Image Analysis of Hydrophobicity of Polymer Insulators by Observing at Microscopic Area

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Abstract

Hydrophobicity of polymeric insulating material surface such as silicone rubber (SIR) and ethylene propylene diene monomer rubber (EPDM) insulator was studied by using image data analysis of the sample surface. Using a very high-speed microscope CCD camcorder, we digitized the hydrophobic surface image under the spraying of the mist of water. Even the size of the observed image area is only about 2 mm^2, the effect of aging in water and its recovery in air on the hydrophobicity of specimens were measured by their surface images of water droplets on the sample surface.

Using this microscopic image, we can determine the hydrophobicity class (STRI's HC level) without the effect of gravity or inclination of surface to the formation of water droplets on the surface. Image data analysis can calculate the image indexes such as size and shape factor of the droplets. They are also helpful to define the hydrophobicity class more accurately.

1. Introduction

Polymeric insulating materials such as EPDM and SIR are widely used in the manufacture of weather-sheds of outdoor insulators [1,2]. These materials have many advantages including an inherent property of a low surface free energy that renders a hydrophobic quality to the polymer surface.

The hydrophobicity is reduced by water absorption during aging with increasing environmental temperature and contamination buildup [3]. However, it recovers during the rest time in air at room temperature. A part of recovery of hydrophobicity is related to the evaporation process of the water in the specimen. In addition, specimens show excellent recovery of hydrophobicity if they have a low molecular weight (LMW) material in the matrix and it migrate to the sample surface during recovery, where LMW has a low surface free energy.

Hydrophobicity is usually measured by a contact angle of a droplet of distilled water on the surface. However it sometimes shows hysteresis, time dependence and location dependence of the measured point. Therefore, hydrophobic image of the surface is used to determine the STRI's hydrophobicity class (HC level 1 to 7) [4].

A digital image processing method for estimating the level of hydrophobicity of specimens are reported in [5]. The experiment showed that the water droplet patterns depend not only on the hydrophobicity of the sample but also on the inclination of the surface. When HC is smaller, therefore sample is very hydrophobic; the effect of inclination is larger. It means the gravity force cannot ignore compared to adhesion force when the size of the droplet is large.

This paper studies the image data analysis of hydrophobicity by observing at microscopic areas of the specimen, where the effect of gravity should be smaller compared to the effect of surface free energy. Image data indexes such as size-distribution of the very small droplets and shape of the droplets are discussed for the HC indexes. Not only distilled water but also solutions having lower surface free energies are used to evaluate the hydrophobicity class of the specimen surface.

2. Experimental procedure

Specimen tablets of SIR and EPDM insulator weather shed of 46 kV class outdoor insulation were employed. 12 specimens were cut out from each shed which having a diameter of 160 mm^{ϕ} and a thickness of 4 mm (outer) to 9 mm (inner). Each specimen was subjected to a water stress by immersing it in distilled water in a glass container at room temperature. The specimens were periodically removed from the water and the contact angle and weights of the specimens were measured to evaluate the amount of water absorption and solution of LMW fluid from the specimen. The conductivity of distilled water is less than 3 μS/cm. The change in the surface free energy of the immersion water of specimens during aging was also measured to evaluate the solution of LMW in SIR.

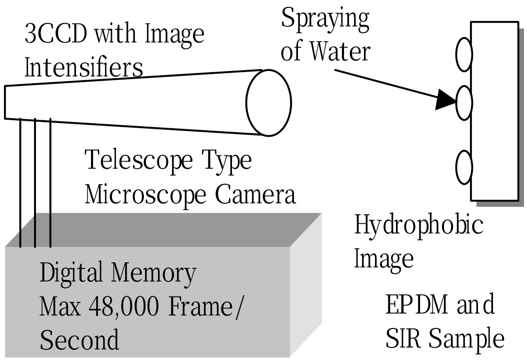

Figure 1. Schematic view of image digitizing system.

To measure the HC image, mist of the distilled water, γ_L =72.8 mN/m, and the solution, γ_L=52.0 mN/m, were sprayed to the sample surface. In this study, the evaluation area of the image is very small. Using 3CCD and image intensifiers the image size is only about 1.5x1.5 mm^2. It is 256x256 pixels with RGB 2^8 each full color resolution. The frame rate of the image we used is 1125 and 4800 FPS. The schematic view of the microscope system is shown in Fig.1.

3. Results and Discussions

3.1 Contact Angle and Size of Droplets of Surfactant Solutions on SIR

Before measuring the microscopic surface image, the relation between surface free energy, γ_L, of surfactant solution and its contact angle, θ, on the SIR is measured. Dodecylsulfate sodium salt, $C_{12}H_{25}NaC_4S$, was used for the surfactant. Above the critical micelles concentration, CMC; 0.15 % in weight, γ_L decreases with increasing the concentration of surfactant at room temperature. θ decreases with decreasing the surface free energy of the droplet [6].

Assuming a unit volume of the droplet, relation between contact angle and its interfacial area on SIR of the droplet can calculate. Figure 2 shows the relation between the size of mean contact area and the surface free energy of the droplet on SIR before aging. In this figure, ◆ shows the calculated result that assumes the volume of the droplet is same. Whereas, ■ is the evaluated mean value of the size of droplets measured by image analysis of 12x9mm^2 SIR surface with spraying of the solutions [6].

Both data show that the decreasing of surface free energy of the droplets increases the size of the contact area of the droplets on SIR. However, the increasing rate of contact area of droplets of ■ is larger than the calculated one that assuming the same unit volume.

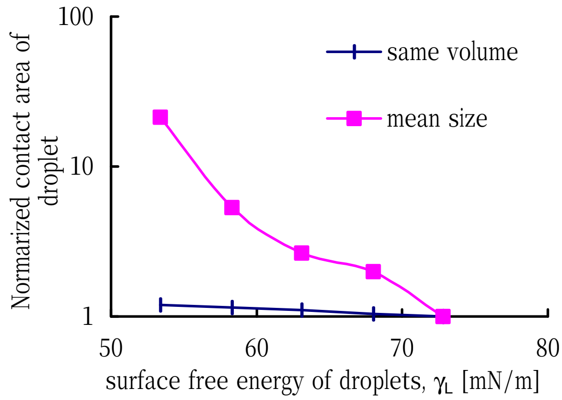

Figure 2. Surface free energy of droplet, γ_L, and its mean contact area on SIR before aging. The size of the droplet at 72.8 mN/m is normalized to be unit.

This figure means the size of mist by spraying is not same. Therefore, the spraying condition, typically the surface free energy of the droplet, is very important to determine the HC level from surface image. The surface free energy of liquid is not only changed by surfactant but also by the temperature of liquid itself that forms the droplet.

Moreover, if the spraying conditions are controlled to same, hydrophobic image still has influenced by the effect of gravity if the size of the droplets are larger and if the solid surface has the inclination. In this case, the early stage of spraying may provide good results. Because the surface tension force is larger compared to the one of gravity for the formation of droplet.

3.2 Microscopic HC Images of Specimens

Figure 3 shows microscopic HC images of SIR at room temperature. Figure 3 (a) shows a HC image made by distilled water of SIR after the sample is dried at room temperature. Figure 3 (b) shows the one of surfactant solution. Figure 3 (c) shows the HC image made by distilled water after the sample is aged in distilled water at room temperature. Figure 4 shows, respectively, the ones for EPDM. The images for surfactant solution after aging in distilled water for both SIR and EPDM are completely wetted.

From reference [6], θ decreases with decreasing the surface free energy of the droplets. It means the increase of surface free energy of solid during aging also decrease the contact angle. Both mean the increase of mean size of contact area of droplet on specimen after the same spraying condition. From microscopic HC images of figures 3 and 4, decreasing γ_L of sprayed water increases the size of water droplets formed on the specimens before aging (From (a) to (b)). This increase of

(a) Distilled Water, after drying. (b) Surfactant solution, after drying. (c) Distilled water, after aging.
Figure 3. Microscopic surface images of SIR before aging; (a), (b) and after aging in distilled water; (c).

(a) Distilled Water, after drying. (b) Surfactant solution, after drying. (c) Distilled water, after aging.
Figure 4. Microscopic surface images of EPDM before aging; (a), (b) and after aging in distilled water; (c).

size of the droplet is also shown in Figure 3 (c) and Figure 4 (c). In this case the specimens are after aging of immersion in distilled water at room temperature.

In this study hydrophobicity of SIR is better than EPDM. Figure 3 (c) and Figure 4 (b) and (c) show the shape of the droplets on the specimens becomes distorted from circular to non-circular. Using lower surface energy liquid or higher surface energy solid, the mist of spray forms non-circular droplets on solid surface. This means not only the non-uniform surface energy of specimen by the location of the surface but also the adhesion of droplets on specimen surface each other from meta-stable condition to more stable condition of total surface free energy when the HC number becomes larger. During spraying and after it the surface image should show dynamic changes of the shape of the water droplet on the specimen.

3.3 Dynamic Changes in HC Images

After the aging in distilled water at room temperature, hydrophobicity of SIR surface was decreased. In this case contact angle sometimes shows time dependent decrease. Figure 5 (a) to (c) show the dynamic change of droplets on SIR after aging in distilled water. From Figure 5 (a) to (c), two circular water droplets at the center of the figures become combine together and make an oval-shaped water droplet. The speed of adhesion of the droplets is within two frames of the images, i.e., less than 1.78 mS.

Figure 6 (a) to (d) show the microscopic images for dried SIR sprayed surfactant solution. In this case the size of mist should larger than the one of distilled water and the size of droplets on SIR becomes larger by the effect of both the size of mist and the decrease of contact angle (See 3.2). In this case droplet 1 and 2 combined at first (b), then droplet 3 combined it to make a crescent like droplet (c). Finally, it becomes circular by the effect of surface free energy of liquid that becomes smaller the surface area of the droplet (d). In this case the speed of combine of the droplets is also less than 1.78 mS and thereafter the relaxation of a shape of a droplet requires 23 mS (from(c) to (d)).

For Figures 5 and 6 the movements of the droplets are not vertically but seem to every direction to the surface. This means the force of gravity is less than the one of surface tension to make more stable energy formation for very small droplets. Therefore, early stage of the wetting of the solid surface may not affect by the inclination of the surface. In this case it affected by both the surface free energy of the liquid and solid, therefore, the temperature of the mist becomes very important parameter for HC evaluation.

ACKNOWLEDGEMENTS

This research is supported by Grant-in-Aid for Scientific Research (B) (2) of the Ministry of Education, Science, Sports and Culture of Japan and by the research foundation for the Electrotechnology of Chubu. We thank to Mr. Sawada and Mr. Hasegawa for their help of experiments.

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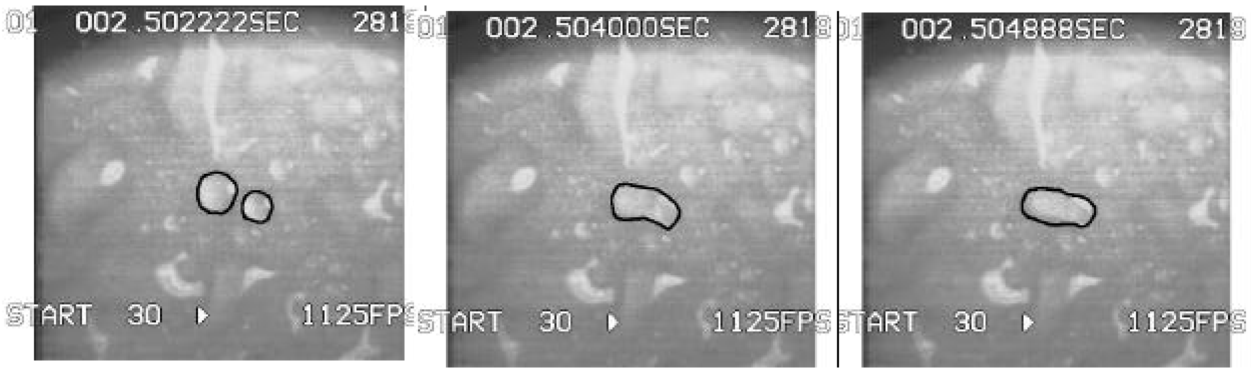
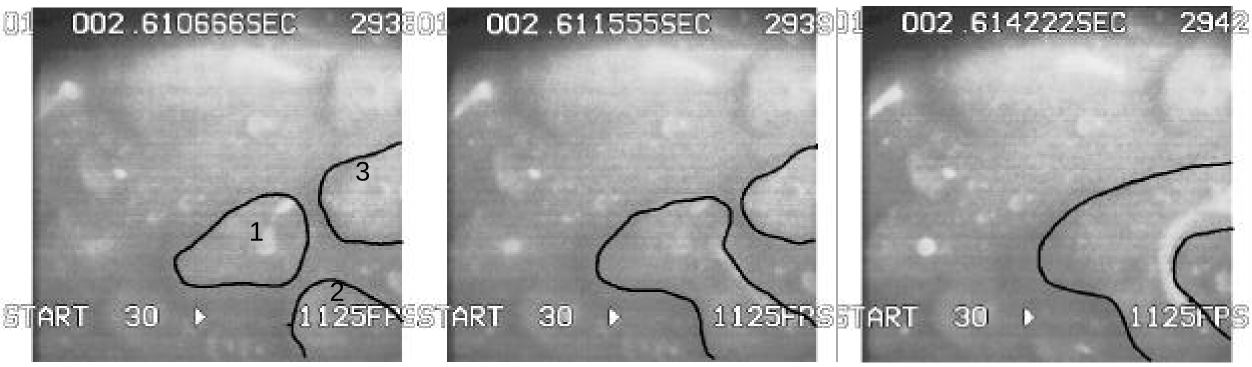
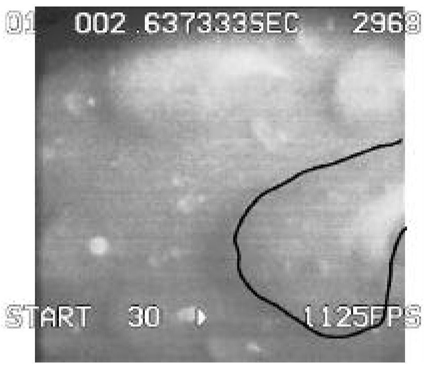


(a) Before adhesion. (b) Just after adhesion. (c) Becoming Stable form

Figure 5 Microscopic surface image of SIR after aging in distilled water. Distilled water was sprayed.





(a) Before adhesion of three droplets.
(b) Just after an adhesion of droplets 1 and 2.
(c) Just after another adhesion of the third droplet.
(d) Becoming more stable form.

Figure 6. Microscopic surface image of SIR after drying in air at room temperature. Surfactant solution was sprayed. From left to right (a), (b) and (c), under; (d).