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A Comperative Study on the Performance of Side-by-side Hollow Bicomponent Yarns

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ABSTRACT

Using hollow yarns can change and improve many qualities of fabrics including thermal, acoustic, or mechanical properties. Using technical yarns in commercial textile products has been studied extensively to bring them some sort of functionality. In this study, side-by-side 50%/50% bicomponent yarns made from different raw materials were tested and evaluated to determine their processing behaviour and performance characteristics. All yarns have co-polyester (coPET) as one component where the other component is Polyester (PET), recycled PET (rPET) and Polyamide 6 (PA6), respectively. Afterwards, the coPET component is dissolved from all yarns by alkalization, thus making the hollow yarns, and the samples were textured by heat treatment. The mechanical and physical properties were evaluated by various tests, including unevenness, crimp testing, hollow ratio, and shear test. Their thermal and thermomechanical properties were evaluated with Differential Scanning Calorimeter (DSC) analysis and Thermal Gravimetric Analysis (TGA). Also, X-ray Diffraction Analysis (XRD) analysis was carried out in order to observe the crystalline behaviour of the samples. All evaluations were done on the non-textured and textured state of the yarns to see the effect of the heat treatment. The physical and mechanical test results revealed that despite the alkalization, the textured yarns demonstrated better strength and dimensional resistance. DSC and TGA analysis showed that the alkalization and heat treatment caused an increase in the polymer mobilization, which resulted in an increase in the decomposition enthalpy and a lower decomposition temperature. As a final note, XRD results indicated that for the PET/coPET and rPET/coPET samples, the texturization process significantly increased the crystallinity of the samples, which is unexpected and therefore needs further investigation.

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1. INTRODUCTION

The physical properties of textiles are critical for every imaginable sceneario, since they tend to dictate many factors, such as processability, usability, lifetime, etc. Recently, functional materials, such as bicomponent yarns, have been used in traditional and commercial textile products to add a new function or feature to the product. Their unique structures and properties, as well as their modifiability attracts considerable attention. As such, their processing parameters and final properties are being extensively studied [1]. Bicomponent fibers are manufactured by pumping two different polymers from different channels into the same nozzle. By changing the nozzle head, bicomponent fibers with different shapes and different ratios can be manufactured. These fibers can then either be spun into yarns, made into nonwovens, or used in

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other materials such as a reinforcement material in composites. Depending on the chemical composition of the polymers, the components can be connected by only physical means and not due to a chemical reaction of some sort. This allows for neither polymer to lose its intrinsic properties. This property of bicomponent materials makes them a popular material to be used and researched, since the final product will carry the properties of both materials. The components can also be chemically bonded if the two polymers are compatible with each other, in that case the interface between the components can be utilized in order to strengthen the material [1].

In terms of the shape, bicomponent fibers can be classified into four main categories: side-by-side, shell/core, islands-in-the-sea, or segmented-pie type. Side-by-side type bicomponent fibers are made by extruding two polymers with different shrinkage or viscosity values next to each other. Their biggest advantage is that they can be used to create a permanent crimp on the material, imitating a wool yarn. When subjected to some type of heat treatment or stretching action, the mechanical difference between the two polymers causes a permanent crimp on the fiber. By adjusting the polymer type, the drawing temperature and the drawing ratio, crimp levels as high as 42% can be achieved [2]. In shell/core type fibers, the two polymers are fed individually, and the “shell” or the “sheath” part completely covers the “core” part. These fibers are mainly used to take advantage of both components; the shell part gives the visual or handle properties such as luster, dyeability, or or thermal insulation whereas the core part gives mechanical properties such as high strength, stability, or it can be used to decrease the cost of the material for commercial or mass-produced products. Due to the composite-like structure of a bicomponent fiber, they can be made into a nonwoven and then mixed into a resin without the need of an additional binding agent. This has the advantage of not only eliminating a step for speeding up the production in an industrial setting, but also decrases the production cost altogether [3]. In a different approach, both components can be utilized to make a high-performance product. For example, researchers have made a poly (vinyl pyrrolidone) (PVP) and poly (D,L-lactide) (PLA) shell/core bicomponent fiber by utilizing coaxial electrospinning method. The final product had a lower tensile strength and a higher water uptake level than pure PLA. With PLA being a biodegradable polymer, the final product can be utilized to load bioactive molecules for drug delivery and tissue regeneration applications [4]. Islands-in-the-sea type is composed of a component called the islands, distributed inside the sea component [1]. In this type, the island segments inside the fiber can be dissolved in order to create a ultrafine yarn, which is highly utilizible. This type of fiber is commonly used to manufacture hollow yarns by removing one of the components. Such a fiber has been utilized in making a needle-punhched nonwoven which is then made into a filtering bag. The resulting product had a superior tensile strength, bursting strength and dust-removal efficiency than some of the commercially available products on the market [5]. In a different approach, researchers made a nonwoven sheet using a Polyamide-6 (PA6) as the island and polyethylene (PE) as the sea bicomponent fiber and then dissolved the sea component after the hydroentanglement. The resulting material had up to 25% weight loss after the dissolution of the sea polymer. Also, since the removal of the sea component enhances the fibrillation of the remaining component, the sound absorption coefficient of the nonwoven web has increased as the number of islands increase. This can be utilized to make a lightweight, cheap, and bulky acoustic application material [6]. In the segmented-pie type, two polymers that are not compatible with each other are extruded together and then rapidly cooled down to mold it into a shape that resembles a pie chart [1]. This can again be utilized to make a hollow fiber or an ultrafine fiber for different applications. A polyester/polyamide 6 segmented-pie bicomponent fiber is made into a leather base by making it into a nonwoven to be used in artificial leather production. Comparing the final product with the commercial artificial leathers in terms of their air permeability, water vapour permeability and thermal insulation proved that the nonwoven has superior properties. This is not only a cheaper alternative for the apparel industry, but also a more sustainable method of producing artificial leather and a more ethical approach to real leather [7].

Bicomponent yarns can also be manufactured as hollow yarns by using two materials with different melting temperatures or different thermal/hydrogsopic properties, spinning it into a yarn, and then melting the polymer with the lower melting point afterwards or dissolving one of the components by means of a heat or water treatment either after spinning or in the fabric form. Neutral fibers such as cotton or wool can also be made into a hollow yarn by using the neutral fiber as a sheat with a generally water-soluble polymer in the middle (such as PVA), then subsequently removing the core part by a water treatment. This increases the bulkiness of the yarn with decreasing its weight at the same time [8]. Also, the air gap in the middle acts as a major insulator that increases the thermal and acoustic properties of the yarn. Using hollow yarns in the structure enhances many properties, such as yarn strength, thermophysiological comfort, moisture and air permeability, and sound absorption[9, 10]. Previous study comparing fabrics knitted with 100% cotton fiber versus a hollow cotton fiber show that fabrics with a hollow cotton fiber show better permeability, absorbency, wicking, drying and thermal resistance properties. In both studies, the hollowness of the cotton yarns is achieved by spinning a cotton & poly (vinyl alcohol)(PVA) yarn with PVA in the core, and subsequently dissolving the PVA. [11, 12]. Another study found that the mechanical strength of a hollow cotton yarn is the same as the conventional cotton yarn but it has a better elongation, while being softer and bulkier at the same time [13]. Aytac and Gurkan Unal (2018), produced hollow yarns with cotton, viscose, wool, and polyester as the sheath and PVA in the core, with different sheath-core ratios. The hollow yarns, regardless of the material in the sheat, have shown better comfort properties and decreased pilling tendency. Also, it is found that air and water vapour permeability levels can be increased in all cases by adjusting the sheath-core ratio accordingly [14].

Also, bicomponent fibers and yarns open the road for a more greener approach, where a recycled material can be combined with a high-performance material in order to maintain its superior property while still being a more sustainable alternative [15]. Recycled PET (rPET) has been redrawn with a nano-structure titanium dioxide (nano-TiO2) to make an antibacterial bicomponent multifilament yarn as a commercial potential to make antibacterial carpets. Here, the rPET allows for repurposing PET water bottles and bringing the necessary tensile properties whereas the TiO2 provides the antibacteriality [16]. Textile industry, specifically coloration and printing section is a widely known environmental pollutant. A study made a core-shell type bicomponent fiber by using cotton waste as the core and colored textile waste as the sheet as a mean of creating a more sustainable material. The resulting material showed the same color retency and intensity as a single component regenerated cellulose fiber even though it already has dye material on it. This has the benefit of dyeing this fiber with using less dyestuff in order to achieve the same color effect [17].

It is evident that bicomponent materials are gaining popularity day by day due to their high modifiability and cost decreasing properties and they are rapidly finding themselves applications in commercial areas. In this study, three types of side-by-side hollow bicomponent yarns having different raw materials have been developed and compared in terms of their physical, mechanical, and thermomechanical properties. By doing so, it is aimed to contribute the literature by giving an in-depth study of the mechanical and thermomechanical properties of side-by-side hollow bicomponent yarns manufactured from various source materials. This study also discusses the properties of both textured and nontextured yarns presenting a complete understanding of the impact of heat treatment and alkalization on yarn properties. To our best knowledge, the aforementioned points have not been thoroughly evaluated and discussed in the literature. As a final word, all of the developed yarns are intended to be used in commercial blackout curtain fabrics in an attempt to enhance the sound absorbing quality of the blackouts from bicomponent hollow yarns, in addition to their main function, namely light blocking out.

2. MATERIAL AND METHOD

2.1 Material

Six different bicomponent yarn samples were developed and evaluated by collaborating with the KFS Company operating in Türkiye. The yarns consist of PET/coPET, rPET/coPET, and PA6/coPET in both their nontextured and textured forms, making a total of six samples. Here, rPET denotes recycled polyester and coPET denotes co-polyester. The coPET components were dissolved by alkalization treatment. The properties of the raw materials were given in Table 1, and the compositions of the yarn samples are given in Table 2. All the samples are partially oriented yarns (POY). In the sample coding, samples that have "T" next to them are the textured yarns where the ones without the letter T were not texturized. The yarn counts for the non-textured yarns were taken before the dissolving of the coPET component and they are reduced to the desired yarn count by dissolving them in fabric form afterwards. The yarn counts were tested according to the TS 244 EN ISO 2060 standard and the number of filaments were determined by the firm accordingly to their in-house testing method.

Table 1. Raw material properties

Material	Viscosity (dl/g)	Moisture (PPM)	Melting Point (°C)
PET	0,66	1477,99	252,7
coPET	0,685	1487,27	238,7
rPET	0,709	1572,14	253,6
PA6	2,4	891,42	218

Table 2. Sample properties

Sample ID	Composition	Yarn Count (DN)	Number of Filaments
1	50% PET & 50% coPET	248,48	72
1T	50% PET & 50% coPET	152,52	72
2	50% rPET & 50% coPET	248,48	72
2T	50% rPET & 50% coPET	157,47	72
3	50% PA6 & 50% coPET	251,23	72
3T	50% PA6 & 50% coPET	156,91	72

2.2 Method

The nontextured and textured yarns were tested on their breaking force and elongation at break according to DIN EN ISO 2062, hot air shrinkages according to DIN EN 14621, and fat content by the NMR method. The nontextured yarns were also evaluated on their unevenness according to TS2394 standard and the textured yarns were additionally evaluated on their number of nips and nip stability, which was determined manually, and their crimp contraction and mechanical crimp retentions according to DIN 53840 standard. Their cross-sectional images were taken by Scanning Electron Microscope (SEM). The hollowness ratios of the yarns were determined with the help of a program written on MATLAB from the images taken from the SEM. The images taken from MATLAB program can be found in Figure 1. As it can be seen, the alkalization treatment dissolved the coPET component completely in all samples. The hollowness ratio of the PET, rPET, and PA6 yarns after the coPET has been melted were determined as 24,61%, 18,15%, and 38,03% respectively.

Differential Scanning Calorimetry (DSC) analysis and Thermal Gravimetric Analysis (TGA) were done on all the samples to see the effect of the texturization process on the yarns in terms of their thermomechanical properties, as well as to see the different thermal behaviour of yarns having different raw materials. DSC analysis was carried out using a Perkin-Elmer DSC-4000 device and an average of 3mg of material. For the PET/coPET yarns, the samples were heated from 25°C to 300°C at a heating rate of 10°C/min and then the samples were cooled to 25°C at a rate of 10°C/min. The rPET/coPET yarns were heated from 0°C to 300°C at a heating rate of 10°C/min and then the samples were cooled down to 0°C at a rate of 10°C/min. The PA6/coPET yarns were heated from 20°C to 300°C at a heating rate of 20°C/min and then cooled back down to 20°C at a rate of 20°C/min. TGA was carried out using a TA Instruments SDT Q600 device using an average of 9mg of material. The tests were done in a nitrogen atmosphere with a flow rate of 100 ml/min and all the samples were tested in a temperature range of 0-650°C with a heating rate of 10°C/min.

The crystallization behaviour of the samples was investigated by X-ray diffraction (XRD) with a Bruker D8 ADVANCE device ($\lambda = 1{,}54060$). The 2θ scanning range was 0-55°.

3. RESULTS AND DISCUSSION

The mechanical test results for the nontextured and textured yarns can be found at Table 3.

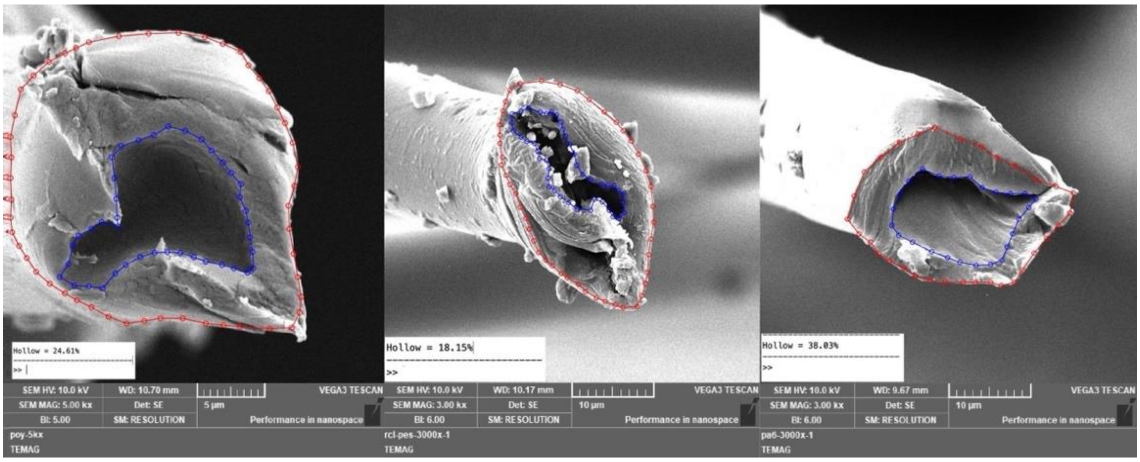

Figure 1. Hollowness ratios of the samples

Table 3. Test results for textured and nontextured yarns

ID	Breaking Force (cN)	Elongation at Break (%)	Boiling Shrinkage (%)	Fat Content	Unevenness (CV%)	Number of Nips	Nip Retention (%)	Crimp Contraction (%)	Crimp Retention
1	1,79	123,4	72	0,457	1,1	-	--	-	-
1T	3,16	22,8	72	1,245	-	80	4646	33,06	53,09
2	1,79	123,4	72	0,457	1,2	-	-	-	-
2T	2,89	25,78	72	1,81	-	52	33	32,59	54,66
3	2,15	131,27	72	0,377	1,02	-	-	-	-
3T	3,86	27,57	72	1,526	-	82	60	27,98	63,24

The textured yarns have better dimensional resistance and improved strength when compared to their nontextured counterparts. The heating during the texturization improves crystallinity and density due to a greater number of immobile polymer chains with less elongation. This enhances strength while decreasing elongation. Alkalization, however, causes a reduction in the fiber diameter which results in lower tensile properties due to finer fibers breaking apart from the structure easily. Nevertheless, the texturization seems to play a bigger role as the breaking force and elongation results show that the textured yarns are stronger than their nontextured counterparts.

The results of the DSC analysis for the PET/coPET sample, rPET/coPET sample and PA6/coPET sample can be found in Figure 2, Figure 3, and Figure 4, respectively. In all the figures, the graph on the top shows the results for the nontextured yarns and the graph on the bottom shows the results for the textured yarns.

DSC analysis performed on the nontextured and textured yarns shows a double-peaked graph, as expected from bicomponent yarns. The melting properties of PET samples are very complex depending on the experimental conditions chosen for the measurements, isothermal temperature or non-isothermal crystallization conditions, thermal history, and heating rate. The observed multiple melting endotherms are a result of the balance between melting and recrystallization and lamella thickness distribution present in the sample prior to heating. The presence of polymelt endotherms as observed with DSC is very common and is observed for many semicrystalline polymers, copolymers, and blends. When two endotherms, I and II, are present, it is confirmed that they are due to the presence of a double lamella thickness distribution produced during crystallization. The peak points of the curves during the heating stage, thus the melting temperatures, of all four of the components were compatible with the polymer properties given in Table 1.

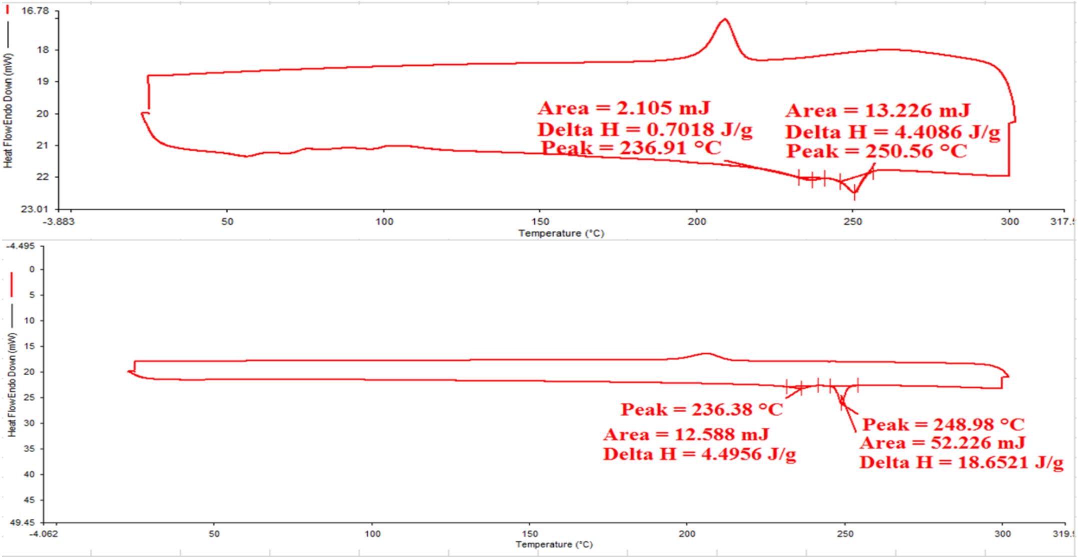

Figure 2. DSC results for nontextured and textured PET/coPET yarns.

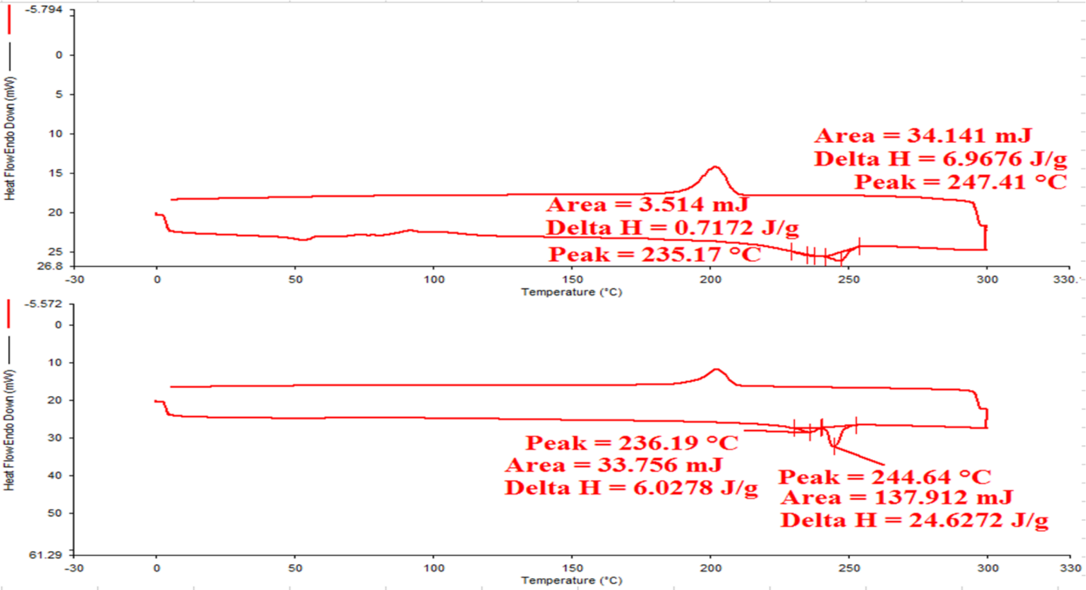

Figure 3. DSC results for nontextured and textured rPET/coPET yarns

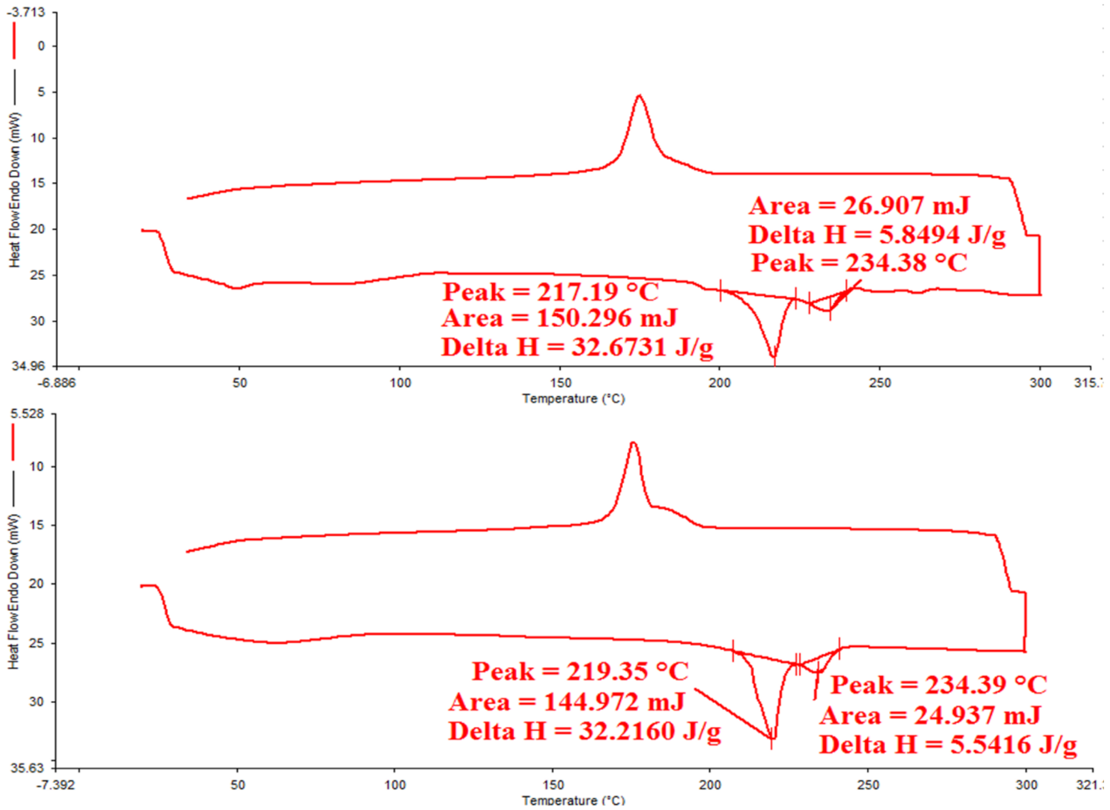

Figure 4. DSC Results for Nontextured and Textured PA6/coPET yarns.

The enthalpy (ΔH) values have had a massive increase for all samples after the texturization. The enthalpy value is dependent on the polymer content of the sample. The heat treatment done by texturization indicates that the texturing process makes it difficult for the fiber to crystallize, which led to an increase in their ΔH values.

The endothermic curves also show different trends. For the nontextured samples, the melting peak is sharper and narrower, but the curve gets wider with the texturization process. The same trend can be observed for the re-crystallization during the cooling stage. Another observation is that for PET/coPET blend, the peak of PET is narrower whereas for the rPET/coPET blend, the rPET has a broader peak. This can be correlated to the thickness difference between PET and rPET materials. PET fibers' melting temperature is higher and is more peaked than rPET fibers. This difference can be attributed to the use of virgin raw materials and the absence of contamination in the PET/coPET sample. The smaller thickness of the rPET fiber crystallites is due to thermo-mechanical deterioration during the recycling and replication stages.

The TGA graphs for the PET/coPET sample, rPET/coPET sample and PA6/coPET sample can be found in Figures 5 to 7, respectively. In all the figures, the graph on the top is for the nontextured sample whereas the graph on the bottom is for the textured counterpart of that sample. The graphs show the weight change of the samples with increasing temperature.

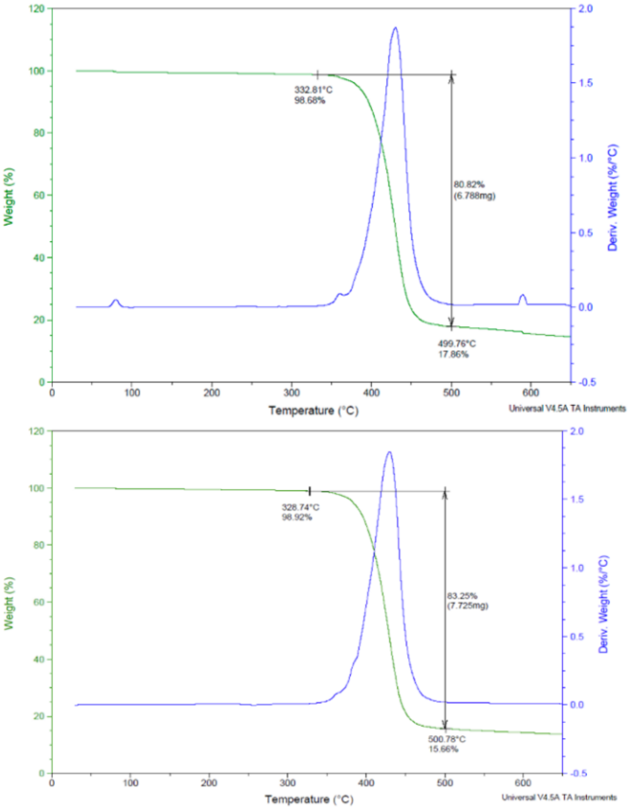

Figure 5. TGA results for nontextured and textured PET/coPET yarns.

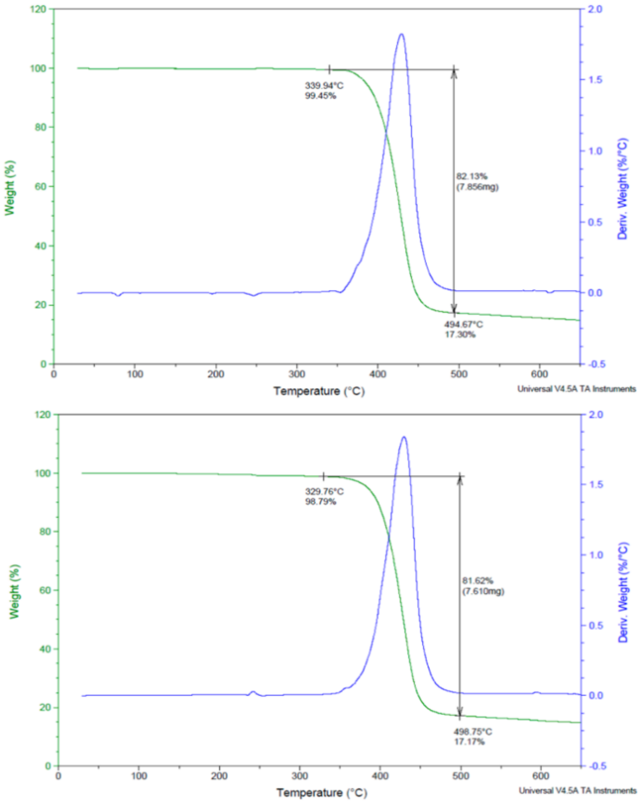

Figure 6. TGA results for nontextured and textured rPET/coPET yarns.

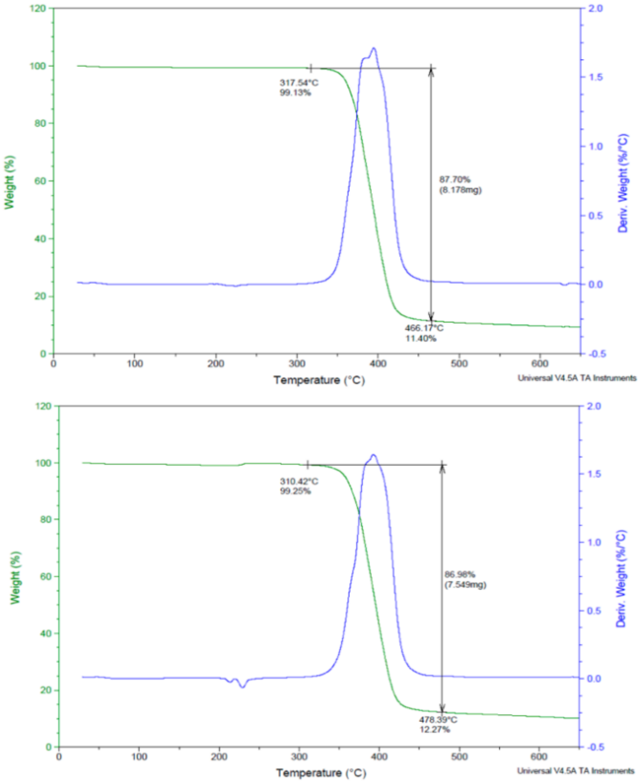

Figure 7. TGA results for nontextured and textured PA6/coPET yarns.

The starting temperature marked in the figures is the temperature at which a sharp drop in sample weight begins. When polymers are heated to sufficiently high temperatures, the weakest covalent bonds in the polymer structure starts to break down and the polymer begins to degrade, which is called the 'decomposition temperature'. Polymers decompose before boiling. As can be seen from all figures, for all samples the materials began to decompose at lower temperatures after the texturization process. The decomposition temperature drops down from 332,81°C to 328,74°C for the PET/coPET yarn, from 339,94°C to 329,76°C for the rPET/coPET yarn, and from 317,54°C to 310,42°C for the PA6/coPET yarn. This may be due to the increase in polymer chain mobility after texturing. In addition, recycled PET showed less weight loss compared to the virgin PET sample, which can be explained by the dampness of the damaged surface of rPET [18]. For the PA6/coPET yarn, in both textured and and nontextured forms, the degredation starts at lower temperatures compared to the PET/coPET and rPET/coPET yarns. This may be due to the fact that PA6 has a lower moisture content, which can be seen from the material properties at Table 1. In TGA analysis, the materials in general initially evaporates the moisture inside it, and then starts breaking down [19]. Since the moisture content of the yarn is also going to be relatively low, there is not much water content in the structure to be evaporated before the decomposition, thus the decomposition can begin at a lower temperature than the other samples.

The crystallinity and amorphism ratios of the samples according to the XRD results can be found in Table 4, and the XRD graphs of the samples are given in Figure 8, Figure 9, and Figure 10 for the PET/coPET sample, rPET/coPET sample and the PA6/coPET sample, in turn. In all of the graphs, the nontextured samples are denoted with “NT” and their textured counterparts are denoted with “T”.

Table 4. XRD results.

Sample ID	Crystallinity (%)	Amorphism (%)
1	1,0	99,0
1T	14,8	85,2
2	0,7	99,3
2T	14,6	85,4
3	12,3	87,7
3T	2,7	97,3

As can be seen both from the tables and the graphs, XRD results indicate that for the PET/coPET and rPET/coPET samples, the texturization process significantly increased the crystallinity of the samples, which is an interesting result. In XRD analysis, an X-ray beam is directed onto the sample in a predetermined angle, and then the reflected scattering of the beam from the sample is measured as a function of the reflection angle. In general, if the sample has a high crystallinity, the diffraction shows as peaks whereas if the graph is smoother without any sharp peaks, the sample has a more amorphous form. But a broadened XRD pattern can also have other causes such as a non-flat material surface, high sample porosity, or a noise in the analysis itself [20]. Nevertheless, the texturization and alkalization parameters should be further investigated and studied in order to see their effect on the crystallization since both processes may affect the polymer structure and the overall yarn behaviour after the coPET component has been removed. Previous studies on the thermomechanical analysis of polymers have proven that heat setting parameters not only drastically effects the crystal and amorphous regions inside the structure, but also effects the mechanical properties of the final yarn as well [21].

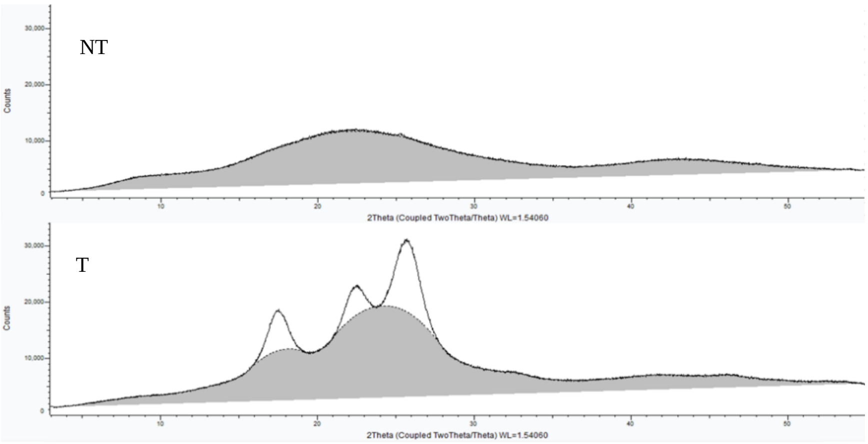

Figure 8. XRD results for nontextured and textured PET/coPET yarns.

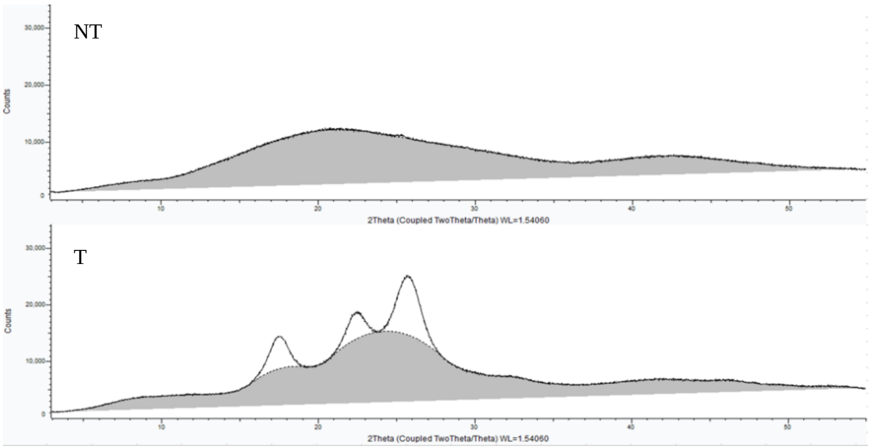

Figure 9. XRD results for nontextured and textured rPET/coPET yarns.

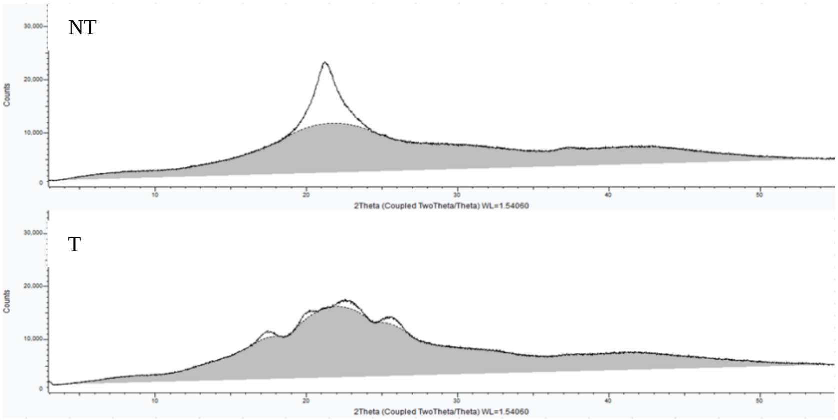

Figure 10. XRD results for nontextured and textured PA6/coPET yarns.

PA6/coPET sample shows the highest crystalline behaviour amongst all the samples in their nontextued forms. Contrary to the other samples, the PA6/coPET blend shows an opposite behaviour where the crystallinity is already at a high percentage but drops down afterwards. Crystallinity behaviour of polymers is dependant on many different properties such as the molecular weight, synthesization conditions, polymer architecture and so on. Polyethylene (PET) chains are mainly linked with dipole-dipole bonds whereas polyamides (PA) are linked with hydrogen bonds which has a dissociacion energy almost ten times of a dipole-dipole bond. Also, the hydrogen bonds can be formed in a parallel form (α) or an anti-parallel form (γ) in PA6. In parallel form, the adjacent polymer chains are in the same directionality but in anti-parallel form, the chains have opposite directionality. In the parallel form, the hydrogen bonding occurs between the adjacent chains on the same sheet but in the anti-parallel form the hydrogen bonds occur between chains that are on adjacent sheets. Since the bonds between adjacent planes are stronger than bonds formed on the same sheet, the bonds are much stronger, thus increasing the crystallinity and the rigidity of the polymer [22, 23]. Nevertheless, the PA shows a different behaviour in a material context which is consistent with the other results in the study, but again it is essential to study the effects of the texturization and alkalization processes to get a better understanding of the situation.

4. CONCLUSION

This study evaluated and compared the mechanical and thermomechanical properties of three different bicomponent yarns. The tests were carried out in both the textured and nontextured forms of the samples to observe the effect of heat treatment and alkalization on the final properties. The results indicate the importance of choosing an appropriate raw material for bicomponent yarn production, since the chosen raw material carries its' intrinsic properties to the yarn stage and greatly affects the properties of the final material. It also demonstrates that alkalization and texturization have a significant impact on the properties of the polymers and the final yarns. An important result is that the textured yarns had better mechanical properties, even though they went through a heavy chemical process such as alkalization and half of the filament volume was removed. It is evident that texturization process appeared to play a more significant role than the alkalization; the heating process involved in texturization improved the crystallinity and density by increasing the number of immobile polymer chains with reduced elongation, as supported by literature [24]. This shows that hollow yarns have high mechanical strength and that they can be used in places where both insulation and strength are needed. The observed increase in the strength of all types of filaments proves that both components of a bicomponent yarn can be chosen and modified according to the desired application area and the required properties from the product without having to sacrifice from the tensile properties. Thermomechanical analysis revealed that heat treatment and alkalization results in a higher polymer chain mobility, which caused an increase in the enthalpy values and decreased the decomposition temperature of the polymers. The unexpected rise in crystallinity seen in the XRD measurements for the PET/coPET and rPET/coPET samples following texturization may be explained by the fact that texturization includes the use of heat and mechanical processing, and the combination of these parameters may have resulted in changes in the polymer structure. According to the literature [21], mechanical deformation and orientation during texturization might impact polymer chain arrangement, potentially decreasing crystalline development. It is possible that the combination of heat and mechanical forces during texturization resulted in a unique set of conditions enabling crystalline development in the bicomponent yarns in the setting of this study. This unexpected result highlights the complex interactions of processing parameters and the need for additional research to identify the specific factors leading to the observed increase in crystallinity. Future work on the area should focus on the effect of the alkalization and texturization parametrers as both processes seem to majorly affect the filament properties.

The study underlines the significance of choosing appropriate raw materials for bicomponent yarn manufacturing, since the basic characteristics of the chosen materials have a significant effect on the end result. Furthermore, the study indicates the ability of hollow yarns to improve mechanical strength and dimensional resistance even after chemical processes such as alkalization. The thermomechanical study provides helpful information on the enhanced polymer chain mobility caused by heat treatment and alkalization, which affects the yarn's enthalpy values and decomposition temperature.

Bicomponent fibers have been a popular application due to their many advantages, one of them being that they can be made into hollow yarns by removing one of the components. Hollow bicomponent yarns provide greater bulk with less weight to a textile material. They are, therefore, often used to provide acoustic or thermal insulation. Bicomponent hollow yarns are suitable candidates to replace their traditional counterparts, thanks to their modifiability, enhanced properties, and availability for a more sustainable approach. In the future, with the development of new materials and new methods, the use and importance of bicomponent yarns and products made from these yarns will increase, and thus this study contributes valuable knowledge to developing functional textiles with improved properties for future applications.

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