

# Spinning Fibers from Poly(ethylene terephthalate) Bottle-Grade Waste

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**ABSTRACT:** Poly(ethylene terephthalate) bottle-grade (BG) waste was converted into spinnable chips and spun on a laboratory-scale melt-spinning apparatus into filaments. Virgin fiber-grade (FG) polyester chips were blended with BG waste during melt spinning so that the influence of blending on the fiber properties could be studied. Subsequently, the scaling-up of the process was carried out in a polyester recycling plant so that staple fibers could be obtained. In this part of the study, the spinning of blends of BG waste and FG waste was carried out. The BG waste was

found to be superior feed stock for melt processing. Fibers with unique properties were obtained from the BG waste. Staple fibers obtained by the blending of FG and BG waste showed properties different from those of fibers spun from BG waste alone. This study also showed that using blends of BG and FG waste could improve the melt processing and staple-fiber properties. © 2003 Wiley Periodicals, Inc. *J Appl Polym Sci* 90: 3536–3545, 2003

**Key words:** fibers; melt; polyesters; recycling; waste

## INTRODUCTION

The first use of polyester [or poly(ethylene terephthalate) (PET)] in packaging was in the 1970s when DuPont developed highly oriented plastic containers from high-molecular-weight polyesters. Since then, factors such as light weight, easy disposability, recyclability, and an environmentally friendly nature have made PET the preferred material for packaging. Presently, a wide variety of products, such as mineral water, soft drinks, and food, are being packed in PET containers, and many more are being added to the list every day. This domination is set to continue unless a high-performance biodegradable plastic is found.<sup>1</sup> However, the increased use of PET has resulted in postconsumer waste in garbage. The accumulation of this nonbiodegradable waste has led to serious ecological problems. However, unlike other plastic waste, PET can be recycled into superior and useful end products. The technology of recycling PET bottles is widely available in the West.<sup>2,3</sup> Presently, neither the technology nor the awareness is available to recycle PET in India. Very little information on the technology is available in the literature. This study has demonstrated how recycled bottle-grade (BG) polyester can be recycled to obtain fibers with unique properties. These fibers have been subsequently used to develop a variety of technical textile products.<sup>4</sup>

Polyester has been used for the production of fibers since the 1950s. However, the properties desired in polyester resins for bottle manufacturing are different. A PET BG resin differs from a fiber-grade (FG) polymer in having<sup>5</sup>

- A higher intrinsic viscosity of 0.80–0.85 (cf. 0.60–0.62 for FG).
- A higher crystallinity.
- A higher opacity.
- A lower residual acetaldehyde concentration of less than 2 ppm.
- A lower cyclic oligomer level of less than 0.5% (w/w).
- The presence of 10–12% of a comonomer, such as isophthalic acid or cyclohexane dimethanol.

Recycling FG polyester waste is well established in India and around the world. Because of the differences in the characteristics, the recycling of waste from PET involves certain additional steps. Wellman is a pioneer in the recycling of these bottles, having adopted direct extrusion technology.<sup>6</sup> The major difference in the processing of BG waste and FG waste lies in the sourcing of the raw material.<sup>7</sup> The FG waste being commercially used is usually from a factory. However, BG waste is available predominantly as postconsumer waste. The postconsumer bottles are invariably soiled and may contain other substances such as polypropylene, paper, and metals. This means recyclers of BG waste have some additional factors to handle:

- Efficient bottle collection systems.
- Separation of other plastics.

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**TABLE I**  
**Spinning Parameters Used for Spinning Blends of BG Waste and Virgin FG Chips on a Laboratory-Scale Spinning Machine**

Sample	Virgin FG chips (wt %)	Densified PET BG waste chips (wt %)	Spinning temperature (°C)	Draw ratio	Denier
1	100	0	279	4	33.4
2	75	25	285	4	32.4
3	25	75	285	4	30.2
4	0	100	287	4	28.1

- Proper washing for the removal of contaminants and so forth.

The technology of PET bottle recycling involves two distinct steps:

- PET bottle collection.
- PET recycling, which can be further subdivided into (1) preparatory processes such as sorting, grinding, washing, and densification and (2) fiber spinning (or molding, etc.) involving drying and crystallizing, melt extrusion, and postspinning operations.

In this work, efforts have been made to characterize BG waste as feed stock for melt spinning, to optimize spinning and drawing conditions for these polymers on a laboratory-scale melt-spinning machine, and to scale-up the spinning process.

## EXPERIMENTAL

### Materials

Presently, the PET bottle waste available in India can be categorized as follows:

- Waste generated at preform manufacturers.
- Waste generated at bottle manufacturers.
- Postconsumer waste.

For our study, clean PET bottle rejects generated in a local bottle manufacturing plant were used. Commercially available FG waste and virgin FG polyester chips procured locally were used for blending with BG waste.

Some of the physical parameters of the bottles collected were as follows:

- Weight range of 35–55 g per bottle.
- Noncolored, transparent bottles.
- Little or no soiling.
- No other contaminant or plastic.

### Preparatory processes

Clear PET bottle rejects were deliberately chosen for the study so that operations such as the sorting of other polymers and washing could be avoided. The first preparatory step was breaking down these bottles into flakes. A plastic-scrap grinding machine (output = 120 kg/h), designed specifically for PET bottle grinding, was used. This was followed by densification, in which ground flakes were converted into irregularly shaped popcorn-like chips. This process was preferred to pelletization because densification was a nonmelting step that would not lead to a loss of intrinsic viscosity.

### Laboratory spinning of PET into filaments

A Bradford University laboratory-scale melt-spinning unit was employed for this study with the following configuration: 200-mL hopper capacity, ram-type extruder, 1–10 cm/min extruder speed, 2000-kg ram pressure, single-hole spinneret type, 20- $\mu$  spinneret dimension, a take-up speed of up to 150 meters/min (adjusted to the draw ratio), and an extrusion temperature of 260–300°C (adjusted as required). The drawing unit had an electric heater and used a variable drawing temperature (up to 200°C).

For the evaluation of the effect of blending virgin FG chips with BG waste on the fiber properties, spinning was carried out in four blend ratios, as shown in Table I. All the samples were dried in a hot air oven at 190°C for 2 h before the spinning. The dried materials were immediately put into the cylinder of a spinning block, and the servomotor-driven ram was lowered. The ram was lowered at higher speeds to facilitate extrusion. Once the filaments started coming out, the ram speed was stabilized at 1 mm/min throughout. The filaments were collected and drawn to specified draw ratios, as shown in Table I.

The filaments, spun from densified BG waste chips without any other component, were further subjected to drawing for the evaluation of the effect of drawing on the fiber properties. Draw ratios of 3 and 4 were achieved in a single step with a drawing temperature

**TABLE II**  
**Drawing Parameters for Filaments Spun from**  
**Densified 100% BG Waste During Laboratory-Scale**  
**Spinning Studies**

Sample	Draw ratio	Denier
1	Undrawn	132
2	3	47.1
3	4	28.1
4	5.1	25.3
5	5.8	21.8

of 80°C. Draw ratios of 5.1 and 5.8 were achieved by the second-stage drawing of samples drawn to a draw ratio of 3 in the first stage. The second-stage drawing was performed at a higher drawing temperature of 105°C and draw ratios of 1.7 and 1.9. The draw ratios used and the corresponding denier values are shown in Table II.

#### Industrial spinning of polyester staple fibers (PSFs)

The preparatory processes followed for the industrial spinning of PSFs were similar to those described previously. The spinning of densified chips was carried out at a local polyester fiber recycler.

Some of the technical details pertaining to the setup were as follows. The drying unit was rotary-screw type with a capacity for material circulation inside; its capacity was 1 ton, its temperature was 195°C, and its duration was 2 h. Screw conveyors transported the material to the hopper of the extruder.

The extruder unit was a 74-mm screw extruder with a length/diameter ratio of 30, a screw speed of 54 rpm, six zones, and a throughput of 75 kg/h. The screen changer was a double-filter mesh (40 mesh/in.) The number of holes in the spinneret was 600, and the spinneret diameter was 0.9 mm. The extrusion temperature was adjusted as required in the range of 260–290°C, the quenching was performed with a water jet and air, the quenching length was 10 mts, and the winding speed was 680 m/min. The collected bobbins were transferred to a separate drawing and

crimping unit in which batchwise drawing was carried out.

As for the drawing line, the creel capacity was 400, the drawing type was single-stage, the drawing temperature was 85°C, the number of draw rollers was 7 each, and the draw ratio was 4.5. The final bath temperature was 80°C, the crimper type was a stuffer box, the drying temperature was 180°C, and the cutter was a lumen.

The densified BG waste chips were mixed in specified proportions with the densified FG waste chips. The drying of these materials was performed at 195°C for 2 h. Table III indicates the proportions of the two varieties of chips in the blends as well as the spinning temperatures used. The materials after drying were unloaded into the screw conveyor and conveyed to the hopper of the screw extruder. Once the filaments started coming out of the spinneret, adjustments to the temperatures in the individual zones of the extruder were made to stabilize a continuous polymer flow. The quenching of these filaments was achieved with water jets initially, and this was followed by quenching in ambient air. The filaments were then wound into packages of 15 kg each. The tow size was for 600 filaments.

The as-spun, undrawn filaments were then collected and assembled for drawing, finish application, and crimping in a continuous drawing line. The draw ratio was 4.5. The tow was applied with a finish and sent to the stuffer box, in which crimping was performed. The tow was then passed through an annealing section consisting of a set of seven drying chambers and three cooling chambers. Subsequently, the tow was cut into staples on a lumen cutter and formed into bales.

#### Evaluation techniques used for the polymer and staple fibers

Determination of the intrinsic viscosity

For BG PET, the intrinsic viscosity was determined, with a mixture of phenol and 1,1,2,2-tetrachloroethane in a ratio of 3:2 (w/w) as the solvent, with an Ubbelohde viscometer at a temperature of  $25 \pm 0.5^\circ\text{C}$ .

**TABLE III**  
**Spinning Conditions Used for Spinning BG Polyester Wastes in Blends with**  
**FG Polyester Waste on a Commercial Staple Fiber Line**

Sample	FG waste chips (wt %)	BG waste chips (wt %)	Spinning temperature ( $^\circ\text{C}$ ) zone						Denier average
			1	2	3	4	5	6	
1	100	0	240	250	255	275	275	260	8.9
2	75	25	240	252	255	280	285	265	9.2
3	50	50	245	255	255	280	285	268	8.8
4	25	75	245	257	258	285	285	270	8.4
5	0	100	248	260	260	286	286	270	8.1

**TABLE IV**  
**Properties of PET Polymers of Different Grades Used in the Study**

Sample	Intrinsic viscosity (dL/gm)	Crystallinity (%)	Melting point <sup>a</sup> (°C)
1 Ground BG waste	0.741	25.46	270
2 Densified BG waste	0.757	45.60	271
3 Densified FG waste	0.584	37.90	265
4 Virgin FG chips	0.627	38.20	267

<sup>a</sup> Determined on hot-stage microscope.

#### Determination of the crystallinity (density method)

A density gradient column was used to determine the crystallinity of the polymeric chips used in the study. Carbon tetrachloride and toluene mixtures with densities of 0.95 and 1.25 g L<sup>-1</sup> were used as the liquids.

#### Determination of the melting point

The melting points for all the polymers used in this study were determined on a hot-stage microscope (Reichert Thermovar, A. Jurgens & Co., Germany).

#### Differential scanning calorimetry (DSC) characterization

The thermal studies on the various polyester feed materials used were carried out on a Mettler TA-4000 (DSC-30, Mettler, USA) thermoanalyzer system. Each sample (7.5–8 mg) was weighed and sealed in the aluminum crucible. It was heated under an atmosphere of N<sub>2</sub> from 30 to 300°C at a heating rate of 10°C/min. An empty aluminum crucible was used as the standard.

#### Denier

The denier determinations of the filaments and fibers were carried out on a Lenzing 400 vibroscope (Lenzing Technik, Austria).

#### Determination of the tensile properties

##### As-spun yarns

A Shimadzu AGS 500-G universal testing machine (Shimadzu Co., Japan) was used for determining the

tensile characteristics of as-spun fibers produced during laboratory-scale studies and industrial trials. The tensile characteristics of the filaments spun on a laboratory scale were also determined with this equipment. The testing was carried out at a gauge length of 101.5 mm and a crosshead speed of 300 mm/min.

##### Staple fibers

The aforementioned equipment was also used to evaluate the tensile characteristics of staple fibers. To increase the accuracy of the results, spring-loaded fiber grips in conjunction with a load cell of 100 gf were used. On the tensile tester, a gauge length of 10 mm and a crosshead speed of 50 mm/min were used.

## RESULTS AND DISCUSSIONS

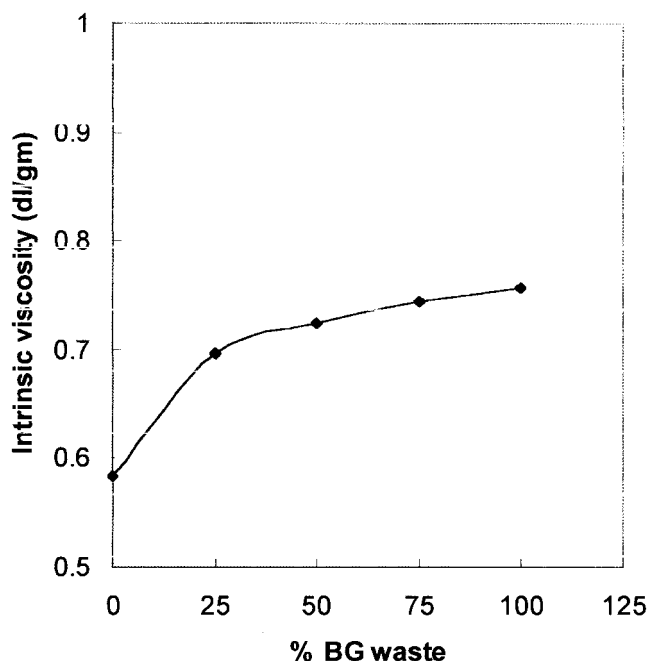
### Characterization of the polymer

PET polymers of different grades were tested for their intrinsic viscosity, crystallinity, and melting point to evaluate their processing behavior. The results are listed in Table IV. The BG waste had a higher intrinsic viscosity than both FG waste and virgin FG chips. Moreover, for the BG waste, densification did not result in a loss of intrinsic viscosity. On the contrary, a marginal increase was observed, which suggested that it was advantageous to use densification instead of pelletization in the preparation of chips for melt spinning. The pelletization step would have resulted in a loss of intrinsic viscosity and consequently led to inferior fiber properties. In addition, the crystallinity of the BG waste increased significantly on densification to a level at which the flow behavior was optimum for melt spinning. BG waste ground flakes had a crystal-

**TABLE V**  
**Thermal Properties of PET Polymers of Different Grades Used in the Study by DSC**

Sample	Onset temperature (°C)	End-set temperature (°C)	Peak melting temperature (°C)	$\Delta H_m$ (J/gm)
1 Ground BG waste	220.0	261.5	249.9	48.4
2 Densified BG waste	211.2	261.9	251.0	51.9
3 Densified FG waste	228.6	271.0	254.6	39.5
4 Virgin FG chips	229.2	266.3	256.9	60.3

$\Delta H_m$ , heat of melting.



**Figure 1** Effect of blending BG waste and FG waste on the intrinsic viscosity.

linity of only 25.46%, which densification increased to 45.6%. Polyester is known to crystallize at different rates over a range of temperatures between its glass-transition temperature and melting point. The temperature during densification may have been in the range of around 110 to 150°C, and this facilitated crystallization.

The intrinsic viscosity and crystallinity for the densified chips from the FG waste were far from optimum, and this indicated their relatively inferior quality as feed stock for melt spinning. Additionally, the intrinsic viscosity of FG waste can be expected to vary highly as the waste is collected from different stages of polyester fiber manufacturing. These factors restrict the use of FG waste to the production of limited-quality fibers for some low-end applications only.

The molecular weight of the BG waste was significantly higher than that of the FG waste and virgin FG chips, as indicated by their high intrinsic viscosity.

Hence, the melting point of these polymers may have been expected to be higher. However, as shown in Table IV, the melting point of the BG chips was only slightly higher. This could be attributed to the presence of a comonomer (isophthalic acid) in them. The presence of the comonomer should have facilitated the melt processability during spinning. The melting point in this case was determined with a hot-stage microscope. To understand the combined effect of a higher molecular weight and the presence of a comonomer on the thermal behavior of BG waste, we carried out a further characterization with DSC. Table V gives a summary of the thermal properties of these polymers determined by DSC. The peak melting points of the BG waste were lower than those of the FG waste and FG virgin chips, and this confirmed the effect of the presence of the comonomer on the thermal behavior of the polymers. Despite the very high molecular weights of the BG polyesters, the presence of comonomers in them ensured that the spinning temperatures did not need to be set very high. Also, polymers from the FG waste and BG waste showed a broad range of melting temperatures in comparison with the virgin FG chips. This may be reflective of a broader crystal size distribution.

One of our objectives in industrial spinning was to improve the process and product conditions of FG waste recycling through blending with BG waste. Figure 1 shows the effect of blending BG waste and FG waste on the intrinsic viscosity. There is a progressive increase in the intrinsic viscosity with an increasing proportion of BG waste in the blend. The initial increase is steep and is followed by plateauing in the latter part. This implies that the incorporation of a small percentage of BG waste in FG waste can affect the melt processability considerably.

From the characterization of the different grades of PET used in this study, it can be observed that BG waste is good feed stock for melt spinning and may be expected to yield fibers with properties superior to those of both FG waste and virgin FG polymers. This may be achieved with slight modifications to the processing conditions.

**TABLE VI**  
Tensile Properties of PET Filaments Spun on a Laboratory-Scale Melt-Spinning Unit

Sample	% BG waste (%)	Draw ratio	Denier	Denier CV (%)	Breaking load (gf)	Stress at break (gf/den)	Stress CV (%)	Breaking strain (%)	Breaking strain CV %	Elastic modulus (gf/den)	Energy (gf mm)
1	0	4	33.4	5.1	116.25	3.481	8.8	34.0	13.1	27.79	3110
2	25	4	32.4	5.5	120.00	3.704	9.4	36.6	19.6	43.62	3357
3	75	4	30.2	4.6	113.75	3.767	8.4	41.4	18.4	46.34	3529
4	100	4	28.1	3.4	116.25	4.137	6.1	63.5	9.2	58.91	3743

The undrawn filament denier was between 132 and 140.

### Laboratory spinning of PET into filaments

Effect of blending BG waste with virgin FG chips during spinning

We performed laboratory-scale spinning to study the optimum conditions required for spinning and drawing and to observe the effect of blending densified BG waste and virgin FG chips. Table VI gives the results of the tensile properties of the fibers produced in various blend ratios. The spinning conditions have been elaborated in an earlier section. Figure 2 shows the effect of increasing the percentage of the BG waste component in the polymer on the stress at break for the spun filaments. Additionally, the effect of the increasing percentage of the BG waste component in the polymer on the coefficient of variation [CV (%)] of stress at break of filaments is plotted on the secondary axis. CV is a measure of variability in the samples. There is a progressive increase in the stress at break of filaments with an increase in the BG waste component in the blend. This may be attributed to the higher molecular weight of the BG polymer, which may facilitate better orientation during spinning, resulting in increased fiber strength. Another interesting aspect is the variation of CV with an increase in the BG waste component in the blend. Initially, CV increases. However, as the BG component further increases, CV drops. A similar trend is shown by the CV of denier, as given in Table VI. The initial increase in CV may be attributed to nonhomogeneity in the polymer properties brought about by the incorporation of another polymer with melt-flow properties different from those of virgin FG polymers. As the BG waste component increases, the melt flow may now be more dependent on the flow characteristics of the BG polymer alone. In addition, fibers spun from 100% BG waste show the lowest CV, and this implies that the BG polymer is more homogenous than even the virgin FG

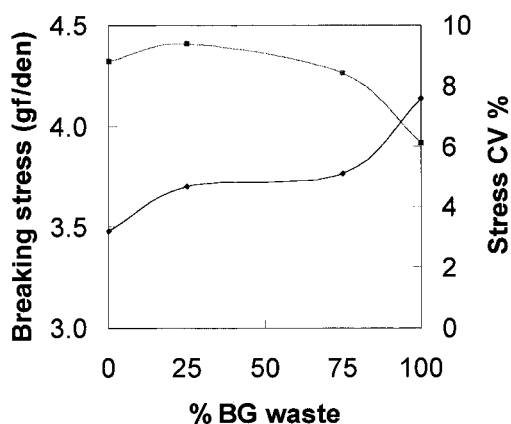


Figure 2 Effect of increasing the percentage of BG waste on (◆) the stress at break of filaments (gf/den) and (■) the stress-at-break CV.

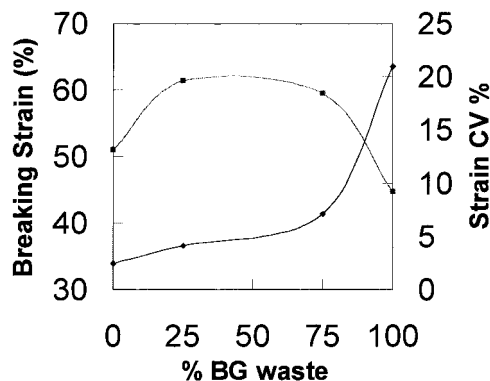


Figure 3 Effect of increasing the percentage of BG waste on (◆) the breaking strain of filaments and (■) the breaking-strain CV.

polymers. This may be in contrast to conventional observations. However, it holds true because the study entails the use of first-hand rejected bottles from a bottle manufacturing plant. It may be expected that predominantly postconsumer waste will not give similar results.

Figure 3 shows the effect of increasing the BG waste component in the polymer blend on the breaking-strain percentage of the spun filaments. The effect of increasing the BG waste component in the polymer blend on the breaking-strain CV percentage is plotted on the secondary axis. The breaking-strain percentage shows a consistent increase with an increase in the BG waste component. This means that the incorporation of the BG waste into the polymer blend results in an increase in both the strength and elongation. This is in contrast to conventional observations that an increase in strength is usually accompanied by a lowering of strain. This may not hold true here because the incorporation of a component of a higher molecular weight also results in improved drawability of the filaments. This may be attributed to the presence of a comonomer. The BG waste polymers used in the study contained 12% isophthalic acid as a comonomer. However, as similar draw ratios were used for even the filaments with higher drawability, they tended to retain higher extensibility. The trends with respect to the variation of CV are similar to the observations made for the effect of increasing the BG waste component on the stress at break. The effect of an increase in the bottle waste component on the elastic modulus and energy (work of rupture) of the fibers is shown in Table VI. Both parameters show consistent increases with an increase in the bottle waste component.

The most interesting observation to be made from Table VI is that the stress at break of fibers spun from 100% PET BG waste polymer was nearly 1.2 times that of the fibers spun from 100% virgin FG chips. The breaking strain for the two fibers in question was nearly double. The combined effect of the two param-

**TABLE VII**  
Effect of Drawing on the Tensile Properties of Fibers from 100% BG Waste

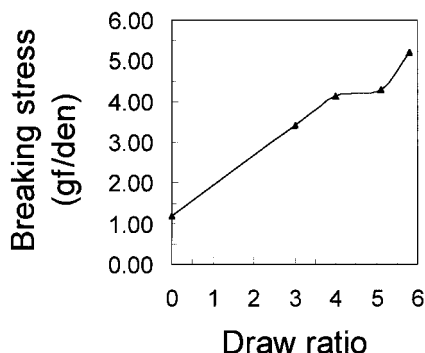
Sample	Draw ratio	Denier	Breaking load (gf)	Breaking stress (gf/den)	Strain (%)	Elastic modulus (gf/den)
1	Undrawn	132	156.25	1.184	530.1	16.34
2	3	47.1	161.25	3.424	200.59	36.45
3	4	28.1	116.25	4.137	63.50	58.91
4	5.1	25.3	108.75	4.298	37.25	71.47
5	5.8	21.8	113.75	5.218	33.98	91.33

eters was reflected in the high energy values for the fibers spun from the BG waste polymer. Therefore, it may be said that fibers spun from BG waste showed a unique combination of high strength and high elongation. The tensile modulus was also high. The study reveals that by the physical blending of BG waste and virgin FG chips, it is possible to obtain fibers with different tensile characteristics.

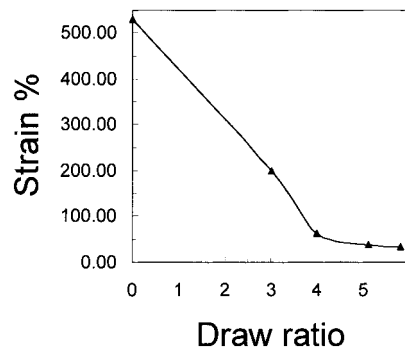
Effect of drawing on the tensile properties of fibers spun from 100% BG waste

It was inferred in an earlier discussion that fibers obtained from 100% BG waste might have higher drawability. In other words, these fibers could be drawn to a higher draw ratio to obtain further improvements in the strength of these fibers. With this objective in mind, we subjected the as-spun fibers obtained from 100% BG waste to draw ratios of 3–5.8, and the tensile properties of the fibers thus obtained are shown in Table VII.

As stated previously, the higher draw ratios of 5.1 and 5.8 could be achieved by two-stage drawing of the fibers. The draw ratio was 3 in the first stage. Figure 4 shows the effect of drawing on the stress at break of fibers spun from 100% BG waste. As the draw ratio is increased, the stress at break increases as expected because of the better orientation achieved. The improvement is substantial at higher draw ratios. The



**Figure 4** Effect of drawing on (▲) the stress at break of fibers spun from 100% BG waste.



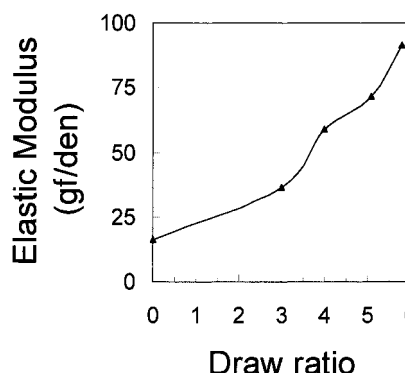
**Figure 5** Effect of drawing on (▲) the breaking strain of fibers spun from 100% BG waste.

fiber drawn to a draw ratio of 5.8 has a stress at break of 5.21, which is 1.5 times that of a fiber spun from virgin FG chips. The effect of drawing on the breaking strain of the fibers is shown in Figure 5. As expected, the breaking strain decreases with an increasing draw ratio. Figure 6 shows the effect of drawing on the elastic modulus of fibers spun from 100% BG waste. The modulus increases progressively with an increasing draw ratio.

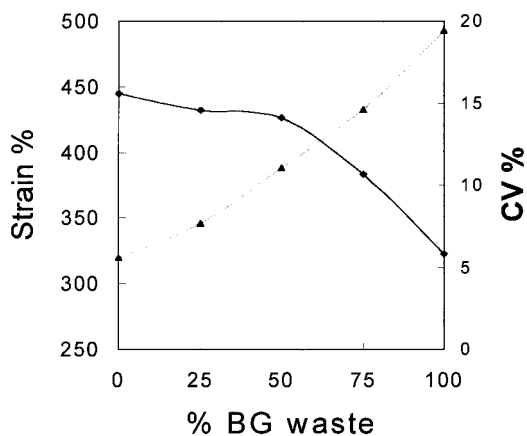
These results indicate that fibers with high strength and high modulus can be obtained from PET BG waste by the optimization of the drawing conditions. The optimization of blending, spinning, and drawing conditions may yield fibers of desired strength and modulus.

Industrial spinning of PSFs

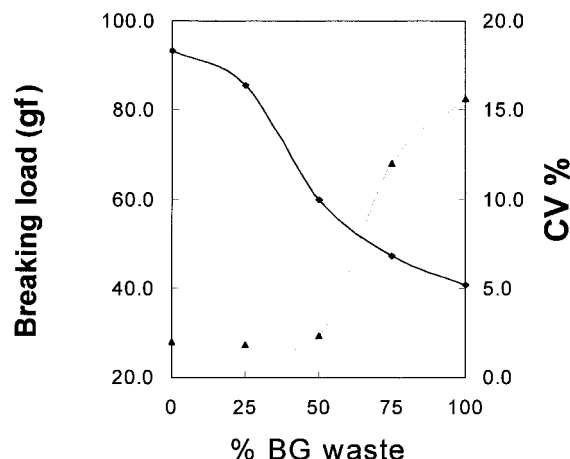
The laboratory-scale studies have indicated how the incorporation of BG waste into blends with virgin FG polyester chips can result in improved properties of the spun filaments. With this background, staple fibers were spun on an industrial-scale plant, which usually recycled FG polyester waste. The objective was to produce staple fibers from 100% BG waste and to



**Figure 6** Effect of drawing on (▲) the elastic modulus of fibers spun from 100% BG waste.



**Figure 7** Effect of increasing the BG waste percentage in polymer blends on the breaking strain of as-spun filaments in industrial-scale trials: (▲) breaking strain and (◆) breaking-strain strain CV.



**Figure 8** Effect of increasing the BG waste percentage in polymer blends on the breaking load of as-spun filaments in industrial-scale trials: (▲) breaking load and (◆) breaking-load CV.

observe improvements in the spinning of FG waste through blending with BG waste. The processing conditions are described in detail in the Experimental section.

Properties of the as-spun fibers

The maximum spinning speed possible during the industrial-scale studies was 680 m/min. The as-spun fibers collected before drawing could, therefore, be termed *lowly oriented yarn* (LOY). The effect of the increase in the BG waste percentage in the polymer blend on the breaking strain of the as-spun filaments is shown in Figure 7. The breaking strain increases with an increase in the BG waste in the blend. For the as-spun filaments from 100% BG waste, it is nearly 1.5 times that of the one spun from 100% FG waste. This implies that the drawability of fibers spun from 100% BG waste is superior to that of fibers spun from FG waste. Moreover, the variability or CV decreases with an increase in the BG waste content. For as-spun filaments from 100% BG waste, it is least, where it is higher for 100% FG waste. These results are largely reflective of the quality of the feed stock. The feed

stock in the case of FG waste is a mixture of fiber, lump, and chip waste collected at various stages of polyester fiber manufacturing and, therefore, results in high variability. In the case of the reject bottles used in this study, the feed stock was more homogenous. Similar trends can be observed for the effect of increasing BG waste content on the breaking load of as-spun filament yarns in Figure 8. The figure implies that it is possible to draw as-spun filaments obtained from 100% BG waste to a greater extent than those from FG waste. These observations on the increased drawability of fibers from 100% BG waste are consistent with observations of filaments spun at the laboratory.

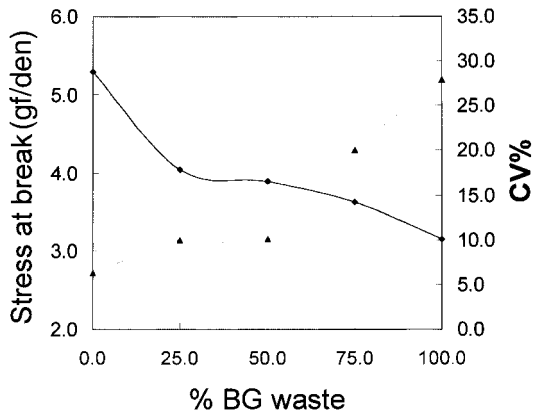
Properties of staple fibers

The aforementioned as-spun fibers or LOY was further processed on a drawing line, as detailed in the Experimental section, and converted into staple fibers. The staple fibers thus obtained were evaluated for their tensile characteristics. The results of the evaluation of the staple fibers are given in Table VIII. Figure 9 shows the effect of increasing BG waste in the blend

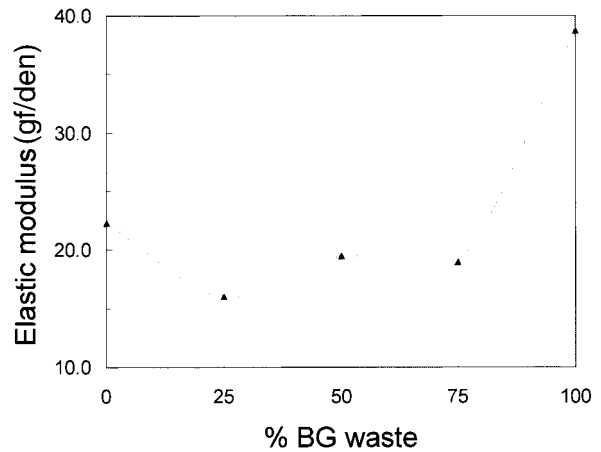
**TABLE VIII**  
Effect of Increasing BG Waste in the Blends on the Tensile Properties of PET Staple Fibers Spun in Industrial-Scale Trials

Sample	Bottle waste (%)	Denier	Denier CV (%)	Breaking load (gf)	Stress at break (gf/den)	Stress at break CV (%)	Strain (%)	Strain CV (%)	Elastic modulus (gf/den)	Energy (gf mm)
1	0.0	8.9	24.6	24.2	2.7	28.8	104.1	30.2	22.3	188.9
2	25.0	9.2	18.9	28.9	3.1	17.8	124.4	18.2	16.1	272.8
3	50.0	8.8	13.4	27.7	3.2	16.6	132.1	17.7	19.5	256.9
4	75.0	8.4	10.2	36.0	4.3	14.3	139.1	13.9	19.0	349.9
5	100.0	8.1	8.9	42.1	5.2	10.1	154.2	10.7	38.7	464.3





**Figure 9** Effect of increasing the BG waste percentage in blends on the stress at break of staple fibers in industrial-scale trials: (▲) the stress at break (gf/den) and (◆) the stress-at-break CV.



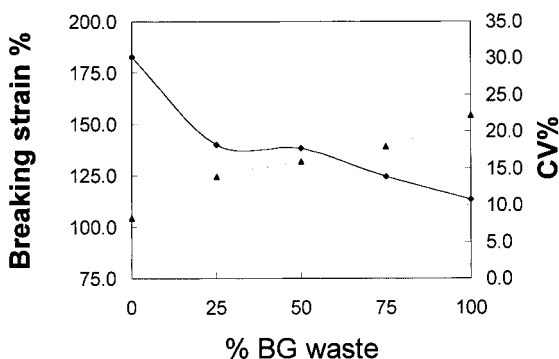
**Figure 11** Effect of increasing the BG waste percentage in blends on the elastic modulus of staple fibers in industrial-scale trials.

on the stress at break for the staple fibers. As the BG waste percentage increases, the stress at break also increases. The variation of CV with the BG percentage is plotted on the secondary axis in the same figure. CV consistently decreases with an increasing BG waste percentage. The breaking strain of the staple fibers also increases with the BG waste percentage, as shown in Figure 10. This trend of increases in both the stress and strain of fibers with an increasing BG waste component in the polymer blends is consistent with our previous observations. This may be attributed to the combined effect of better orientation due to increased molecular weight and better drawability due to the presence of a comonomer. The effects of increasing the BG waste percentage on two other important fiber tensile properties, the elastic modulus and energy (otherwise called the work of rupture), are shown in Figures 11 and 12, respectively. Both show consistent increases with an increase in the BG waste percentage.

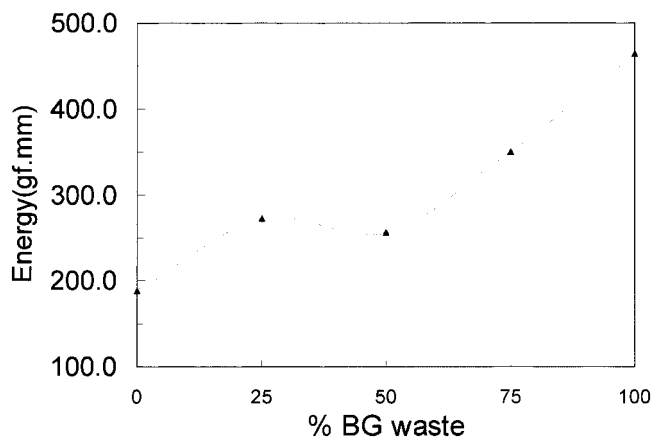
These observations indicate that fibers with a unique combination of high strength and high exten-

sibility can be obtained from 100% BG waste. The BG waste can also be considered a superior feed stock for recycling because the staple fibers produced from it show lower variability than those from FG waste. The higher elastic modulus and energy also imply that the fibers from BG waste can be effectively used in industrial applications as well. Staple fibers obtained from blends of BG waste and FG waste do, however, show properties different from those obtained from pure BG or FG waste.

It follows from these observations that it would amount to a gross underutilization of BG recycled fibers if they were only used for applications in which FG recycled fibers have traditionally been used, such as fiber fills. Subsequent work carried out by the Synthetic and Art Silk Mills' Research Association has demonstrated their utility in a variety of technical textile applications, such as high-bulk blankets, insulation batting, automotive floor carpets, conventional floor carpets, geotextiles, and shoe linings.<sup>8</sup>



**Figure 10** Effect of increasing the BG waste percentage in blends on the breaking strain of staple fibers in industrial-scale trials: (▲) breaking strain and (◆) breaking-strain CV.



**Figure 12** Effect of increasing the BG waste percentage in blends on the energy of staple fibers in industrial-scale trials.

## CONCLUSIONS

This study indicates that polyester BG waste has a higher molecular weight than FG waste and virgin FG polyester. The light-weight amorphous BG waste feed stock can be converted into spinnable chips with grinding and nonmelting steps such as densification. Densification, unlike pelletization, does not result in a loss of intrinsic viscosity. The laboratory-scale spinning studies have indicated that the presence of a comonomer in BG waste ensures that spinning temperatures do not need to be kept high, despite the high molecular weight. The BG waste can be blended with virgin FG chips to bring about improvements in the tensile properties of polyester filaments.

The results of industrial trials have shown that staple fibers obtained from BG waste possess a unique combination of high strength and high extensibility. The variability is also much lower for these fibers. Such fibers can be put to effective use not only in traditional applications but also in technical textile applications previously unknown for recycled fibers. Fibers of blends of FG and BG waste show properties different from those of pure BG waste. The blending of FG waste and BG waste improves the melt processing

of FG waste and the properties of fibers produced from it.

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