Paper

Evaluation of Leakage Current on Various Types of Polymeric Materials Used for HV Outdoor Insulation in Salt-fog Condition

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Leakage current levels of various types of polymeric materials able to be used in HV outdoor insulation are evaluated using salt-fog chamber test. Silicone rubbers could resist leakage current development during this test. Larger leakage current is allowed on non-silicone polymeric materials than hydrophilic glass materials. The reduction magnitudes of the hydrophobicity of material surfaces and their recover rates during a restoration are in agreement with the levels of leakage current and subjected damages. Hydrophobic stability of silicone rubbers seems to be a key to suppress leakage current in polluted environments. It is suggested that hydrophobic behavior of polymeric materials in the early stage of their installations affect their electrical performances and aging levels.

Keywords: HV outdoor insulation, leakage current, polymeric materials, salt-fog test, hydrophobicity

1. Introduction

Leakage current level in wet and contaminated condition is one of significant indicators to assess electrical performances of materials used in HV outdoor insulation [1, 2]. A combination of contamination buildup and sustained moisture can form electrolyte films on material surfaces, and it allows leakage current to develop. Joule's energy generated by leakage current evaporates electrolyte and forms dry-band where electric field is locally enhanced. Enhanced electric field induces electrical discharges bridging dry-band. These electrical discharges called dry-band arcing produce high temperature spots that cause a severe material decomposition leading to tracking and erosion [3-8]. Even if leakage current is insufficient to induce dry-band arcing, it results in energy loss and reduction in flashover strength [9, 10]. Suppression of leakage current has technical merits both to prolong material lifetime and to improve a reliability of power systems [11, 12]. Leakage current is associated with the levels of contamination buildup and wetting on material surfaces. Wetting on materials is dependent on surface free energy of materials [13, 14]. Porcelain and glass materials having high surface free energy are readily wetted and permit a formation of electrolyte films. Polymeric materials of which surface free energy is much lower than that of porcelain and glass materials can resist wetting and a formation of electrolyte films. Suppression of leakage current practically using hydrophobicity of polymeric materials may give several advantages to outdoor insulation systems. However, when exposed to electric stress, contamination and moisture for a long time, surfaces of polymeric materials may allow gradual reduction in hydrophobicity and therefore leakage current development. At present, various types of polymeric materials are being in use worldwide. Polyolefins (EPDM, EPR and EVA), silicone rubbers, their alloys and cycloaliphatic epoxy resins are representative materials for outdoor uses [15], However, few reports on the comprehensive and systematic evaluation for leakage current levels on them in simulated and controlled conditions which correlates with outdoors well have been presented. Conventional laboratory tests, *e.g.,* inclined-plane and rotating wheel dip tests are intended for producing excessively severe conditions leading to distinct material failures caused by tracking or erosion. Because the excessive severity neglects materials' surface hydrophobicity which controls leakage current most effectively in field levels, a poor correlation between field and laboratory performances is sometimes observed, particularly for silicone-based materials. Leakage current levels on materials in salt-fog condition have a high relevance to the electrical performances in outdoor environments reflecting hydrophobic states of their surfaces. In this paper, leakage current on various types of polymeric materials in salt-fog is compared using salt-fog chamber method. Hydrophobicity and surface roughness are also evaluated to correlate leakage current level with material wetting and aging levels.

2. Experimental

2. 1 Samples

Various types of polymeric materials as well as reference glass materials are prepared. Detailed descriptions for sample materials are presented in Table 1.

2. 2 Salt-fog (SF) test

Fig. 1 presents the diagram and appearance of the SF test. Slab (120×50×3.9-6.0 mm^3) samples are used. Distances between electrodes made of stainless steel is 80 mm. Ac 4.8 kV is applied to them to produce average 60 V_{rms}/mm electric field. An oscillator equipped in a commercial humidifier is used to put fog into the chamber. Diameter range of fog generated from commercial oscillators is reported to be ranged from 1 to 20 μm [16]. This range is similar to that of natural fog. In order to quantify the leakage current level, cumulative charges of leakage current are measured. The definition of cumulative charge is shown in Fig. 2. Six samples are simultaneously tested, so that leakage current on each sample is rotationally acquired. First, wave form of leakage current for 0.5 sec (10 cycles) is stored in a digital oscilloscope (HP, 54520A) and calculated effective and peak value are sent to PC via GPIB interface. Repeating this procedure which takes about 1.2 sec for 5 min, average effective value and highest peak value are obtained. Finally, these are hourly plotted as in Fig. 2.

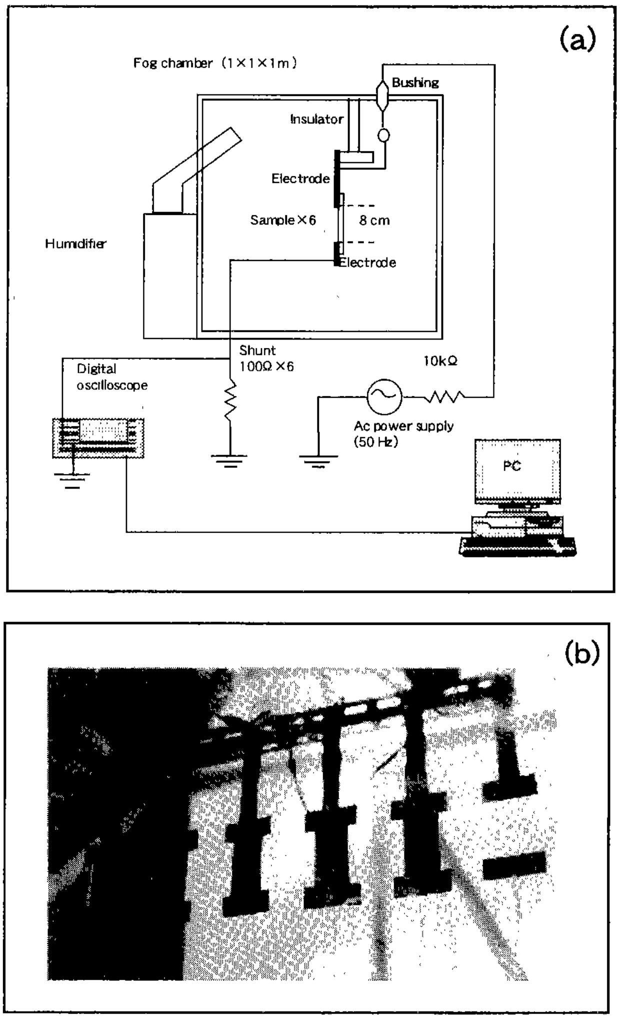

Fig. 1. Experimental details for the salt-fog test. (a) diagram of the salt-fog test equipment, (b) sample arrangement.

2. 3 Hydrophobicty and Surface Roughness Evaluation

Hydrophobicity of a solid surface is determined by its surface free energy and is well correlated with static contact angle (θ). Distilled water of about 5 μl is dropped on the samples by an injector and 30 sec later (static) contact angle is measured at room temperature. The measurement system for static contact angles is illustrated in Fig. 3. The surface roughness profiles in uncontact with samples are obtained. Laser focus displacement meter (LT series, KEYENCE, Osaka) is used. The resolution of the roughness measurement is 0.1 μm.

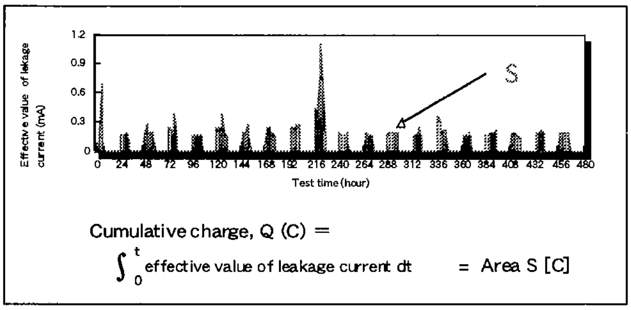

Fig. 2. Definition of cumulative charge for the salt-fog test.

Table 1. Descriptions for sample materials.

Sample	Basic polymer	Filler
EVA	EVA*1	ATH*2 40% wt
MSR A	EVA: HTV-SIR*3 = 9: 1 (in weight)	ATH 50% wt
MSR B	EVA: HTV-SIR= 9: 1 (in weight)	MDH*4 20% wt + ATH 30% wt
MSR C	EVA: HTV-SIR= 1: 1 (in weight)	ATH 40%
HTV A	HTV-SIR*5	ATH 30% wt
HTV C	HTV-SIR*5	ATH 60% wt
RTV	RTV-SIR*6	no filler
EX	Cycloaliphatic epoxy resin	SiO_2 66.7% wt

Notes, *1: Ethylene vinyl acetate rubber, *2: Alumina trihydrate. *3: High temperature vulcanizing silicone rubber *4: Magnesia dihydrate, $Mg(OH)_2$, *5: different formulation, *6: Room temperature vulcanizing silicone rubber.

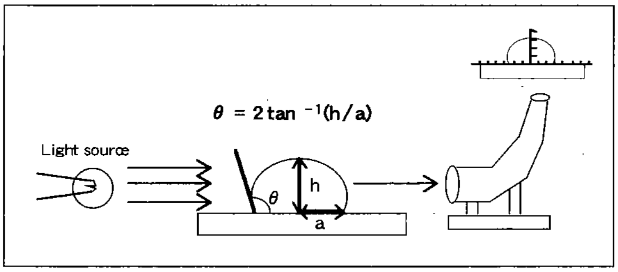

Fig. 3. The measurement system for static contact angles.

3. Results

3. 1 Leakage Current Comparison

SF test is conducted in accordance with the schedule that 0-8 h fog and voltage are on, 8-10 h only voltage is on and 10-24 h both are off (resting). Continuous voltage application in 8-10 h is for discharges that can appear without salt-fog [17]. Leakage current levels of various polymeric materials are presented in Fig. 4. Because cumulative charge is obtained by temporally integrating leakage current, larger cumulative charge indicates that the material tested allowed higher and more repetitive leakage current. It is observed that all the materials except for pure silicone rubbers (HTV A, RTV and HTV C) permit higher leakage current than reference glass material. Non-silicone rubbers (EX and EVA) and alloys in a low silicone ratio (MSR B and MSR A) permit higher leakage current than that in a high silicone ratio (MSR C, silicone: EVA = 1: 1) does. Leakage current on pure silicone rubbers (HTV A, RTV and HTV C) was excellently suppressed.

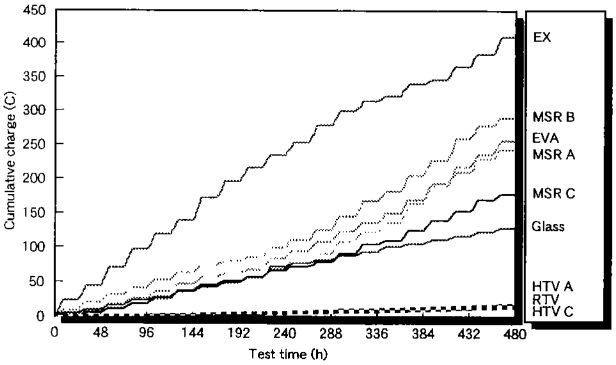

Fig. 4. Cumulative charges of various types of polymeric materials *vs.* salt-fog test duration. Fog flow rate: 300 ml/h, conductivity of saline water: 1600 μS/cm, electric field: 60 V_{rms}/mm, 1 cycle (24 h): 0-8h, fog and voltage application, 8-10 h, only voltage application, 10-24 h, resting.

3. 2 Structural Damages Owing to Leakage Current

Photographs of several samples before and after being aged in SF test having 20 cycles (480 h) are shown in Fig. 5. EX, that allows highest cumulative charge, displays serious discoloration and narrow track paths attributable to dry-band arcing involved in leakage current. HTV A30 on which little cumulative charge is recorded shows no changes in the appearance. No damages are also observed on RTV and HTV C of pure silicone rubbers. MSR C allows chalking phenomenon that filler appear at the surface. Narrow and slight tracking paths are observed near the top electrode of EVA as well as MSR A and MSR B, that permit higher cumulative charge than MSR C. Fine physical damages owing to leakage current are also evaluated by using an uncontact surface roughness analyzer. The roughness at the point that is placed around the center of samples and is not subjected to severe damages such as discoloration, tracking and erosion is analyzed. Fig. 6 presents surface roughness profiles for these samples. The roughness of EX increases largely after being aged in SF test, while that of HTV A subjected to little leakage current shows, of course, little change. The roughness of MSR C after salt-fog aging is marginally lower than that of EVA. This would be attributed to lower leakage current level. It is confirmed that leakage current suppression contributes to a considerable reduction in material damage.

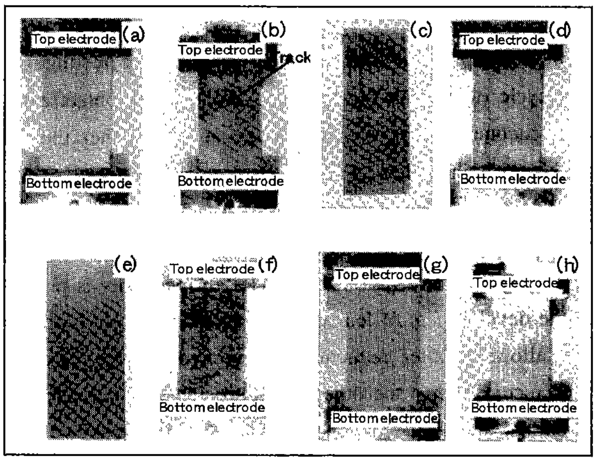

Fig. 5. Photographs for EX, EVA, MSR C and HTV A before and after being aged in salt-fog test having 20 cycles (480 h). (a) EX before the test, (b) EX after the test, (c) EVA before the test, (d) EVA after the test, (e) MSR C before the test, (f) MSR C after the test, (g) HTV A before the test, (h) HTV A after the test.

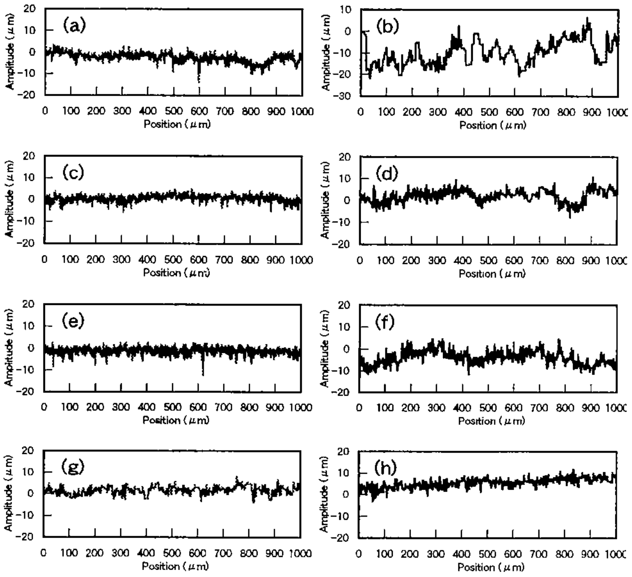

Fig. 6. Surface roughness profiles for EX, EVA, MSR C and HTV A before and after being aged in salt-fog test having 20 cycles (480 h). The roughness at the point that is placed around the center of samples and is not subjected to severe damages is evaluated. (a) EX before the test, (b) EX after the test, (c) EVA before the test, (d) EVA after the test, (e) MSR C before the test, (f) MSR C after the test, (g) HTV A before the test, (h) HTV A after the test.

3. 3 Correlation of Hydrophobicity with Leakage Current and Damages Involved

The experimental results obtained in the above indicate that leakage current levels on pure silicone rubbers or an alloy in a high silicone ratio are much lower than those on non-silicone rubbers or alloys in a low silicone ratio. As a result, HTV A, RTV and HTV C of pure silicone rubbers prevent damages completely even in the severe condition of salt-fog and voltage application. MSR C, an alloy in a high silicone ratio, avoids tracking path formation while EX, MSR A, MSR B and EVA permit. Fig. 7 shows hydrophobicity for these samples during resting time in 20th cycle of the salt-fog test. It is found that contact angles of pure silicone rubbers do not change at all whether their initial values are high or low. The contact angles for non-pure silicone rubbers are reduced just after the stop of salt-fog input. The reduced contact angles can recover with resting time. This means that the reduction or loss of material hydrophobicity is responsible for the development of leakage current. MSR C in a high silicone ratio allows smaller reduction in the hydrophobicity and more quick recovery than the others do. Particularly, hydrophobicity of EX is lost and then recovers marginally during resting time. The hydrophobicity of inorganic glass materials is completely lost and the recovery with resting time is not observed.

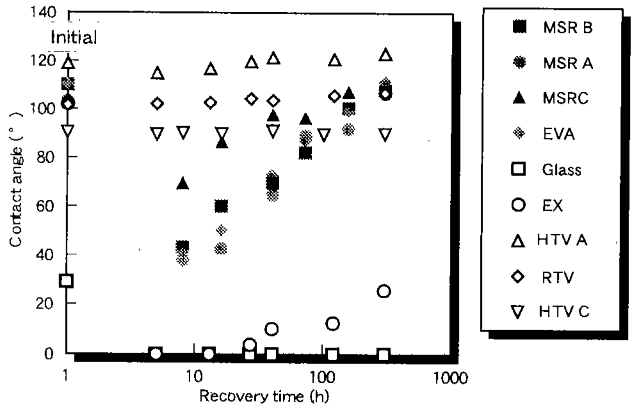

Fig. 7. Time dependence of hydrophobicity during the resting (dry) period in 20th cycle of the salt-fog test. Presented values of contact angles are average of 8 (4 +4) points near the respective top and bottom electrodes.

4. Discussion

Obtained results indicate that leakage current on polymeric materials in salt-fog condition is very sensitive to their surface wetting level. In the early stage of this test, most polymer surfaces resist being wetted because of their inherent low surface free energies and allow extremely low leakage current. With the test duration, the polymer surfaces gradually transfer to wet and allow leakage current to develop. Material's surface wetting in salt-fog condition affects considerably the behavior of discharges accompanied by leakage current. It is shown that the reduction magnitude and the recovery speed for materials during SF test correlates well with leakage current level thereon. Initial hydrophobicity and its stability against ambient environments are materials' inherent qualities that would be determined by various material parameters such as composition, formulation and filler level. In this sense, silicone rubbers possessing the hydrophobicity which is stable in the multiple condition of salt-fog and voltage application are expected to be best materials for suppressing leakage current and material aging in outdoors. Such the results in both laboratory and actual outdoor tests are reported in [7, 18-20]. On the other hand, it is turned out that non-silicone materials allow higher leakage current than inorganic glass materials of which hydrophobicity is initially low and the lost one never recovers. When hydrophobicity is completely lost, very thick electrolyte film forms on the material surface. Joule's energy of leakage current through such the thick electrolyte film needs to be high to evaporate it and to form dry-band arcing. Hence, leakage current on glass sample contains most resistive current, which flows constantly but induces low current level. When hydrophobicity is not completely lost, the material surface is scattered with thin electrolyte films. This formation would lead to non-linear current and thus non-linear current with dry-band arcing. Dry-band arcing can leap on electrolytic surfaces, which reduces leakage distance and increases current level [21]. Therefore, higher leakage current was observed on non-silicone materials than glass materials.

5. Conclusion

In this study, leakage current levels of polymeric materials able to be used in outdoor environments are evaluated using salt-fog chamber test. Ethylene vinyl acetate rubber, silicone rubbers, their alloys and cycloaliphatic epoxy resin are presented to the test. In all the presented samples, silicone rubbers could resist leakage current development during this test. This indicates that dealing with the hydrophobicity of silicone rubbers seems to be significant to suppress leakage current in polluted environments. It is also shown that, in salt-fog condition, the reduction magnitude of the hydrophobicity of material surfaces and its recover rate during a restoration are in agreement with the levels of leakage current and subjected damages.

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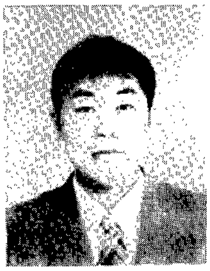

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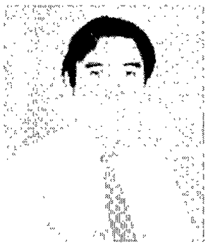

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