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Field Test of Hydrophobic and Superhydrophobic Surfaces in a Paper Machine for Easy-to-Clean Application

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Abstract

Hydrophobic and superhydrophobic surfaces were field-tested on two locations in a paper machine to see the easy-to-clean property, compared with a reference surface. One test site was near machine wire which was wet place exposed to fibres and wood extracts, and the other was at size roll, where was much drier and surfaces were exposed to glue aerosol. The test period was 16 days. At the end of the field test, all the surfaces were covered with substances collected from the paper machine environment. The surfaces were then washed by pressurized water. For the surfaces tested near the machine wire, the collected substances could only be washed away slightly and therefore no surface was easy-to-clean. However, for the surfaces tested at the size roll, the washed hydrophobic and superhydrophobic surfaces became quite clean. The field-tested surfaces were characterized visually and by stereomicroscopy, scanning electron microscopy and contact angle measurement. The results show that the application of hydrophobic and superhydrophobic surface as easy-to-clean surface depends on the testing location where different types of substances exist. The hydrophobic surface works almost as good as the superhydrophobic surface in size roll to have easy-to-clean property..

Keywords: Hydrophobic, Superhydrophobic, Easy-to-clean, Field test, Paper machine

BADANIA EKSPLOATACYJNE POWIERZCHNI HYDROFOBOWYCH I SUPERHYDROFOBOWYCH W MASZYNIE PAPIERNICZEJ W PRZYPADKU ZASTOSOWANIA ŁATWY DO CZYSZCZENIA

Powierzchnie hydrofobowe i superhydrofobowe poddano badaniom eksploatacyjnym w dwóch miejscach maszyny papierniczej, aby obserwować cechę łatwości oczyszczania w porównaniu z powierzchnią odniesienia. Jedno badane miejsce znajdowało się w pobliżu prętów maszyny i było mokrym miejscem wystawionym na działanie włókien i ekstraktów drewnianych; drugie badane miejsce znajdowało się przy walcu formatowym, gdzie było bardziej sucho, a powierzchnie były wystawione na działanie aerozolu klejowego. Okres badania wynosił 16 dni. Po zakończeniu badań eksploatacyjnych wszystkie powierzchnie pokryły substancjami zebranymi ze środowiska maszyny papierniczej. Powierzchnie te umyto następnie wodą pod ciśnieniem. W przypadku powierzchni badanych w pobliżu prętów maszyny, zgromadzone substancje można było zmyć tylko częściowo i dlatego żadna powierzchnia nie charakteryzowała się łatwością czyszczenia. Jednakże w przypadku powierzchni badanych przy walcu formatowym, powierzchnie hydrofobowa i superhydrofobowa poddane myciu były całkowicie czyste. Powierzchnie poddane badaniom eksploatacyjnym zostały scharakteryzowane wizualnie, za pomocą mikroskopu stereoskopowego i skaningowego oraz za pomocą pomiarów konta zwilżania. Wyniki pokazują, że zastosowanie powierzchni hydrofobowej i superhydrofobowej jako powierzchni łatwej do oczyszczania zależy od miejsca badania, gdzie występują substancje różnego typu. Powierzchnia hydrofobowa pracuje na wałku formatowym prawie tak samo dobrze jak powierzchni superhydrofobowa, wykazując właściwość łatwości czyszczenia.

Słowa kluczowe: hydrofobowy, superhydrofobowy, łatwy w czyszczeniu, badania eksploatacyjne, maszyna papiernicza

1. Introduction

Superhydrophobic surface, inspired by lotus leaf, is well known to have easy-to-clean property [1]. Due to the two scale micro/nano surface topography/roughness and a low surface energy on lotus leaf, the contact area and therefore the adhesion between mud/dust and the surface is small. Water droplet stands on the lotus leaf, i.e. has the contact angle of more than 150º and a very small roll-off angle of less than 5º. Therefore, the water droplet could easily roll off and take the mud/dust away when the surface is slightly inclined. In this way the surface could be cleaned by water without using any detergents. Typically, the surface can be hydrolyzed by fluoroalkysilanes with low surface energy molecules. However, when a flat surface is treated with fluoroalkysilane, the maximum contact angle for water is about 120º. In order to obtain superhydrophobicity with contact angle for water of more than 150º, surface roughness/topography has to be combined with the low surface energy [2, 3].

In paper making process the primary pulp slush consists of wood fibres and fillers mixed in water. The function of paper machine is to remove water by different steps to obtain dry and homogeneous paper. Depending on the end use of the paper, different kinds of coatings with organic and/or inorganic materials are deposited on the paper with one or more than one layer. Therefore paper machine surfaces also collect substances from the pulp slush and the production environment. As a result, it requires regular shut-down for maintenance and cleaning purpose.

In a previous study, a superhydrophobic flaky γ-alumina surface was field-tested in the size roll at the paper machine, as compared with a reference surface [4]. The superhydrophobic surface showed good easy-to-clean property. The durability of the superhydrophobic surface was also tested by the field test and nanoindentation. In this study, a more extensive field test was carried out on three types of surfaces (superhydrophobic, hydrophobic and reference surface) in two test locations (machine wire and size roll) in the paper machine. The machine wire site is wet and exposed to fibres and wood extracts, and the size roll is dry site where surfaces are exposed to glue aerosol. The results reported in this study are more systematic, showing that no surface was easy-to-clean in the machine wire site, but both the hydrophobic and superhydrophobic surface had quite good easy-to-clean property in the dry size roll site. Therefore, the hydrophobic surface is more competitive as easy-to-clean surface in size roll since fluoroalkysilane treatment is much easier than the preparation of superhydrophobic surface.

2. Experimental

Three different types of surfaces (reference, hydrophobic, superhydrophobic) were prepared for the field test. The substrate material for all the surfaces was stainless steel AISI 316 L: EN 1.4404 with 2B surface quality. The superhydrophobic flaky g-alumina surface was made by a sol-gel method. The raw materials are aluminium tri-sec-butoxide (denoted as $Al(O\text{-}sec\text{-}Bu)_3$, $C_{12}H_{27}AlO_3$ > 97 %, VWR), isopropyl alcohol (denoted as i-PrOH, C_3H_7OH > 99 %, VWR) and ethyl acetoacetate (denoted as EAcAc, $C_6H_{10}O_3$ > 98 %, VWR). Firstly, 3 g $Al(O\text{-}sec\text{-}Bu)_3$ and 30 ml i-PrOH were mixed and stirred at room temperature for 1 h. Then 2 ml EAcAc was introduced, and the solution was stirred for 1 h. After that, the mixture of 1 ml water and 5 ml i-PrOH was added and with mixing for another 2 h the solution was ready for spin coating at 1500 rpm for 20 s. The coating was first heat-treated at 400 °C in air for 15 min, followed by immersion into boiling water for 10 min and a subsequent heat-treatment at 600 °C for 30 min in air to form flaky g-alumina coating. The surface chemistry was finally modified by (heptadecafluoro-1,1,2,2-tetrahydrodecyl) trimethoxysilane ($CF_3(CF_2)_7CH_2CH_2Si(OCH_3)_3$, denoted as FAS, ABCR GmbH & Co. KG, Karlsruhe, Germany). The FAS solution was prepared by mixing 1 ml FAS and 50 ml ethanol for 1 h. Then the flaky g-alumina coating was immersed into the FAS solution for 1 h, followed by heating at 180 °C for 1 h in air. More details about the morphology, topography and phase structure of the superhydrophobic g-alumina coating have been reported elsewhere [4-8]. On the other hand, the hydrophobic surface was made by only coating the substrate with FAS. The FAS top layer has a thickness of about 7 nm. The FAS modified stainless steel has a water contact angle of 112° which indicates that the surface is hydrophobic.

The field test was done in two locations in a paper machine producing release base paper for labeling. The first one is in machine wire, which is situated in the wet end of the paper machine. Machine wire site is very wet, with fibres, additives and other dirt flied to machine surface and dried by the air flow in the wire section. After drying the dirt is strongly attached on the surfaces and thus the surface needs careful periodical washing. The second test site is size roll, which is situated at the dry end of the paper machine and it spreads glue onto the paper. The size roll site is dry, and small glue droplets fly, accumulate and strongly attached to the machine surface. Teflon-plates mounted with the test samples by AISI316L steel screws were attached on steel rails bolted on the test sites. The temperatures measured near the samples were 32 °C and 43 °C in the machine wire and the size roll respectively. The sizes of the samples were about 20 mm x 75 mm and the test lasted for 16 days. After that, the samples were washed by pressurized water in a similar manner as washing the paper machine parts and frame.

The field-tested surfaces before and after washing were characterized in different ways to study the easy-to-clean property. The macro/micro-scale accumulation of the substances from the testing environment was observed visually and by stereomicroscopy (Leica Microsystems AG). The micro/nano-scale morphology was examined by field emission scanning electron microscopy (FESEM, Zeiss ULTRAplus). Water contact angles were measured by a system (Pisara, FotoComp Oy, Jyväskylä, Finland), which is composed of a microliter syringe for releasing the water droplet and an optical system connected to a computer for data analysis. The size of the water droplet was 5 μl in the measurement. Droplets were placed at five positions and the average value was accepted as the final contact angle value.

a)

b)

Fig. 1. Images of the on-site samples on the 9th testing day near machine wire (a) and on 13th testing day in size roll (b).

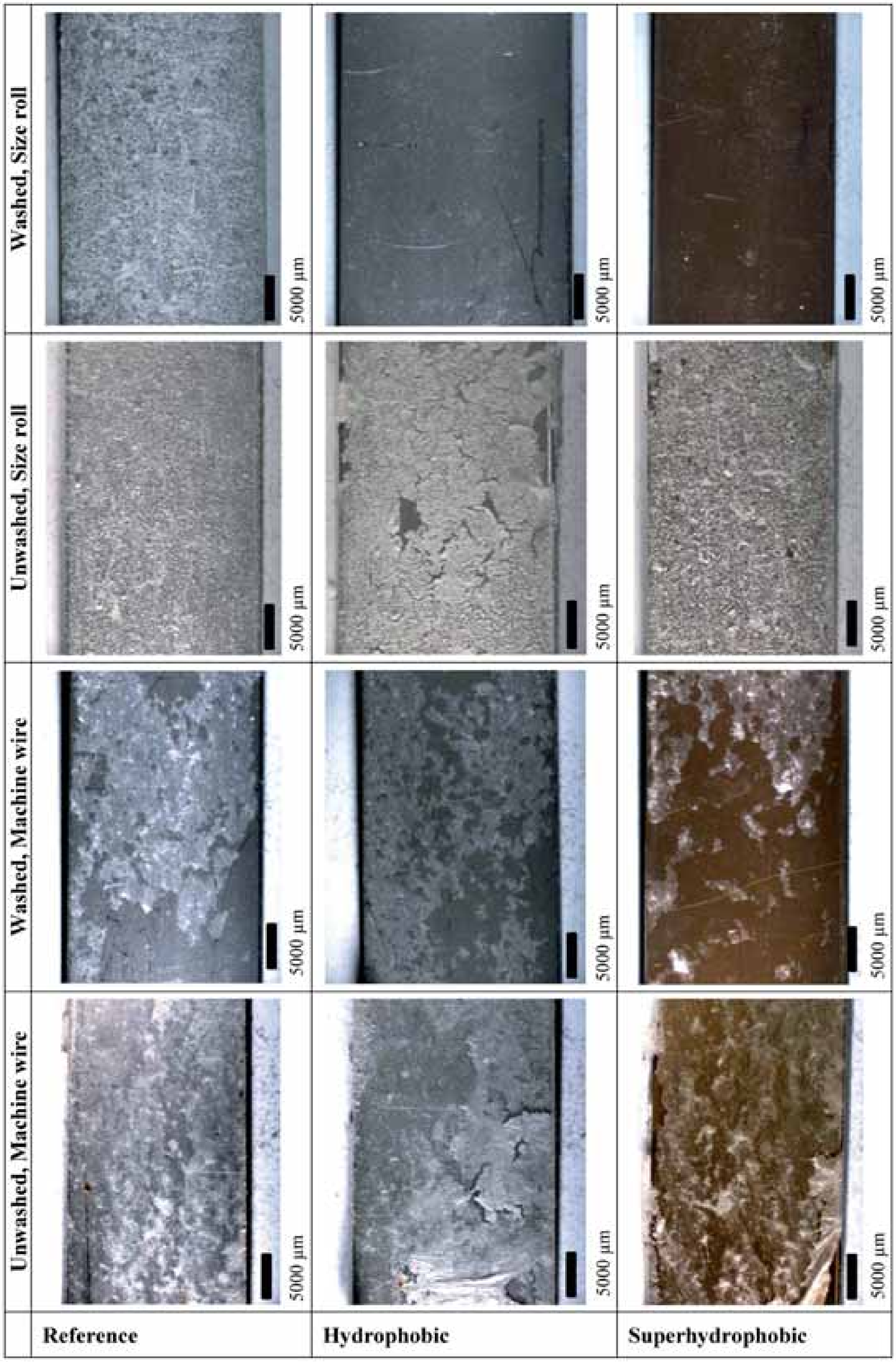


Fig. 2. The photographs of the unwashed and washed samples tested for 16 days in machine wire and size roll in the paper machine. Bar scale = 5000 µm in all the images.

3. Results and Discussion

The situation of the test surfaces near machine wire (wet site) on the 9th testing day, as compared with the surfaces tested in size roll (dry site) on the 13th testing day is shown in Fig. 1. The pictures were taken on the test sites when the test was still going on. On the on-site test surfaces near machine wire, the collected substances were very wet, while the collected substances on the surfaces in size roll were dry.

After 16 days, all the surfaces were fully covered with the white substances. The samples were taken off from the testing sites and the wet surfaces from machine wire site became dry. The stereomicroscopy images of the non-washed and washed samples from the two sites are collected and com-

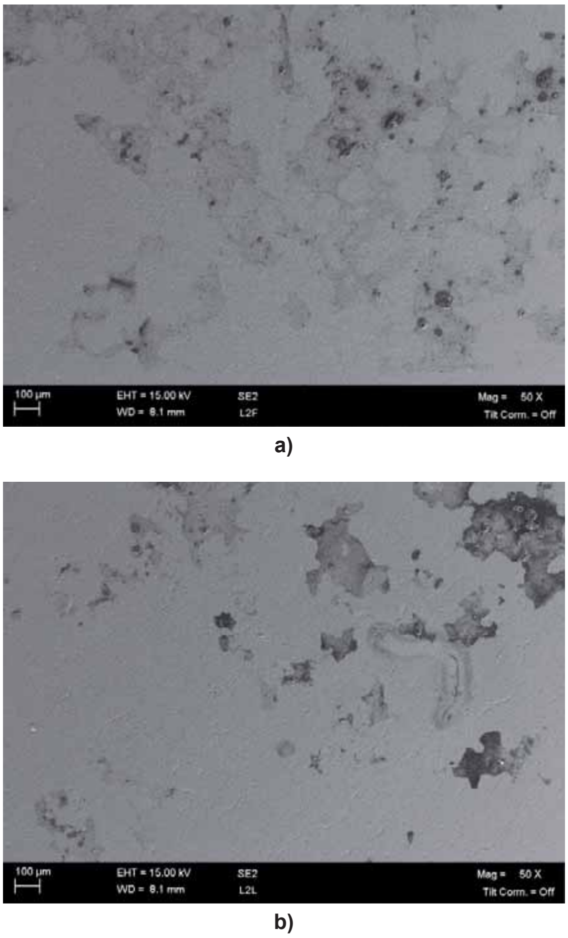


Fig. 3. SEM images of the washed hydrophobic (a) and superhydrophobic (b) surface tested in the size roll site.

pared in Fig. 2. After drying, some of the collected substance seems to detach on the hydrophobic and superhydrophobic surfaces tested in machine wire, indicating weak bonding of the substance to the surfaces.

After washing, the weakly bonded substances were removed from the surfaces. However, a large amount of the substances were still remained on the surfaces and no surfaces tested in the machine wire site were really easy-to-clean. The cleanability of the reference, hydrophobic and superhydrophobic surfaces was almost the same. On the other hand, although all the surfaces tested at size roll were fully covered with the white substances, the hydrophobic and superhydrophobic surface became almost clean after washing by pressurized water. Only a small amount of the substance remained on the hydrophobic and superhydrophobic surface, as indicated by the darker areas in Figs. 3a and 3b. The images in Fig. 3 look almost the same, showing that the cleanability of the hydrophobic surface is comparable to that of the superhydrophobic surface.

SEM images of the unwashed reference surfaces after the field test showing the difference of the collected substances from the machine wire and size roll testing sites are given in Fig. 4. The substances collected from the machine wire site are fibres together with small particles (Fig. 4a), and the fibres had a continous coverage to the surface (Fig. 4b). On the other hand the substances collected from the size roll site were larger particles (Fig. 4c) and a layer of much smaller particles under the larger ones (Fig. 4d).

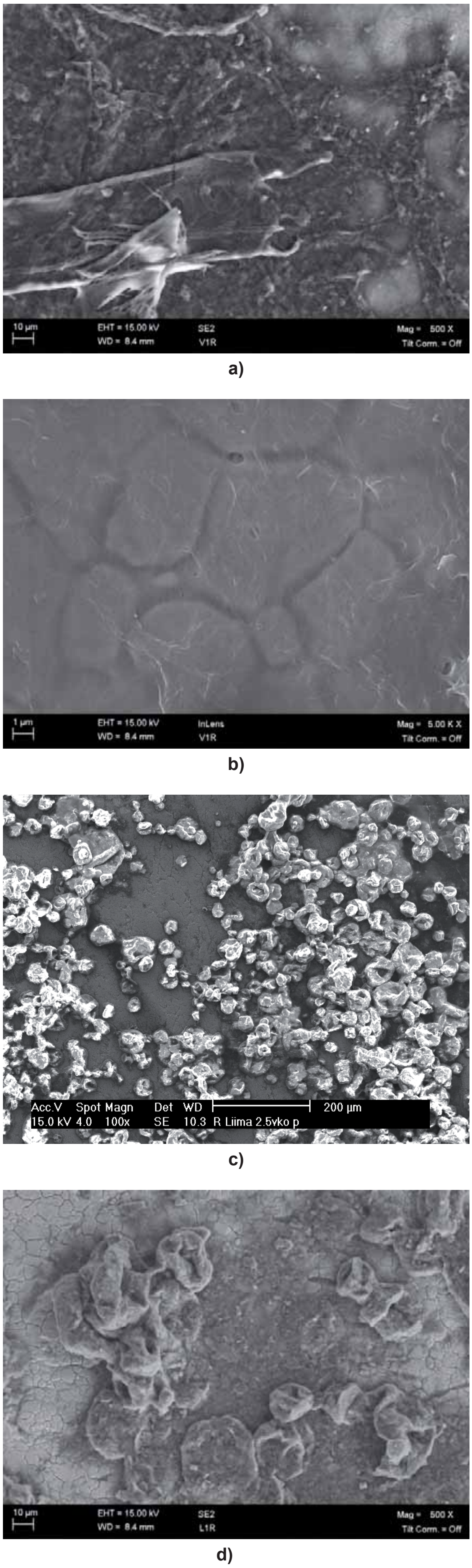
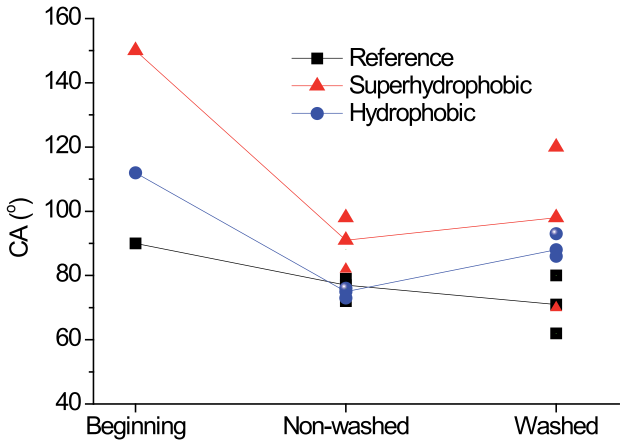
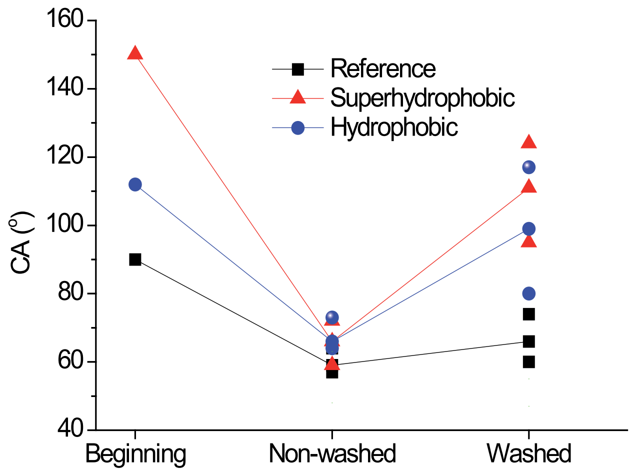


Fig. 4. SEM images of the unwashed reference surface tested in machine wire (a, b) and size roll (c, d), showing the different nature of the collected substances.



a)



b)

Fig. 5. Contact angle (CA) values for water of the reference, hydrophobic and superhydrophobic surface tested in machine wire (a) and size roll (b). The average values are connected by lines, and the variations are shown by the maximum and minimum values marked with scattered symbols.

Contact angle is very sensitive to the surface property and therefore contact angle values have a good indication to the cleanness of the surfaces. The contact angles for water measured on the different surfaces tested in machine wire site are shown in figure 5 (a).

At the beginning before the field test, the contact angles for water of the reference, superhydrophobic and hydrophobic surface were 90°, 150°, and 112°, respectively. After the field test, all the surfaces tested in the machine wire were covered with large amount of substances, therefore contact angles of the surfaces were much lower than that of before the field test, indicating that the collected substances had hydrophilic nature. The variation of the contact angle values between 70° and 100° is due to the uneven distribution of the collected substances. After washing, the contact angles of superhydrophobic and hydrophobic surface recovered a little bit, which indicated that some amount of the collected substances on the these surfaces had been removed by washing. However, the contact angle of the reference surface remained the same after washing, indicating that the collected substances had stronger bonding to the reference surface than that to the hydrophobic and superhydrophobic surface in machine wire. The contact angles for water on the different surfaces from the size roll are shown in Fig. 5b. The contact angles for the non-washed surfaces were almost same, lower than 90°, and the deviation was low from 56° to 73°. After washing, the contact angles on the hydrophobic and superhydrophobic surface returned to above 90°. This was due to the removal of the major collected substances by washing. The contact angle of the washed hydrophobic surface was close to the original value, indicating a good attainment of the surface cleanness and surface property after washing. However, the contact angle of the washed superhydrophobic surface was only about 110°, which was not superhydrophobic anymore. As reported previously, this was due to an attached thin organic layer and the degradation of surface topography and surface chemistry during the field test [4].

4. Conclusions

The field test shows that the application of hydrophobic and superhydrophobic surface as easy-to-clean surface depends on the testing location where different types of substances exist. No surface was easy-to-clean in the wet machine wire section, but both the hydrophobic and superhydrophobic surfaces had quite good and comparable easy-to-clean property in the dry size roll site. The different behaviours of the same surface in different testing sites are possibly determined by the nature of the substances in the different testing sites. Therefore the application of hydrophobic and superhydrophobic surfaces as easy-to-clean surface depends on the production environment in the paper machine and the hydrophobic surface is more competitive as easy-to-clean surface in the dry size roll site since surface fluoroalkysilane treatment is much easier than the preparation of superhydrophobic surfaces.

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