Antibacterial Cotton Fabric Prepared by a “Grafting to” Strategy using a QAC Copolymer

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Abstract

Quaternary ammonium compounds (QACs) have outstanding antimicrobial effect, but their immobilization onto cotton fiber surfaces remains a challenge. Herein, a QAC monomer, [2-(Methacryloyloxy) ethyl] trimethyl ammonium chloride (DMC) was co-polymerized with methyl acrylate (MA) to prepare an antibacterial copolymer, poly(DMC-co-MA). To graft the copolymer with an improved grafting efficiency, cotton fabric was treated using carboxymethyl chitosan (CMC) to establish an amino-functionalized fiber surface first. This treatment allows the amidation reactions between the amino groups and the pendant ester groups in the poly(DMC-co-MA) to take place, achieving a durable QAC coating onto the fiber surfaces with remarkably antibacterial effect. Characterization results indicated that when DMC/MA monomer ratio was 100:1, the resulting copolymer endows the modified cotton fabric with antibacterial capability that inactivates all *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*). Even after 50 laundering cycles, more than 98.0% of the antibacterial rate could still be retained. Moreover, the wearing comfort properties such as softness, water absorption and air permeability of the finishing cotton fabrics have been insignificantly changed by comparing to the untreated cotton fabric.

Introduction

Cotton fabric occupies a large market share in the textile industry due to its wearing comfort properties (Bhuiyan et al. 2017; Xu et al. 2019; Xu et al. 2020a; Xu et al. 2020c). However, the cotton textiles offer proper conditions like moisture, temperature, oxygen and nutrients (Gu et al. 2018; Antunes et al. 2021; Gulati et al. 2021) for bacteria growth. The propagation of the microorganisms in the textiles not only causes appearance defection such as yellowing and spot formation (Anwar et al. 2021), but also induces deterioration in mechanical properties, unpleasant odors and even serious diseases (Rogachev et al. 2013; Martin et al. 2020; Xu et al. 2021). These problems motivated researchers to develop antibacterial cotton fabrics with acceptable durability (Rohaeti and Rakhmawati 2017; Cai et al. 2018; Gao et al. 2021).

As a result, numerous antibacterial agents for cotton fabrics have been explored. Most of the antibacterial chemicals reported can be classified into two categories: inorganic compounds and organic compounds (Ji and Zhang 2009; Gedik et al. 2018; Granados et al. 2021). Silver nanoparticles (AgNPs) are the representative among the inorganic antibacterial agents. The class of AgNPs has been well recognized as an efficient antibacterial agent that has been widely adopted in the fabric finishing industry to date (Zhang et al. 2016; Xu et al. 2019; Caschera et al. 2020; Andra et al. 2020). Other inorganic agents such as CuO (Katwal et al. 2015; Xie et al. 2020), TiO₂ (Riaz et al. 2019) and ZnO (Perelshtein et al. 2009; Yazhini and Prabu 2015; Wang et al. 2016) nanoparticles were also been reported as efficient candidates for the antibacterial applications. However, several scholars published a considerable number of warning reports about the carcinogenic risk and harmful environmental impact of these inorganic agents (Paul et al. 2019; Ma et al. 2020; Zhang et al. 2020; Zhang et al. 2021).

On the other hand, a variety of organic antimicrobial agents, including quaternary ammonium compounds (QACs) (Ladhari et al. 2007; Jain et al. 2014; Yao et al. 2015; Oblak et al. 2016; Wang et al.

2021), chitosan derivatives (Pan et al. 2020; Xin et al. 2020; Ding et al. 2021), haloamines (Gao et al. 2016; Peng et al. 2021; Wang et al. 2021; Xu et al. 2021), alkylguanidines (Song et al. 2012; Du et al. 2016; Gao et al. 2020) and polyethylenimine (Meng et al. 2019), have attracted more attention in recent years. Especially, the class of QACs has been widely applied in daily chemicals such as laundry detergents, cosmetics and disinfectants due to their broad spectrum of antimicrobial activity (Nikfarjam et al. 2021; Vereshchagin et al. 2021). QACs generally damage the microorganisms via the interaction with the cellular membrane (Vieira and Carmona-Ribeiro 2006; Jiao et al. 2017; Emam 2019). Their cationic moieties play a key role to electrostatically interact with the negatively charged compounds in the microbial membrane, leading to inactivation and even death of the microorganisms (Ding et al. 2018; Bures 2019; Zheng et al. 2020). However, a major challenge for the QAC modification of cotton fabric is to immobilize the QACs molecules covalently onto cotton fiber surface (Ladhari et al. 2007; Lei et al. 2018; Xu et al. 2019).

Recently, we have explored a “grafting to” strategy for modifying cotton fabrics to impart surficial functionalities (Xu et al. 2020a; Xu et al. 2020c). These works allowed scalable and simple approaches to construct polymeric layer onto cotton fiber surface with an improved grafting efficiency than the traditional “grafting from” methodologies. In the present work, the successful “grafting to” strategy is tried to immobilize QAC molecules onto fiber surface for achieving effectively and durably antimicrobial effect.

First, a QAC monomer, [2-(methacryloyloxy) ethyl] trimethyl ammonium chloride (DMC), is selected for the implementation of the strategy because it possesses both quaternary ammonium and methacrylate moieties. Second, methyl acrylate (MA) is employed as a co-monomer to modulate DMC composition in the prepolymer. Further, to improve the grafting efficiency, carboxymethyl chitosan (CMC) is covalently linked onto cotton fiber surface via the esterification reactions between the carboxyl groups of CMC and the hydroxyl groups of the cellulose molecules on the fiber surface, for building an amino-functionalized fiber surface. Finally, the cationic copolymer, poly(DMC-co-MA), which was prepared via a free radical copolymerization of DMC and MA monomers, is anchored onto the activated surface by the amidation reactions between the amino groups on fiber surface and the pendant ester groups in the copolymer.

To the best of our knowledge, this is the first example of the “grafting to” strategy to graft QAC polymers onto cotton fabric. After the surface modification using the QAC copolymer, the surface morphology of the modified fibers is investigated by scanning electron microscope (SEM), and the coating structure is characterized by attenuated total reflection fourier transformed infrared (ATR-FTIR), X-ray photoelectron spectroscopy (XPS), and X-ray diffraction (XRD) technologies. Finally, the antibacterial activity and laundering durability of the finished fabric are evaluated as well.

Experimental Section

Materials

[2-(Methacryloyloxy) ethyl] trimethyl ammonium chloride (DMC) aqueous solution (75 wt%) and potassium persulfate (> 99.0%) were purchased from Shanghai Aladdin Co., Ltd. (China). Methyl acrylate (MA, > 99.0%) was bought from Tianjin Komiou Chemical Reagent Co., Ltd. (China). All chemicals were used without further purification. Cotton fabrics (109 g/m²) were obtained from Suzhou Ke Chuan Textile Co., Ltd. (China). Before modification, the fabrics (5.00 cm × 5.00 cm, 10 pieces) were ultrasonically cleaned in a sodium lauryl sulfonate solution (100 mL, 2 wt%) for 5 min, washed using ethanol (100 mL, 95.0 wt%) and distilled water (100 mL, 3 time), and finally dried at 100 °C.

Copolymerization of poly(methacryloyloxyethyltrimethyl ammonium chloride-co-methyl acrylate) [poly(DMC-co-MA)]

The copolymers were denoted as PD_xM₁, (x = 10, 50 and 100, meaning the mole ratios of DMC/MA are 10:1, 50:1 and 100:1, respectively). For example, DMC (8.29 g, 39.9 mmol) and MA (34.3 g, 0.399 mmol) monomers were dissolved in distilled water (100 mL). The initiator of potassium persulfate (270 mg, 0.998 mmol) was added into the mixture, heated at 70 °C for 8 h, concentrated by rotary evaporation to approximately 30 mL, precipitated using acetone (80 mL), purified by repeating the treatments of dissolving it in distilled water (10 mL) and precipitating using acetone (50 mL) for 3 times, and finally dried at 100 °C for 1 h to obtain light yellow solid of the copolymer, PD₁₀₀M₁. Samples of PD₅₀M₁ and PD₁₀M₁ were prepared via a similar treatment as PD₁₀₀M₁ but with different molar ratios of DMC/MA.

Surface modification of cotton fabric using CMC

Original cotton fabrics (5.00 cm × 5.00 cm, 5 pieces) were immersed in a CMC aqueous solution (100 mL, 0.2 wt%) at 25 °C for 15 min, padded and controlled the wet weight up to 200 ± 2%, heated at 180 °C for 5 min, rinsed with distilled water (50 mL × 3 times), and finally dried at 100 °C for 1 h to obtain CMC-Cotton fabric samples.

Grafting PD_xM₁ onto the CMC treated fabric surface

CMC-Cotton fabric samples (5.00 cm × 5.00 cm, 5 pieces) were immersed in a PD₁₀₀M₁ solution (50 mL, 0.08 g/L) at 25 °C for 2 min, padded and controlled the wet weight up to 200 ± 2%, heated at 180 °C for 5 min, rinsed with distilled water (50 mL × 3 times), and dried at 100 °C for 1 h to obtain PD₁₀₀M₁-CMC-Cotton fabric samples. Samples of PD₅₀M₁-CMC-Cotton and PD₁₀M₁-CMC-Cotton were prepared via a similar treatment but with different molar ratios of the DMC/MA, respectively. For comparison, samples of PD₁₀₀M₁-Cotton, PD₅₀M₁-Cotton, PD₁₀M₁-Cotton and PDMC-Cotton were also prepared without coating CMC.

Characterizations

Surface morphologies of the cotton fabrics were observed using a FE-SEM set (Ultra-55, Zeiss, Germany) after gold coating (thickness of approximately 10 nm). Fourier transform infrared (FTIR) measurements were performed on a Nicolet Avatar 370 spectrometer (Nicolet Company, Madison, USA) with an attenuated total reflection (ATR) accessory. Nuclear magnetic resonance (^1H NMR) spectra were obtained on a 400 MHz ASCEND spectrometer. XPS analysis was performed by an AXIS multifunctional X-ray photoelectron spectrometer (ULTRA DLD, Shimadzu Ltd., Japan) at a power of 450 W.

Escherichia coli (*E. coli*, ATCC 1555) and *Staphylococcus aureus* (*S. aureus*, ATCC 547) were used as the model micro-organisms (Xu et al. 2018) for the antimicrobial tests according to an improved AATCC 100-1999 method before each assay. The bacteria were activated with Lethen broth (LB) fluid nutrient medium (containing 5 g/L yeast extract, 10 g/L peptone, 10 g/L NaCl and adjust pH to 7.4) at 37 °C for 24 h in a constant temperature incubator. Then the activated bacterial solution was diluted to a concentration of about 1×10^8 CFU/mL. An aliquot of 20.0 μL of the diluted bacterial solution was added to the center of two pieces of samples (16.0 mm $\times$ 16.0 mm) in a sterile petri dish. After contacting, the samples were transferred to tubes contained 5.00 mL of physiological saline and vortex for 10 min. The supernatant was diluted to an appropriate concentration, dispersed onto LB agar plants, and incubated at 37 °C for 24 h. The bacteriostatic reduction rate (BR) was calculated as following,

$$\text{BR} = \frac{B - A}{B} \times 100\% \quad (1)$$

where A and B are the number of colony-forming units (CFU)/mL of the surviving microorganisms for an agar plate containing modified cotton fabrics and control sample, respectively.

To estimate the quantity of poly(DMC-co-MA) grafting on the cotton fabrics, concentration decrease of a methyl orange solution that caused by a fabric adsorption was measured. The modified cotton fabric (5 cm $\times$ 5 cm) was immersed in a methyl orange solution (30 mL, 0.011 mmol/L) for 20 min. After removing the fabric, absorbance value at 460 nm of the solution was measured using the UV–Vis spectrophotometry to determine the concentration of methyl orange. This test was repeated for three times, and the adsorbed quantity of poly(DMC-co-MA) was calculated according to the following formula (2)

$$m = \frac{C \times V \times M_1}{M_2} \quad (2)$$

where C (mmol/L) is the concentration decrease, V (L) is the solution volume, M_1 (g/mol) is the mole mass of DMC, M_2 (g) is the quality of the fabrics, and m (g/kg) is the quality of DMC units adsorbed on

each gram of cotton fabric.

Antimicrobial durability, Water vapor permeability (Xu et al. 2017), tensile strength, water absorbability, flexibility of the fabric samples were described in the “Supplementary Material” part.

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Results And Discussion

Three kinds of poly(DMC-co-MA) copolymers were prepared via free radical copolymerization of DMC and MA with a variety of DMC/MA mole ratios (**Fig. S1**). Fig. 1 compares the $^1\text{H-NMR}$ spectra of the poly(DMC-co-MA) copolymers. They exhibit characteristic signals at 1.01 ppm (a), 3.19 ppm (d) and 4.42 ppm (g), which are attributed to the methyl proton in RCH_3 , methyl groups in $\text{RCH}_2\text{-N}(\text{CH}_3)_3$, and methylene in RCOOCH_2^- , respectively. While, the peaks corresponding to the methylene groups in $\text{RCH}_2\text{-N}(\text{CH}_3)_3$ (e) and RCOOCH_3 (f) are overlapped at 3.79 ppm. By integrating the NMR peaks (e, f and g) of $\text{PD}_{100}\text{M}_1$, PD_{50}M_1 and $\text{PD}_{100}\text{M}_1$, the molar ratio of the DMC and MA units in the copolymers was estimated. As shown in **Table S1**, they are in good agreement with design.

As shown in Fig. 2, PMA, PDMC and $\text{PD}_{100}\text{M}_1$ all show FTIR characteristic peak at 1727 cm^{-1} , corresponding to the ester C=O bond. $\text{PD}_{100}\text{M}_1$ and PDMC show characteristic peaks at 1483 cm^{-1} and 1152 cm^{-1} , which are assigned to the $\text{CH}_3\text{-N}^+$

bond (Duan et al. 2020) and C-N bond (Xu et al. 2020b), respectively. The antibacterial cotton fabrics were prepared according to the schematic diagram shown in Fig. 3. Carboxymethyl chitosan (CMC) was grafted onto cotton fiber via an esterification reaction of the CMC carboxyl groups with the hydroxyl groups of cellulose on the fiber surface (CMC-Cotton). Then the poly(DMC-co-MA) copolymers were further linked on the CMC-Cotton fabrics to form poly(DMC-co-MA)-CMC-Cotton via the reaction of the ester groups with the amino groups of CMC to form amide bonds. It was speculated that the CMC molecules tend to react with the MA unites rather than with the quaternary ammonium ionic DMC unites if a considerable number of CMC amino groups were positively charged and then repelled by the cationic ones. As a comparison, the $\text{PD}_{100}\text{M}_1$ copolymers were linked on cotton fabrics to form the $\text{PD}_{100}\text{M}_1$ -Cotton fabrics.

Scanning electron microscopy (SEM) was employed to study the cotton fabrics surface coated with poly(DMC-co-MA) (Fig. 4). Significant changes were hard to find in low-magnification SEM images (Fig. 4c, f, i and l) after the modification, indicating that the $\text{PD}_{100}\text{M}_1$ copolymers and CMC were mainly coated on the fiber surface but not occupied the voids between the fibers. The high-magnification SEM images reveal that the surface modifications changed the surface morphology significantly. Original cotton fabrics surface are wrinkly (Fig. 4a-c), but the modified fabrics exhibit a wrinkle-free surface morphology

like a coating layer. To further explore the coating structure, we wetted the modified fabrics and freeze-dried them for high-magnification SEM observation. The SEM images shown in Fig. 4e, h and k indicate that the fiber surfaces become smoother after the freeze-drying treatment. This result runs counter to the common senses that freeze-drying of a hydrogel leads to a porous morphology. Undoubtedly, the grafted copolymers render a hydrophilic layer on the fiber surfaces because of the large amount of the cationic DMC units in the copolymer. Therefore, we speculate that the grafting copolymer layer is so thin that unable to cover large water droplets.

Figure 5 shows the ATR-FTIR spectra of PD₁₀₀M₁-Cotton, PD₁₀₀M₁-CMC-Cotton and the untreated fabrics. The three fabric samples show FTIR peaks at 3338 cm⁻¹ and 2896 cm⁻¹, which correspond to the -OH (Xu et al. 2017) and -CH₂- groups of cellulose, respectively. The modified cotton fabrics show new peaks at 1723 cm⁻¹ belonging to the stretching of the C=O (ester groups). The PD₁₀₀M₁-CMC-Cotton fabric shows a characteristic peak corresponding to -CONH- (amide groups) at 1661 cm⁻¹, suggesting that the copolymer of PD₁₀₀M₁ are grafted onto the CMC-Cotton fabric via the amide bonds that formed via the reactions between the copolymer and CMC.

XPS is a powerful way for analysis of chemical structure of material surfaces. Here, we collected the XPS spectra of the treated fabric surfaces to analyze their chemical compositions and environments of the surfaces to a depth of tens of nanometers. Fig. 6a and b compare the wide-range XPS spectra of the cotton fabrics before and after PD₁₀₀M₁ modification. As shown in Fig. 6a, by comparing with the XPS spectrum of original cotton fabric (shows only C 1s and O 1s signals at 285.7 eV and 533.0 eV), additional N 1s (at 400.4 eV) (Xu et al. 2018) signal is found in the XPS spectra of PD₁₀₀M₁-CMC-Cotton fabric (Fig. 6a and b), and the elemental information of the surficial layer obtained by the XPS scans further confirmed the existence of nitrogen and chlorine (**Table S2**). We further examined their C 1s high resolution XPS spectra (Fig. 6c and d) to analyze the chemical structures of the coating on the surface of cotton fibers. The high-resolution C 1s peak of original fabric can be deconvoluted into three peaks at 284.3 eV (C-C), 286.2 eV (C-OH), and 287.2 eV (C-O-C) (Fig. 6c). In contrast, PD₁₀₀M₁-CMC-Cotton fabric exhibits additional peaks at 287.8 eV and 285.7 eV (Fig. 6d), corresponding to the C=O and CH₃-N⁺ bonds, respectively (Duan et al. 2020). Together with the FTIR analyses (Fig. 6), the XPS results demonstrate the PD₁₀₀M₁ molecules grafting onto the cotton fiber surface. The poly(DMC-co-MA)s linked on cotton fabrics were estimated by an adsorption test of methyl orange. Having been immersed in a methyl orange solution, the modified fabrics will adsorb methyl orange molecules by ionic effect. The reduced concentration of methyl orange was measured using UV-Vis spectrophotometry. As shown in **Fig. S2** and **Table S3**, for one kilogram cotton fabric, 0.579 g, 0.394 g and 0.237 g of PD₁₀₀M₁, PD₅₀M₁ and PD₁₀M₁ were grafted, respectively.

Table 1 and Fig. 7 represent antibacterial activity of the modified fabrics. The PD₁₀₀M₁-CMC-Cotton fabric achieves the best antibacterial effect, showing 100% BR values against both the *E. coli* and *S. aureus*. In the present work, CMC acts as a polymer binder to link more poly(DMC-co-MA)s copolymers onto the cotton fabrics.

Table 1
Information and antibacterial rate of the cotton fabrics.

samples	BR (%)	
	<i>E. coli</i>	<i>S. aureus</i>
PD ₁₀₀ M ₁ -CMC-Cotton	100	100
PD ₅₀ M ₁ -CMC-Cotton	99.4 ± 0.05	99.1 ± 0.25
PD ₁₀ M ₁ -CMC-Cotton	98.5 ± 0.35	97.2 ± 0.60
PD ₁₀₀ M ₁ -Cotton	85.7 ± 0.45	85.2 ± 0.64
PDMC-CMC-Cotton	84.4 ± 0.47	84.0 ± 0.55

Because amino group is more reactive than hydroxyl group, introduction of CMC improves the reactivity of the cotton fiber surface, leading to more copolymers grafted onto the cotton fabric. As shown in Table 1, without CMC involvement, the antibacterial capability of PD₁₀₀M₁-Cotton dramatically degraded to less than 90%. On the other hand, PDMC-CMC-Cotton showed weakened antibacterial activity than the PD₁₀₀M₁-CMC-Cotton fabric does, revealing that MA units in the copolymer exert positive effect on antibacterial function. However, incorporation of overmuch MA units into the copolymer makes the DMC constitute reduced, resulting in BR decreases, which were found at PD₅₀M₁-CMC-Cotton and PD₁₀M₁-CMC-Cotton fabric samples. Antibacterial capability of PD₁₀₀M₁-Cotton dramatically degraded to less than 90%. On the other hand, PDMC-CMC-Cotton showed weakened antibacterial activity than the PD₁₀₀M₁-CMC-Cotton fabric does, revealing that MA units in the copolymer exert positive effect on antibacterial function. However, incorporation of overmuch MA units into the copolymer makes the DMC constitute reduced, resulting in BR decreases, which were found at PD₅₀M₁-CMC-Cotton and PD₁₀M₁-CMC-Cotton fabric samples.

Figure 8 displays antibacterial durability of the modified fabrics. The BR of PD₁₀₀M₁-CMC-Cotton fabric against *E. coli* and *S. aureus* both remained above 98% after 50 laundering cycles (Fig. 8a), whereas the BR rates of PD₁₀₀M₁-Cotton against *E. coli* and *S. aureus* dropped to 74.1% and 74.0% (Fig. 8d), respectively. These results suggest that CMC play an important role on the antibacterial durability. In addition, PD₅₀M₁-CMC-Cotton and PD₁₀M₁-CMC-Cotton fabrics show weakened durability against both *E. coli* and *S. aureus* after 50 laundering cycles (Fig. 8b and c). These results mean that the MA units in the copolymer affect the laundering durability of the modified cotton fabrics.

To explain the effect of the MA units on the antibacterial activity and laundering durability, a mechanism was proposed in Fig. 9. It was premised that the grafted poly(DMC-co-MA) copolymers on the cotton fiber surfaces should have suitable movable DMC segments to exert the antibacterial role. Due to the repulsion effect caused by the positively charged amino groups, the DMC units must be of lower reactivity than the

MA units when undergoing the aminolysis reaction with the grafted CMC chains, which have a considerable number of positively charged amino groups. As shown in Fig. 9, it is comprehensible that increased DMC units tend to increase the ionic density of the fiber surface, leading to an extension of the grafted poly(DMC-co-MA) copolymers. The charged DMC segments are movable to form more adequate contact with the bacterial cell membrane, exhibiting an enhanced antibacterial function. When compared to PD₁₀₀M₁, PD₁₀M₁ and PD₅₀M₁ have more MA units. This may result in shorter DMC segments on the fiber surface, constraining their movement, thereby decreasing the contact to bacterial cell membrane, and weakening the antibacterial efficiency of the grafted coating.

Water absorbability and water vapor permeability are typical wearing comfort properties of cotton fabrics. To evaluate the damage of the modification process on the important properties, both water absorbability and water vapor permeability were assessed. As shown in Fig. 10a and 10b, PD₁₀₀M₁-CMC-Cotton fabric shows higher water absorbability (191.4%) and vapor permeability (679.3 g·m⁻²·d⁻¹) than original fabric. This can be attributed to the hydrophilic coating of poly(DMC-co-MA) copolymer. Moreover, Fig. 10c shows that the fabric flexibility has not been significantly changed by the modification process.

Conclusions

In the present work, we have presented a novel “grafting to” strategy to graft QAC, a meticulously designed cationic copolymer onto cotton fabric pretreated by CMC for imparting antibacterial capability. This new strategy enables a durably antibacterial effect without significant sacrifice of the cotton characteristics such as water absorbability, water vapor permeability and flexibility. The cationic copolymer, poly(DMC-co-MA), which was prepared via a free radical copolymerization, has been demonstrated as the foremost contributor to the antibacterial effect, while employing methyl acrylate as a co-monomer to modulate DMC composition in the prepolymer was found to exert determining role on the antibacterial efficiency and durability. In addition, CMC fulfills a binder role to link the poly(DMC-co-MA) copolymers onto the cotton fibers by converting the hydroxyl groups of cellulose on the fiber surface to amino groups. When PD₁₀₀M₁ copolymer was linked on the CMC treated cotton fibers, the resulting PD₁₀₀M₁-CMC-Cotton fabric show 100% BR values against both *E. coli* and *S. aureus*, and its laundering durability can stand 50 rigorous laundering cycles to keep the BR values greater than 98.0%. The success of this study in achieving antibacterial properties on cotton fabric via grafting organic polymers provides a reference for textile modification, showing great potential for practical applications in textile industries.

Declarations

Acknowledgement

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Conflict of interest

The authors declare that they have no conflicts of interest.

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Figures

Figure 1

¹H-NMR spectra of PDMC and the poly(DMC-co-MA)s.

Figure 2

FT-IR spectra of PMA, PDMC and PD100M1.

Figure 3

The schematic illustration of preparation of antibacterial cotton fabrics.

Figure 4

SEM images of (a-c) original cotton, (d-f) PD10M1-CMC-Cotton, (g-i) PD50M1-CMC-Cotton, and (j-l) PD100M1-CMC-Cotton fabrics. The center column (b, e, h and k) shows the freeze-drying fiber surfaces.

Figure 5

ATR-FTIR spectra of original cotton and the treated fabrics of PD100M1-Cotton and PD100M1-CMC-Cotton.

Figure 6

XPS survey spectra of the cotton fabric samples on a wide range (a), the deconvoluted C 1s XPS spectra of original cotton fabric (b) and PD100M1-CMC-Cotton (c), and N 1s spectra of PD100M1-CMC-Cotton (d).

Figure 7

Optical images of the antibacterial tests of original and the modified cotton afbrics.

Figure 8

Laundering durability of the PD100M1-CMC-Cotton (a), PD50M1-CMC-Cotton (b), PD10M1-CMC-Cotton (c) and PDMC-Cotton (d) fabrics.

Figure 9

Antibacterial mechanism of the grafted DMC-co-MA copolymer on cotton fiber surface.

Figure 10

Influence of the surface modification on the comfort properties of cotton fabric, including (a) water absorbability, (b) water vapor transmissibility, and (c) flexibility.

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