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Effect of Twist Stabilisation and Dyeing on the Structural and Physical Properties of Agricultural Strings

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Abstract

A production technology for agricultural biodegradable strings composed of polylactide (PLA) staple fibres was developed that uses the ring spinning method. During complete relaxation, strings with an unbalanced twist tend to detwist because of torque, which can be eliminated by thermal stabilisation. This study assessed the effects of fibre twist stabilisation on the PLA crystalline structure and also analysed the effect of those crystalline structure changes on strength. In addition, some strings were dyed a dark colour to analyse the effect of dyeing on the structural and physical properties. Dyeing at 80 - 90 °C with a TERASIL Schwarz B, dyeing with a TERASIL Schwarz W-NS without a carrier and stabilising undyed strings in water at 80 °C resulted in considerable reduction in unbalanced twist while maintaining a reasonable tenacity of 10 cN/tex. The quality of the strings processed met the requirements for application in horticulture.

Key words: string, twist stabilisation, dyeing, polylactide, structural properties.

Introduction

Strings are usually made from raw materials such as mineral, natural or chemical fibres. In the past, among mineral fibres asbestos has found the greatest use, while from the group of natural fibres cotton, silk and bast fibres such as sisal, abaca, flax, hemp and ramie fibres are mostly used. Raw materials from the group of chemical fibres include viscose, polyamide, polyester, polyethylene and polypropylene fibres. For agricultural applications, the market mostly offers strings made of tapes produced by fibrillation of polypropylene film. Polypropylene strings belong to products whose degradation in the environment takes a hundred years, posing a considerable hazard to the environment [1]. In the age of sustainable development, one can observe trends towards the replacement of polyolefins with biodegradable thermoplastic polymers made from renewable raw materials [2]. Within the scope of the synthesis of such polymers, the most advanced are technologies based on polylactide (PLA) [3].

PLA fibres and PLA fibrous products are resistant to atmospheric degradation while in use [4, 5]. PLA products degrade at the elevated temperatures and humidity typical of waste composting. PLA decomposition proceeds by hydrolysis followed by bioconversion to H₂O and CO₂. This process occurs fastest at elevated temperatures in a compost medium (up to 3 - 4 months); however, in water and soil at ambient temperature, decomposition takes considerably longer (even over 12 months) [6]. PLA fibre mechanical properties do not differ considerably from polyamide fibres and other polyester fibres.

PLA fibres are most often characterised by a tenacity of 35 - 45 cN/tex. Moreover these fibres exhibit resistance appropriate for use in durable textiles [4]. The glass transition temperature (T_g) of PLA (55 - 65 °C) is comparable to that of poly(ethylene terephthalate) (PET), and its melting point (T_m) (160 - 180 °C) is similar to that of polypropylene (PP). PLA fibres are resistant to UV radiation, exhibit a good elasticity, possess a low density (1.24 g/cm³) compared with standard polyester fibres and emit less smoke during combustion. In addition, PLA possesses a considerably higher oxygen index (LOI = 26%) than typical synthetic fibres [7].

PLA is synthesised by polycondensation or ring opening polymerisation and has

lactic acid (2-hydroxypropionic) (LAc) as its monomer. LAc is the simplest hydroxyl acid, containing a symmetric carbon atom. It exists as two enantiomers, L-LAc and D-LAc, which are shown in **Figure 1** [8].

Most lactic acid is obtained through the fermentation of agricultural hydrocarbons (e.g., corn, potatoes, waste biomass) using the bacteria *Lactobacilli*.

Lactide (LA), however, is prepared through the depolymerisation of LAc oligomers. The two centres of chirality present in LA lead to three possible diastereoisomers: D,D-LA, L,L-LA and D,L-LA (**Figure 2**) [8].

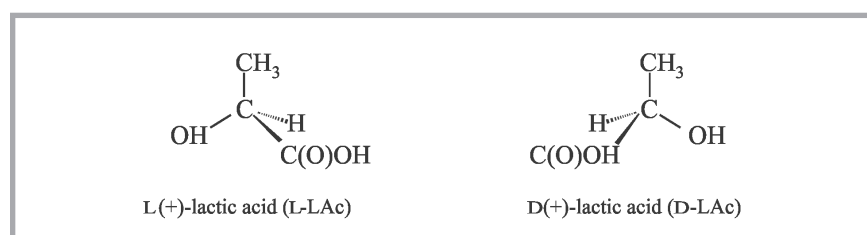


Figure 1. Structural formulas of the two stereoisomeric forms of lactic acid according to [8].

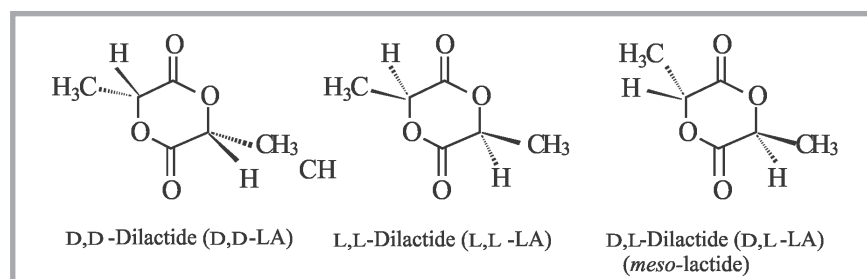


Figure 2. Three diastereoisomers of lactide according to [8].

Table 1. Parameters of staple SLN 2660D fibres.

Parameter	Unit	Value	Standards
Linear density	dtex	6.6	PN-ISO 1973:1997
Average length	mm	64.0	PN-ISO 6989:2000
Tenacity	cN/tex	22.0	PN-EN ISO 5079:1999
Elongation	%	37.0	PN-EN ISO 5079:1999

Table 2. Plan of string spinning from staple SLN 2660D fibres

Machine	Number of doublings D	Draft ratio R	Linear density of the product, tex
Laboratory carding machine	Feeding – fibre batch 80 g	-	3500
Revolving flat card	1	100	3.5
Drawing frame I	6		
Drawing frame II			
Fly frame	1	7.8	450 (twist Z 72 t.p.m)
Fly frame	2	-	450×2 (twist Z 72 t.p.m)

The polymerisation of lactide, usually initiated by covalent alcoholates (Mt(OR)_n), results in polylactide macromolecules with one terminal ester and one terminal hydroxyl [8]. Using different lactide stereoisomers leads to different PLA supramolecular structures. These supramolecular structures influence the final products' physical properties and their biodegradability.

Having units of different chirality within a PLA chain reduces its ability to crystallise. The poly(L-lactide) homopolymer can crystallise in three different polymorphous forms: α , β and γ [9, 10]. The form most frequently observed is pseudo-orthorhombic α' (parameters of cell: $a = 1.060$ nm, $b = 0.610$ nm, $c = 2.880$ nm, and $\alpha = \beta = \gamma = 90^\circ$). The second form most frequently observed is orthorhombic α ($a = 1.050$ nm, $b = 0.610$ nm, $c = 2.880$ nm, and $\alpha = \beta = \gamma = 90^\circ$), which crystallises from melt or solution under normal conditions [11]. The β and γ forms are seldom observed in poly(L-lactide). The trigonal β ($a = 1.052$ nm, $b = 1.052$ nm, $c = 0.880$ nm, and $\alpha = \beta = 90^\circ$, and $\gamma = 120^\circ$) or orthorhombic γ form ($a = 1.031$ nm, $b = 1.821$ nm, $c = 0.900$ nm, and $\alpha = \beta = \gamma = 90^\circ$) of PLA is produced by stretching at high drawing ratios and temperatures. The orthorhombic γ form ($a = 0.995$ nm, $b = 0.625$ nm, $c = 0.880$ nm, and $\alpha = \beta = \gamma = 90^\circ$) is produced through epitaxial crystallisation [12 - 14].

Pan *et al.* in 2007 [15] and Zhang *et al.* in 2008 [16] demonstrated that for poly(L-lactide) homopolymer, the disordered α' and ordered α polymorphs are formed

during crystallisations below 100 °C and above 120 °C, respectively. In the intermediate temperature range of 100 °C to 120 °C, however, both forms crystallise. The α form content increases with increasing crystallisation temperature, whereas the α' form decreases. Moreover, the disorder-to-order phase transition (α' to α form) is observed during heating. Notably the difference between the α' and α cell parameters is minor; cell parameters c and b of α' are similar to those parameters in α cells, except the cell parameter in α' (1.072 nm) is larger. The influence of structural differences between α and α' crystals on macroscopic parameters such as tensile strength has not been clearly reported.

Therefore the crystalline structure for a particular PLA will depend largely on the thermal conditions used in the manufacturing and finishing processes.

This study assessed the effect of fibre twist stabilisation (used to eliminate torsional stresses resulting from thread twisting) on the crystalline structure of PLA used for agricultural strings, as well as analysed the effect of crystalline structure changes on strength. The strings were produced from commercially available fibres by ring spinning. Finally twist stabilisation was conducted in a hot water bath simultaneously with dyeing.

Experimental details

Materials

Commercial staple PLA fibres produced by Far Eastern New Century Corporation (Taipei, Taiwan) (catalogue number SLN

2660D) were used to create the string tested in this study. The parameters of these fibres are listed in *Table 1*.

Two types of dyestuffs were used: TERASIL Schwarz B (HUNTSMAN, Gateway East, Singapore) and TERASIL Schwartz W-NS (HUNTSMAN, Gateway East, Singapore). To enhance the black colour imparted by TERASIL Schwarz W-NS, the strings were also dyed using the carrier ZS-ECOCARRIER CAB (ZSCHIMMER & SCHWARZ MOHSDORF GmbH & Co KG, Burgstädt, Germany).

Spinning process of strings

The strings were spun according to the spinning plan given in *Table 2*.

A basic string parameter is twist. The most important properties of strings (e.g., strength, elongation, twist unbalance) depend on their twist. Up to the optimum level, the twisting of strings increases their strength, decreases non-uniformity and additionally imparts new properties. The twist number was changed to 40 – 72 twist rotations per meter (t.p.m.). The breaking force of strings required for horticulture applications was assumed to be approximately 10,000 cN. Therefore to fulfill the mechanical properties required, a maximum t.p.m. value of 72 was set for the first and second steps of the twisting process. During complete relaxation, strings with an unbalanced twist tend to detwist and form spirals and loops because of torque. This string torque can be eliminated by thermal stabilisation [17].

String dyeing and thermal stabilisation of twist

String thermal stabilisation processes are most commonly performed in water, saturated steam or hot air. The selection of thermal stabilisation parameters is empirical in nature. In selecting the stabilisation temperature, one should choose a heating medium capable of fulfilling the following condition: $T_g < T_{\text{stabilisation}} < T_m$ [18]. Thermal stabilisation for the dyed strings was performed in hot water dyeing baths. For the undyed samples, twist stabilisation was performed in water bath under comparable conditions.

To dye the strings black, an aqueous bath of dye TERASIL Schwarz B (HUNTSMAN, Gateway East, Singapore) was prepared at a 5 wt% concentration relative to the string weight, at a liquor ratio

of 25:1 (ml:g) and at a pH of 5. String skeins were immersed in this dyeing bath at 25 ± 2 °C. The bath was heated at 3 °/min. to 80 ± 2 °C and maintained at that temperature for 60 min. Afterwards the string was rinsed to remove excess dye and dried in air. Hence dyeing and thermal stabilisation of the string twist was performed concurrently.

The undyed string was thermally stabilised using the same conditions as for the dyed strings. A water bath was prepared at a liquor ratio of 25:1, pH of 5 and temperature of 25 ± 2 °C. The bath was heated at 3 °/min to 80 ± 2 °C and maintained at that temperature for 60 min. The undyed string was rinsed with cold water and dried in air.

In a second dyeing variant, an aqueous bath of dye TERASIL Schwartz W-NS (HUNTSMAN, Gateway East, Singapore) was prepared at a concentration of 5 wt% relative to the string weight, at a liquor ratio of 25:1 and pH of 5. String skeins were immersed in this dyeing bath at 25 ± 2 °C. In this variant, the bath was heated at 3 °/min to 90 ± 2 °C and maintained at that temperature for 40 min. Afterwards the dyed string was rinsed of excess dye and dried in air. This second dyeing variant resulted in a brown-coloured string.

To obtain a black-coloured string using the second dyeing variant, we employed dye carrier ZS-ECOCARRIER CAB (ZSCHIMMER & SCHWARZ MOHSDORF GmbH & Co KG, Burgstädt, Germany). This carrier is a compound functionalised with multiple carboxyl acids; moreover, it is free from aliphatic hydrocarbons, phenylphenols and halogenated aromatics. The carrier rinses off easily, is ecologically harmless and biodegrades readily.

The following dyeing procedure employing ZS-ECOCARRIER CAB was used: the carrier, in a quantity of 3 g per mol of string, was dissolved in water at a liquor ratio of 20:1 (ml:g). String skeins were immersed in the carrier bath and heated to 60 ± 2 °C. The string was held at that temperature for 15 min., and an aqueous dye solution was then added (5 wt% relative to the dry string weight), increasing the liquor ratio to 25:1 (ml:g). The pH of the bath was maintained at 5. The bath was heated to 90 ± 2 °C, and dyeing was performed for 40 min. Finally the string was rinsed of excess dye and dried in air.

For comparison, natural string was thermally stabilised with the carrier under similar conditions. The string skeins were immersed in water at a liquor ratio of 25:1, pH of 4 and 25 ± 2 °C. The bath was then heated at 3 °/min to 90 ± 2 °C. After maintaining that temperature for 40 min., the strings were rinsed with cold water and dried in air.

Analytical methods for fibre characterisations and PLA crystalline structure determination at successive phases of the string-making process

Fibre molecular weight changes were monitored after each successive finishing process by SEC-MALS, and the supramolecular structures were assessed by WAXS.

The SEC-MALS system was composed of an 1100 Agilent isocratic pump, an autosampler, a degasser, a thermostatic box for the columns, a DAWN® EOS™ MALS photometer (Wyatt Technology Corporation, Santa Barbara, CA, USA), and an Optilab® rEX differential refractometer. ASTRA® 4.90.07 software (Wyatt Technology Corporation, Santa Barbara, CA, USA) was used for data collection and processing. Two PLgel 5 micron Mixed-C columns were used for separation. Samples were dissolved in methylene chloride and introduced to the system via a 100 µL injection loop. Methylene chloride was used as a mobile phase at a flow rate of 0.8 ml·min⁻¹.

The DAWN EOS was calibrated with p. a. grade toluene and normalised with a 30000 g/mol polystyrene standard. The measurements were performed at room temperature [19].

For dn/dc calculations, ASTRA software requires that the mass of the sample introduced be known. We measured the dn/dc with the columns on line. We inputted the initial injected mass into ASTRA assuming that a negligible amount of polymer was lost through interaction with the columns. The dn/dc value determined was 0.035.

Changes in the supramolecular structure of the PLA fibres after each processing phase were analysed by the WAXSFIT program [20]. This program enabled quantitative and qualitative assessment of structural changes by revealing the crystalline phase content and crystalline area sizes. Diffraction patterns were analysed by the Hindeleh and Johnson method, which consisted of fitting the experimental data to theoretical curves, accomplished through the addition of peaks corresponding to the X-ray deflection on crystalline and amorphous areas (**Figure 3**).

The theoretical curve determined enabled calculation of the surface areas under the crystalline and amorphous curves, from which the crystalline phase content (χ_c – crystallinity degree) was calculated according to the equation [21]:

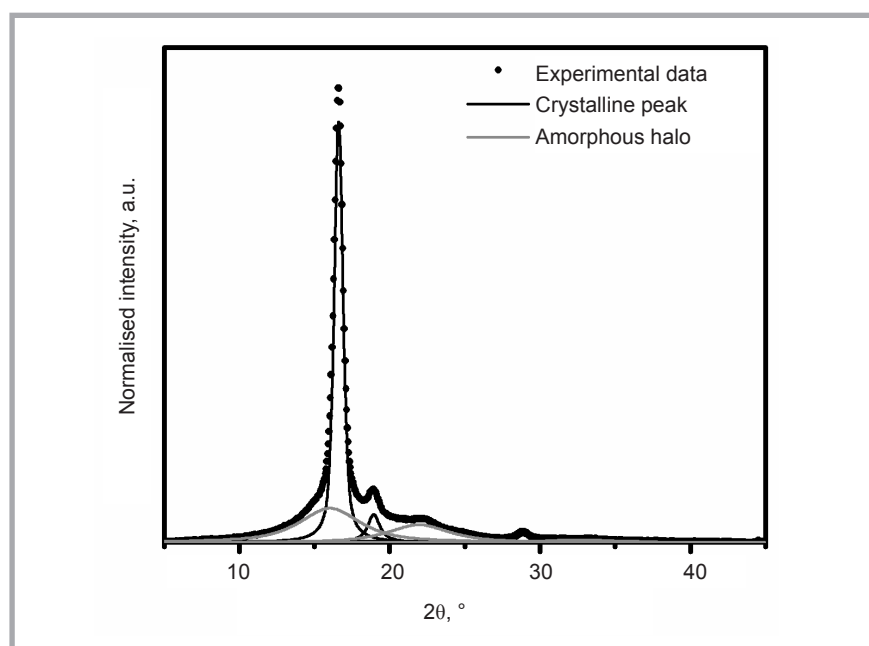


Figure 3. WAXS diffraction patterns of naturally coloured PLA string stabilised in water after calculation using WAXSFIT software.

Table 3. Molecular weights of PLA after successive finishing treatments.

Sample	Type of dye	$M_n \times 10^4$, g/mol	D (M_w/M_n)
Natural colour unstabilised (fibres)	-	4.820	1.34
Natural colour stabilised in water	-	4.860	1.36
Natural colour stabilised in water with carrier	-	5.090	1.30
Brown colour stabilised without carrier	TERASIL Schwartz W-NS	3.690	1.50
Black colour stabilised with carrier	TERASIL Schwartz W-NS with carrier ZS-ECOCARRIER CAB	4.560	1.95
Black colour stabilised without carrier	TERASIL Schwartz B	3.760	1.43

$$\chi_c = \frac{A_c}{A_c + A_A} \quad (1)$$

where A_A and A_C are the areas calculated under the amorphous and crystalline curves, respectively.

The crystalline area sizes were determined from diffraction peak widths using Scherrer's formula [21]:

$$L_{(hkl)} = \frac{K\lambda}{B \cos \theta} \quad (2)$$

where $L_{(hkl)}$ – average size of crystalline areas perpendicular to lattice planes (hkl), θ – Bragg angle for planes (hkl), λ – wavelength of X-ray radiation (for $\text{CuK}\alpha$ $\lambda = 0.154$ nm), B – half width of the diffraction peak for planes (hkl), K – Scherrer constant for the particular polymer (in this case 0.9).

Powdered fibres and strings were pressed together to minimise background diffraction from air. A maximum pressure of 2.5 MPa afforded uniform tablets weighing 300 mg each. WAXS spectra were obtained using an X'Pert PRO diffractometer from PANalytical (Almelo, The Netherlands) employing $\text{CuK}\alpha$ radiation ($\lambda = 0.154$ nm). The spectra were gathered under the following acquisition parameters: 40 kV accelerating volt-

age, 30 mA anode current density, an X'Celerator semiconductor counter for detection and a range of 2θ : $5^\circ - 45^\circ$.

Analysis of the qualitative and quantitative parameters of PLA strings

String variants were analysed to determine their qualitative and quantitative parameters: linear density according to Standard PN-P-04653:1997, the number of twists according to Standard PN-EN ISO 2061:1997, the breaking force, elongation and tenacity according to Standard PN-EN ISO 2062:1997 and the twist unbalance according to Standard PN-P 04805:1975.

Results and discussion

Table 3 portrays PLA molecular weight changes resulting from various dyeing and stabilisation steps; **Table 4** lists the PLA fibre crystallinity degree and structural parameters through successive phases of processing.

The stabilisation processes of natural colour strings did not significantly change the molecular weights of the PLA. The number average molecular weight (M_n) was 48 - 50 kg/mol and the molecular weight dispersity ($D = M_w/M_n$) 1.30 - 1.95.

The stabilisation of undyed strings in aqueous baths with and without a carrier changed neither their molecular weights nor their dispersities. Additionally dyeing the strings black with the use of a carrier at 90°C caused no significant decrease in the polymer molecular weight. In contrast, dyeing the strings with TERASIL Schwartz W-NS without a carrier at 90°C (where the brown colour was obtained) resulted in a decrease in M_n to 36.9 kg/mol. Dyeing with TERASIL Schwarz B without a carrier at 80°C also decreased the PLA molecular weight ($M_n = 37.6$ kg/mol). However, these results may contain some error resulting from the analytical method chosen (MALLS). Measuring light scattering from coloured macromolecules may be imprecise because of disrupting optical phenomena (e.g., absorption of scattered radiation), and an imprecise light scattering measurement would result in an imprecise molecular weight determination. We concluded that, in general, the treatment in pure water at 80°C did not considerably decrease the molecular weight of the PLA strings. Dyeing during the water treatment caused an approximately 20% drop in molecular weight; however, the addition of a carrier prevented this molecular weight loss.

The data in **Table 4** clearly indicated PLA structural changes when a carrier was used in the stabilisation process. Structural changes were observed for both natural PLA string stabilised in water at 90°C with a carrier and string dyed with TERASIL Schwarz W-NS with a carrier. The increase in the crystallinity degree did not result from an increase in crystallite size (lamellae); the increase resulted from a change in the ordered state of the polymer chains. We observed transitions to the stable form α with rhombic elemen-

Table 4. Crystallinity degree and structural parameters of PLA fibres in the successive phases of processing.

Sample	Type of dye	(hkl)	Reflex 2θ , °	Crystallite size, Å	Crystalline form of PLA	Crystallinity degree, %
Natural colour unstabilised (fibres)	-	(200)/(110)	16.38	125	α'	52.1
		(203)	18.81	130		
Natural colour stabilised in water	-	(200)/(110)	16.41	136	α'	55.7
		(203)	18.76	116		
Natural colour stabilised in water with carrier	-	(200)/(110)	16.61	129	α	55.3
		(203)	18.94	93		
Brown colour stabilised without carrier	TERASIL Schwartz W-NS	(200)/(110)	16.55	140	α'	56.0
		(203)	18.86	102		
Black colour stabilised with carrier	TERASIL Schwartz W-NS with carrier ZS-ECOCARRIER CAB	(200)/(110)	16.68	131	α	56.7
		(203)	18.99	74		
Black colour stabilised without carrier	TERASIL Schwartz B	(200)/(110)	16.48	153	α'	56.0
		(203)	18.81	130		

Table 5. Qualitative and quantitative parameters of PLA strings; * u_c – measurement uncertainty calculated in accordance with ISO Guide to the Expression of Uncertainty in Measurement [22].

Parameter	String of commercial staple SLN 2660D fibres					
	Natural colour			Brown stabilised without carrier	Black stabilised	
	unstabilised (fibres)	stabilised in water	stabilised in water with carrier		without carrier	with carrier
Type of dye	-	-	-	TERASIL Schwarz W-NS	TERASIL Schwarz W-NS with carrier ZS-ECOCARRIER CAB	TERASIL Schwarz B
Linear density, tex	975	1072	1129	1265	1098	1313
Variation coefficient of linear density, %	7	13.0	7.9	7.7	13.6	6.4
u_c * of linear density, tex	15	31	20	22	33	19
Breaking force, cN	13961	10759	7502	12139	11701	9228
Variation coefficient of breaking force, %	10.5	16.6	10.5	4.8	8.6	13.3
u_c * of breaking force, cN	328	399	176	132	225	275
Elongation at break, %	31.70	42.10	26.46	36.55	40.27	33.05
Variation coefficient of elongation, %	13.10	11.50	12.83	5.09	7.65	16.11
u_c * of elongation, %	0.93	1.08	0.76	0.42	0.69	1.19
Tenacity, cN/tex	14.30	10.00	6.64	9.60	10.66	7.03
u_c * of tenacity, cN/tex	0.40	0.47	0.20	0.20	0.38	0.23
Twist number, t.p.m.	71	91	80	86	88	82
Variation coefficient of twist number, %	3.5	4.6	4.3	4.7	3.7	2.9
Twist unbalance number, t.p.m.	36	8	8	3	6	4
Percentage of unbalanced twists, %	50.7	8.8	10.0	3.5	6.8	4.9

tary cells, smaller crystallites (lamellae) and a slight increase in the crystallinity degree (up to 56%) compared to unstabilised films. These changes most likely result from the increase in the number of crystallites in the polymer.

The dyeing process at 80 - 90 °C that used TERASIL Schwarz B, that which used TERASIL Schwarz W-NS without a carrier and the stabilisation of undyed strings in water at 80 °C also slightly increased the crystallinity degree (up to 56%). However, this crystallinity increase did not result from transition to form α , as was observed in the presence of a carrier.

Notably the dye contained no metal or crystalline small molecules, as demonstrated by the lack of X-ray diffraction peaks other than those derived from PLA. Moreover X-ray diffractometry as a method for chemical phase analysis has a sensitivity of several wt%.

Table 5 shows the results of the qualitative and quantitative parameters investigated. These results were used to estimate the effect of changes in the PLA molecular and supramolecular structure on the physical properties of the strings.

Based on **Table 5**, we concluded that the thermal stabilisation influenced the mass non-uniformity, breaking force, elongation, tenacity and twist unbalance. The twist unbalance of the strings after stabilisation were considerably smaller than

before stabilisation. Depending on the particular conditions, the twist unbalance dropped from 36 to 3 - 8. The thermal stabilisation of strings caused an increase in their non-uniformity on long sections and, in most cases, an increase in elongation at break.

The thermal stabilisation of strings in water and dyeing baths resulted in a decrease in the breaking force and, consequently, in the tenacity. A considerable decrease in strength – 40% – was observed for strings dyed with a carrier. The transition of the crystallite polymorphic form from α' to α seemed to be a decisive factor in decreasing the strength of the strings. This phenomenon was previously observed while investigating changes in the crystalline structure of nonwovens made by the spun-bonded technique. These nonwovens were subjected to stabilisation at different temperatures of calender [23]. The dyeing process at 80 - 90 °C using TERASIL Schwarz B, that using TERASIL Schwarz W-NS without a carrier and the stabilisation of undyed strings in water at 80 °C reduced the breaking force by approximately 28% compared with unstabilised strings. Nevertheless stabilisation without a carrier maintained a breaking force above the 10,000 cN level required.

Conclusions

1. The thermal stabilisation of PLA strings caused an increase in the crys-

tallinity degree from 52% to approximately 56%.

1. Thermal stabilisation at 90°C in dyeing baths with a carrier and in aqueous baths changed the PLA crystallites from the α' to α form.
2. Thermal stabilisation at 80-90°C in dyeing baths without a carrier decreased the polymer molecular weight by approximately 20%. The process of stabilisation applied was effective. The twist unbalance of staple fibres after stabilisation was lower than before stabilisation.
3. The thermal stabilisation of strings resulted in a decrease in the breaking force, a decrease in tenacity and an increase in elongation. The changes in string strength resulted from changes in the PLA molecular and supramolecular structure and from those in the physical structure of the string itself. A considerable decrease in strength, 40%, was observed for strings dyed with a carrier.
4. Dyeing at 80-90°C with TERASIL Schwarz B, with TERASIL Schwarz W-NS without a carrier and stabilisation of undyed strings in water at 80°C resulted in a considerable reduction in unbalanced twists while keeping a reasonable tenacity of 10 cN/tex. The quality of the strings elaborated met the requirements for application in horticulture.



Acknowledgements

- We are grateful to Prof. Tadeusz Biela from the Centre of Molecular and Macromolecular Studies PAS in Lodz for his contribution to this work.
- This research was performed within the framework of a key project titled "Biodegradable fibrous products" (acronym: Biogratex) supported by the European Regional Development Fund – Agreement No. POIG.01.03.01-00-007/08-00.

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■ Received 28.11.2012 Reviewed 29.05.2013

UNIVERSITY OF BIELSKO-BIAŁA

Faculty of Textile Engineering and Environmental Protection

The Faculty was founded in 1969 as the Faculty of Textile Engineering of the Technical University of Łódź, Branch in Bielsko-Biała. It offers several courses for a Bachelor of Science degree and a Master of Science degree in the field of Textile Engineering and Environmental Engineering and Protection.

The Faculty considers modern trends in science and technology as well as the current needs of regional and national industries. At present, the Faculty consists of:

■ The Institute of Textile Engineering and Polymer Materials, divided into the following Departments:

- Polymer Materials
- Physics and Structural Research
- Textile Engineering and Commodity
- Applied Informatics

■ The Institute of Engineering and Environmental Protection, divided into the following Departments:

- Biology and Environmental Chemistry
- Hydrology and Water Engineering
- Ecology and Applied Microbiology
- Sustainable Development
- Processes and Environmental Technology
- Air Pollution Control



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