Wettability Gradient-driven Directional Water Transport Across Thin Fibrous Materials

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INTRODUCTION

Recently, novel properties have been observed when superhydrophobic and superhydrophilic surfaces are combined. For example, the Stenocara beetle, an insect in the Namib Desert, has an incredible ability to capture fresh water from air for its survival in the dry desert environment [1]. Such a feature derives from its special wing that has a hydrophilic-patterned superhydrophobic surface. Materials having a similar surface feature also exhibited a similar water-harvesting function [2]. A spider silk has been reported to show a periodic alternation of hydrophobic and hydrophilic surfaces along the fiber-length direction [3], which can quickly collect water from air. It was also observed that water droplets moved in one direction along a superhydrophobic-to-superhydrophilic gradient surface [4]. However, all these works are based on two dimension surfaces. The work on water transfer through porous media induced by a gradient wettability change has received little attention until very recently [5].

In this study, we have developed a simple, but very effective and versatile, method to produce wettability gradient across the thickness of fabrics, and demonstrated that the fabrics have the ability to spontaneously transfer water unidirectionally through the fibrous architecture. A plain weave polyester fabric was mainly used as a sample material.

APPROACH

The coating solution was prepared by hydrolysis of titanium tetraisopropoxide with two silanes, tridecafluorooctyl triethoxysilane (FAS) and 3-trimethoxysilylpropane thiol-1 (TMSPT). The coating solution was applied to the fabric through a dip-coating process. To achieve the directional water transfer effect, one side of the coated fabric was exposed to a multi-wavelength ultra-violet (UV) beam.

RESULTS AND DISCUSSION

As illustrated in Figure 1, the coated fabric became superhydrophobic. Water drop on the coated fabric formed a spherical droplet that could stay on the fabric for a long time (Fig 1a). The water contact angle measurement revealed that the contact angle of the treated fabric was as high as 170 º. In comparison, water drop on the un-coated pristine polyester fabric only stayed for a few seconds before spreading into the fibrous matrix (Figure 1b), although the fabric itself was hydrophobic with a water contact angle of 117 º.

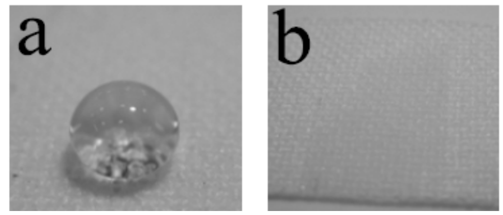

FIGURE 1. Water drops on (a) coated, and (b) pristine polyester fabrics

When the coated fabric was irradiated with UV light just from one side at 60 ºC for 2 hours, the irradiated surface changed its wettability significantly. Figure 2 shows the process of dropping water on the treated fabric. On the UV irradiated fabric surface, water just spread rapidly along the fabric, but not moved to the opposite surface (Figure 2a). The contact angle measurement indicated that the directly irradiated surface changed the water contact angle from 170 º to 39 º. Similar results were observed by repeatedly dropping water droplets onto the UV-irradiated side of the coated fabric.

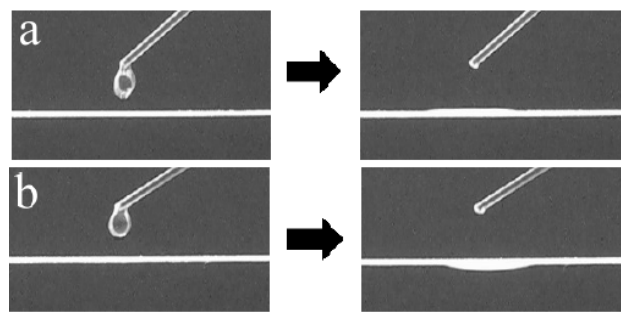

FIGURE 2. Photos of dropping water on the treated polyester fabric. (a) Upper surface was UV treated, (b) down surface was UV treated.

When water was dropped onto the back side of the fabric, which was not directly irradiated by UV light, the water drop moved immediately across the fabric thickness and spread on the UV irradiated front side, although a large contact angle was maintained between the droplet and the fabric (Figure 2b). Repeatedly dropping water on the fabric led to the same result. These results clearly reveal that the UV treatment renders the fabric with a directional water-transfer effect. Because of this water transfer effect, directly measuring the water contact angle of the opposite fabric surface was difficult. Instead, an indirect method in which two layers of the same treated fabric were closely pressed together and irradiated by UV light under the same condition was used. In this case, the water contact angle for the front side of the second fabric layer should be very close to that on the back side of the first one, which changed only from 170 º to 156 º (Figure 3) after the UV treatment. This result indicates that the UV treatment has very little influence on the back side of the irradiated fabric and the back surface still maintained its superhydrophobic feature.

Figure 3 also shows the breakthrough pressure of the fabrics, which can be used to understand water transport across the fabric. For the uncoated pristine polyester fabric, only 2 cmH_2O of pressure was formed when water started to pass through the fabric, and there was no difference between the two fabric sides. For the coated fabric, the breakthrough pressure increased to 35 cmH_2O, and side difference was not observed either. However, for the UV-treated fabric, the breakthrough pressure was side dependent. On the UV-irradiated surface, a breakthrough pressure of 25 cmH_2O was measured, which is slightly lower than the coated fabric without any UV treatment. The breakthrough water pressure on the back side of the UV irradiated surface was only 4 cmH_2O, which is similar to the pristine fabric. The different breakthrough pressures between the two fabric sides could be another indication of the directional water-transfer effect. The changes in wettability and breakthrough pressure due to the UV irradiation did not happen for the uncoated pristine polyester fabric.

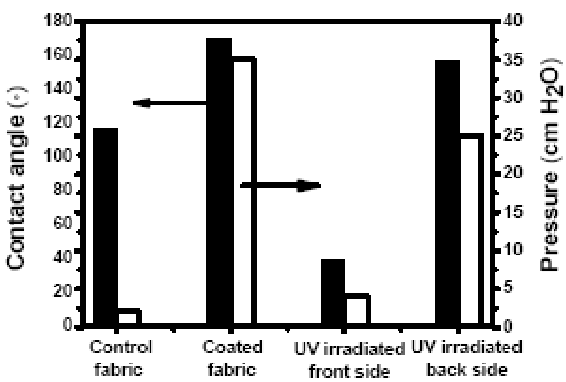

FIGURE 3. Water contact angles and breakthrough pressures on the fabrics

The chemical functionalities of the treated surface were examined by X-ray photoelectron spectroscopy. It was found that -COOH and -SO_3H groups were formed on the irradiated fabric surface, and the formation of the water absorptive groups was the main reason for the surface to become hydrophilic after the irradiation treatment. Because of the intensity dependence, the photo oxidation reaction on the fabric surface that received the strongest UV light had the highest reaction yield, rendering the surface with the largest decrease in the water contact angle, while the light intensity decayed along the fabric thickness, leading to gradually reduced photo oxidation reaction. As a result, a gradient change from hydrophilicity to hydrophobicity across the fabric was created.

The UV treatment time affected the wettability and breakthrough pressure. A longer UV irradiation period led to lower contact angles and reduced breakthrough pressure on both the fabric sides. The changes of the wettability also resulted in difference in water-transfer effects. When the UV treatment was longer than 2 hours, water was able to transfer from both fabric sides, despite the difference in the breakthrough pressure. When the treatment time was shorter, e.g. less than 30 minutes, the directional water transfer became very slow, taking about a few seconds to allow a droplet to transfer through.

Apart from the polyester fabric, other fabrics from wool and cotton, paper, carbon fiber nonwoven membrane and thin porous foam were also studied.

CONCLUSIONS

We have demonstrated that a wettability gradient from superhydrophobicity to hydrophilicity can enable the fabrics to have a directional water-transport function: water can easily transfer across the fabric from the superhydrophobic side to the hydrophilic one, but not in the opposite direction unless a sufficient external force is applied. The directional water-transfer fabrics also showed an apparent difference in the critical pressure allowing water to break through from the two fabric sides. The directional water transfer fabrics may find applications in various areas especially for those that involve fluid transport in both daily life and industry.

ACKNOWLEDGMENT

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