



Superabsorbent Fibers for Comfortable Disposable Medical Protective Clothing

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Abstract

Disposable medical protective clothing for 2019-nCoV mainly consists of stacked layers with nanopore films, polymer coated nonwoven fabrics and melt-blown nonwoven fabrics against anti-microbial and anti-liquid penetration. However, such structures lack moisture permeability and breathability leading to an uncomfortable, stuffy wearing experience. Here, we propose a novel medical protective clothing material with a superabsorbent layer to enhance moisture absorption. Poly(acrylic acid-co-acrylamide)/polyvinyl alcohol superabsorbent fibers (PAAAM/PVA fibers) were prepared via wet spinning. And the superabsorbent composite layer was stacked from PAAAM/PVA fibers, bamboo pulp fibers (BPF) and ethylene-propylene side by side fibers (ESF). The novel disposable medical protective composite fabric was obtained through gluing the superabsorbent layer to the inner surface of strong antistatic polypropylene nonwoven fabric. The resultant composite fabric possesses excellent absorption and retention capacity for sweat, up to 12.3 g/g and 63.8%, and a maximum hygroscopic rate of 1.04 g/h, higher than that of the conventional material (only 0.53 g/h). The moisture permeability of the novel material reached 12,638.5 g/(m² d), which was 307.6% of the conventional material. The novel material can effectively reduce the humidity inside the protective clothing and significantly improve the comfort of medical staff.

Keywords Poly(acrylic acid-co-acrylamide)/polyvinyl alcohol superabsorbent fiber · Sweat absorption · Hygroscopicity nonwoven · Medical protective clothing · Thermal and moisture comfort

Introduction

The novel coronavirus (2019-nCoV) outbreak is a public health emergency of international concern (PHEIC) [1]. The virus is primarily spread by small droplets produced by talking, coughing or sneezing [2–5]. It is most contagious during the first three days after onset of symptoms, although

spread before symptoms is possible [6–8]. As of March 7, 2020, 80,695 confirmed cases had been identified in the People's Republic of China, with 3097 deaths [9]. To prevent infection with 2019-nCoV, it is necessary to wear medical protective clothing that meets virus protection standards, such as ANSI/AAMI PB70-2012, EN 14126-2003, GB 19082-2009. Polypropylene spun bond/melt-blown/spun-bond (SMS) nonwoven fabric, polymer coated fabrics and polyethylene breathable film/nonwoven composite fabrics

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are the main medical protective clothing materials [10], but they have poor breathability and moisture permeability [11]. Sweat moisture accumulation in the inner layer of the fabric causes the wearer discomfort [12]. In addition, it is prone to medical disoperation in long (4–8 h) and high-intensity working conditions. Therefore, evaporative transmittance is considered an important factor concerning the comfort of fabric. Medical protective clothing is developed through the formation a permeable surface on the fabric by coating [13] or configuration of a respirator. However, these strategies undesirably change the comfort of clothing. Superabsorbent fiber with hydrophilic groups has the ability to retain and absorb a large proportion of water [14–19], resulting in quick absorption of sweat and reduction of humidity in the air layer under clothing.

Here, we demonstrate a double-layer medical protective composite structure with a highly hygroscopic inner layer and a protective outer layer. The raw material of the inner layer with superabsorbent performance was prepared from acrylic acid (AA), acrylamide (AM) and polyvinyl alcohol (PVA) via wet spinning to obtain poly(acrylic acid-co-acrylamide)/polyvinyl alcohol (PAAAM/PVA) superabsorbent fibers. Then, the inner layer was prepared from PAAAM/PVA fibers, bamboo pulp fibers (BPF) and ethylene-propylene side by side fibers (ESF) through hot air and needle punching processing. By using polyacrylate pressure-sensitive adhesive, the novel medical protective clothing material was obtained through gluing the superabsorbent layer to the inner surface of strong antistatic polypropylene nonwoven fabric with a breathable polyethylene film. The prepared material exhibited outstanding sweat absorption and retention performance, as well as thermal and moisture comfort, which met the requirements of medical disposable protective clothing. In addition, the sweat absorption and retention, thermal and moisture comfort profile of PAAAM/PVA fibers were evaluated. This novel medical protective clothing material can significantly reduce the air humidity in clothing and improve the wearing comfort, helping to improve the working status of medical staff, and also provide a reference for the improvement of other types of protective clothing.

Experiment

Materials

Acrylic acid (AA), acrylamide (AM), polyvinyl alcohol 1799 (PVA), ammonium persulfate (APS), sodium hydroxide, *N,N*-methylenebisacrylamide (MBA), absolute ethanol, *L*-histidine hydrochloride monohydrate, sodium chloride, and disodium hydrogen phosphate dehydrate were purchased from Sinopharm Chemical Reagent Co., Ltd., China.

Sodium dihydrogen phosphate dihydrate was bought from Shanghai Runjie Chemical Reagent Co., Ltd., China. Polyacrylate pressure sensitive adhesive was purchased from Shenzhen Hongshengrong Technology Co., Ltd., China. Strong antistatic polypropylene nonwoven fabric covered with breathable polyethylene film (charge amount < 0.2 $\mu\text{C}/\text{m}^2$, static decay time < 0.3 s) was bought from Zibo Dekun Film Co., Ltd., China. Bamboo pulp fiber was obtained from Jilin Chemical Fiber Group Co., Ltd., China. Ethylene-propylene side by side fiber was supplied by Jiangsu Jiangnan High Fiber Co., Ltd., China.

Preparation of PAAAM/PVA fibers

The schematic diagram of the preparation processes of superabsorbent fibers (PAAAM/PVA fibers) is illustrated in Fig. 1a. In detail, acrylic acid/sodium acrylate solution with 80% neutralization was prepared in an ice-water bath. The acrylic/sodium acrylate solution with 80% neutralization, acrylamide, 0.1 wt% *N,N*-methylenebisacrylamide aqueous solution, 10 wt% polyvinyl alcohol aqueous solution and deionized water were mixed in a three-necked flask under robust stirring. The mixture was placed in a thermostatic water bath while stirring with a passing N_2 atmosphere. The mass ratio of the mixture was set as $w_{\text{AM}}:w_{\text{AA}} = 1:4$, $w_{\text{PVA}}:w_{\text{AA+AM}} = 1:4$, $w_{\text{MBA}}:w_{\text{AA+AM}} = 0.03:50$, (AA + AM + PVA) wt% = 18%. When the water bath was heated to 60 °C, 4 wt% ammonium persulfate aqueous solution was slowly added to the mixture drop by drop with a mass ratio of $w_{\text{APS}}:w_{\text{AA+AM}} = 0.1:25$, and the solution remained at 60 °C for 1 h. The water bath was then heated to 70 °C and stirring continued for 1 h until P(AA-co-AM)/PVA polymer solution formed. The product was then cooled to room temperature.

The mixture solution of P(AA-co-AM)/PVA was then spun into fibers using a laboratorial wet spinning system. The solution was added into the spinning pot of the wet spinning system and stood for 24 h to defoam. The 50% (V/V) ethanol solution at 30 °C was employed as the coagulation bath to obtain P(AA-co-AM)/PVA fibers. The prepared fiber was dried in a hot-drawing oven at 45 °C for 5 min, and then cross-linked in an oven at 105 °C for 20 min to obtain poly(acrylic acid-co-acrylamide)/polyvinyl alcohol (PAAAM/PVA) superabsorbent fibers.

Preparation of Highly Hygroscopic and Strong Antistatic Medical Protective Composite Nonwoven Fabric

The preparation process of the highly hygroscopic and strong antistatic medical protective composite nonwoven fabric is shown in Fig. 1b. An AS181A carding machine was used to fully mix PAAAM/PVA fiber/BPF/ESF with a mass

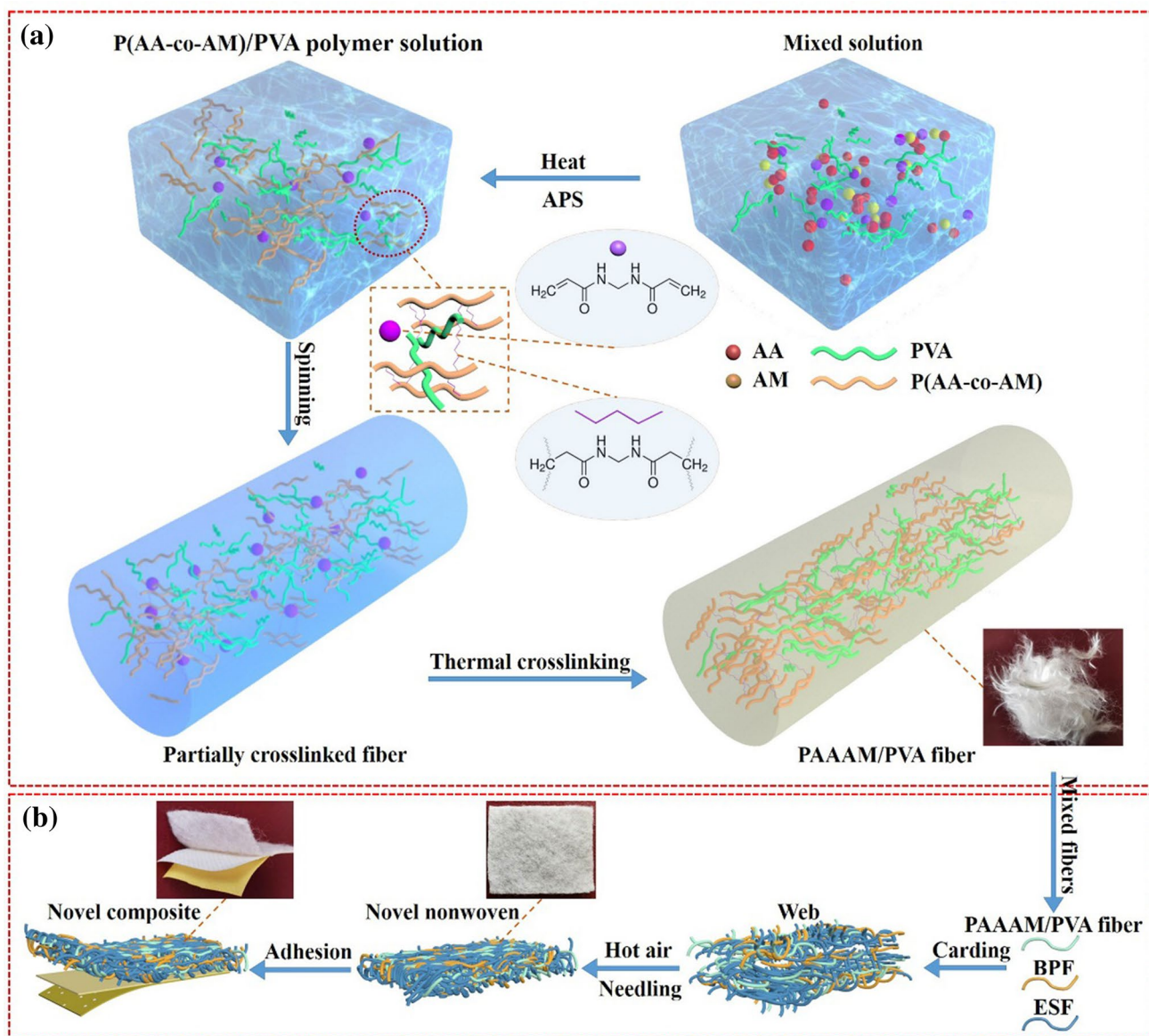


Fig. 1 Preparation processes of **a** PAAAM/PVA fibers and **b** highly hygroscopic and strong antistatic medical protective clothing material

ratio of 25/15/60 into a web. The fiber web was heat-bonded at 140 °C in an electric blast constant-temperature oven for 25 min, then needle punched to obtain a highly hygroscopic nonwoven fabric.

The novel medical protective composite nonwoven fabric was obtained through gluing the highly hygroscopic nonwoven fabric to the inner surface of the strong antistatic polypropylene nonwoven fabric covered with a breathable polyethylene film by polyacrylate pressure-sensitive adhesion.

Characterization

The surface morphology of PAAAM/PVA fibers was characterized by SEM (TESCAN VEGA3, Kohoutovice, Czech

Republic). The surface structure of the resultant fibers was measured by FTIR (Nicolet 5700, Madison, USA) with a spectral range of 400–4000 cm^{-1} . A fiber fineness analyzer (YG002C, Ningbo, China) was used to study the swelling behavior of the fibers.

Sweat Absorption and Retention of Composite Nonwoven Fabric

Acid and alkaline sweats were prepared according to ISO 105-E04:2013. The absorption rate of PAAAM/PVA fibers or materials was measured by the tea bag method [20]. 2.00 g of dried fibers or 5.00 g dried material was immersed into sweat at 37 °C for different durations. A 300-mesh nylon

mesh bag was used to filtrate. The fibers or materials were weighed when dripping had ceased [21,22].

The retention rate was determined by the pressing loss method [23–25]. The fibers or materials were weighed at room temperature after having fully absorbed the sweat. The fibers were then distributed as evenly as possible in a ϕ 100 mm petri dish covered with a 300-mesh nylon mesh. A load of 200 g/m^2 was applied for a certain period and then the sample was weighed. The materials were put into a ϕ 150 mm petri dish and a load of 200 g/m^2 was applied, then put them in a polyethylene bag as a whole to seal, and placed them in an oven at 37°C with different times. The results for the novel material were compared with those for the conventional material (strong antistatic polypropylene nonwoven fabric covered with breathable polyethylene film).

Hygroscopicity of Composite Nonwoven Fabric

In order to evaluate the hygroscopicity of the novel material, self-made equipment was developed. In detail, 100 g of distilled water was added into a 150 mL beaker, and then the beaker was sealed with the novel material and the conventional material, respectively. These two beakers were placed on a heating plate at 80°C , and the water mist on the cup wall was observed and compared. The moisture absorption rate was calculated by measuring the weight differences of the covered materials at different time points.

Thermal and Moisture Comfort of Composite Nonwoven Fabric

The moisture permeability and thermal resistance were used to evaluate the thermal and moisture comfort of the novel material. The hygroscopic method was used to measure the moisture permeability [26, 27], the test conditions were at 37°C and 90% humidity with air flow velocity 0.3 m/s, and the polyethylene film was facing up. The thermal resistance of the novel material was tested using a flat-type fabric thermal insulation instrument [28] according to ISO 11092:2014. The results of the novel material were compared with those of the conventional material.

Results and discussion

The morphology of PAAAM/PVA fibers is shown in Fig. 2. As shown in the SEM image of Fig. 2a, b, micro-scale grooves and strips can be obviously observed on the PAAAM/PVA fiber surface. These grooves and strips increase the contact area between fiber and water, leading to an increase in water absorption. As can be seen in Fig. 2c, d, microscale pores with a diameter of less than $1 \mu\text{m}$ are distributed inside the fiber. Water molecules can penetrate into the fiber through these microscale pores, resulting in an increase in water absorption and retention. Microscale protrusions can be seen on the surface and cross section of the fiber, which illustrates a micro phase separation structure of P(AA-co-AM) and polyvinyl alcohol.

The FTIR spectrum of PAAAM/PVA fibers is shown in Fig. 2e. The peak at 3413 cm^{-1} is a typical peak formed by

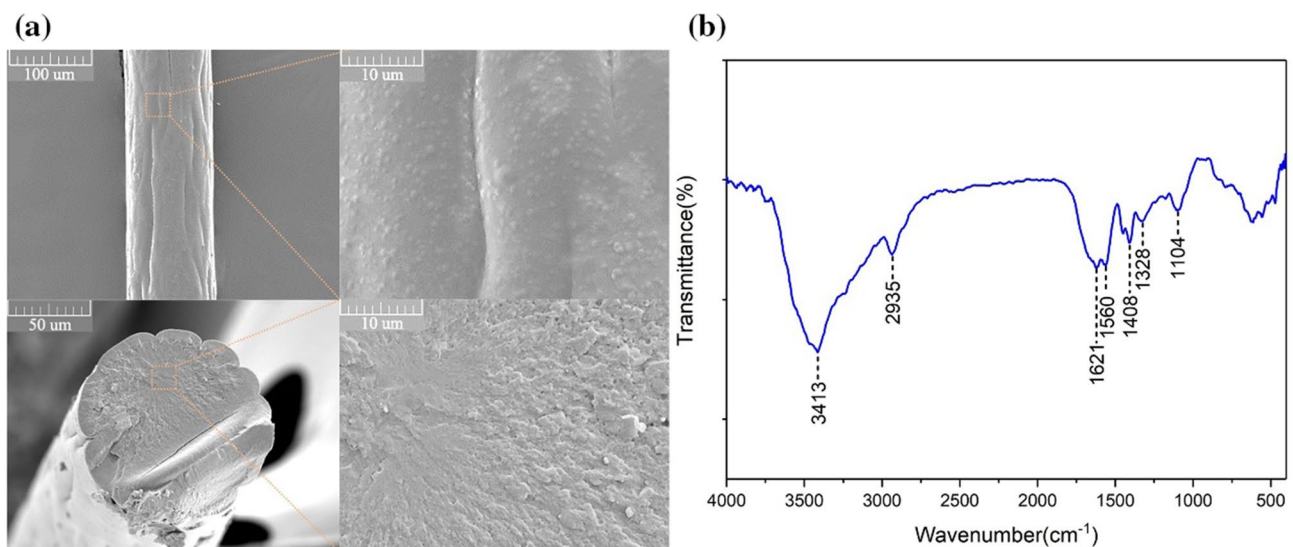
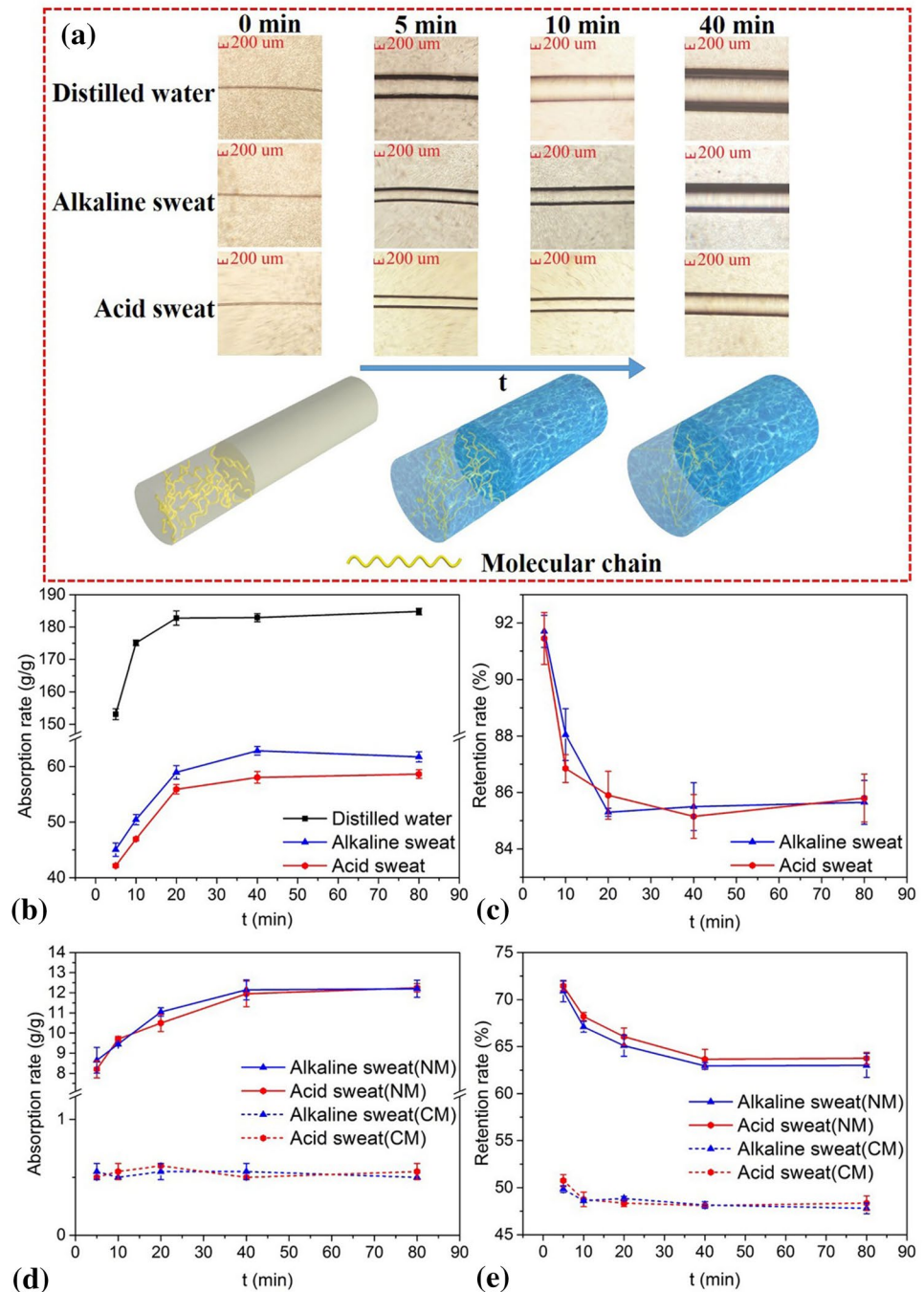


Fig. 2 SEM images of PAAAM/PVA fibers **a** the longitudinal surface and **b** high magnification view, **c** the cross-section and **d** high magnification view. **e** FTIR spectra of PAAAM/PVA fibers

the stretching vibration of the hydroxide bond. The peak at about 2935 cm^{-1} corresponds to C–H stretching vibration. The vibration peaks at 1621 , 1560 and 1328 cm^{-1} are formed by C=O stretching, N–H bending and C–N stretching vibrations of acylamino, respectively. The peak at about 1408 cm^{-1} corresponds to COO^- stretching vibration. The vibration peak at 1104 cm^{-1} is formed by C–O stretching vibration of polyvinyl alcohol [29]. The characteristic peaks of PAAAM/PVA fibers demonstrate that there are both acrylic-co-acrylamide and polyvinyl alcohol.

The swelling behavior of PAAAM/PVA fibers is illustrated in Fig. 3a. The structure of PAAAM/PVA fibers is a lightly cross-linked macromolecular network. The network structure with a large number of hydrophilic groups such as $-\text{COOH}$ and $-\text{COONa}$ consists of chemical crosslinks and intertwined macromolecular chains. Macromolecular chains in fiber are tightly contracted together under dry conditions. However, when the fiber contacts water, the $-\text{COONa}$ group dissociates with $-\text{COO}^-$ fixed in the macromolecular chain to generate an electrostatic repulsive force leading

Figure 3 **a** Swelling behavior and mechanism of PAAAM/PVA fibers in different liquids. **b** The absorption rate-time curve of PAAAM/PVA fibers in alkaline and acid sweats. **c** The retention rate-time curve of PAAAM/PVA fibers in alkaline and acid sweats. **d** The absorption rate-time curve of NM and CM in alkaline and acid sweats. **e** The retention rate-time curve of NM and CM in alkaline and acid sweats.



to expansion of the network structure. Meanwhile, most of Na^+ is trapped inside the network due to the increasing of osmotic pressure [30]. So, the fiber can absorb water and swell. With the increasing absorbance of water, the osmotic pressure reaches equilibrium. Meanwhile, the expansion of the network is also limited by chemical bonds and elastic shrinkage of the network structure. As a result, the fiber has the ability to absorb and retain water to a certain extent.

The absorption rate-time curves of PAAAM/PVA fibers in different solutions can be seen in Fig. 3b. The three curves exhibit the same tendency and the maximum sweat absorption rates of PAAAM/PVA fibers could reach 62.9 g/g and 58.1 g/g at 40 min in alkaline and acid sweats respectively, which are much lower than those of distilled water. This is mainly due to the bond between water molecules and hydrophilic groups on molecular chains of PAAAM/PVA being inhibited by ions in sweat. Therefore, the osmotic pressure inside and outside of the network structure reduces, causing a reduction of water molecules entering the fiber. As a result, the maximum liquid absorption rate reduces. It has little effect on the maximum liquid absorption of PAAAM/PVA fibers in acid sweat and alkaline sweat due to weak acidity and basicity. PAAAM/PVA fibers reach the fastest liquid absorption rate at 5 min, which is the result of the interaction of hydrophilic groups and osmotic pressure. The liquid absorption rate decreases with reduction in osmotic pressure and the shrinking force caused by the network expansion.

Retention of PAAAM/PVA fibers is shown in Fig. 3c. Sweat retention rates of PAAAM/PVA fibers could reach 85.6% and 85.8% at 40 min in alkaline and acid sweats, respectively. The main sweat loss of the fibers appears within 10 min, because water is easily squeezed out on fiber surfaces and among fibers under pressure. Then, sweat loss decreases due to difficulty in the disruption of the bond between water and the hydrophilic group.

The comparison of the sweat absorption between the novel material (NM) and the conventional material (CM) is shown in Fig. 3d. The maximum sweat absorption rates of the NM reach 12.2 g/g and 12.3 g/g at 40 min in alkaline and acid sweats, respectively, much higher rates than for the CM. It can be seen that PAAAM/PVA fibers and bamboo pulp fibers [31, 32] can absorb a large amount of liquid due to the hydrophilic groups and structures. Furthermore, the densely entangled network structure and internal voids of the NM result in a good physical adsorption effect on sweat. The NM reaches the fastest sweat absorption rate at 5 min. Then, the rate decreases as the fiber absorption gradually approaches saturation and the expanded PAAAM/PVA fibers occupy the internal voids.

The sweat retentions between the NM and CM are compared and illustrated in Fig. 3e. It can be seen that the sweat retention rates of the NM reach 63.0% and 63.8% in alkaline and acid sweats, respectively, which are significantly higher

than those of the CM. Meanwhile, both materials have fastest sweat loss rates within 5 min. The sweat in the voids of the NM is absorbed by physical action resulting in a poor binding force; it is easily diffused or squeezed out under a certain pressure, resulting in faster sweat loss in the first 5 min. It is difficult to disrupt the bond between water and hydrophilic groups, and the moisture is absorbed by the NM again with sweat evaporating inside of the polyethylene bag. As a result, the sweat loss rate decreases in the later period and the retention rate gradually reaches stability. Compared with the NM, the structure of the CM is denser. Once water molecules enter into the fiber and nonwoven fiber, it is difficult to squeeze it out. That is the reason why the CM has a certain liquid retention rate.

In addition, a moisture absorption experiment was run and thermal moisture comforts between the NM and the CM were compared. The moisture absorption processes of the NM and CM can be seen in Fig. 4a. Both materials (NM and CM) can block the release of water vapor from the beaker. Water mist on the beaker covered with the CM can be obviously observed at 5 min, and the formed water droplets slipped down at 10 min. On the contrary, for the NM case, the beaker surface is almost transparent at 5 min. Water mist only appears on the beaker surface at 30 min, which illustrates that the humidity is lower. Therefore, we propose that the highly hygroscopic functional layer of the NM can efficiently absorb water vapor in the air for a long time and reduce the humidity of the air, protecting medical staff from pathogen damage. Furthermore, the moisture absorption rates of the NM and CM are calculated and shown in Fig. 4b. The curves show the moisture absorption rate of the NM dramatically increases along with heating time, reaching 1.04 g/h. For the CM case, the moisture absorption reaches 0.53 g/h. The results indicate that the high moisture absorption functional layer has a strong ability to absorb water vapor and lasts a long time. But PAAAM/PVA fibers in the surface layer gradually become gelatinous after absorbing moisture, which hinders the entry of water vapor. Therefore, the increase in moisture absorption rate slows down after 2 h.

It can be seen from Fig. 4c that the moisture permeability of the NM reaches 12,638.5 $\text{g}/(\text{m}^2 \text{d})$, which is 307.6% that of the CM. Medical protective clothing has strict requirements for filtration efficiency of pathogens through the formation of an impermeable surface on the fabric by coating or laminating, resulting in a low moisture permeability. However, the NM absorbs a large amount of water vapor to keep a low humidity in the air layer under the clothing by using the strong hygroscopicity and liquid retention of PAAAM/PVA fibers as well as the porous structure of the novel nonwoven fabric. The thermal resistance of the NM is higher than that of the CM due to the greater thickness of the NM. The thermal insulation effect of the novel nonwoven fabric

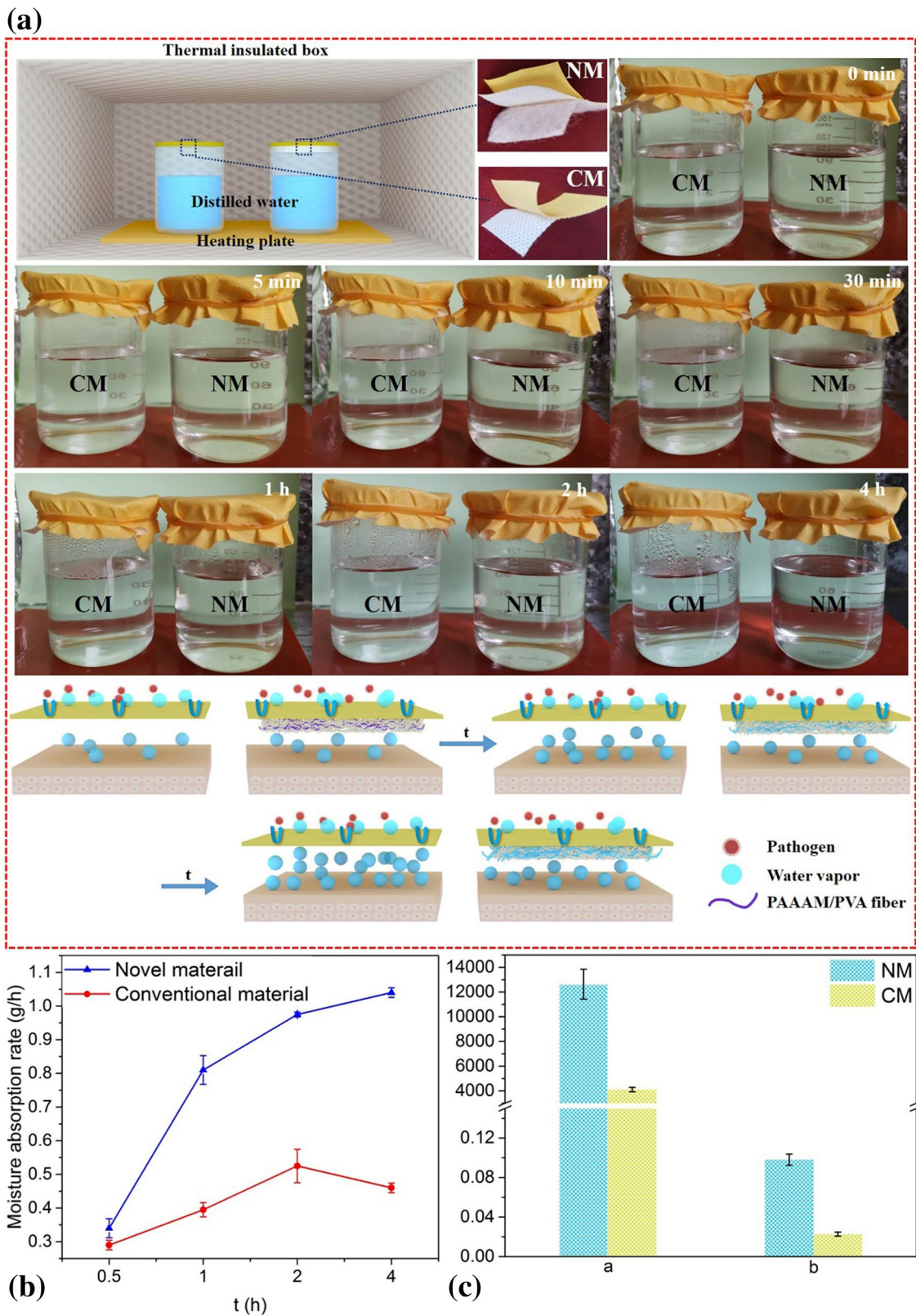


Figure 4 a Simulated moisture absorption experiment. b Moisture absorption rate of NM and CM. c Thermal and moisture comfort comparison between NM and CM (a Water vapor permeability, $\text{g}/(\text{m}^2 \text{ d})$; b Thermal resistance, $\text{m}^2 \text{ K}/\text{W}$).

is better than that of the CM due to its loose and porous structure [33]. As a result, the NM can be used in parts of protective clothing to ensure low thermal resistance.

Conclusions

PAAAM/PVA superabsorbent fibers were prepared from acrylic acid, acrylamide and polyvinyl alcohol via wet spinning, achieving high hygroscopicity and water retention. The maximum sweat absorption rate and retention rate of PAAAM/PVA fibers were 62.9 g/g and 85.8%, respectively. The absorption rate of the novel material had little difference in alkaline and acid sweats, with a maximum value of 12.3 g/g. The maximum sweat retention rate of the novel material (63.8%) was higher than that of the conventional material. The maximum moisture absorption rate of the novel material reached 1.04 g/h, more than that of the control case (only 0.53 g/h). The moisture permeability of the novel material reached 12,638.5 g/(m² d), which was 307.6% that of the conventional material. The novel medical protective clothing material has excellent hygroscopicity and can significantly improve the comfort of medical staff. However, the thermal resistance of the novel material was slightly higher than that of the conventional material. Therefore, the novel material can be used in parts of the protective clothing to ensure low thermal resistance.

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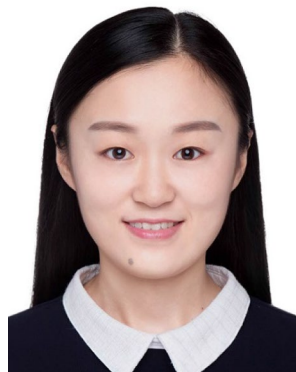
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Lin Yang is an engineer of Shandong Textile Research Institute. He received his master degree from Qingdao University. His main research directions include: (1) Preparation and application research of medical nonwoven materials; (2) Structure and function design of hydrogel fibers.



Yan Zhang master graduated from Perking Union Medical College and is currently working in the Affiliated Hospital of Qingdao University. Her research focus on patients care and application of fiber materials in clinical nursing to improve nursing care quality.



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