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Eco-friendly and Durable Antibacterial Cotton Fabrics Prepared with Polysulfopropylbetaine

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Abstract: A novel antibacterial agent polysulfopropylbetaine (PSPB) bearing carboxyl groups was synthesized and its application on cotton fabric to provide durable antibacterial property was also presented. The successful synthesis of PSPB and its immobilization onto the cotton fabric surface were verified by a series of tests including FTIR, ^{1}H NMR, XPS and SEM. Viable cell counting method was employed to investigate antibacterial properties of the finished cotton fabrics. It was found that the cotton fabrics treated with PSPB were endowed with desirable antibacterial activity against both gram-negative bacteria *Esherichia coli* (*E.coli,* AATCC 6538) and gram-positive bacteria *Staphylococcus aureus* (*S.aureus,* AATCC 25922), with the bacterisotatic rates of 99.69 % and 99.95 %, respectively. Notably, the bacterial reduction rates still maintained over 90 % against both bacteria even after 50 consecutive laundering cycles. Moreover, tests concerning the hydrophilicity, air permeability, water vapor transmission, mechanical properties as well as thermal properties were carried out systematically. The experimental results indicated the hydrophilic performance, air permeability and moisture penetrability of the cotton fabrics finished with PSPB were improved greatly in spite of a slight reduction in thermal performance and little obvious influence on mechanical performance. The antibacterial cotton fabric has the potential to be applied in sportswear, underwear, household textiles, medical fields and much more.

Keywords: Antibacteria, Betaine, Cotton fabric, Finishing, Durability

Introduction

Cotton textile has been highly favored owing to its excellent moisture permeability, wearing comfortability and good biodegradability, etc [1-3]. Nevertheless, its extremely easy to cause the growth of bacteria bringing about the degradation of wearability exerts adverse effect on human health [4,5]. Therefore, the development of cotton textiles with antibacterial activity is especially necessary and significant. Currently, effective antibacterial finishing agents cover inorganic antibacterial agents such as heavy metal ions, metal oxide nanoparticles [6,7] and photocatalytic metal compounds [8,9], organic antibacterial agents including quaternary ammonium compounds (QACs) [10-12], halamine compounds [13,14], etc, as well as natural antibacterial agents consisting of chitosan and its derivatives [15-17]. There are some disadvantages existing in these antibacterial agents mentioned above which limit the scope of their application. Specifically, the heavy metals and their ions such as Ag and Cu toxic to the environment, are liable to leach gradually from the textiles, which brings about pollution and lessens fabric luster. While the photocatalytic metal oxides only possess the exact antibacterial activities when they are exposed to the UV light, which may cause the biodegradation of cotton textiles. In addition, QACs also hold pointed weaknesses. Apart from their poor compatibility with anionic adjuvants and poor thermal stability, QACs antibacterial finishing agents give rise to drug resistance. The deficiency of N-halamine antibacterial finishing agents lies in chlorine residues on cotton textiles producing strong smell and damaging the fibers. On the other hand, chitosan and its derivatives used as antibacterial finishing agents tend to be confined to acidic conditions and poor in durability, thermostability and water-solubility. As well, the handle of textiles finished with chitosan remains to be improved [18-20]. Consequently, it is vitally significant to explore a new eco-friendly antibacterial finishing agent exhibiting high-efficiency, broad-spectrum and durable antimicrobial activity, nontoxicity to human body, and little effect on the intrinsic properties of cotton fabrics.

In recent years, betaine, regarded as a new research hotspot, has received increasingly attention due to its broad-spectrum antibacterial activity, environmental friendliness and other properties. Remarkably, betaine refers to a kind of zwitterionic material comprising both cationic groups like QACs and anionic groups such as sulfo-, carboxy-, and phosphoric acid in the same structure unit [21,22]. Furthermore, betaine, having favorable biodegradability, innocuity and no stimulation, could be equipped with antipolyelectrolyte characterization, electrolyte-response, biocompatibility and antibacterial adhesiveness concurrently [23,24]. In view of these predominant properties, betaine and its derivative compounds have been widely used in biological materials, tissue engineering, drug delivery systems (DDS) and so forth. Particularly, they have emerged promising future of applications in antibacterial textiles.

Previously, Ward *et al.* [25] developed new polymethacrylic sulfopropylbetaine copolymers imparting favorable anti-

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bacterial activity against both *E.coli* and *S.aureus*. Nonetheless, these antibacterial agents have no reactive groups available to be covalently bonded with the substrates. Chen *et al.* [19] proposed that polysiloxane sulfopropylbetaine, bearing reactive groups, could form stable coating on the surface of cotton fabrics, for silanol groups (Si-OH), obtained after the hydrolysis of siloxane groups, could react with hydroxyl groups (-OH) on the cotton fiber. However, the agent tends to self-condensate, leading to weak resistance to long-term repeated launderings. Alternatively, Chen *et al.* [26] produced isocyanate sulfopropylbetaine containing isocyanate group (-NCO), capable of forming chemical bonds with -OH of cotton fiber to intensify the fastness between betaine and cotton fiber. But the application of this antibacterial agent has not been expanded widely owing to its complicated preparation process and rigorous reaction conditions for cotton fibers. He *et al.* [27] proved that cotton fabrics finished with triazine sulfopropylbetaine presented a good persistent antibacterial activity on account that trazinyl groups could be covalently bonded with hydroxyl groups -OH of the cellulose. Whereas this antibacterial agent is hardly put into industralized applications owing to its relatively longer preparation process.

Polysulfopropylbetain (PSPB) bearing reactive groups was investigated in this article and its application in antibacterial finishing of cotton fabrics was also presented. Accordingly, cotton fabrics finished with PSPB were tested systematically in terms of hydrophilicity, air and moisture permeability, mechanical properties, thermal properties as well as antibacterial properties. PSPB, characteristic of relatively simple preparation technology, was environmentally friendly and safe to human body, and remarkably, it can be immobilized onto materials. The cotton fabric finished with PSPB would be put into industrial application of clothing textile, household textile, medical textile and much more.

Experimental

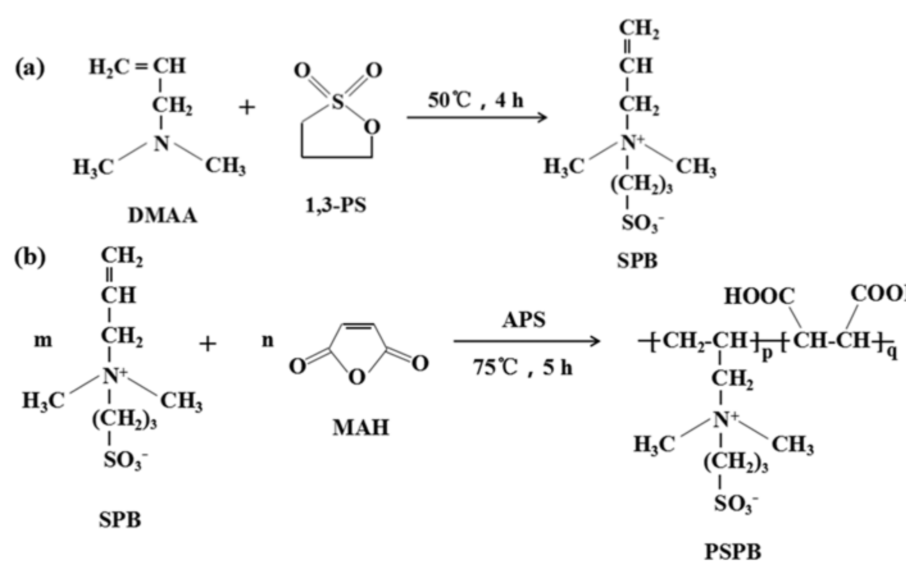
Materials

Cotton fabrics (plain weave, 52 ends/cm×28 picks/cm, 14.58 tex×14.58 tex) were purchased from Huafang Co., Ltd. (China). N,N-dimethyallylamine (DMAA, 98.0 %), 1,3-Propanesultone (1,3-PS, 99.5 %), tetrahydrofuran (THF, AR), maleic anhydride (MAH, AR), ammonium persulfate (APS, AR) and sodium hypophosphite (SHP, AR) were obtained from Sinopharm Chemical Reagent Co., Ltd. (China) and used without further purification. *E.coli* (AATCC 25922) and *S.aureus* (AATCC 6538) were purchased from Shanghai Lu Micro Technology Co., Ltd. (China).

Syntheses of SPB and PSPB

The synthesis of sulfopropylbetaine (SPB) involved the addition of DMAA (0.1 mol) into a 250 m*l* round-bottomed flask provided with N_2-tube, mechanical stirrer, reflux condenser and a thermometer. Subsequently, when the reaction temperature heated up to 50 °C, under the continuous stirring and nitrogen, 1,3-PS (0.1 mol, dissolved in 100 m*l* THF) was dropwise added into the flask by using a constant-voltage funnel. The reaction was conducted at 50 °C for 4 h after the completing of dropping, and then, the initial white precipitate was gained. After further rotary evaporation, the SPB monomer was obtained.

SPB (0.05 mol), MAH (0.05 mol) together with APS acting as a initiator were dissolved in deionized water (100 m*l*). Half of the mixed solution was added into the reaction device to react at 70 °C for 1 h under the agitation and nitrogen conditions. Thereafter, the rest mixture was dropwise



Scheme 1. Synthetic Routine of (a) SPB and (b) PSPB.

added into the reaction system above and the reaction proceeded at 70 °C for another 4 h. Ultimately, PSPB, purified by acetone and dried under vaccum, was obtained. The synthetic routine of SPB and PSPB is exhibited elaborately in Scheme 1.

Preparation of Cotton Fabric Finished with PSPB

Cotton fabrics were cleaned with ethanol first, and then rinsed with distilled water. Thereafter, the dried fabrics were immersed into 18 g/*l* PSPB antibacterial water solution (liquor ratio 1:30) under acidic condition (pH 5.0) with SHP (6 % of PSPB weight) acting as a catalyst. The antibacterial cotton fabrics finished with PSPB were gained with pad-dry-cure process (dried at 70 °C for 5 min, cured at 160 °C for 2 min). Then the fabrics were laundered adequately in distilled water and dried at 45 °C.

Characterization

Chemical groups of SPB and PSPB were characterized by a FT-IR spectrometer (NICOLET is10, Thermo Fisher, USA). The presser samples were made by compressing the homogeneous mixture of samples and KBr. FT-IR spectra were obtained in the wavenumber range 4000-500 cm^{-1} by 32 scans at a resolution of 4 cm^{-1}. ^1H NMR spectrum of SPB was recorded with a nuclear magnetic resonance spectrometer (Ascend400, Bruker, Germany), using D_2O as the solvent and tetramethylsilane (TMS) as an internal standard. XPS analysis was conducted by X-ray photoelectron spectroscopy (ESCALAB 250XI, Thermo Fisher, US) to analyze the surface composition of the PSPB, raw fabric and PSPB finished fabric. A survey scan was collected in the range of 0-1300 eV and the take off angle of the photoelectron was set at 75 °. The surface morphologies of cotton fabrics were investigated using scanning electron microscope (SEM, Hitachi, SU-1510, Japan). The samples were coated with gold under vacuum and pasted on a conducing surface with carbon paste before scanning. Thermo-gravimetric analysis (TGA) was performed on a thermo-gravimetric analyzer (Q500, TA Instruments, USA) with a flow capacity of 40 m*l*/min under nitrogen atmosphere. The scan was carried out at a heating rate of 10 °C/min from 40 °C to 700 °C.

Evaluation on Hydrophilicity of Cotton Fabric Finished with PSPB

Hydrophilicity of cotton fabrics before and after treated with PSPB were tested based on ISO 9073-6-2000 standard method. Schematically, cotton fabrics before and after finishing were cut into three specimens (250 mm length, 30 mm width), respectively. Under the ambient temperature of 25±2 °C and relative humidity of 65±3 %, deionized water together with red ink was added into the vessel, flushing with the zero-scale mark of ruler which is perpendicular to the vessel. Thereafter, one side of the specimens was fixed on the scaffold and the other side, clipped with clamps, sank vertically into the vessel below 15±2 mm of the zero graduation of the ruler. Then, wicking height of the samples at different time was recorded for the final analysis. The hydrophilic results are means of 3 tests.

Evaluation on Air Permeability and Moisture Penetrability of Cotton Fabric Finished with PSPB

Air permeability of cotton fabrics before and after finished with PSPB was evaluated under the circumstance of testing differential pressure of 200 Pa and the testing area of 20 cm^2 according to ASTM D737-2004 standard method. Different parts of the same sample were tested 5 times and the final result is the average value.

Moisture penetrability of cotton fabrics before and after finished with PSPB was evaluated on the conditions that the ambient temperature was at 38±2 °C and the relative humidity was 90±2 % in terms of GB/T12704.1-2009 standard method. Three specimens were investigated for 1 h under the moisture permeability rate of 0.8-0.9 m/s. The testing results are means of 3 tests. The formula of water vapor transmission (WVT) is given in the followings:

$$WVT = \frac{24 \cdot \Delta m}{A \cdot t} \tag{1}$$

where WVT (g/($m^2 \cdot 24$ h)) refers to the water vapor transmission of 24 h per square meter, Δm (g) involves with weight differences of two tests of the same sample in the same experimental group, A (m^2) relates to effective experimental area and t (h) indicates testing time.

Evaluation on Mechanical Properties of Cotton Fabric Finished with PSPB

Mechanical property of cotton fabrics before and after finished with PSPB was evaluated in accordance with ISO 9073 part 3 (Srip Method). The tensile tests were carried out under clamping strength of 50 mm, stretching velocity of 100 mm/min. Five specimens were investigated both in warp and weft. The final effective data were the averages of the tensile tests.

Evaluation on Antibacterial Properties of Cotton Fabrics Finished with PSPB

According to FZ/T 73023-2006 standard method, antibacterial properties of cotton fabrics before and after finished with PSPB against *E.coli* and *S.aureus* were assessed and the washing fastness of cotton fabrics finished with PSPB was evaluated after 50 cycles of washing. Specifically, 0.75 g sample, cut into small pieces (5 mm× 5 mm), was dipped in a flask containing 70 m*l* of 0.3 mM PBS (phosphate buffer solution, pH=7.2-7.4) with a cell concentration of 3×10^5-4×10^5 cfu/m*l*. The flask was shaken at 24 °C and 150 rpm for 18 h. Then, the agar plate where 1 m*l* of solution, taken from the flask, was diluted and distributed, was incubated at 37 °C for 18-24 h. The number of formed colonies were recorded and the final result was the average of three testing runs. Bacteriostatic rate can be calculated with the formula below.

$$BR = \frac{W_t - Q_t}{W_t} \times 100\% \quad (2)$$

where BR concerns the bacteriostatic rate, W_t refers to the number of the bacterial colonies on the untreated cotton fabrics after 24 h contact and Q_t means the number of the bacterial colonies on the cotton fabrics finished with PSPB after 24 h contact.

Results and Discussion

Structural Analyses of SPB and PSPB

FTIR spectra concerning MAH, SPB and PSPB are presented in Figure 1. In the spectrum of SPB, the bands at 1037 and 1202 cm^{-1} are ascribed to the symmetric and asymmetric stretching vibration of SO_3^- group and absorption peaks at 528 and 608 cm^{-1} also indicate the presence of the SO_3^- [28]. The stretching vibration absorption of C-N group and $-CH_3$ group appear at 1426 cm^{-1} and 1487 cm^{-1} respectively [29]. The absorption peaks at 2920 $cm^{-1}$and 3012 cm^{-1} are assigned to the $-CH_2$ group. The groups above are the main basic groups of betaine, which demonstrates SPB is synthesized successfully. Apart from characteristic groups of betaine mentioned above, a new absorption peak, identified as stretching vibration absorption of C=O appearing in MAH spectrum, is observed in the spectrum of PSPB, confirming the successful reaction between SPB and MAH. Besides, the ^1H NMR spectrum also presents the precise structure of SPB (as seen in Figure 2). Relevant data are given as follows: δ (ppm) 2.17 (CH_2-CH_2-CH_2-SO_3, 2H), 2.90 (CH_2-CH_2-CH_2-SO_3, 2H), 3.01 ($(CH_3)_2$-N^+, 6H), 3.37 (CH_2-CH_2-CH_2-SO_3, 2H), 3.88 (CH_2=CH-CH_2-N^+, 2H), 5.65 (CH_2=CH-CH_2-N^+, 2H), 5.97 (CH_2=CH-CH_2-N^+,1H).

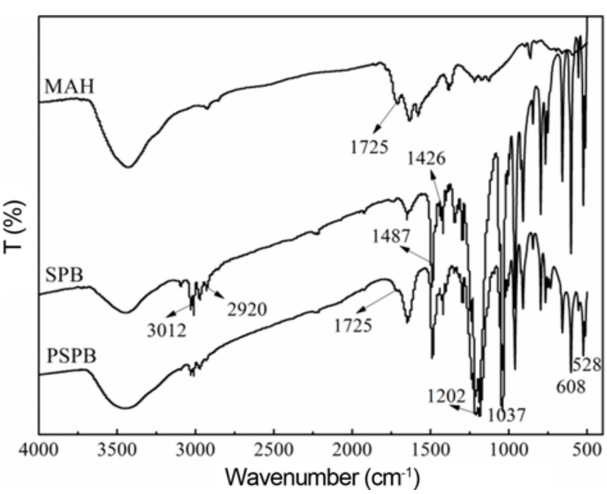


Figure 1. FTIR spectra of MAH, SPB and PSPB.

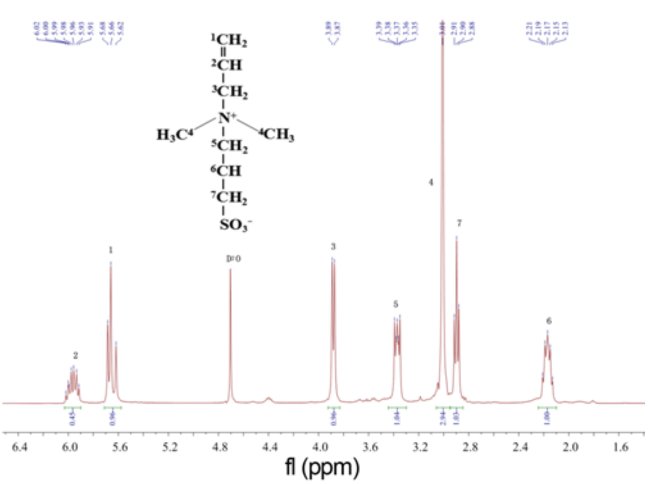


Figure 2. ^1H NMR spectrum of SPB in D_2O.

XPS Analysis

Figure 3 introduces the XPS spectra of PSPB, raw cotton fabric and cotton fabric finished with PSPB. S2p, C1s, and N1s signals centering at 169, 285 and 402 eV respectively can be detected in the XPS survey scans [30]. Moreover, only one nitrogen peak in accordance with positively charged nitrogen (N^+) of quaternary ammonium salts at 401.8 eV can be observed in the high-resolution N1s spectrum of PSPB, which further confirms the generation of sulfopropylbetaine. In addition, the tertiary ammonium of DMAA is completely transformed into the quaternary ammonium of SPB. On the other hand, in view of the XPS spectrum of cotton fabric finished with PSPB, a new peak corresponding to S2p emerges at 168 eV while there is no such peak in the XPS spectrum of raw cotton fabric. In the high-resolution spectra of N1s, N^+ of quaternary ammonium at 401.8 eV and N1s of tertiary ammonium at 399.3 eV appear in the cotton fabric finished with PSPB. By contrast,

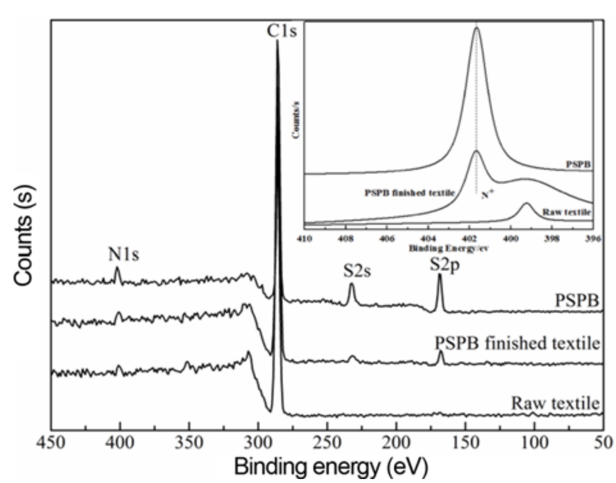
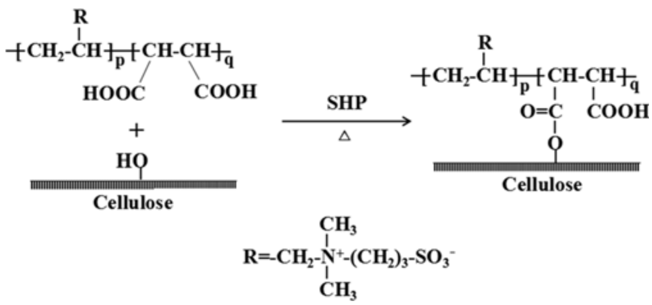


Figure 3. XPS spectra of PSPB, raw cotton fabric and cotton fabric finished with PSPB.



Scheme 2. Reaction mechanism of immobilization of PSPB onto cotton fabric.

only N1s, which is its intrinsic element can be found in the raw cotton fabric spectrum. Thus, it is confirmed that PSPB is grafted onto the cotton fabrics successfully. The reaction mechanism of the immobilization of PSPB onto cotton fabrics is presented in Scheme 2. Expectedly, cotton fabrics were endowed with long-lasting antibacterial activity during the formation of covalent bonds between -COOH groups of the PSPB and -OH groups of the cotton fabrics.

Surface Morphology Analysis

Scanning electron microscope (SEM) was adopted to explore the surface morphologies of raw cotton fabric and cotton fabric finished with PSPB. The testing results are shown in Figure 4. Compared with the raw cotton fabric characteristic of relatively clean and smooth surface, surface of the cotton fabric finished with PSPB tends to be evidently rough and covered with discontinuous thin floccules and nanoscale particles, which is ascribed to the effective immobilization of PSPB onto cotton fabric generating distinct changes of surface morphology.

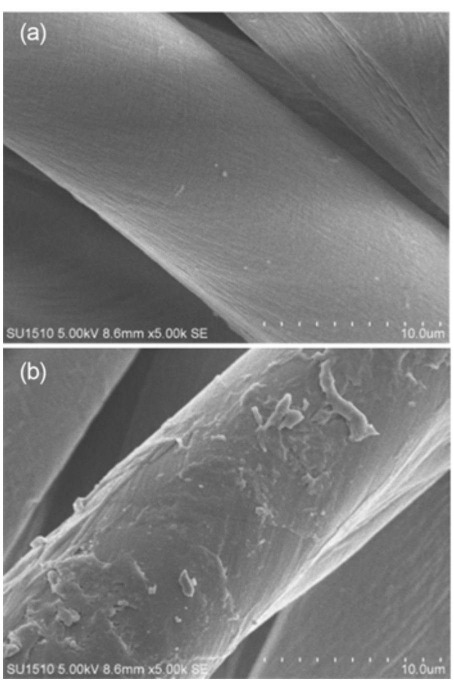


Figure 4. SEM pictures of (a) raw cotton fabric and (b) cotton fabric finished with PSPB.

Antibacterial Properties of Cotton Fabric Finished with PSPB

Viable cell counting method was employed to conduct quantitative tests on antibacterial activities of cotton fabrics finished with PSPB. Figure 5 presents the antibacterial activities of cotton fabrics finished with PSPB against *E.coli* and *S.aureus*, regarding the raw cotton fabrics as the control samples. It can be obviously observed that viable bacterial count reduces greatly in the samples finished with PSPB compared with the control groups. Consequently, it turns out that the cotton fabrics finished with PSPB impart excellent antibacterial activities against both *E.coli* and bacteria *S.aureus*, with 99.69 % and 99.95 % in bacteriostatic rate, respectively. According to literature [26,31], the potential antibacterial mechanism of polysulfopropylbetaine could be concluded as (i) inhibiting the big molecular biosynthesis and interfering with the bacterial metabolism by binding to proteins on the bacterial membrane; (ii) producing ROS (reactive oxygen species) through binding to the cell membrane, and resulting in cell toxicity, cell growth arrest and cell death in the end.

The antibacterial function of textiles is easily achieved through the finishing of antibacterial agents onto textiles

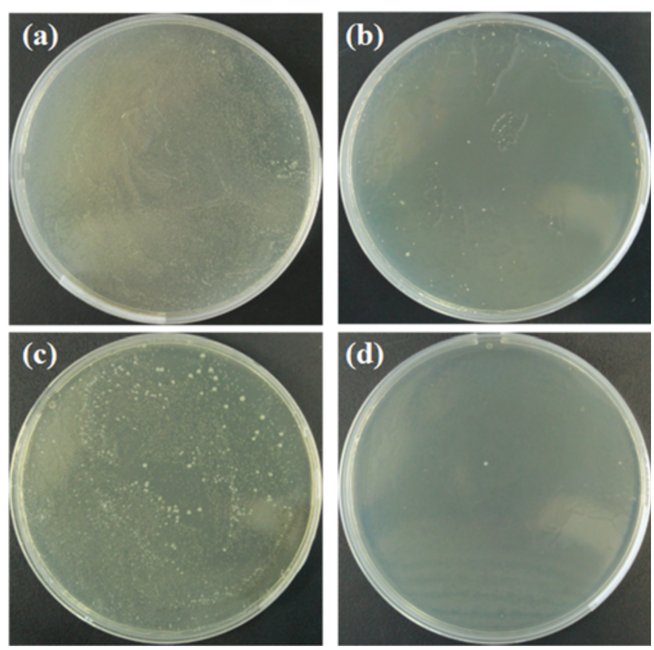


Figure 5. Antibacterial activities of cotton fabrics finished with PSPB against *E.coli* and *S.aureus*: (a) *E.coli*, raw cotton fabric, (b) *E.coli*, cotton fabric finished with PSPB, (c) *S.aureus*, raw cotton fabric, and (d) *S.aureus*, cotton fabric finished with PSPB.

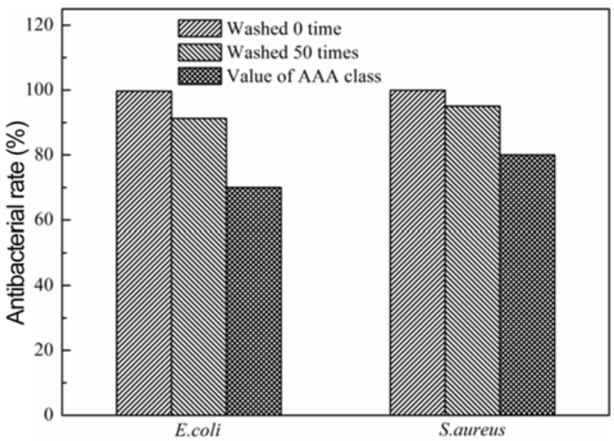


Figure 6. Photographs of antibacterial activities against *E.coli*/ *S.aureus* of cotton fabrics finished with PSPB after 50 laundering circles.

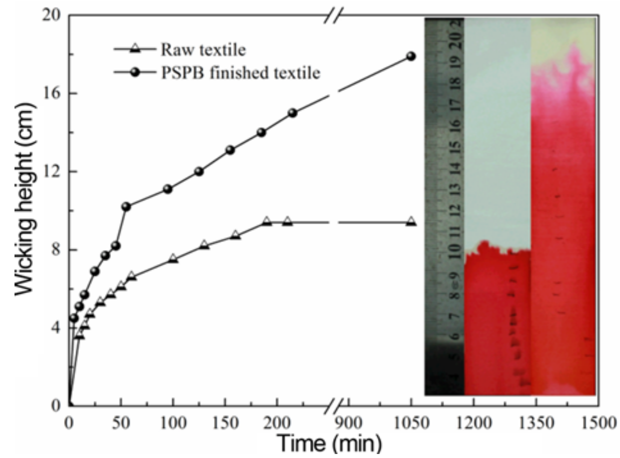


Figure 7. Capillary effect of raw cotton fabric and cotton fabric finished with PSPB.

while its durability depends on the interactions between the agents and textile fibers, which affects the amount of agents on textiles after laundering [32]. Viable cell counting method was used to detect the antibacterial effect of cotton fabrics finished with PSPB after laundering 50 times so as to verify its antibacterial durability. According to the analysis of Figure 6, it is concluded that the antibacterial rate of the finished cotton fabrics after washing process can reach 91.23 % and 95.09 %, respectively against *E.coli* and *S.aureus*, a slight reduction but still much higher than the reference inhibition rate (70 % and 80 %, respectively) of AAA class antibacterial textile. Results indicate cotton fabrics finished with PSPB still have desirable antibacterial properties even after repeated washing, ascertaining its excellent fastness to washing.

Hydrophilicity of Cotton Fabric Finished with PSPB

Figure 7 illustrates the capillary effect of raw cotton fabric and cotton fabric finished with PSPB. Observably, at each test point, both the water wicking height and absorption rate of cotton fabric finished with PSPB are higher than those of the untreated cotton fabric. Besides, the water wicking height of raw cotton fabric rises gradually to 9.4 cm within 180 min, thereafter keeping stable value and stopping growing, whereas the water wicking height of cotton fabric finished with PSPB increases continually within 1050 min up to 17.9 cm. Therefore, it verifies that the hydrophilicity of cotton fabric finished with PSPB is improved significantly, resulting from excellent hydrophilicity of betaine and discontinuous thin film of PSPB on the finished cotton fabric forming relatively rough surface [26].

Air Permeability and Moisture Penetrability of Cotton Fabric Finished with PSPB

Moisture and air transmission of fabrics are of great

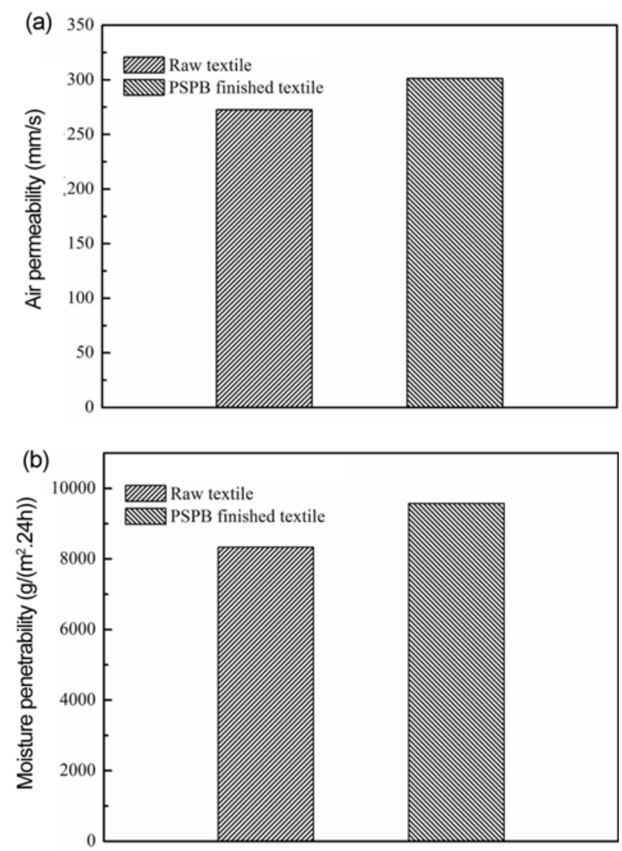


Figure 8. (a) Air permeability and (b) moisture penetrability of raw cotton fabric and cotton fabric finished with PSPB.

significance to the thermophysiological comfort of human body [33]. Figure 8 reveals air and moisture permeability of raw cotton fabric and cotton fabric finished with PSPB. The air permeability of cotton fabric finished with PSPB improves from 272.66 mm/s to 301.26 mm/s, rising by

10.49 % according to analysis of Figure 8(a). Concurrently, the vapor transmission rate of the finished cotton fabric increases by 14.88 %, from 8331.21 g/(m^2·24 h) to 9571.12 g/(m^2·24 h) by reference to Figure 8(b). Tests manifest that cotton fabric finished with PSPB exhibits remarkable air and moisture permeability superior to the raw cotton fabric, which does not agree with the results of related researches, that is, the penetrability of finished textiles tends to decline due to the reduction of the treated fabrics' pore and gap [34]. Its mechanism can be expounded that the PSPB-finished cotton fabric endowed with anti-fouling performance possesses much cleaner surfaces and bigger interspaces between fibers, and then, enhances the penetrability of air and moisture by comparison of the untreated cotton fabric.

Mechanical Properties of Cotton Fabric Finished with PSPB

Figure 9 states the mechanical properties of raw cotton fabric and cotton fabric finished with PSPB. From Figure 9(a), it can be analyzed that the breaking strength of cotton fabric finished with PSPB reduces from 785.7 N to 722.3 N in the warp direction, with the breaking strength retention of 91.93 % and the breaking strength of cotton fabric finished with PSPB drops from 381.1 N to 359.4 N in the weft direction, with the breaking strength retention of 94.31 %. Degradation of the breaking strength is ascribed to the changes that anhydroglucose of the cotton fiber appears to be dehydrated and its polymerization degree tends to drop, on account of the high temperatures of baking process. The breaking strength decrease is in agreement with others' observations during the antibacterial finishing process [35,36]. Generally, there is a slight decline in breaking strength, but within the admissible range. As is shown in Figure 9(b), the breaking elongation of cotton fabrics finished with PSPB ranges from 8.01 % to 8.81 % in the warp direction, rising by 8.84 % while the breaking elongation of cotton fabrics finished with PSPB increases by 6.63 %, from 15.34 % to 16.27 % in the weft direction. The breaking elongation tends to be improved. Above all, PSPB applied in antibacterial finishing of cotton fabrics exerts no obviously negative effect on the mechanical properties.

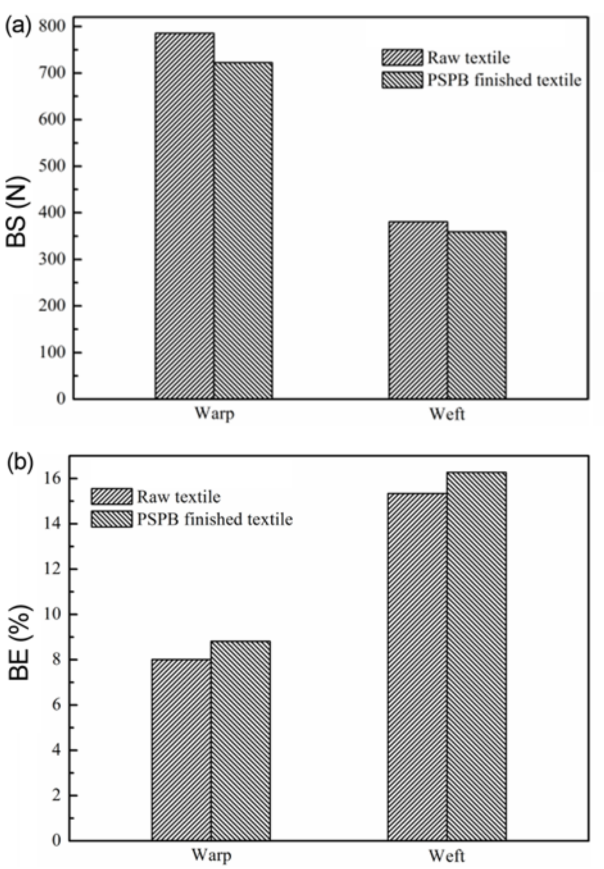


Figure 9. Mechanical properties of raw cotton fabric and cotton fabric finished with PSPB; (a) breaking strength and (b) breaking elongation.

Thermal Properties of Cotton Fabric Finished with PSPB

Thermagravimetric (TG) analysis and derivative thermogravimetry (DTG) analysis were employed to investigate the thermostability of raw cotton fabric and cotton fabric finished with PSPB. The testing results are elaborated expressly in Figure 10. Obviously, the initial decomposition temperature of untreated cotton fabric is about 238 °C and the weight loss ratio is about 4 % when the temperature is up to 305 °C according to TG and DTG curves of raw cotton fabric. During this stage, slight weight loss of cotton fabric mainly arises from water evaporation. Weight of raw cotton fabric tends to decline sharply when the temperature heats up from 310 °C to 350 °C. The maximum rate of weight loss occurs at 334 °C with 1.68 % of residual weight, during which degradation of the saccharide rings and decomposition of the fiber macromolecular chains bring about the weight

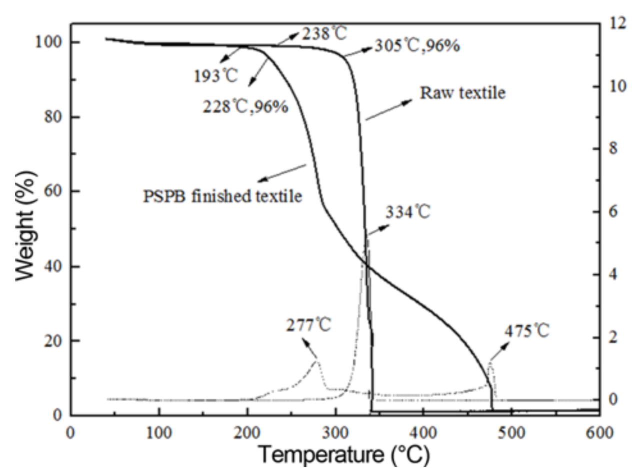


Figure 10. TG and DTG curves of raw cotton fabric and cotton fabric finished with PSPB.

loss of raw cotton fabric [37]. On the other hand, decomposition process of cotton fabric finished with PSPB can be divided into two phases on basis of the graph above. In the first phase, the decomposition of cotton fabric finished with PSPB starts at 193 °C and the decomposing rate proceeds at a relatively faster speed until 277 °C at which the maximum weight loss occurs with 35 % of weight loss rate. At this stage, degradation of sugar rings bearing sulfopropylbetaine groups and distintegration of fiber macromolecular chains give rise to weight loss of the finished cotton fabric. Thereafter, in the second phase, with the increase of temperature, decomposition of cotton fabric finished with PSPB proceeds at a relatively slower rate until 500 °C, during which the maximum occurs at 475 °C with 2.33 % of residual weight. By comparing TG and DTG curves of the two samples, it finds that both initial decomposition temperature (T_i) and temperature of the maximum weight loss rate (T_{max}) of cotton fabric finished with PSPB are lower than those of raw cotton fabric, for the breakage temperature of chemical bonds of PSPB is lower than that of cotton fiber. Whereas, residues of the cotton fabric finished with PSPB outweigh the remnants of the untreated cotton fabric, for the heat stability of PSPB is superior to the intrinsic thermal property of raw cotton fabric [38].

Conclusion

A novel antibacterial agent with the feature of simple preparation process and environmental protection, PSPB and its application in antibacterial finishing of cotton fabrics were introduced in this paper. Characterization analysis was carried out to elucidate the chemical structure of PSPB and its immobilization onto cotton fabrics. Additionally, Tests on hydrophilicity, air and moisture permeability, mechanical properties as well as antibacterial properties were performed systematically. Main conclusions can be drawn as follows:

1. PSPB possesses positively charged quaternary ammonium groups and negatively charged sulfonic groups, simultaneously. And the formation of covalent bonds between -COOH groups of PSPB and -OH groups of cotton fabric facilitates the successful immobilization of PSPB onto surface of the cotton fabric.
2. Cotton fabrics finished with PSPB bear efficient and durable antibacterial activities, with inhibitory rate against both *E.coli* and *S.aureus* reaching over 90 % even after 50 circles of washing.
3. The hydrophilicity, air permeability and moisture penetrability of cotton fabrics finished with PSPB have been improved with no effect to the original mechanical properties.

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