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Effects of different production processing stages on mechanical and surface characteristics of polylactic acid and PET fibre fabrics

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This paper reports study on the polylactic acid (PLA) and polyester (PET) knitted fabrics mechanical and surface characteristics at low-stress and the influence of typical commercially applied different production processing stages on the properties. The KES-FB is used for the investigation of low-stress bending, compression, tensile, shear and surface characteristics. The results show remarkable changes after each processing stage, such as scouring, drying, dyeing, heat setting and softening, in mechanical and surface characteristics of PLA and PET fibre knitted fabrics. PLA knitted fabrics represent higher values in bending, shear and surface properties after different processing stages as compared to PET knitted fabrics. The values of bending rigidity (B), bending hysteresis (2HB), shear stiffness (G), and shear hysteresis (2HG and 2HG3) have been significantly decreased after the scouring treatment. There is a considerable decrease in B, 2HB, G, 2HG and 2HG3 values and an improvement in tensile elongation (EMT) after dyeing of PET and PLA fabrics. A slight reduction in shear and bending properties of polylactic acid fibre fabrics shows that softening treatment decreases the inter fibre and inter yarn friction. LT (linearity of load-extension curve), RT (recovery from tensile deformation), LC (linearity of compression curve) and RC (recovery from compression deformation) properties are not found quite sensitive for different production processing stages in case of both the fabrics.

Keywords: Low-stress mechanical properties, Polylactic acid fabric, Polyester fabric, Polylactic acid fabric, Polyester fabric, Surface characteristics

1 Introduction

Polylactic acid (PLA), as the first natural-based synthetic fibre as well as sustainable and renewable, shows ecological advantages with excellent performance in textiles[1, 2]. PLA effectively bridges the gap between synthetic and natural fibres and finds a wide range of uses, from medical and pharmaceutical applications to environmentally benign film and fibres for packaging, housewares, and clothing[3]. Ease of melt processing, unique property spectrum, renewable source origin, and ease of composting and recycling at the end of its useful life has led to PLA fibres achieve growing interest and acceptance over a range of commercial textile sectors. That is why, many studies were carried out regarding wet processing of this biodegradable aliphatic polyester fibre (PLA)[4-18].

End-use products displaying unlike utility and aesthetic characteristics can be achieved from the same un-finished fabric by using numerous finishing processes[19]. The journey of textile garment which could be bought from the retail stores starts from the greige fabric step. Various processes are then carried out to the greige textile materials to create the ultimate finished textile materials. Scouring, dyeing, drying, heat-setting and finishing (softening, etc.) processes can be applied to the materials to achieve the final intended finished fabric. Those various processing types unavoidably influence the mechanical and surface characteristics of the textile materials, leading to change in fabric handle.

There are very few data on the knitted fabrics as well as on the effect of processing and finishing procedures on the quality of knits[20, 21]. Earlier we have studied the effects of softeners and laundering on the handle of PLA fabrics[22] and compared low-stress mechanical properties of PLA and PET fabrics softened with many different softeners[23]. Moreover, we have also studied a mathematical method, i.e. the Weighted Euclidean Distance method, in order to obtain indirect assignation of total hand value from the Kawabata Evaluation for Fabrics parameters of

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processed PLA and PET fabrics[24]. Yang and Kan[25] also studied the effect of heat setting parameters (treatment time, treatment temperature, and tension) on some handle properties of PLA knitted fabric.

In this study, we examine and compare the mechanical and surface characteristics of PET and PLA fibre fabrics before and after each typical commercially applied different production process stages using Kawabata evaluation method. A particular objective is to investigate the effect of different processing steps (scouring, dyeing, heat treatment and softening) from greige state to the final finished state on basic mechanical (tensile, bending, shearing & compression) and surface properties of both fabrics.

2 Materials and Methods

This study employed two sets of identically-constructed 'piqué' type of knitted fabrics provided by NatureWorks LLC, USA and derived from 150/144 dtex/filament PLA (Ingeo™ fibre) and 150/144 dtex/filament PET yarns (PET fibre) respectively. "Ingeo™ fibre" is the trademark of NatureWorks LLC's polylactic acid polymer produced from corn starch.

2.1 Experimental Procedures

Different wet production stages were carried out to both PLA and PET fibre knitted fabrics to cover mostly applied industrial process types. Different codes are assigned to different processing stages for ease of understanding, as shown below:

- GF — Greige (untreated) fabric
- SG — Scoured fabrics
- SDF — Greige scoured + Drying
- SDHF — Scouring + Drying + Heat setting
- DGF — Scouring + Dyeing + Clearing
- DDF — Scouring + Dyeing + Clearing + Drying
- HDDF — Scouring + Dyeing + Clearing + Drying + Heat setting
- DHSF — Scouring + Dyeing + Clearing + Softening + Drying + Heat setting.

It is important to state that for all processing stages, for both PLA and PET fabrics, drying process was carried out at 110 °C for 1 min. In the case of heat setting process, PLA and PET fabrics were heat set at 130°C for 30s and at 180°C for 30s respectively, due to the heat sensitivity of PLA fibre[26].

2.1.1 Scouring of Substrates

Scouring indeed minimizes the risk of poor dye uniformity, soils and color fastness problems by removing waxes, fats and oils which might be existing in knitted fabrics[27, 28]. Greige PLA and PET fibres were scoured in a clearing-bath having 1 g/L of "Kieralon Jet B" (a non-ionic surfactant, BASF) and 1 g/L of sodium carbonate at 60°C for 15 min. After scouring, the materials were washed with tap water for 10 min and dried at room temperature.

2.1.2 Dyeing of Knitted Fabrics

Dyeing was carried out with a mixture of 0.02% Dianix Blue ACE + 0.007% Dianix Red ACE + 0.003% Dianix Yellow ACE, according to the respective typical industrial dyeing procedures as shown in Figs 1 and 2 using a laboratory-scale Mathis Labomat Infra-red dyeing machine (Werner Mathis, Zurich, Switzerland) with a liquor ratio of 10:1 and temperatures of 130°C and 110°C for PET and PLA respectively[29]. All dyes were supplied from DyStar.

Dyeing auxiliary, Setamol BL (anionic dispersing agent ex BASF) was added to the dye-bath at the start of each dyeing operation, along with acetic acid and/or sodium acetate. These latter chemicals were used to arrange the *p*H 4 for PET and *p*H 5 for PLA. After dyeing, the fabrics were rinsed for 5 min with warm water and then for 2 min with cold water. After that the fabrics were left at room temperature for drying.

2.1.3 Reduction Clearing

Alkaline reduction clearing was applied to deport un-fixed dye from the surface of the dyed materials. PLA and PET fibres were treated with 2 g/L sodium carbonate and 2 g/L sodium dithionite for 15 min at 60°C [30]. PLA and PET materials were then rinsed in

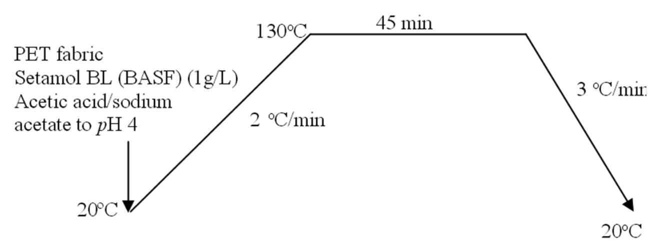

Fig. 1—Dyeing procedure used for the PET fabric

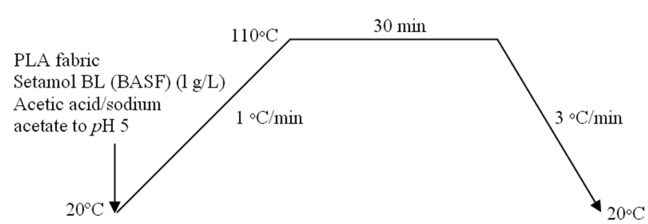

Fig. 2—Dyeing procedure used for the PLA fabric

warm water, then in cold water until neutral, and left as such at room temperature for drying.

2.1.4 Drying and Heat Setting

Post heat setting is frequently desired to produce dimensionally stable material to a desired width and/or when treating with chemical finish. Scoured, dyed and cleaned PLA and PET fibres were dried at 110°C for 1 min via Werner Mathis AG DHE-18874 stenter. Polylactic acid and PET fibres were heat set for 30 s at 130°C and 180°C respectively. This variance in heat setting temperatures was owing to the low melting temperature of polylactic acid fibre (~170 ºC) [3].

2.1.5 Application of Softener to Dyed Substrates

Chosen softener was impregnated by padding process to the dyed polylactic acid and PET fibres at a concentration of 30 g/L and *p*H of 5.0-5.5 (acetic acid) with a 90% pick-up. Softened PLA and PET fibres were then dried on a Werner Mathis AG DHE-18874 at 110°C for 1 min and then heat-set under typical industrial or commercial conditions (30 s at 130°C for PLA; and 30 s at 180°C for PET).

2.1.6 KES-FB Analysis for Fabrics

The basic mechanical properties, such as the tensile, bending, shearing, compression, and surface characteristics of the fabric samples were investigated by Kawabata Evaluation System for Fabrics system [31] using the set-up of knits standard sensitivity [32].

For each production process stage, each measurement was carried out twice on three different samples which were cut from the middle of the fabrics, and six resultant values were averaged. Samples of 200 mm × 200 mm were examined in the course and wale directions. As anisotropy is a concern in knitted fabrics, eleven of the tests (shear, tensile, bending and surface properties) were investigated in both wale and course directions. Average of the wale and course evaluations was determined for further evaluation. Sample preparation, pre-conditioning, and measurements comprised standard conditions of 20°C ±2°C and 65% ±2% RH.

3 Results and Discussion

3.1 Tensile Properties

Tensile properties, tensile linearity (LT), tensile energy (WT), tensile resilience (RT) and elongation (EM) of PLA and PET fibres before and after various processing stages are presented in Table 1. LT reflects the elasticity of the fabric, the higher the LT value the stiffer is the material. WT is the work done during extending of the fabric, and a greater WT value responds to a higher tensile strength of the fabric. RT reflects the recovery capability of a textile material after being extended [33].

In general, tensile properties of PET samples are found higher than the comparable PLA samples. The results show that after scouring and coloration, there is a notable rise in EM and WT values for both fibres. The alterations in these properties expose that the friction between fibres has been decreased by relaxation during scouring and dyeing treatments that cause the fabrics more extensible with better elastic recovery. After drying and heat setting, a reduction in extensibility and tensile energy is detected for both PLA and PET fabrics leading to less extensible and stiffer nature.

A remarkable decrease in extensibility and tensile energy is detected after heat setting process. This could be explained by the limitation of the yarn and fibre motion in fabric structure after such heat treatment process as a result of better dimensional stability of both materials. On the other hand, the heat setting process causes an increase in the recovery capability and elasticity of both materials. Softening

Table 1 — Changes in tensile properties of PLA and PET fabrics throughout different production processing stages

Sample	EM, %		LT		WT, g.cm/cm		RT, %	
	PLA	PET	PLA	PET	PLA	PET	PLA	PET
GF	2.50	3.66	0.760	0.818	0.44	0.75	22.91	35.71
SGF	7.38	5.17	0.826	0.749	1.48	0.97	32.31	38.14
SDF	3.29	4.10	0.982	0.773	0.73	0.77	32.05	38.80
SDHF	2.12	2.87	0.792	0.953	0.41	0.69	32.19	42.81
DGF	7.85	6.84	0.908	0.772	1.70	1.22	37.82	44.54
DDF	6.95	5.07	0.847	0.807	1.40	1.03	38.18	33.69
HDDF	6.26	3.70	0.820	0.869	1.22	0.77	39.17	45.24
DHSF	8.16	4.23	0.760	0.861	1.46	0.94	42.52	45.06

GF— Greige fabric, SGF— Scoured fabric, SDF— Dried fabric after scouring, SDHF—heat setting after drying, DGF— dyed fabrics, DDF— drying after dyeing, HDDF—heat setting after dyeing and drying, and DHSF— drying and heat setting after softening.

process increases the tensile energy, tensile resilience and extensibility of the both fabrics. The softening agent facilitates the movement of fibre and yarn in fabric structure by the reduction of inter-fibre and -yarn friction.

3.2 Shear Properties of Knitted Fabrics

Shear properties, including shear stiffness (G), shear hysteresis at 0.3° (2HG) and shear hysteresis at 3° (2HG3), of PLA and PET materials before and after various processing steps are shown in Table 2. Shear stiffness (G) is the resistance of a material to deformation at various angles to the direction of the individual yarns to pull against one another. Lower value indicates less resistance to the shearing movement, corresponding to a softer material having better drape. The hysteresis 2HG is the energy loss in the final shear deformation in cooperation with the initial part of the deformation. The easier the yarns glide over each other, the smaller the fabric hysteresis[34].

The shear properties (G, 2HG and 2HG3) of PLA fabric exhibit 44%, 25% and 21% reduction after scouring process respectively. The reduction in shear characteristics of PET fabrics is not found significant after scouring. Similar results are also observed for bending properties. These results are indicative of the reduced inter-yarn friction in fabrics and reduced number of fibre-to-fibre contacts at yarn crossover points. Dyeing results in a reduction in shear properties. Drying treatment causes an increase in the shear characteristics of scoured PLA and PET materials. It might be owing to the fabric shrinkage and higher inter-fibre and inter-yarn pressure in fabric structure. Approximately, 39%, 29% and 23% decrease in G, 2HG and 2HG3 is observed in dyed PLA fabric. Respective changes are 18%, 20% and 23% for dyed PET fabrics respectively.

A substantial increase is observed in shear properties of scoured PLA fabric after applying drying and heat-set (SDH) processes. A slight increase is observed in the case of scoured PET fabric. This could be explained due to the different heat setting conditions for two fabrics (130°C versus 180°C). The results show a decrease in shear properties of PLA fabrics and an increase in PET fabrics after softening and heat setting. It seems that the heat setting process has a greater effect to change the shear properties of PET fabrics than the softening. A slight reduction in shear properties of PLA fabrics shows that the softening treatment decreases inter-fibre and inter-yarn friction.

3.3 Bending Properties of Knitted Fabrics

The results of the bending properties of polylactic acid and PET fibre fabrics at different production process stages are shown in Table 2, including bending stiffness (B) and bending hysteresis (2HB). Bending rigidity reflects the flexibility of the fabric; higher B values indicate greater resistance to bending motions. Bending hysteresis indicates the ability of the fabric to recover after being bent. The smaller the 2HB value the better the bending recovery ability of the fabric [32]. The results show that the greige and finished polylactic acid fibre fabrics exhibit higher values of bending properties in comparison to PET fabrics. This can be described by different bending modulus of the polylactic acid and PET.

A noteworthy reduction in B and 2HB values is observed after scouring on PLA fibre materials. It shows 39.3% decrease in B and 17% decrease in 2HB of the treated PLA fabrics, in comparison to greige fabrics. A slight decrease is observed in B and 2HB values after scouring of PET knitted fabrics. This means that the fabric becomes pliable, springy and elastic after scouring as well as relaxation stage. This is due to the reduction in residual tension in the fabric after scouring that increases the mobility of the constituent yarns and fibres.

Table 2 — Changes in shear and bending properties of PLA and PET fabrics throughout different production

Sample	G, g/cm. deg		2HG, g/cm		2HG3, g/cm		B, g.cm/cm		2HB, g.cm/cm	
	PLA	PET	PLA	PET	PLA	PLA	PET	PET	PLA	PET
GF	1.250	0.77	3.56	2.08	4.565	3.145	0.092	0.052	0.091	0.040
SGF	0.695	0.75	2.56	2.03	3.606	3.116	0.056	0.050	0.075	0.039
SDF	1.000	0.82	3.26	2.30	4.321	3.323	0.072	0.055	0.079	0.041
SDHF	1.655	0.89	4.23	2.35	5.235	3.422	0.166	0.079	0.150	0.099
DGF	0.760	0.63	2.53	1.67	3.530	2.706	0.055	0.035	0.056	0.023
DDF	0.890	0.62	2.70	1.70	3.700	2.723	0.063	0.035	0.059	0.028
HDDF	0.830	0.96	2.65	2.13	3.650	3.172	0.060	0.076	0.072	0.057
DHSF	0.760	0.78	2.31	2.10	3.310	3.100	0.058	0.062	0.046	0.043

Also dyeing as a relaxation process decreases the inter-fibre friction with significant reduction in bending rigidity and hysteresis. Due to the longer dyeing period and various conditions as compared to scouring, the adverse effect of heat setting on bending properties is reduced significantly. Slight increase in B and 2HB values after drying and a remarkable increase after heat setting are observed for both PLA and PET fibre fabrics. It can be attributable to fabric shrinkage and consequently the restriction of fibre and yarn movement within the fabric structure after these processes. The greatest effect on bending properties of both fabrics is observed after heat setting process. Decrease in B value is detected after softening of dyed PLA and PET materials. This could be explained by the decrease in inter-fibre and inter-yarn friction, and relaxation in stresses caused in the course of knitting. Approximately 35% and 25% reduction in bending hysteresis is detected for PLA and PET knitted fabrics after softening, which indicates the increased yarn and fibre mobility within the structure.

3.4 Compression Properties of Knitted Fabrics

The compressional characteristics of PLA and PET fibre fabrics after various production process stages are presented in Table 3. The compression energy reflects the fluffy feeling of the fabric. The fabric will appear fluffier when the value of compression energy is increased [35]. *RC* is the % of the extent of recovery, or the regain in fabric thickness when the applied force is removed. The greater the *RC* values the better is the retention ability of the fullness of the fabric after compression[36, 37]. Compression linearity reflects the elasticity of fabric after the removal of compression load.

The greige PET fibre exhibits higher compression values than the greige PLA fibre. Therefore, greige PET fabric becomes fluffier than greige PLA fabrics. It might be owing to the tighter and more compact structure of the PLA fibre fabrics. Also greige PET fabrics represent higher values of LC than greige PLA fabrics. Due to stronger changes in compressional properties after different production process stages, PLA fabrics show higher values of WC as compared to the finished PET fabrics. In this study, WC increases for both fabrics after each production process stage. In polylactic acid fibre fabrics, compression energy is increased by 23 % and 40 % after scouring and dyeing stages respectively. Overall, RC values of polylactic acid fibre and PET fibre fabrics decrease after scouring process and increase again after drying and heat setting. RC increase during different production process stages is much more in the case of PET fabrics in comparison to PLA fabrics. There is also an increase in compressional linearity for both knitted fabrics during different production process stages. The results show a slight development in compressional properties after the softening. This is most probably owing to the slight reduction in thickness and fabric volume. These softened fabrics display the highest value of LT in comparison to other finished materials for both fabrics.

3.5 Fabric Thickness and Weight

The changes in thickness and weight of PLA and PET fibre fabrics introduced by the different production process steps are shown in Table 3. There is a rise in fabric thickness and weight after different production process stages for both fabrics. This could be due to relaxation shrinkage after finishing stages. These changes are observed much more on PLA fabrics as compared to PET fabrics.

3.6 Surface Properties of Knitted Fabrics

The surface properties of the treated PLA and PET fabrics are shown in Table 4, which includes the friction coefficient (MIU), the mean deviation of friction

Table 3 — Changes in compression properties, weight and thickness of PLA and PET fabrics throughout different production processing stages

Sample	LC		WC, g.cm/cm		RC, %		W, g/m^2		T, mm	
	PLA	PET	PLA	PLA	PLA	PET	PET	PET	PLA	PET
GF	0.335	0.529	0.155	44.52	44.52	47.28	18.2	19.1	0.78	0.80
SGF	0.417	0.556	0.270	36.67	36.67	43.88	21.8	20.5	0.92	0.83
SDF	0.540	0.559	0.201	40.30	40.30	46.84	20.3	20.01	0.83	0.82
SDHF	0.459	0.570	0.171	41.52	41.52	49.71	21.3	20.4	0.84	0.80
DGF	0.538	0.606	0.246	41.06	41.06	50.49	24.8	20.5	0.92	0.83
DDF	0.479	0.578	0.225	40.44	40.44	49.78	24.7	20.3	0.92	0.84
HDDF	0.554	0.575	0.223	42.60	42.60	57.59	23.1	20.2	0.84	0.80
DHSF	0.585	0.637	0.228	40.79	40.79	47.54	22.5	20.6	0.84	0.80

Table 4 — Changes in surface properties of PLA and PET fabrics throughout different production processing stages

Sample	MIU		MMD		SMD, μm	
	PLA	PET	PLA	PET	PLA	PET
GF	0.368	0.333	0.107	0.079	10.66	9.02
SGF	0.288	0.270	0.066	0.076	10.51	7.62
SDF	0.247	0.253	0.040	0.036	7.370	7.67
SDHF	0.208	0.254	0.017	0.016	5.230	4.35
DGF	0.247	0.236	0.024	0.038	6.710	7.50
DDF	0.236	0.21	0.032	0.021	6.470	5.56
HDDF	0.207	0.219	0.031	0.022	5.870	4.14
DHSF	0.276	0.246	0.022	0.018	5.600	3.54

(MMD) and the geometrical roughness (SMD). The surface roughness is contingent upon yarn spacing irregularity and fabric geometrical factors. MIU indicates fabric smoothness, roughness and crispness. Higher MIU values correspond to greater friction or resistance to drag.

The findings show higher surface properties of PLA materials than PET materials. This means that the textile materials produced from polylactic acid fibre will be rougher than fabrics made from PET fibre. These results show a remarkable change in the properties during the production process stages for PLA and PET materials as compared to greige fabrics. Friction coefficient values decrease after scouring and dyeing steps for all processed samples. Relaxation shrinkage during scouring, drying, dyeing and heat setting reduces MIU, MMD and SMD values of both fabrics. It might be attributable to the tighter and more compact structure of the fabrics after shrinkage, resulting in the smoother fabric surface. Friction is determined not only by the contact surface, but also by the deformation at the contact points[36]. Another reason for the lower MIU value in the dyed fabrics could be due to the long treatment time at high temperature.

SMD decreases by 17 % and 52% after softening for PLA and PET fabrics respectively. After softening treatment, the yarns become softer and fewer spaces are left among them. In addition, softeners mask the irregularity of the knitted fabrics. In this way, the smoother fabric surface exhibits more contact with probe tip and it leads to increase the MIU value. After softening process, the coefficient of friction increases by 11% and 4 % for PLA and PET fabrics respectively.

4 Conclusion

The results exhibit remarkable changes in mechanical and surface characteristics of PLA and PET knitted fabrics after each processing stages, such as scouring, drying, dyeing, heat setting and softening treatments. PLA knitted fabrics represent higher values in bending, shear and surface properties after different processing stages in comparison to PET knitted fabrics. The scouring process results in the most remarkable changes in low-stress mechanical characteristics of PLA and PET fabrics. The values of bending rigidity (B), bending hysteresis (2HB), shear stiffness (G), and shear hysteresis (2HG and 2HG3) significantly decrease after the scouring treatment of knitted fabrics. On the other hand, tensile energy (WT), tensile elongation (EMT) and surface friction (MIU) increase. There are considerable decreases in bending rigidity (B), bending hysteresis (2HB), shear stiffness (G), and shear hysteresis (2HG and 2HG3), and an improvement in tensile elongation (EM) after dyeing of PET and PLA fabrics. A slight reduction in shear and bending properties of PLA fabrics shows that softener treatment decreases the inter-fibre and inter-yarn friction. LT (linearity of load-extension curve), RT (recovery from tensile deformation), LC (linearity of compression curve) and RC (recovery from compression deformation) properties are not found quite sensitive for different production processing stages for both fabrics.

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