weight (yarn number) of the determined length of the dyed yarn was calculated. The tension of 100 m of yarn, which is passed through tension and yarn adjustment guides and tied to the spinning wheel, was determined as 0.051 g/dtex. This process was repeated 3 times for each of the 5 yarn samples. Yarn strength tests were carried out in the STATIMAT brand test device according to the DIN EN ISO 2062 standard. In this device the distance between the clamps is 500 mm, the test speed is 400 mm/min and the pre-tension value is 0.051 g/tex.

Measurements were made on the color charts in CIELAB color space with the X-rite spectrophotometer device at the laboratory unit of

Polyteks. The CIELAB color system is developed from the XYZ color system. This method is used to calculate the color difference between a specified standard color and a sample color. L*: is the luminance value, the axis perpendicular to the color space, 0º for black and 100º for white, it changes between these two values, the higher the L* value, the brighter the color. a* and b*: are chromatic coordinates, in CIELAB color space +a* indicates red direction, -a* indicates green, +b* indicates yellow and -b* indicates blue. Measurements were made 3 times on the charts and the color chart number 5 was taken as a reference (100% PET) [20, 21, 23]. Additionally, the whiteness indices were calculated according to Equation (1) [24, 25].

$$\text{Whiteness index} = 100 - \sqrt{(100-L^*)^2 + a^2+b^2} \quad (1)$$

RESULTS AND DISCUSSION

The results of the experimental studies on the properties of recycled and virgin POY textured yarns as well as the effect of different mixing ratios are given below.

Properties of filament yarns

Table 4 shows the mechanical properties of POY yarns. The evenness, dtex number and tenacity of the yarns were similar. The elongation at break of rPET yarn was found to be slightly lower compared to the virgin PET yarns. The cross-sections of the yarns are shown in Figure 3.

Table 4. Mechanical properties of POY yarns

	Dtex/F[a]	Dtex	Elongation at break, (%)	Tenacity (cN/ dtex)	Evenness	K/C[c]
rPET	78/72	138.7	121.6±2.6	2.5	0.82	52.7
PET	78/72	138.8	124±2.8	2.4	0.83	63.4

[a]F: number of filaments, [c]K/C: shrinkage

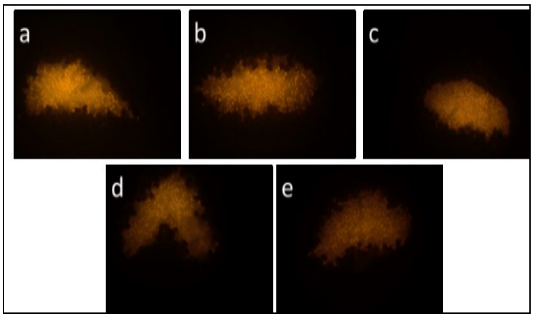

Figure 3. Images of the cross section of the yarns: a.P3 b. P4, c.P5, d. P1 e. P2

Thermal properties

The thermal properties of the yarns were determined using DSC. DSC curves of yarn samples are given in Figure 4. In DSC curves, the endothermic peaks of the fibers showed similar shapes. The melting temperatures of rPET and virgin PET were determined as 247.9 and 253.9 °C, respectively (Table 5). The melting temperatures of the blended yarns were close to that of virgin PET. The melting temperature of the blended yarns decreased with the increased rPET ratio.

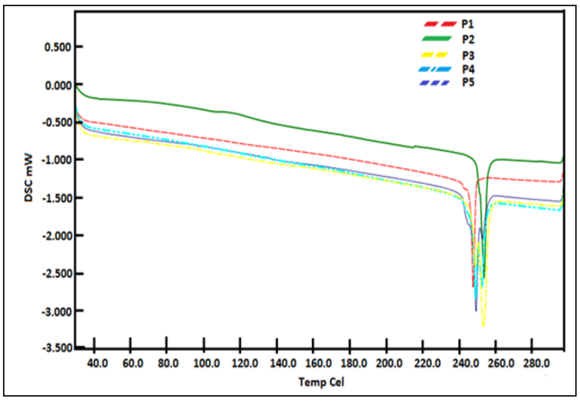

Figure 4. DSC curves with overlapping of the yarns samples. (DSC thermograms)

Table 5. Thermal properties of yarns from DSC

Sample	Blending Ratio of rPET: PET (%w/w)	Heat storage capacity (Cp) (mJ/mg)	T_m (°C)
P1	100:0	5.33	247.9
P2	0:100	3.55	253.9
P3	25:75	6.58	253.6
P4	50:50	7.42	249.1
P5	75:25	7.95	249.6

Mechanical properties of textured undyed and dyed yarns

Comparison of mechanical results of textured undyed and dyed yarns are shown in Table 6**.** Apparently, the dyed yarns have higher dtex value than the undyed ones. The elongation at break of undyed yarns were ranged between 17.13 – 23.21 %, while dyed samples were ranged between 24.35 - 29.15 %. The elongation at break of rPET yarns were lower than the virgin PET yarns. The elongation at break of both undyed and dyed yarns were reduced with the increased rPET ratio as expected.

The undyed virgin PET fiber (P2) have higher tenacity than that of undyed rPET fiber (P1). The tenacity of neat rPET (P1) and PET (P2) yarn found to be 3.57 and 3.78 cN/dtex, respectively. The undyed blended sample that have higher virgin PET ratio (P3) showed the highest tenacity (3.87 cN/tex). This increase was supposed due to the higher tenacity of PET fibers than rPET fibers [26].

Color of dyed textured yarns

The effect of blending ratio on the color characteristics of the yarns is shown in Table 7. Also, the visual appearances of the yarns are shown in Figure 5. There is not any apparent variation in dyeability between different PET yarns as a function of blending ratio. The blending ratio lead to very small changes in color coordinates. When the dyeability of the yarns is compared, it is seen that the L* values are as P3>P5>P4>P1>P2, while +a* and -b* values determined to be P1>P2= P3> P5> P4 and P2=P3>P1>P4>P5, respectively.

Table 6. Comparison of mechanical testing of textured undyed and dyed yarns

Sample code	Blending ratio (rPET: PET) % w/w	Dtex/F	Dtex	Elongation at break (%)	Maximum force (cN)	Tenacity (cN/dtex)
P1(undyed)	100:0	334/288	360.5	17.51	1285.43	3.57
P1 (dyed)			380.4	24.35	1302.96	3.43
P2 (undyed)	0:100	334/288	360.7	23.18	1360.51	3.78
P2 (dyed)			398.3	25.34	1314.81	3.30
P3 (undyed)	25:75	334/288	360.8	23.21	1394.92	3.87
P3 (dyed)			380.6	29.15	1376.95	3.62
P4 (undyed)	50:50	334/288	360.4	18.92	1223.37	3.40
P4 (dyed)			380.5	27.96	1337.99	3.52
P5 (undyed)	75:25	334/288	360.5	17.13	1269.19	3.53
P5 (dyed)			380.3	25.90	1278.23	3.36

Table 7. Color coordinates of blue dyed textured yarns

Sample	Mixing content (rpet:PET %w/w)	L*	a*	b*	ΔE	Whiteness index
P1	100:0	37.65	0.98	-41.32	3.12	25.19
P2	0:100	35.38	0.96	-41.41	-	23.24
P3	25:75	38.04	0.96	-41.41	3.46	25.46
P4	50:50	37.78	0.58	-40.95	2.95	25.51
P5	75:25	37.96	0.70	-40.86	2.98	25.71

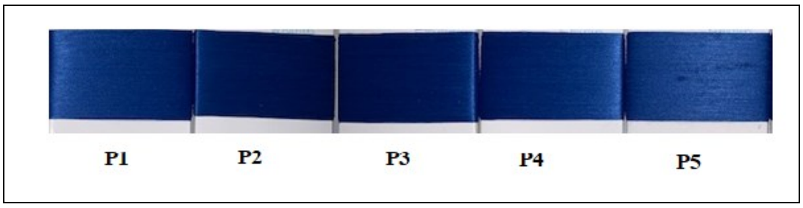

Figure 5. Color charts of dyed yarns

CONCLUSION

Recycled PET-based yarns were blended with virgin yarns to achieve circular economy goals for textile applications. The main conclusions are as follows:

- The blending ratio of rPET:PET showed no apparent effect on the dyeing properties of yarns.

- There was a reduction on elongation at break of both undyed and dyed yarns with the increased rPET ratio.
- Moreover, the melting temperature of the blended yarns slightly decreased with the increased rPET ratio.

This study brings important contributions to development possibility of blended polyester yarns from waste and virgin polyethylene terephthalate showing comparable characteristics with that of the virgin polyester yarns. The production of final yarns can provide environmental benefits due to evaluation of recycled polyethylene terephthalate.

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