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ORIGINAL RESEARCH

A simple method of simultaneously endowing paper or fluff pulp with both high softness or appropriate fluffing properties and antimicrobial properties

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Abstract As the living standard improves, disposable sanitary and household paper requires not only softness or easy to fluff in a dry state, but also good antibacterial property. In this study, a series of alkyl quaternary ammonium salts (*AQAS*), a kinds of antibacterial-debonding agents, were synthesized by using a two-step process. The SN2 nucleophilic substitution reaction was designed between triethanolamine and sulfoxide chloride, and followed subsequent quaternization by tertiaryamines with different long alkyl chains. The obtained products can be used as an antibacterial and softening/debonding agent for improving the performance of paper or fluff pulp. The results showed that these new compounds can endow antibacterial function and high softness to paper or control appropriate burst strength to fluff pulp. These *AQAS* products can be not only used in daily disposable sanitary products, but also have potential applications in other products such as glass spacer paper, advanced household paper, or antibacterial tissue products to prevent microbial contamination.

Keywords Antibacterial activity · Softness · Debonding agent · Fluff pulp · Paper

Introduction

With an improvement in people's living standard, there has been an increasing demand for disposable sanitary products, such as women's sanitary napkins, baby diapers and adult incontinence products (Cordella et al. 2015; Ajmeri and Ajmeri 2016; Widen et al. 2017; Mendoza et al. 2019). Since most disposable sanitary products have close contact with human body, high antibacterial activity during uses is usually desired. However, in most cases, the main material, fluff pulp, used to prepare these disposable sanitary products has no antibacterial activity (Forsgren-Brusk et al. 2017). In addition, a large number of microorganisms exist in the natural environment and they can mass propagate once the conditions are suitable, which can cause bacterial infection and create health problem for people (Asri et al. 2014; Paterson and Harris 2016; Mc Carlie et al. 2020; Wang et al. 2020). Therefore, the development of materials with antibacterial

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activity has attracted significant interest in new material research (El-Naggar et al. 2018; Noorian et al. 2020).

In addition, with the increasing demand for household papers, such as toilet paper, napkins, beauty paper and paper towels, there are increasing requirements for quality and performance of these products, especially the softness (Gashti and Adibzadeh 2014). However, in the manufacturing process of household papers, in order to reduce the production costs, a large amount of non-wood and secondary fibers used (Guan et al. 2019; An et al. 2020), which usually makes such products dense and their surface stiff (İlleez et al. 2015; Liu et al. 2020). Although creping is an effective way to increase the softness, it has limited impact. Hence, much attention has been paid to develop novel paper softeners (Tang et al. 2017; Mazzon et al. 2019). In the textile industry, softeners are used widely, but textile softeners are seldom used in papermaking due to some disadvantages, such as the large loading, high cost and poor effectiveness. Therefore, there is a clear need to develop special softening agents for this kind of papers or debonding agents for fluff pulp. In order to make the final tissue products possess high antibacterial activity and at the same time create enough softness or appropriate burst strength, antibacterial agents (Hayashi et al. 2019; Xu et al. 2020) and softening/debonding agent (Igarashi et al. 2016) are usually added together during the papermaking process. However, there are few reports on chemical additives which have both antibacterial and softening/debonding effects. Hence, it is imperative to come up with a concoction as antibacterial-debonding agent to endow paper or fluff pulp with antibacterial and softening/debonding effects.

At present, antibacterial agents have two main types: inorganic and organic agents. Inorganic antibacterial agents such as Au (Lai et al. 2015), Ag (Alahmadi et al. 2018; Caschera et al. 2020; Rabbi et al. 2020; Yousaf et al. 2020), Cu (Jose et al. 2020; Li et al. 2021), TiO2 (Alizadeh-Sani et al. 2020) and Zn (Zhao et al. 2017; Lallo da Silva et al. 2019; Farooq et al. 2020) and other metal nanoparticles have the advantages of good antibacterial properties, but at the same time there are disadvantages such as easy discoloration, manufacturing difficulties, and complex processes that limit their application in real life. Organic antibacterial agents such as chitosan (Salari et al. 2018; Tu et al. 2019), chlorhexidine (Bashir et al. 2019), triclosan (Alfhili and Lee 2019), polyethyleneimine (Wahid et al. 2019), quaternary ammonium salts (Quinlan et al. 2015; Jiao et al. 2017; Li et al. 2018) have the advantages of fast sterilization speed, strong sterilization ability, convenient processing, and good color stability. The quaternary ammonium salts have been studied by a large number of researchers because of their convenient synthesis and excellent antibacterial ability, and have been greatly developed. Li et al. (Li et al. 2018) achieved functionality by surface modification of cellulose nanocrystals grafted 2-(dimethylamino) ethyl methacrylate (DMAEMA) onto the surface of CNCs to prepare CNCs-g-pdmaema. Subsequently, the tertiary amine group of CNCs-g-PDMAEMA was transferred to the quaternary ammonium group by adding alkyl bromide (C10-C18) with different carbon chain lengths. The results of the study showed that the antimicrobial activity of the prepared antimicrobial materials was related to the alkyl chains of the prepared materials. The best antimicrobial effect was observed for the materials containing C10 alkyl groups in the quaternary ammonium salts.

In a word, compared with other antibacterial agents, organic antibacterial agent with quaternary ammonium group has been widely studied by researchers worldwide because of its advantages of low cost, high antibacterial efficiency, good safety and convenience for applications (Ma et al. 2012; Liu et al. 2015; Jung et al. 2020). Also, the alkyl group on the side chain of QAS has a certain hydrophobicity, which can improve the softness of tissue products (Gao et al. 2019) and may weaken the bonding strength between fibers as debonding agent for fluff pulp.

In this work, a series of multibranched long-chain alkyl quaternary ammonium salt compounds (*AQAS*), a kind of antibacterial-debonding agents, was synthesized, which played double roles in fluff pulp or paper preparation. Subsequently, the effect of the amount of *AQAS* on the physical properties of fluff plup and paper was evaluated and analysed. The softness is changed mainly due to an increase of the length of alkyl chains and the number of long alkyl chains on the side chains in the *AQAS* molecules. The antibacterial effect is mainly due to an increase of the number of nitrogen positive ions in the *AQAS* molecules, and the antibacterial properties of the product are measured by the inhibition circle method based on the antibacterial mechanism of nitrogen positive ions. These *AQAS*

products have potential applications in daily disposable sanitary products and other antibacterial tissue products to prevent microbial contamination. The research results have important application value for developing compound functional chemicals and improving the quality of disposable sanitary products, household paper and industrial paper for special needs.

Materials and methods

Materials

Triethanolamine, ethyl acetate and absolute ethanol were obtained from Tianjin Tianli Chemical Reagent Co., Ltd. Sulfoxide chloride, chloroform, and N,N-dimethylhexadecylamine were obtained from Sinopharm Chemical Reagent Co., Ltd. N,N-dimethyloctylamine was obtained from Aladdin Reagent Co., Ltd., China. N,N-dimethyltetradecylamine was obtained from TCI Tokyo Chemical Industry Co., Ltd, and all chemicals and reagents were used as received. Bleached softwood and hardwood pulps (in dry lap form) were all provided by Guangxi Fenghuang Co., Ltd., China. In addition, nutrient agar used for antibacterial test was obtained from Beijing Aobox Biotechnology Co., Ltd.

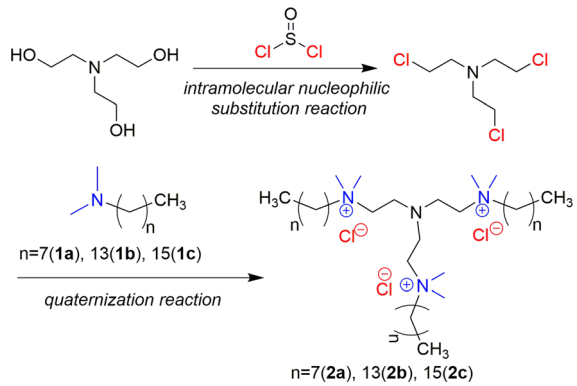
Methods

The synthesis schematic of AQAS

The *AQAS* with different long alkyl chains was synthesized by using a two-step process. The SN_2 nucleophilic substitution reaction was carried out first via the reaction between triethanolamine and sulfoxide chloride, resulting in tris(2-chloroethy)amine and then long-chain alkyl groups were introduced to the molecule of tris(2-chloroethy)amine by the quaternization reactions with different alkyl tertiaryamines (Scheme 1).

The synthesis of tris(2-chloroethy)amine

Chloroform (0.3 mol) and triethanolamine (0.075 mol) were added into a 250 mL three mouth flask, and then sulfoxide chloride was dropped into the reaction mixture. The above solution was stirred in an ice-water bath. During reaction, there was a slow release of gas, which was absorbed by the sodium hydroxide solution. After the addition, the reaction temperature was slowly raised to 30 °C and the reactor was kept stirring for 3 h, and then heated up to 60 °C and stirred until no gas was released. Finally, the flask was cooled in ice-water and a large amount of white solid was precipitated, which was then filtered and repeatedly washed with chloroform and ethanol absolute and dried at 50 °C to obtain the intermediate product tris(2-chloroethy)amine hydrochloride white crystals.



Scheme 1 Synthesis schematic of *AQAS* with different long alkyl chains

The synthesis of AQAS

Tris(2-chloroethy)amine (0.0083 mol) was first added into a 250 mL glass flask. Dilute sodium hydroxide solution was added dropwise into aqueous emulsion to adjust the pH value of the system within a certain range. After heating up to 60 °C, and N,N-dimethyloctylamine (N,N-dimethyl-tetradecylamine and N,N-dimethyl-octadecylamine) (0.0332 mol) were gently dropped into the three flasks to react with the intermediate product. Afterwards, the mixture was stirred at 90 °C for 7 h. Finally, the flask was cooled in ice water bath and a large amount of yellowish solid was separated out, which was then filtered and washed with ethyl acetate and ethanol absolute several times and dried at 50 °C to obtain the product. The products were named as *AQAS* 2a, *AQAS* 2b and *AQAS* 2c.

The preparation of antibacterial paper (or fluff pulp)

AQAS 2a, *AQAS* 2b and *AQAS* 2c with concentration of 0.01 g ml^{-1} were added into the pulp suspensions

at 0, 0.25%, 0.5% and 0.75%, respectively. A thorough mixing was provided and paper sheets (or fluff pulp) with the basis weight of 60 g m^{-2} (660 g m^{-2}) were then prepared. The wet sheet was pressed three times under 4 MPa for 2 min, and then the two sides of wet paper was dried for the same time at 105 °C in the glazing machine, to ensure the moisture content of the sheet or pad is between 8% ∼ 12%. Finally, the dried papers (fluff pulp) were conditioned in sealable bags for 12 h to stabilize the moisture content (Scheme 2).

Characterization

The ^{1}H nuclear magnetic resonance (^{1}H NMR) spectrum of *AQAS* was recorded using an AVII-500 MHz spectrometer (Bruker, Germany) with deuterated chloroform ($CDCl_3$) as the solvent.

Fourier transform infrared spectroscopy (FTIR) of *AQAS* was recorded on a spectrometer (VECTOR22, Bruker, Germany) in the range of 400 ∼ 4000 cm^{-1}, with an average of 32 scans at the resolution of 4 cm^{-1}. The samples were ground with potassium bromide (KBr) and pressed into transparent pellets..

The burst strength index of fluff pulp was performed on a bursting strength tester (DCP-NPY5600, Changjiang Papermaking Instrument, Sichuan, China) according to GB/T 1539–2007. The fluff-specific volume, absorption rate and absorbility were determined according to GB/T 21,331–2008. The mechanical performance of each specimen was determinated parallelly for three times. The fluff-specific volume (A), absorption rate (B), and absorbility (C) were calculated according to the formula as follow:

$$A = s \cdot h/(10 \cdot x)$$

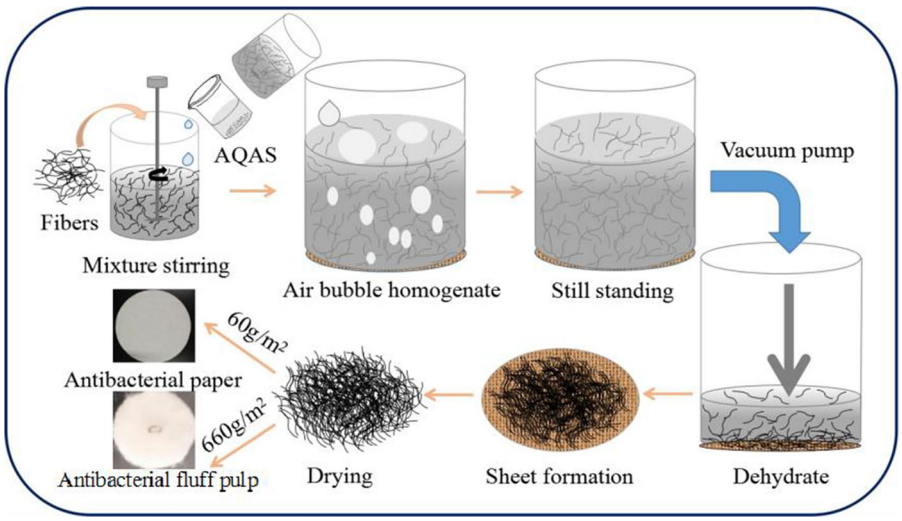
$$B = (y - x)/t$$

$$C = (y - x)/x$$

where s is the area of specimen (19.64 cm^2), h is the initial height of pulp specimens (cm), x is a constant weight (3.00 g) for specimen, y is the weight of specimen with sufficient absorption (g), t is the penetrating time of water from the bottom to top of specimens (s).

The softness of the prepared antibacterial paper was measured on a Tissue Softness Analyzer (Drake Co. Ltd, Shandong, China) according to GB/T 8942 − 2016. Based on the principle, the instrument recorded the maximum vector sum of resistance to bending force of samples and friction between samples and test gap. The smaller of softness value, the more softer of samples.

The surface morphology of antibacterial paper was observed with a scanning electron microscopy (SEM, VEGA 3 S-4800, HITACHI, Tokyo, Japan) at an accelerating voltage of 10 kV. All samples were



Scheme 2 The process of making antibacterial paper and fluff pulp

sputtered with a layer of gold in vacuum for 60 s before analysis.

The antibacterial capability of the prepared antibacterial paper was investigated using the inhibition zone method which is also called the agar disk diffusion method. *E. coil* and *S. aureus* were used in the antibacterial experiment as typical Gram-negative and Gram-positive bacteria, respectively. The medium was prepared as follows: 0.5 g beef extract, 0.5 g sodium chloride, 1.0 g peptone and 1.5 g agar were added into 100 mL distilled water and autoclaved at 121 °C for 15 min. Then 20 mL medium was poured into the sterilized petri dish. After the medium was solidified, 50 mL bacterial suspensions were uniformly smeared over the dish. Then, the cellulosic specimens were cut into circles with a diameter of 12 mm and then were gently placed on Petri dishes. After being incubated for 24 h at 37 °C under 50% relative humidity, the diameter (mm) of the inhibition zone was calculated using the following formula:

$$H = (D - d)/2$$

where H is the bacteriostatic belt width, D is the average outside diameter of inhibition zone, and d is the diameter of the specimens or the control ones.

Results and discussion

The ^{1}H NMR and FT-IR spectra analysis of AQAS 2a

The ^{1}HNMR spectra (500 MHz, $CDCl_3$, 25 °C) of *AQAS* 2a is shown in Fig. 1. The peaks at 0.88, 1.26 and 1.74 ppm originate from the *AQAS* 2a are attributed to the terminal methyl of -CH_2-CH_3, side chain methylene group ((-CH_2-)$_5$) of *AQAS* 2a and methylene of N^+-CH_2-CH_2-, respectively. The peak at 3.35 ppm belonges to methyl of N^+-CH_3, the peak at 3.42 ppm is attributed to the methylene (N^+-CH_2-CH_2-CH_2-) of *AQAS* 2a and the methylene peak of N-CH_2 was observed at 3.62 ppm. In addition, the peak at 4.11 ppm assigned to methylene of N-CH_2-CH_2 (Kang et al. 2016), indicates that the target product has been successfully synthesized (Fig. 1). However, the methyl peak (2.79 ppm) in -CH_2-CH_3, methylene peak (2.94 ppm) in N^+-CH_2-CH_2-, and the peak of N^+-H at around 2.21 ppm are also weakly observed in Fig. 1, which indicates the presence of by-products (tertiary ammonium hydrochloride) in terminal product.

The *AQAS* 2a was further characterized by FT-IR spectra (Fig. 2). The strong absorption peak at 1470 cm^{-1} belongs to methyl bending vibration peak in N^+-$(CH_3)_2$, and the symmetric bending vibration absorption peak of methyl in -CH_2-CH_3 could be observed at 1379 cm^{-1}, which is a characteristic

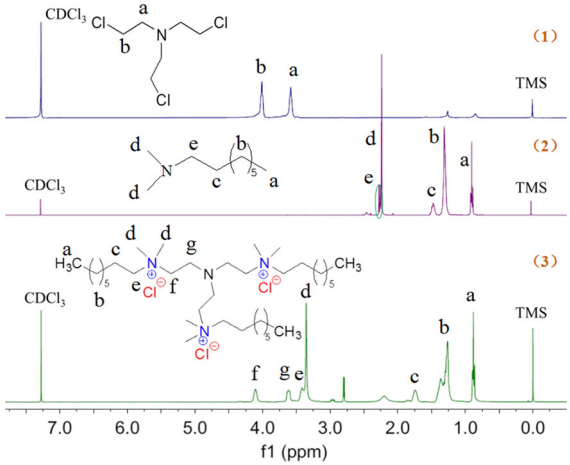


Fig. 1 ^{1}H NMR spectra of **1** tris(2-chloroethy)amine, **2** N, N-dimethyloctylamine and **3** *AQAS* 2a

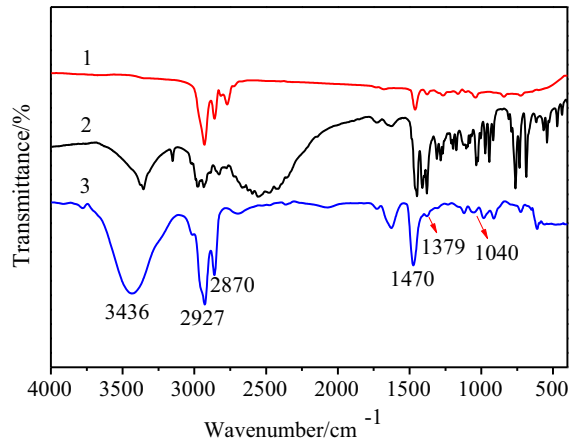


Fig. 2 FT-IR spectra. **1**. N,N-dimethyl-octylamine, **2**. tris(2-chloroethy)amine and **3**. *AQAS* 2a

absorption peak of moderate intensity. The weak absorption peak near 1040 cm^{-1} is the characteristic absorption frequency of quaternary ammonium salt, which confirms the formation of *AQAS* 2a. Compared with Line 2 in Fig. 2, the characteristic absorption peaks of methyl and quaternary ammonium salt group appear for the first time. Besides, there still exist the methylene asymmetric and symmetric stretching vibration absorption peaks at 2927 cm^{-1} and.

2870 cm^{-1} region in NR_2-CH_2-R. In addition, the strong absorption peak at 760 cm^{-1} is weakened, which indicates the weakened C–Cl stretching vibration peak in -CH_2-Cl. This may be attributed to the presence of by-products that incomplete quaternary ammonium salt in the product. We successfully synthesized *AQAS* 2b and *AQAS* 2c by using a similar method to *AQAS* 2a. For detailed characterization and spectra please refer to the supporting information (Fig. S1, Fig. S2, Fig. S3, Fig. S4).

The properties of the fluff pulp and fluff fiber

Apparent density and burst strength index of the fluff pulp

As shown in Fig. 3a, b, the apparent density and burst strength index of of the fluff pulp decrease with increasing the addition of *AQAS*, and the decrease is more significant with the increase of the addition. The decreasing trend of the apparent density and burst strength index becomes flat after the amount of *AQAS* is more than 0.75%. The apparent density of fluff pulp is defined as the ratio of the basis weight of fluff pulp to its thickness. The burst strength index of fluff pulp was measured according to GB/T 1539–2007. It is the ratio of the average burst strength of fluff pulp to its basis weight. It can speculate there is no simple liner relationship between them because of the change in the thickness. From these experiment results, it is deduced that *AQAS* treatment can shield hydroxyl groups on the surface of fibers, resulting the bonding force weaker between fibers and the volume of fluff pulp increase. Then the apparent density and burst strength index of the fluff pulp decrease with increasing the addition of *AQAS*. The effect of long alkyl chain is clearer.

Water absorbility and water absorption rate of the fluff fibers

As the amount of *AQAS* increased, the water absorbility and water absorption rate of fluff pulp show a decreasing trend (Fig. 3c, d). When the amount of *AQAS* is up to 0.5%, the decreasing trend is gradually leveled off. The alkyl chain in *AQAS* plays the role of shielding hydroxyl group, and with the increase of *AQAS*, the shielding effect becomes more clear. The longer the alkyl chain, the greater the shielding effect of the hydroxyl group. More alkyl groups with hydrophobic effect are attached to the surface of the fluff pulp fibers, resulting in lower absorbency of the fibers and consequently lower water absorption rate of the fluff pulp.

Fluff-specific volume of the fluff pulp

As shown in Fig. 3e, with increasing the addition of *AQAS*, the fluff-specific volume tends to rise first and then fall. The three hydrophobic alkyl chains in *AQAS* on the fiber surface hinder the combination between fibers, making the gap between fibers increase and become fluffy, so that the fluff-specific volume of the fluff pulp is on the rise, and when the amount of *AQAS* is high, the three long alkyl chains in *AQAS* are easy to cross and entangle with each other, so that when the pulp is dry dissociated, the fiber network is uneven and appears to be knotted and fall off in pieces. It affects the fluff-specific volume of antibacterial pulp fiber.

The surface morphology of fluff fibers

Surface morphology of antibacterial fluff pulp fibers with *AQAS* 2c was examined using SEM as shown in Fig. 4, we can see that the surface of fibers in the blank sample is very rough, and some microfibrils are broken away from the surface. This would have an adverse impact on the softness of fluff pulp. However, the SEM images of fluff pulp fibers treated by *AQAS* 2c show that the fiber surface is smoother with the increase of the loading of *AQAS* 2c. Therefore, adding proper amounts of *AQAS* 2c to pulp fiber is an effective way of improving the softness of antibacterial paper.

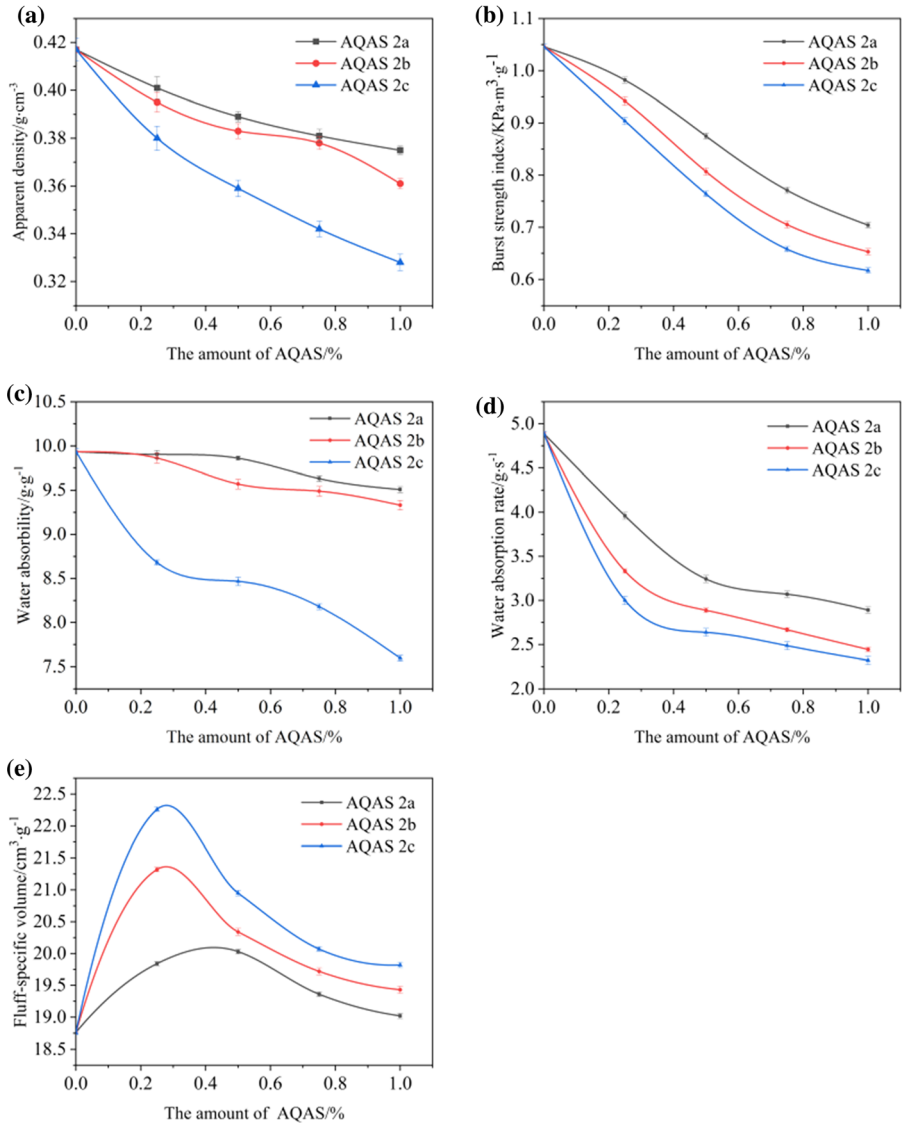


Fig. 3 The properties with the loading amounts of *AQAS* for fluff pulp **a** apparent density, **b** burst strength index, and for fluff fiber **c** water absorbility, **d** water absorption rate, and **e** fluff-specific volume

The air permeability and softness of antibacterial paper

In order to explore the effect of *AQAS* 2a, *AQAS* 2b and *AQAS* 2c on the air permeability and softness of antibacterial paper, the different amounts of *AQAS* were added into pulp suspension to make paper with the basis weight of 60 g m^{-2} (Scheme 2), and the testing results are shown in Fig. 5.

The air permeability of paper gradually increases with the amount of *AQAS* increases, the shielding effect of alkyl chains on fiber hydroxyl groups also increases, and the bonding force between pulp fibers decreases (Fig. 5a). The reason is that the hydrogen bonds between fibers can not form when the *AQAS* was used. On the other hand, the three hydrophobic alkyl chains in *AQAS* on the fiber surface hinder the combination between fibers. And the long alkyl - chains in *AQAS* may tend to cross and tangle with each other, which makes the paper become bulky and the air permeability increase. When the amount of *AQAS* is below 0.25%, that *AQAS*

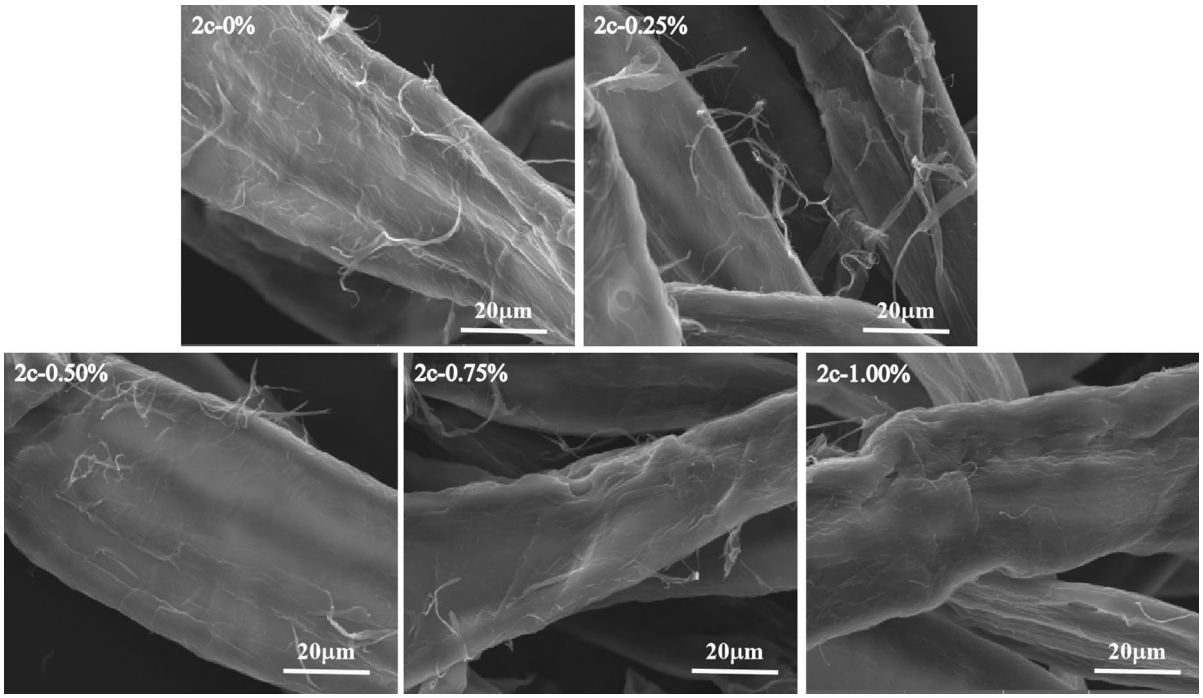


Fig. 4 The surface morphology of fibers with different loading amounts of *AQAS 2c*

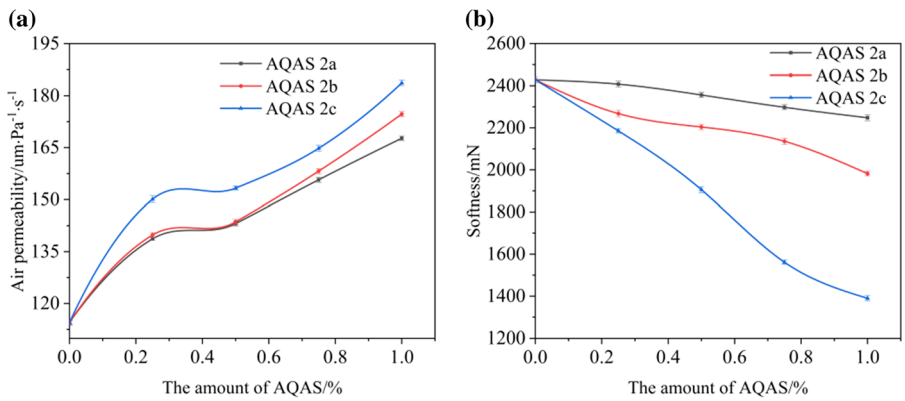


Fig. 5 The properties of paper with different loading amounts of *AQAS*. **a** air permeability, **b** softness

quickly shields free hydroxyl groups on the surface of fibers. When the amount of *AQAS* is between 0.25%-0.5%, the shielding effect on the hydroxyl group may have a lag effect because the free hydroxyl groups are derived from fracturing hydrogen bond fracturing, and then the change for air permeability gradually flattened. When the amount of *AQAS* is more than 0.5%, *AQAS* fills the fiber void, a physical phenomenon, thus the gap between fibers increases and the paper becomes bulky. There may be a replacement between *AQAS* and water in the form of hydrogen bonds with the hydroxyl groups of cellulose.

As shown in Fig. 5b, the softness of control sample is 2428.5 mN. The softness of paper decreased with increasing the amount of *AQAS*, indicating that the softness is constantly improved. The result

supports the conclusion that *AQAS* 2a, *AQAS* 2b and *AQAS* 2c also have softening effect. Moreover, it is found that the softness of all samples decrease slowly with the *AQAS* loading up to 0.25wt%. When their loading is more than 0.25wt%, the softness of paper adding *AQAS* 2a or *AQAS* 2b also drops slowly, but the decreasing trend is clear for adding *AQAS* 2c. This indicates for *AQAS* 2c can endow paper the best softening effect. It may be attributed to the alkyl groups with hydrophobicity of *AQAS* 2c which are more than that of *AQAS* 2a and *AQAS* 2b. The alkyl groups can form hydrophobic external reverse adsorption on the surface of fibers, and reduce the dynamic and static friction factors of paper fiber. Therefore, the *AQAS* 2c can be used as a softener with antibacterial activity for tissue papermaking. According to the former research by our team, when the amount of commercial debonding agent were 0.25%, 0.5%, 0.75%, 1.0%, the softness were 2421mN, 1872mN, 1473mN and 1339mN, respectively. When the amount of *AQAS* was 0.25%, the softness were from top to bottom *AQAS* 2c, *AQAS* 2b, *AQAS* 2a, commercial debonding agent. When the amount was more than 0.5%, the softness of commercial debonding agent was near by *AQAS* 2c, the softness of *AQAS* 2b and *AQAS* 2a were general.

The antibacterial activity of fluff pulp and paper

The antibacterial activity testing results are shown in Fig. 6. It was found that no inhibition zone appeared around the blank sample, indicating the poor antibacterial activity for original fiber. However, the inhibition zone appeared for other samples of paper made with *AQAS* 2a (*AQAS* 2b, *AQAS* 2c), and the inhibition zone increased with the increase of the loading amount of *AQAS*, which all confirmed the addition of 2a (2b, 2c) imparted fluff pulp with antibacterial activity. *AQAS* 2a, *AQAS* 2b and *AQAS* 2c are excellent antibacterial agents against *S. aureus* and *E. coli*. Compared with the cellulose-based Schiffff base-Cu (II) antibacterial complex (5.5 mm) (Xu et al., 2020), this antibacterial paper of this study shows larger inhibition zone width.

The comparison of antibacterial activity of different *AQAS* is shown in Fig. 7, As can be seen on the two plates, the diameter of inhibition zone around the samples decreased significantly with the increase of alkyl group on the side chain of *AQAS*, which means the antibacterial activity of *AQAS* 2a is the strongest against either *S. aureus* or *E. coli*, the second is *AQAS* 2b, and the antibacterial activity of *AQAS* 2c is the weakest. Furthermore, compared with *E. coli*, the antibacterial activity of fluff pulp with different *AQAS* against *S. aureus* is better, which is consistent with the above conclusion in Fig. 3.

The antibacterial and softening mechanism of AQAS

As shown in Scheme 3, when a certain loading of *AQAS* is added to the pulp fiber, the *AQAS* can be attached to the fiber surface by electrostatic adsorption to form something like water film. Then it hinders the

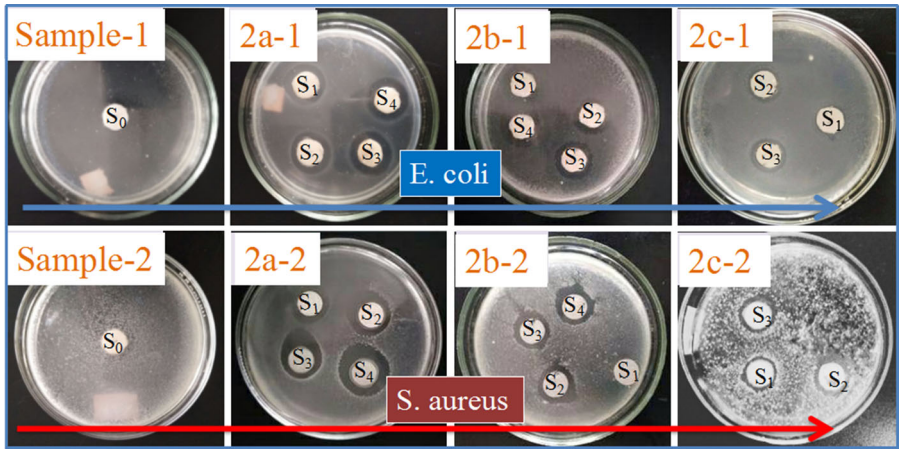


Fig. 6 Antibacterial activity of fluff pulp with different loading amount of *AQAS* 2a, *AQAS* 2b and *AQAS* 2c. S_0, S_1, S_2, S_3 and S_4 stand for the amount of 0, 0.25%, 0.5%, 0.75% and 1.0%, respectively

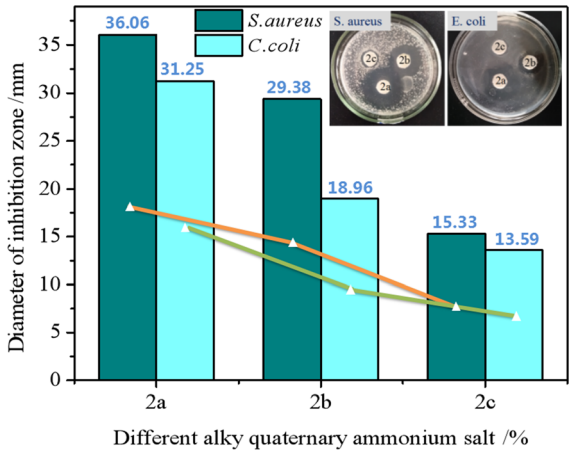
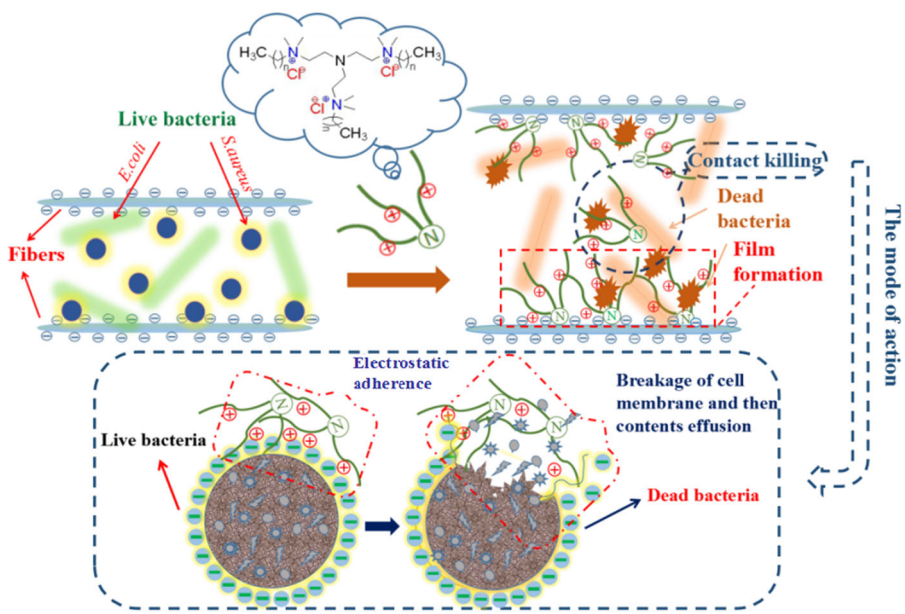


Fig. 7 Antibacterial activity of fluff pulp with different *AQAS*

bacteria from getting closer to achieve certain antibacterial effect. Besides, the *AQAS* contacts with the surface of bacteria, and the structure of bacteria cell membrane is destroyed, so that the bacteria die (Jung et al. 2019), to achieve the purpose of sterilization. The nitrogen positive ions in the *AQAS* is the active species in the bactericidal mechanism. The bactericidal mechanism for S. aureus is similar with E-coli. However, the softening effect can be attributed to: (1) the quaternary nitrogen positive ions combine with free hydroxyl groups on the surface of fibers, reduce the formation of hydrogen bonds, weaken the bond between fibers, decrease the static friction coefficient between fibers, and then the surface of the fibers become smoother, (2) long alkyl chains have a certain hydrophobicity, which reduces the formation of hydrogen bonds between fibers and makes the structure of fibers looser. Therefore, both of them can make the antibacterial products have certain softening effect, and control the burst strength of fluff pulp suitable for dry disintegration.

Conclusions

The antibacterial effect is created mainly by increasing the number of nitrogen positive ions in the *AQAS* molecule, based on the antibacterial mechanism of nitrogen positive ions to achieve the purpose of product antibacterial. The softness is increased mainly by increasing the length of alkyl chains and the number of long alkyl chains on the side chains of *AQAS* molecules, relying on the hydrophobicity of alkyl chains, reducing the hydrogen bonding, and using electrostatic adsorption to attach to the fiber surface, reducing the static friction coefficient



Scheme 3 The antibacterial and softening schematic of *AQAS*

between fibers, so that the product has a certain degree of softness.

A series of *AQAS* products were successfully synthesized and evaluated as antibacterial and softening agents in paper making and debonding agents in fluff pulp. The obtained fluff pulp and paper with these *AQAS* products showed excellent antibacterial activity against *S. aureus* and *E. coli*. At the same time, the softness for the antibacterial tissue and the burst strength for antibacterial fluff pulp has been improved. These *AQAS* products can be used in daily disposable sanitary products, but also have potential applications in other products such as Liquid Crystal Display (LCD) glass spacer paper, premium household paper, or antibacterial tissue products to prevent microbial contamination.

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Data availability Data and materials are available.

Declarations

Conflict of interest The authors declare that they do not have any conflict of interest.

Human and animal participants This manuscript does not involve animal studies or human participants in the study.

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