Antimicrobial behavior, low-stress mechanical properties and comfort of knitted fabrics made from (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid filaments and cotton yarns

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Abstract

This article presents a systematic investigation of knitted fabrics made from various blends of intrinsically antimicrobial poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid filaments and cotton staple fibers. The effects of blend yarn and fabric structures, distributions of fibers on antimicrobial properties of resultant yarns and knitted fabrics were studied. The relationships among fiber distribution, blend ratio and anti-microbial properties were experimentally determined for three blend yarns made by Sirofil, wrap-spun and core-spun spinning technologies. The fabrics made from the Sirofil-spun and wrap-spun yarns show better anti-microbial effect against *Staphylococcus aureus* (*S. aureus*), *Klebsiella pneumoniae* (*K. pneumoniae*) and *Candida albicans* (*C. albicans*) than those of the core-spun yarns, according to the standard AATCC100-2012 Antibacterial Finishes on Textile Materials (American Association of Textile Chemists and Colorists, 2012). An alternative blending method of co-knitting of the pure poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid yarns and cotton yarns achieved excellent antimicrobial effect. Furthermore, a wearing trial of underwear made from the blend knitted fabrics was conducted in a nursing home. The wearing comfort of the garments, low-stress mechanical and surface properties of fabrics were evaluated objectively by Kawabata Evaluation System of Fabric (KESF) system and subjectively by a questionnaire survey to users.

Keywords
Fiber distribution, fiber blending, yarn and fabric structure, antimicrobial property, comfort, performance, poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid

Due to the increased awareness towards health threats imposed by COVID-19 pandemic and environmental protection, much more attentions have been focused on safe and durable anti-viral and anti-bacterial textiles made from renewable bio-based materials[1-7]. Currently, new fibers and textile manufacture technologies have been explored by many researchers, such as environmentally friendly and advanced textile techniques to enhance the mechanical abilities of ramie/PLA composites[8], and for the antimicrobial textiles in the market, they are made from either natural or synthetic antimicrobial fibers or by surface finishing of anti-microbial agents[9-11]. Natural antimicrobial materials such as lignin and chitosan are bio-based, degradable and eco-friendly. However, their antimicrobial effect is limited and inconsistent from batch to batch[12-17]. Synthetic antimicrobial fibers or surface treatments possess good effect, but their functional components are normally added into the fibers thus may fade away in washing. Many of them lead to environmental pollution by the added agents, such as silver (Ag) nanoparticles, ZnO and copper salts[18-24]. Besides, organic antimicrobial materials are also commonly used nowadays, including quaternary ammonium, polybiguanides, and N-halamine materials[25-27]. However, their functional modification on the surface of materials still exhibits poor durability, and this can bring with some serious effects on the environment.[28]

In 2016, we firstly discovered that textile fabrics made from poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA) filaments were bio-based, renewable and degradable, and exhibited wide spectrum antimicrobial effects against *S. aureus*, *K. pneumoniae* and *C. albicans* without any chemical agents[29]. Then, a range of antimicrobial textile products were developed and mass-produced, including yarns, knitted and woven fabrics, socks, compression stockings, shoe uppers, non-adherent absorbent pad and bandage[30]. Low temperature dyeing process was developed specifically for PHBV/PLA textiles with a significant energy saving of 32% as compared with the normal dyeing process of polyester textiles[31]. We also determined the minimum inhibition concentration (MIC) values of the agents required for various microbial types, which are crucial to make effective antimicrobial fibers and textiles. Because of our discovery and determination of MIC values, an effective manufacturing process and quality assurance methods have been developed jointly with the companies for mass producing antimicrobial fibers and fabrics with consistent high quality. The antibacterial ingredient polyhydroxybutyrate (PHB) of PHBV/PLA material is not only a great candidate for antimicrobial modification but also a promising one for biomedical applications. Most importantly, the active ingredient PHB of PHBV/PLA material is also reactive to drug-resistant bacteria. And the antimicrobial mechanisms of the PHB are revealed, mainly including disruption of biofilm and the bacterial wall/membrane, leakage of the intracellular content, inhibition of protein activity, and change in the transmembrane potential[32]. Meanwhile we also investigated the effect of polyethylene glycol (PEG) on the antimicrobial effect of PHB oligomer. It was deducted that PEG promoted the antimicrobial effect of PHB oligomer synergistically through dissolution/dispersion, which improved the hydrophilicity of PHB oligomer[33].

In this study, we explored the effects of blending of anti-microbial PHBV/PLA fibers with natural cotton fibers with respect to yarn or fabric structure and blend ratio. We postulated and tested a hypothesis that the preferential distribution of the anti-microbial fibers in the yarn or fabric structures will produce enhanced antimicrobial property with a low blend ratio. Three blend yarn structures were purposely designed and fabricated by Sirofil, wrap-spun and core-spun production technologies. Poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/Cotton co-knitting fabrics with side-by-side feeding were to be investigated as an alternative way to achieve fiber preferential distribution in a blend fabric. The relationships among the fiber distribution, blend ratio and anti-microbial property of PHBV/PLA/cotton knitted fabrics were investigated. Finally, a wear trial of antimicrobial underwear was carried out by using selected best performing PHBV/PLA/cotton blend fabrics in a nursing home. The comfort and pilling performance were evaluated both objectively and subjectively.

Experimental

Materials Used

PHBV/PLA multi-filaments were obtained from Ningbo Hesu Fibers Co. Ltd, and the cotton was from the Nanjing Bioserica Era Antibacterial Materials Technology Co., Ltd. All of the adopted filaments were fully drawn filament yarns (FDY) with yarn count 150D/48f and 75D/48f (D represents Denier; f represents the no. of mono-filaments), and the linear density of cotton is 6700 metric count and length of fiber 37mm.

Fiber Blending by Yarn Spinning

To achieve the best performance with a reduced material cost, blend yarns are often the preferred choice rather than pure hydrophobic PHBV/PLA yarns. Thus, we aimed at the optimization of antibacterial property of PHBV/PLA/cotton blend yarns and fabrics by adjusting the yarn structure and blend ratio. The schematic diagram of three blend yarn structures are shown in Figure 1, as the cross-sectional distribution of fibers Type 1 (Sirofil): the antimicrobial fibers are located at one side of the yarn; Type 2 (wrap-spun): the antimicrobial fibers at outer side; Type 3 (core-spun): the antimicrobial fiber at the inner part of the yarn. The blue color represents the antimicrobial fibers, such as PHBV/PLA fibers, and the yellow represents the cross-section of non-antimicrobial fibers, such as cotton fibers.

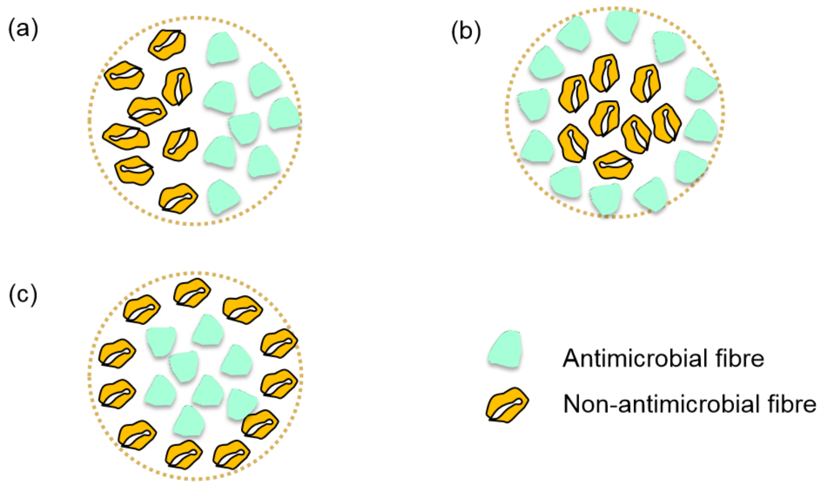


Figure 1. Schematic diagram of distribution of fibers in yarn cross-section. (a) Type 1: sirofil structure with antimicrobial fibers at one side; (b) Type 2: wrap-spun structure with antimicrobial fibers at outer side; (c) Type 3: core-spun structure with antimicrobial fibers inside.

To realize the above distribution of fibers in yarn cross-section, three spinning methods were utilized, including sirofil spinning, wrap spinning, and core spinning as shown in Figure 2. PLA/PHBV/cotton blend yarns have been manufactured by utilizing the three spinning systems: spinning systems: a spinning frame (Zinser 351) was used for sirofil yarn and core-spun yarn spinning, and a wrap machine (Type: SFM32-04) was used for wrapspun yarn spinning. The cross-sectional images of the PLA/PHBV/cotton blend yarns obtained from an optical electron microscope (Leica: DM2700) and Figure 3 shows which distribution of fibers corresponds to the above fiber distribution designs.

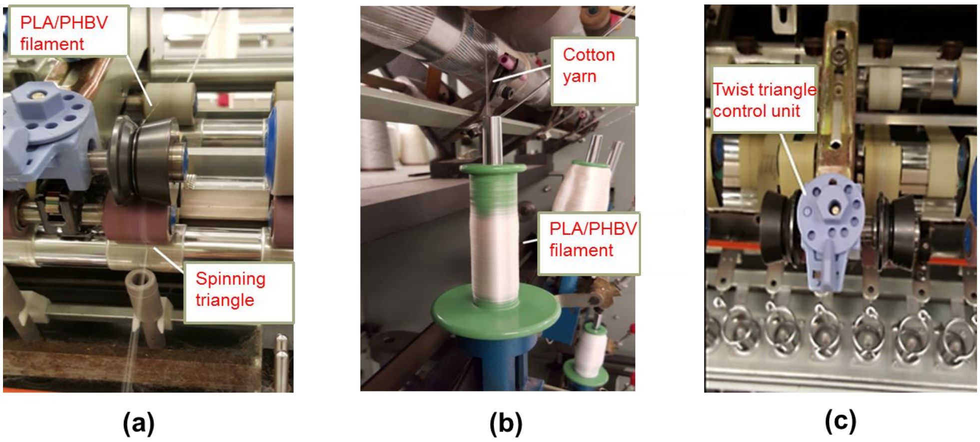


Figure 2. Poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton blend yarn manufacturing systems: (a) sirofil spinning; (b) wrap spinning; (c) core spinning

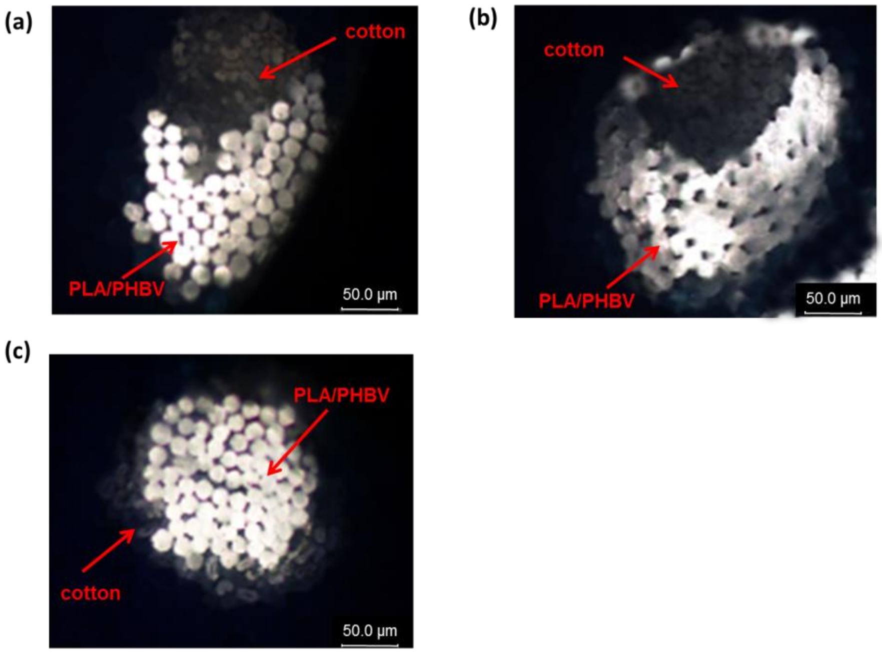


Figure 3. Fiber distribution of poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton blend yarns in crosssection. (a) Type 1: sirofil structure with PHBV/PLA antimicrobial fibers at one side; (b) Type 2: wrap-spun structure with PHBV/PLA antimicrobial fibers at outer side; (c) Type 3: core-spun structure with PHBV/PLA antimicrobial fibers inside

Table 1 lists the specification of various kinds of PHBV/PLA/cotton blend fabrics. There are three PHBV/PLA/cotton blend yarns spun by the sirofil ring spinning machine, three blend yarns spun by the wrap spinning machine, and three blend yarns spun by the ring spinning machine. A Bainlong circular knitting machine with a gauge of 28 needles per inch was adopted for producing single jersey knitted fabrics made of the nine blend yarns, respectively, as shown in Table 1.

Table 1. Specifications of poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton blend single jersey fabrics

Fabric code	Fiber composition	Percentage of PHBV/PLA (%)	Yarn types
Sirofil-22.36	75D/48f PHBV/PLA filament/20Ne cotton yarn	22.36	Sirofil-spun yarns
Sirofil-52.98	150D/48f PHBV/PLA filament/40Ne cotton yarn	52.98	Sirofil-spun yarns
Sirofil-62.96	150D/48f PHBV/PLA filament/60Ne cotton yarn	62.96	Sirofil-spun yarns
Wrap-22.36	75D/48f PHBV/PLA filament/20Ne cotton yarn	22.36	wrap-spun yarns
Wrap-52.98	150D/48f PHBV/PLA filament/40Ne cotton yarn	52.98	wrap-spun yarns
Wrap-62.96	150D/48f PHBV/PLA filament/60Ne cotton yarn	62.96	wrap-spun yarns
Core-22.36	75D/48f PHBV/PLA filament/20Ne cotton yarn	22.36	core-spun yarns
Core-35.62	75D/48f PHBV/PLA filament/40Ne cotton yarn	35.62	core-spun yarns
Core-52.98	150D/48f PHBV/PLA filament/40Ne cotton yarn	52.98	core-spun yarns

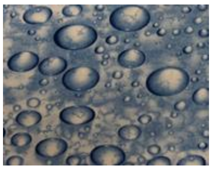
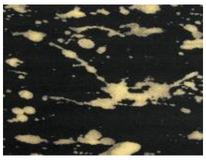
Notes: D is the denier; f is the number of mono-filament; Ne is a multiple of 840 yards of one-pound yarn under a constant moisture regain rate.

Fiber Blending by Co-knitting with Side-to-side Feeding

Alternatively, preferential fiber distribution can be achieved by co-knitting of pure PHBV/PLA and pure cotton yarns using a side-by-side feeding mechanism. The knitted fabrics have two sides, one side made by cotton fiber in front, and the other is made by 100% PHBV/PLA filament in back. Five kinds of such co-knitted interlock fabrics were knitted by Interlock Circular Knitting Machine and printed by Digital Printing Machine (Type: EPSON MONNA LISA EVO TRE). Dye stuffs used with various concentrations, dye-blue and black reducing cleaner of acid (RCA), are from YUANYUAN TEXTILE AUXILIARIES LTD of China. The specifications of the produced PHBV/PLA/Cotton co-knitted fabrics are exhibited in Table 2.

Table 2. Specifications of poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton co-knitted interlock fabrics

Fabric code	View of fabric pattern	Materials	Concentrations of dyes used (ml/meter)	Density of fabric	Fabric weight (g/m^2)	Printing process

S-1		56% PHBV/PLA (B), 44% cotton (F)	0	37.8 wales/inch, 42.0 courses/inch	170	Nil
S-53		56% PHBV/PL (B), 44% cotton (F)	1.5	37.0 wales/inch, 41.0 courses/inch	170	Digital Printing
S-67		56% PHBV/PL (B), 44% cotton(F)	2.0	38.2 wales/inch, 39.0 courses/inch	170	Digital Printing
S-79		56% PHBV/PL (B), 44% cotton (F)	2.0	39.2 wales/inch, 38.0 courses/inch	170	Digital Printing
S-85		56% PHBV/PL (B), 44% cotton (F)	1.0	40.2 wales/inch, 37.0 courses/inch	170	Digital Printing

Procedure of Antimicrobial Test

Microbial: *Staphylococcus aureus (S. aureus)* ATCC (American Type Culture Collection) No. 6538, *Klebsiella pneumoniae (K. pneumoniae)* ATCC (American Type Culture Collection) No. 4352 and *Candida albicans (C. albicans)* ATCC (American Type Culture Collection) No. 10231 were used as the gram-positive, gram-negative and general fungus respectively to investigate the antimicrobial property of the fabrics. The test was on a selected side (back) of the fabric.

Methodology: The antimicrobial property of fabric samples was conducted according to the standard AATCC 100-2012 Antibacterial Finishes on Textile Materials (American Association of Textile Chemists and Colorists, 2012). The equation for calculating the percentage reduction could be expressed as follows:

$$R = (B - A)/B * 100\ \% \quad (1)$$

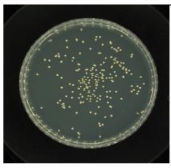
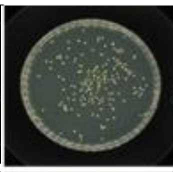
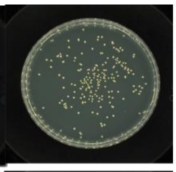
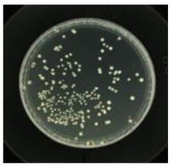
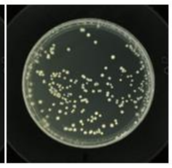
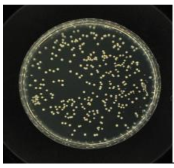
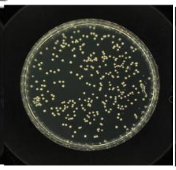
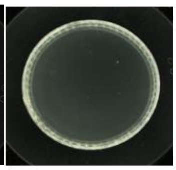
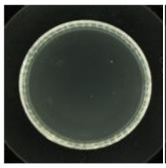
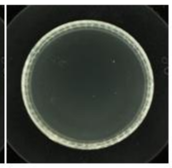
where: R (%) is the percentage reduction, A is the number of bacteria recovered from the inoculated treated test specimen swatches in the jar incubated over the desired contact period (at “18” contact time) B is the number of bacteria recovered from the inoculated treated test specimen swatches in the jar incubated over the desired contact period (at “0” contact time).

Results and discussion

Antimicrobial Property of Fabrics Made from Pure Cotton and PHBV/PLA Yarns

A pure cotton knitted fabric used and a pure PHBV/PLA filament knitted fabric were fabricated by circular knitting machine and chosen to conduct the antimicrobial testing. Table 3 shows the antimicrobial property of the pure cotton fabric and pure PHBV/PLA filament fabric. It is shown clearly that the PHBV/PLA multifilament fabric possesses excellent antimicrobial property by 99.99% reduction against *S. aureus*, *K. pneumonia* and *C. albicans* while the cotton fabric performs no antimicrobial property by 0% against *S. aureus, K. pneumonia* and *C. albicans.*

Table 3. Antimicrobial property of cotton and poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA) filament fabrics used

Fabrics	**Cotton fabric**			**100% PHBV/PLA filament fabric**		
Microbial	*S. aureus*	*K. pneumoniae*	*C. albicans*	*S. aureus*	*K. pneumoniae*	*C. albicans*
0h						
18h						
Percentage Reduction (%)	**0**	**0**	**0**	**> 99.99**	**> 99.99**	**> 99.99**

Effect of Blend Yarn Structure on the Antimicrobial Property

Nine blend fabrics made from Sirofil, wrap- and core-spun yarns have been chosen for the antimicrobial tests conducted according to the standard AATCC 100-2012. The time interval of culture of bacteria and materials is 18 hours. Figure 4 illustrates the percentage reduction against microbial of PHBV/PLA/cotton blend fabrics. As it is apparently demonstrated that the fabrics made by Sirofil-spun and wrap-spun yarns show better microbial inhibition effect against *K. pneumonia, C. albicans* and *S. aureus* than the fabrics made by core-spun yarns for all three types of microbial tested. Meanwhile, it is also apparently illustrated that the microbial inhibition effect against *K. pneumonia, C. albicans* and *S. aureus* of PHBV/PLA/cotton blend fabrics is improved with the increase of blend ratio of PHBV/PLA fibers firstly, then obtains better and stable microbial inhibition as shown in Figure 4. And when the blend ratio of PHBV/PLA fibers is the same, the antimicrobial property is determined by the distribution of the PHBV/PLA fibers. Thereby for the fiber distribution against the antimicrobial property, it is also clearly shown that the samples of Sirofil (Antimicrobial fiber distribution at one side) and wrap-spun (Antimicrobial fiber distribution at outer side) obtain much better percentage reduction of microbial than the samples of core-spun (Antimicrobial fiber distribution at inner side). More specifically, the effective antimicrobial property of PHBV/PLA fiber is related to the location and quantity of antimicrobial fiber in term of the surface of fabrics, such as the PHBV/PLA fiber at one side or outer side obtains much better antimicrobial property than that of inner side. Compared with core-spun fabrics，the sample of wrap-spun has much more antimicrobial PHBV/PLA fiber in the surface of knitted fabric, which performs much better antimicrobial property against *K. pneumonia*, *C. albicans* and *S. aureus*.

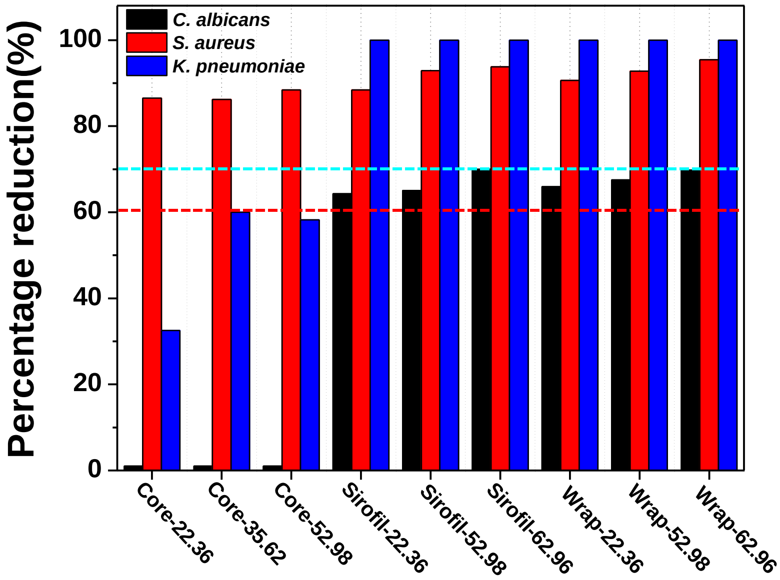


Figure 4. Percentage reduction against microbial of poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton blend fabrics. The purple and green lines represent the industrially acceptance levels for bacteria and fungi, respectively.S. aureus: Staphylococcus aureus; K. pneumoniae: Klebsiella pneumoniae; C. albicans: Candida albicans.

Effect of Co-knitting of Pure Antimicrobial PHBV/PLA and Pure Cotton Yarns

The samples of S-1-B S-53-B, S-67-B, S-79-B and S-85-B had 100% PHBV/PLA filaments at the back of the co-knitted interlock fabrics, while the S-1-F, S-53-F, S-67-F, S-79-F and S-85-F had 100% PHBV/PLA fibers in the front of co-knitted interlock fabrics. The antimicrobial tests were conducted on the back side of fabric samples. Figure 5 presents the percentage reduction against microbial of the PLA/PHBV/cotton knitted fabrics. The red and blue lines are the current industrial requirement for bacteria and fungi, respectively. There is no apparent antimicrobial property at all against *K. pneumoniae*, *C. albicans* and *S. aureus* by all samples S-1-F, S-53-F, S-67-F, S-79-F and S-85-F, where the cotton fibers are located in the back (tested) side. All the samples where PHBV/PLA fibers are located in the tested side display positive antimicrobial effects. They all reach the required antibacterial level indicated by the red line but a printed fabric (S-67-B) with highest concentration of dye stuff 2.0 ml/meter more than other digital printing fabrics fails the required anti-fungi level (blue line).

Among all the samples with PHBV/PLA on the tested back side, the S-1-B sample without printing and S-85-B with printing obtain the best antimicrobial property. Printing does have some effects especially for the fungi reduction, which may be due to usage of different dye stuffs in printing process as shown in Table 2.

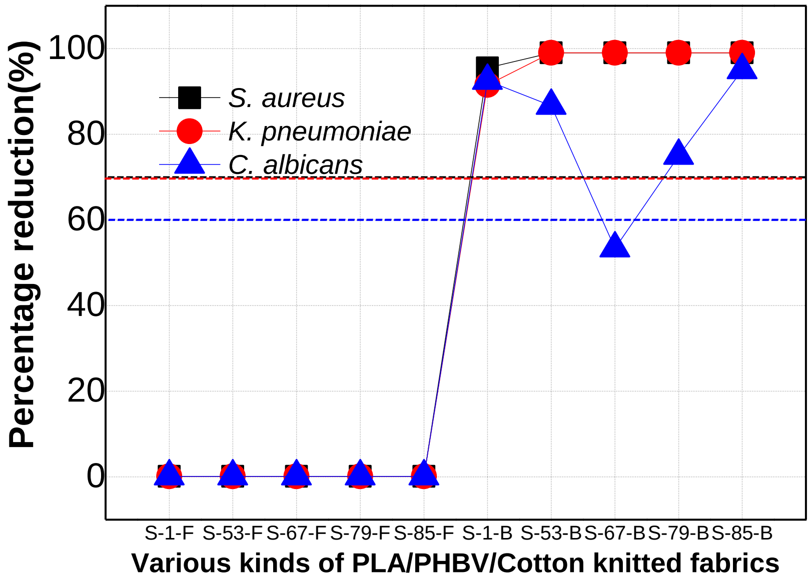


Figure 5. Percentage reduction against microbial of the poly(hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton co-knitted fabrics. The red and blue lines are the current industrial requirement for bacteria and fungi, respectively. S. aureus: Staphylococcus aureus; K. pneumoniae: Klebsiella pneumoniae; C. albicans: Candida albicans.

Handle and Comfort of PHBV/PLA /cotton Co-knitted Fabrics

Based on preferential fiber distribution against antimicrobial and exploration of new produced PHBV/PLA/cotton digital printing fabrics, the performance evaluation tests of the 5 kinds of PHBV/PLA/cotton co-knitted fabrics have been conducted, including tensile and shear, bending property, compression property and surface property.

Figure 6 describes the low-stress mechanical and surface properties of the PHBV/PLA/cotton co-knitted fabrics evaluated by KESF system. The five various kinds of PHBV/PLA/cotton co-knitted fabrics were chosen and conducted the experiments on handle-feeling performance. The tensile and shear property of five co-knitted samples were conducted in terms of extension rate by utilizing an apparatus: KES FB1-AU-A Automatic Tensile &Shear Tester. The higher the extension rate, the greater stretchability of the specimen will have. As exhibited in Figure 6 (a), PHBV/PLA/cotton knitted fabric (S-1) possesses the highest extension rate (27.3% in course and 22.6% in wale) compared with the other fabric samples. The five PHBV/PLA/cotton co-knitted fabrics in course direction possess a relatively higher extension rate, markedly higher than those in wale direction.

The bending characteristic is useful for determining stiffness and fullness, softness, anti-drape stiffness of textiles. The KES-FB2-A Pure Bending Tester analyzes hand movements – referred to as “bending” – performed by artisans and professionals when judging a fabric’s texture. This device performs these movements mechanically, making it possible to obtain objective numerical data. By using KES-FB2-A, the bending rigidity of five types of co-knitted fabrics was measured, as shown in Figure 6(b). Bending rigidity is related to the perceived out-plane deformation resistance of fabric. If the bending rigidity is lower, it is indicated that the fabric is bent more easily. The PHBV/PLA/cotton fabric (S-1) has a moderate bending rigidity of 0.0181 g. cm^2/cm in wale and 0.0133 g.cm^2/cm in course, similar to the fabric S-67. The S-53 has the lowest bending rigidity of 0.0124 g. cm^2/cm in course and 0.121 g. cm^2/cm in wale compared to other printed knitted fabrics.

Compression characteristic is also useful to determine textile fullness, softness, and smoothness. The KES-FB3-A Compression Tester analyzes hand movements– particularly, pushing with a finger – performed by artisans and professionals when judging a fabric's texture. Compression energy of the knitted samples was measured by using KES FB3-A as displayed in Figure 6(c). The higher the compression energy is, then the higher the compression susceptibility is. The PHBV/PLA/cotton (S-1) co-knitted fabric has slightly higher compression energy of 0.369 g. cm^2/cm than that of co-knitted fabrics with digital printing, which results from the cotton fiber without printing treatment obtaining more porosity and high elasticity. The fabric sample S-79 obtains the lowest compression energy of 0.210 g.cm^2/cm, which means it has the highest compression susceptibility. Compared with other samples, the reason is that the higher dyestuffs used by 2.0 ml/m under the same printing process, and thus the fabric gains less fullness leading to lower compression susceptibility.

The geometrical roughness is a characterization of the variation of fabric thickness around the central point, located at the center of the lowest and highest places on the tested fabric surface. Figure 6(d) exhibits the geometrical roughness of co-knitted fabric samples. Geometrical roughness is measured by using the KES FB4-AUTO-A Automatic Surface Tester. The lower the value of geometrical roughness is, the smoother the fabric surface will be. The geometrical roughness of co-knitted fabric sample S-1 (1.440 mm) is close to those of S-67, S-79, and S-85. The S-53 gains the lowest geometrical roughness of 1.110 mm, which demonstrates that it has the smoothest surface.

The thermal properties of the five types of co-knitted fabrics were measured by KES-F7 Thermo Labo II in terms of "Qmax." The sensation of coldness or warmth when skin touches a fabric is referred to as the "coldness and warmth feeling." The feeling of coldness or warmth will vary depending on the amount of heat transferred from the skin to the fabric. This device measures that feeling by evaluating the Qmax value. The Qmax value means the peak value of the heat flow measured immediately when the heated plate touched the fabric specimen surface. The higher the Qmax, then the cooler the person can feel. As illustrated in Figure 6(e), there is no marked difference among the five samples in terms of Qmax. However, it clearly shows that the Qmax value of sample S-1 (fabric without digital printing) is still a little lower than that of the other four digital printing fabrics S-53, S-67, S-79 and S-85, which means that sample S-1 obtains higher warmth compared with other digital fabric samples. The reason is that the cotton fiber without printing treatment has the advantages of more porosity and high elasticity, and thus a lot of air can accumulate among the fibers. As the air is also a poor conductor of heat and electricity, thus the fabric sample S-1 has better warmth preservation.

The permeating resistance to the air of fabric is generally affected by fiber cross-sectional shape and dimension, yarn structure, and fabric structure. The KES-F8-AP1 tester was utilized to test the permeating resistance to the air of the five co-knitted fabrics. The KES-F8-AP1 Air Permeability Tester is designed to quickly and accurately measure the breathability and permeability of a wide range of samples, from those with high permeability, such as stockings, to those with low permeability, such as synthetic leather. Figure 6(f) presents the air permeability of five types of co-knitted fabric samples. The fabric sample S-1 has a higher permeating resistance to the air of 0.064 kPa.s/m than that of the other four printing samples obtaining similar permeating resistance S-53 of 0.0438 kPa.s/m, S-67 of 0.0455 kPa.s/m, S-79 of 0.0397 kPa.s/m, andS-85 of 0.0402 kPa.s/m. The lower the permeating resistance to air, the better the air permeability of the specimen.

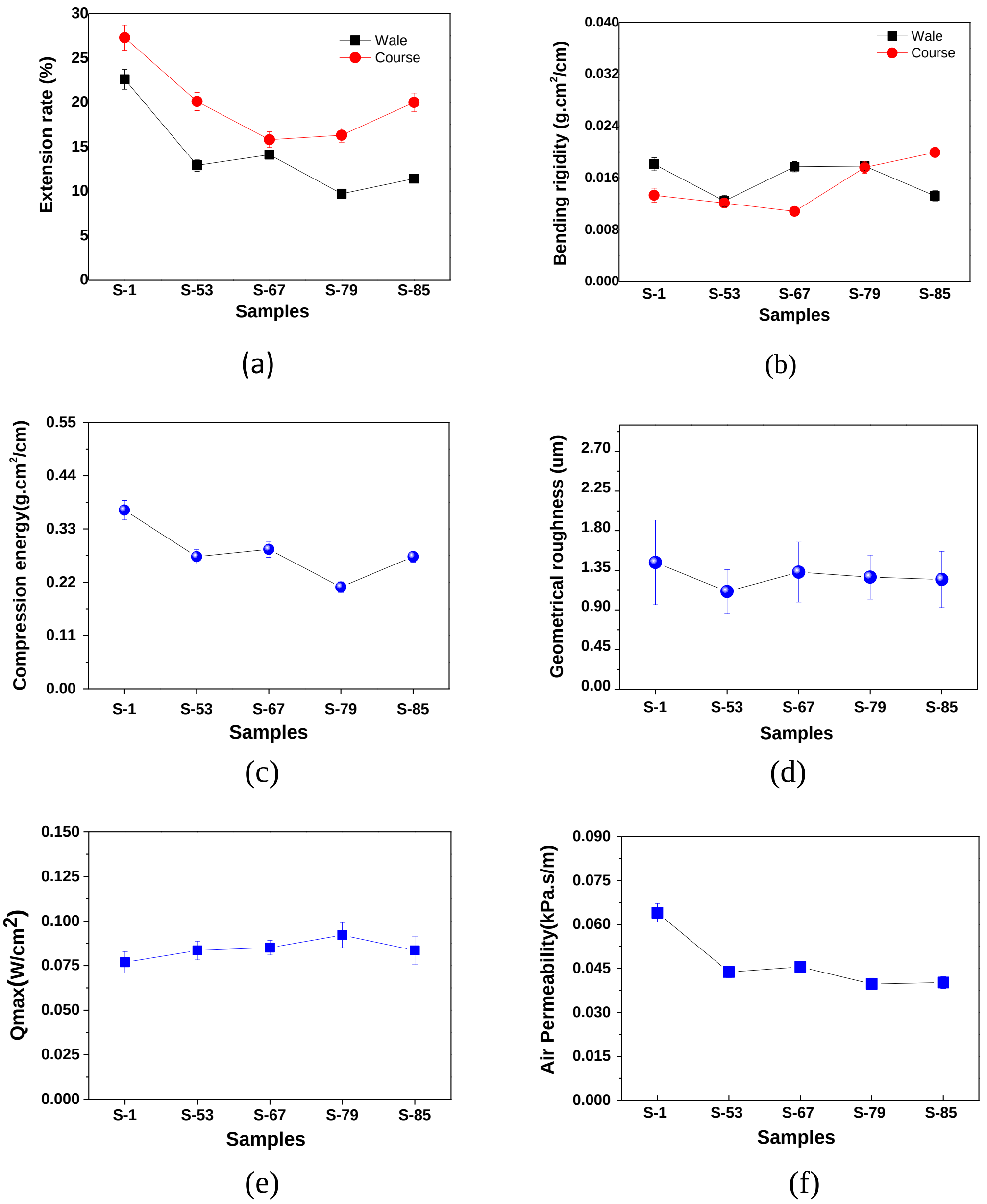


Figure 6. Low-stress mechanical and surface properties of the poly (hydroxybutyrate-co-hydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton co-knitted fabrics evaluated by the Kawabata Evaluation System of Fabric (KESF) system: (a) extension rate of co-knitted fabric samples; (b) bending rigidity of co-knitted fabric samples; (c) compression energy of co-knitted fabric samples; (d) geometrical roughness of co-

knitted fabric samples; (e) Qmax of co-knitted fabric samples; (f) air permeability of co-knitted fabric samples.

Pilling Performance of PHBV/PLA /Cotton Co-knitted Fabrics

The pilling property of the five kinds of PHBV/PLA/cotton co-knitted fabrics S-1, S-53, S-67, S-79, and S-85 have been tested via using the Martindale Method (ASTM D4966-12). Figure 7 illustrates the percentage loss in the mass of PHBV/PLA/cotton co-knitted Fabrics after 2000 and 20,000 cycles of rubbing. It shows that there is no significant difference among the five fabrics after 2000 cycles of rubbing, but after 20,000 cycles of rubbing, the percentage loss in the mass of S 1 (100% cotton fabric) has reached the highest value 12.74% compared to the other four printing fabrics S-53, S-67, S-79, and S-85. This demonstrates that the printed fabric has better resistance to abrasion than that of non-printed cotton fabric. More specifically, the fabric made with PHBV/PLA fiber has better pilling resistance than the knitted fabrics made with cotton fiber.

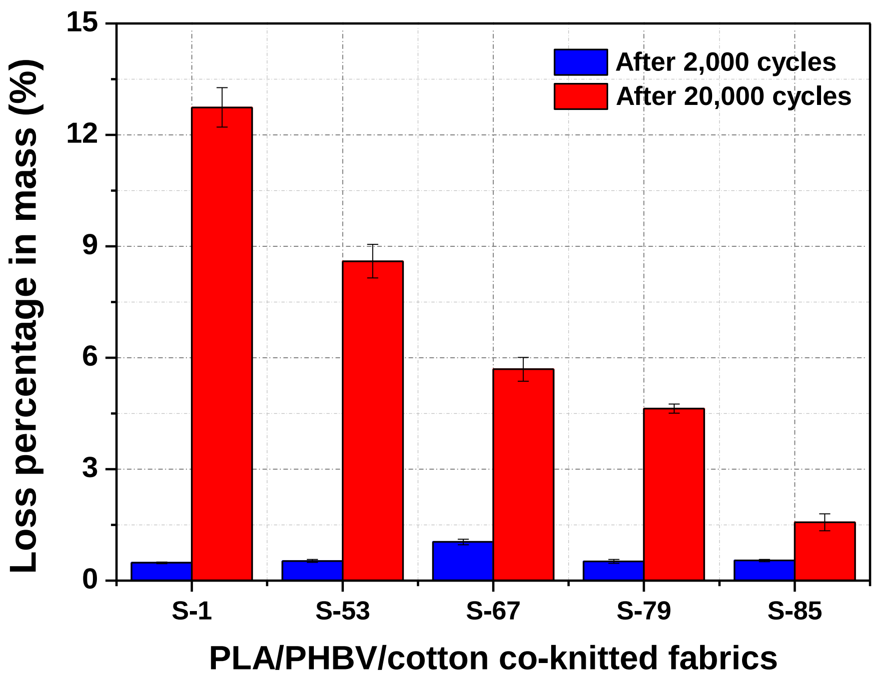


Figure 7. Loss percentage in mass of poly (hydroxybutyrate-cohydroxyvalerate)/polylactide acid (PHBV/PLA)/cotton co-knitted fabrics after 2000 and 20,000 cycles of rubbing

Trial Protocol of Antimicrobial Underwear

To exhibit the apparently the excellent antimicrobial and mechanical performance of PHBV/PLA/cotton textile samples in practical application, a wear trial for elderly with limited mobility was conducted by questionnaires and interview once three weeks in the Lok Sin Tong Benevolent Society Knowledge of Hong Kong. The samples chosen were underwear, including underwear and pants. 40 elderly, 80 to 95 years old, with limited mobility and dry skin problems were involved the wear trial lasting for 12 weeks. The more detailed information is listed as follows: 20 subjects wore Control (cotton) underwear; 20 subjects wore the antimicrobial underwear (56%

PHBV/PLA and 44% cotton co-knitted interlock structure); The elderly have their own individual bags for storing soiled underwear, and their clothes were washed together once every two days by using washing machine with temperature around 33℃ and drying machine with common practice.

Figure 8 displays the subjective assessment of the underwear from questionnaire surveys: (a) softness of the underwear; (b) warmth of the underwear; (c) breathability of the underwear; (d) pilling resistance of the underwear. The performance of underwear was evaluated and marked according to the satisfaction by the subjects in terms of softness, warmth, pilling resistance and breathability. As indicated in Figure 8 (a), our PHBV/PLA/cotton antimicrobial underwear samples obtain better satisfaction by more than 4 grade on the level of softness, similar to the satisfaction of control sample from the questionnaire surveys after 12 weeks, meanwhile compared with control samples there are also similar satisfaction level of PHBV/PLA/cotton in warmth, pilling resistance and breathability when the subjects completed the wear trial as illustrated in Figure 8 (b)-(d).

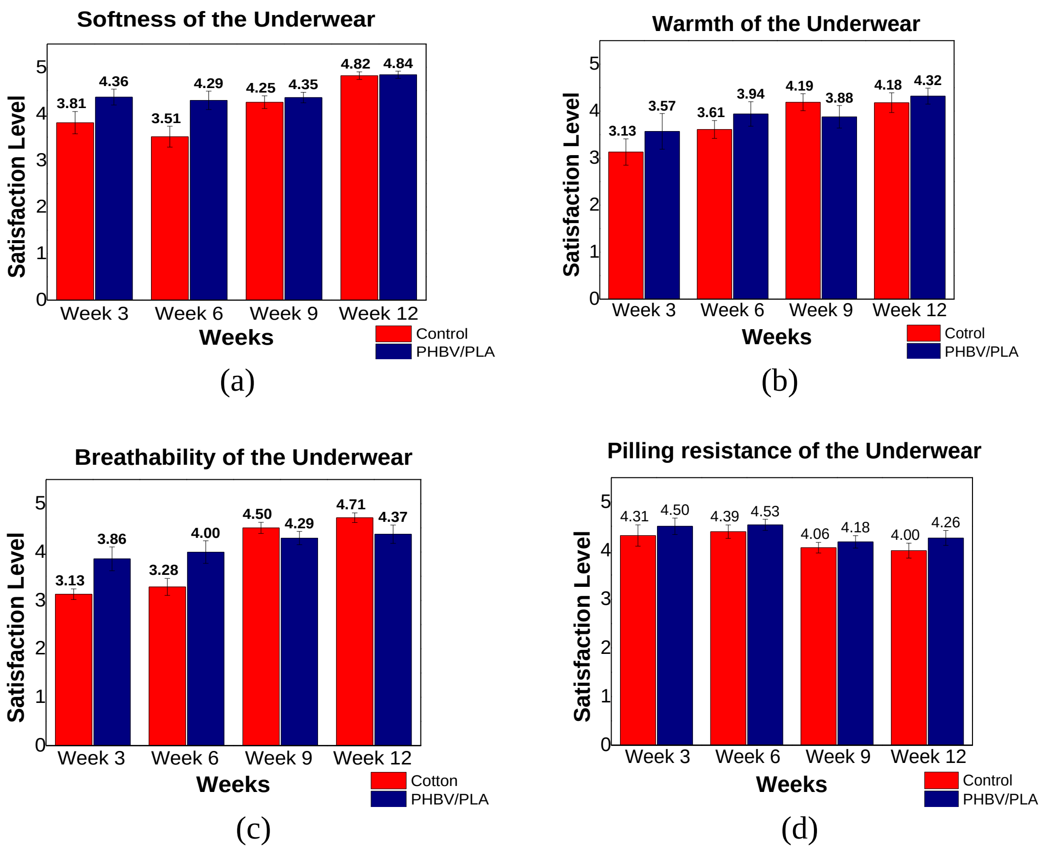


Figure 8. Handle performance of the underwear from questionnaire surveys: (a) softness of the underwear; (b) warmth of the underwear; (c) breathability of the underwear; (d) pilling resistance of the underwear.

Conclusions

In this study, we postulated and tested a hypothesis that the preferential distribution of the anti-microbial fibers in the yarn or fabric structures produces enhanced antimicrobial property with a low blend ratio. The fabrics made from the Sirofil-spun and wrap-spun yarns show better anti-microbial effect against *Staphylococcus aureus* (*S. aureus*), *Klebsiella pneumoniae* (*K. pneumoniae*) and *Candida albicans* (*C. albicans*) than those of the core-spun yarns, according to the standard AATCC100-2012.

An alternative blending method of co-knitting of the pure PHBV/PLA yarns and cotton yarns achieved excellent antimicrobial effect. The relationships among the fiber distribution, blend ratio and anti-microbial property of PHBV/PLA/Cotton knitted fabrics were determined. The effective antimicrobial property of PHBV/PLA/cotton blend fabrics is related to the location and quantity of PHBV/PLA fiber in term of the surface of blend fabrics.

Finally, a wear trial of underwear made from the blend knitted fabrics was conducted in a nursing home. The wearing comfort of the garments, low-stress mechanical and surface properties of fabrics were confirmed by Kawabata Evaluation System of Fabric (KESF) system objectively and by a questionnaire survey among users subjectively.

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