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Hydrophobicity loss of water-soaked silicone rubber in the presence of partial discharges

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Abstract

The primary cause of premature failure of silicone insulators in humid conditions is the loss of hydrophobicity due to partial discharges. It has been experimentally studied how pre-soaking the surface of a silicone rubber sample in NaCl solution affects the process of hydrophobicity loss. Partial discharges occur from droplets rolling down an inclined sample under AC voltage of 35 kV, which corresponds to the average electric field strength of 3.5 kV cm^{-1}. It is demonstrated that the pre-soaking of the sample within 336 hours significantly reduces the rate of droplet runoff, the time of onset of the first partial discharges, and the duration of full hydrophobicity loss. This is observed for three different types of silicone rubber: Silfor, Powersil, RTV.

Keywords: High-voltage silicone insulator, loss of hydrophobicity, water immersion, partial discharges, water droplets.

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1. Introduction

The loss of hydrophobicity in silicone insulators constitutes an adverse event in humid conditions, as it leads to the premature degradation of the insulator [1]. In the presence of water droplets on the insulator's surface, partial discharges occur at the ends of the dripping droplets, and these discharges contribute to the aging of the rubber material [2–4]. However, it remains unclear how the moisture itself influences the process of hydrophobicity loss. Insulators may be situated in coastal regions where fog events are frequent, and therefore, the presence of moisture cannot be disregarded.

There are a number of studies aimed at investigating the impact of moisture on silicone rubber. To simplify, the effects of immersing the sample in water are often considered instead of discrete droplets. For instance, in paper [5–9], samples of silicone rubber are immersed and then the sample weight is measured. This method of measuring moisture impact is related to the fact that silicone rubber readily absorbs water. In addition to sample weight measurement, researchers also assess the static contact angle. Different studies arrive at varying conclusions: moisture either affects the weight and static angle of the rubber, or it does not. Such disparity may be attributed to the fact that, a process of release rubber components into the water might occur apart from water absorption, and these two processes could be counteractive.

When studying the effects of sample immersion, it is insufficient to solely measure weight and static angle, as the visual impact becomes evident during dynamic measurements, such as when water flows off the samples or the receding angle is measured [10–12].

In reality, the presence of moisture on the insulator inevitably leads to discharges. Therefore, it is crucial to consider the combined effects of moisture and discharges on rubber. For instance, in paper [13], the authors investigate the influence of moisture on a sample previously damaged by corona discharge. It turns out that there is an effect of such influence. This is manifested in the fact that water flows more slowly from the area of combined action.

However, there are few studies in which moisture first affects the sample, followed by the influence of partial discharges. Paper [14] demonstrates that water absorption over a period of 10 days (240 hours) can prevent the loss of hydrophobicity in silicone rubber due to subsequent barrier discharges. It is hypothesized that the evaporation of water from the samples influences the barrier discharge and, thus, can protect the silicone samples. The authors compare the receding angle with and without moisture exposure. In [15], samples of silicone rubber are initially immersed for 500 hours, followed by tracking-erosion resistance test. It is shown that the chemical structure of the rubber and the sample roughness differ based on the presence of aging due to water exposure. In [16], experiments with corona discharge are conducted at 93% humidity. The exposure lasts for 16 days (approximately 400 hours). It is demonstrated that the hygroscopicity of the sample increases and water is absorbed due to exposure to corona discharge.

From all the aforementioned articles, it becomes evident that moisture has an influence on rubber and discharge behavior. However, no studies have explored the scenario where droplets drip down rubber that has been pre-soaked, especially in the presence of an electric field. This scenario is close to reality, as the insulator's ribs are inclined, water runoff along them. It is also established that the conventional loss of hydrophobicity scenario is as follows: in the presence of an electric field, discharges appear from water droplets, as a result, hydrophilic regions arise and expand, forming hydrophilic tracks along the trajectory of droplet descent from the insulator [17–20]. It is worth to investigate how the droplet runoff process will alter if a sample is partially pre-soaked. In this case, the path of droplet descent will feature pre-soaked regions that will influence the droplet roll down process.

This study investigates how moisture pretreatment affects the loss of hydrophobicity of silicone rubber. The process of loss of hydrophobicity is achieved through partial discharges on the surface of the treated sample. The purpose of this work is to reach the following three targets: (1) revealing the mechanism of the loss of hydrophobicity in the presence of a soaked area; (2) assessing whether preliminary soaking of the sample affects the nature of the discharges in the electric field; (3) determining the loss of hydrophobicity time of samples without pretreatment by water soaking and that of pre-soaked samples.

2. EXPERIMENTAL SETUP AND PROCEDURES

2.1 Samples

Samples of three types of silicone rubber are used: Silfor, Powersil, RTV. The dimensions of the samples are 6 cm × 3 cm. Silfor thickness is 0.6 cm; that of Powersil and RTV is 0.7 cm.

Before the experiments, the samples are treated with isopropyl alcohol and then rinsed with distilled water. The samples are left in the laboratory where the experiments will take place for a minimum of 24 hours, under the same temperature conditions.

2.2 Experimental setup

Experiments aimed at studying the hydrophobicity loss process of silicone rubber is conducted using the setup depicted in Fig. 1. A sample of silicone rubber is placed on an inclined platform at an angle of 40±3 degrees. Discrete droplets of saline solution are released onto the sample's surface through an aperture in the electrode. After droplets hit the sample surface, the droplets roll down. Plate electrodes are subjected to an alternative voltage V_{rms}= 35 kV, voltage source is AID-70M. The interelectrode gap is 10 cm, that is, the average electric field strength is 3.5 kV cm^{-1}. A capacitor is a current limiter in an electrical circuit. Partial discharges occur during droplet mergings (the discharge is shown by yellow lightning in Fig. 1). A thin dielectric layer is located on the high-voltage electrode so that discharges between the droplets and the electrode do not occur. The droplet frequency is controlled using a peristaltic pump, the pump flow is 1 ± 0.2 mL min^{-1}.

The entire hydrophobicity loss process is monitored by two cameras: one camera captures the droplets, while the second camera captures the discharges. It is noteworthy that the discharges are extremely weak and not visible to the naked eye, necessitating the use of a highly sensitive camera EVS VSC-756. Light filters are used to allow cameras to record discharges and droplets simultaneously.

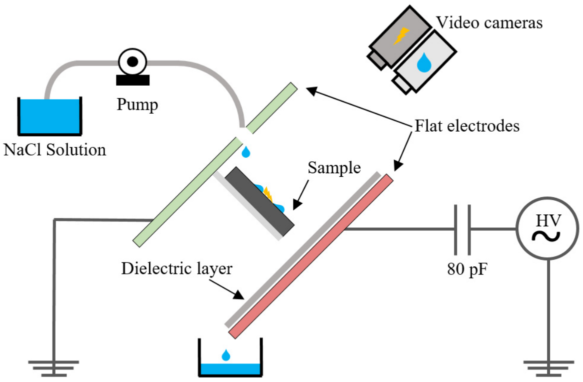


Fig. 1. Scheme of the experimental setup.

Before a sample is tested on the aforementioned setup, it undergoes soaking using a droplet of saline solution (Fig. 2). Water soaking occurs with 4% NaCl solution droplets for 336 hours, the salinity is equivalent to sea fog. To prevent the droplet from evaporating, the sample is placed within a container partially filled with water and sealed tightly, which provides 100% humidity. In this state, the samples are soaked for a duration of 14 days (336 hours).

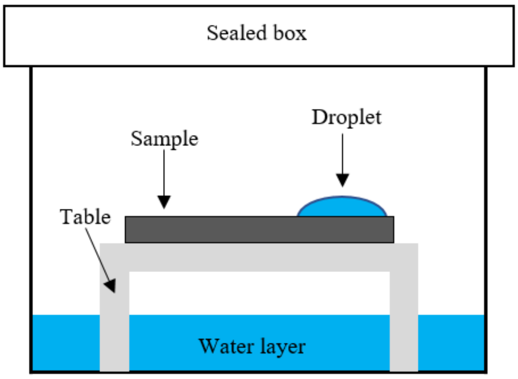


Fig. 2. Illustration of sample soaking with a droplet.

2.3 Measuring methods

The effect of soaking is measured using the following three methods:

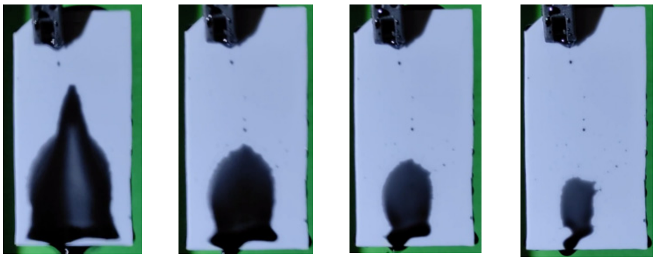
1) Water runoff velocity during vertical extraction of the sample from a water container, as detailed in [10]. The main idea of the setup is to lift up the sample from the container with inked water and record a video of the process of water flowing from the sample.
2) Static contact angle. This is a widely used technique to measure hydrophobicity, and the measurement method is described in detail in [10]. In the present study, the contact angle is measured at 10 points for each sample, both before and after the soaking process.
3) Dripping speed of droplets from the inclined sample on the setup (Fig. 1) without applying voltage. The temporal progression of video frames is examined.

3. Results and discussion

3.1 Runoff of the water layer

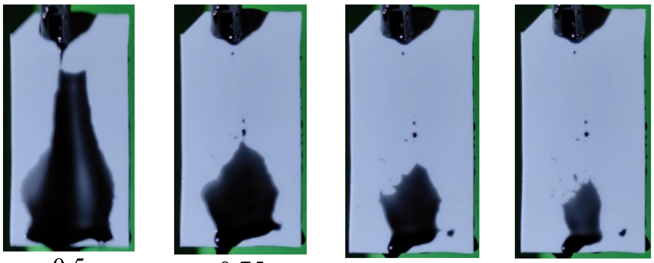
Samples soaked under a droplet of saline solution for 336 hours are extracted from inked water in a vertical position to assess how water flows down them. Fig. 3 shows frames from the video sequence from the duration of the water flowing down for three types of rubber. Time is counted from the moment the sample was lifted.

The black area on top of the sample is the plastic holder that lifts the sample up. The left corner of the samples is cut off in order to position the sample in the same way. It can be seen that in the first fractions of a second, water flows down from the outer area of the sample where there was no droplet impact. After that, the ink water flows more slowly, narrowing in a circle. In about a couple of seconds, it flows down completely. This delayed runoff in the pre-soaked area is observed for all rubber samples. Water flows down the fastest from the Powersil. This indicates that soaking affects different rubber types differently.



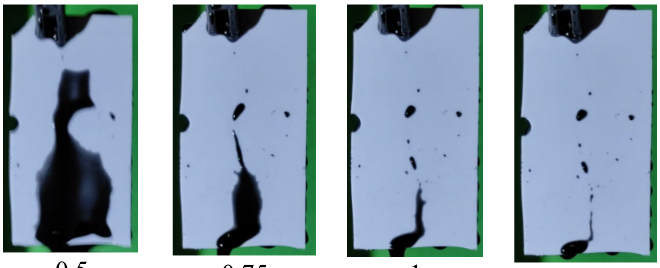
0.5 0.75 1 1.5

Silfor



0.5 0.75 1 1.5

RTV

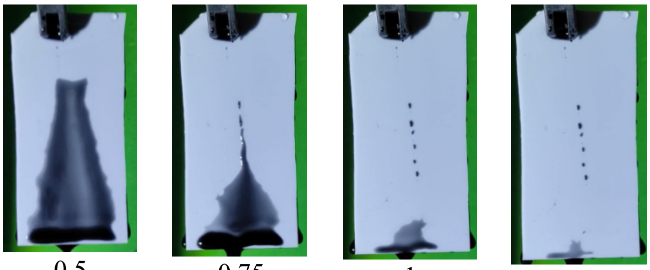


0.5 0.75 1 1.5

Powersil

Fig. 3. Frames from the video sequence for three types of rubber after soaking the samples with a droplet for 336 hours. Frame times are 0.5 s, 0.75 s, 1 s, 1,5 s.

It is worth noting that water flows down faster on undamaged samples, and it flows uniformly across the entire area of the sample without any circular region. An example for undamaged Silfor is shown in Fig. 4, this draining process is similar for other types of rubber for undamaged sample.



0.5 0.75 1 1.5

Silfor

Fig. 4. Frames from the video sequence for undamaged Silfor rubber.

3.2 Contact angle

In addition to capturing the droplet's impact using vertical lifting, the contact angle was measured (Fig. 5). It can be seen that the static angle remained unchanged within the margin of error for all rubber types. This indicates that the runoff of the water layer method is more sensitive than the static method. This fact is also mentioned in [10].

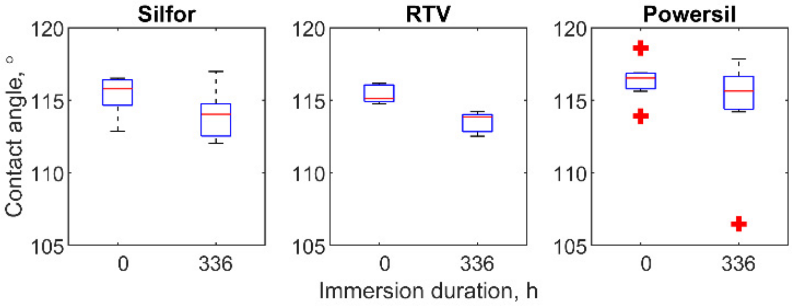


Fig. 5. Measurement of the static angle before and after exposure to a droplet of solution for three types of rubber.

3.3 Rolling droplets from rubber before and after water exposure

The incline setup is used to examine how individual droplets flow down from samples pretreated by water soaking. The measurements take place in the first minutes of experiments with an electric field, when the discharges have not yet changed in any way the behavior of the droplets. In this case, the rubber surface can be considered not yet damaged by the discharges.

Fig. 6 illustrates the area of the sample that was pre-soaked by a large droplet (Fig. 6 (a)) and the corresponding area in the dripping droplet experiment (red circle on the Fig. 6 (b)). The yellow color indicates the region where small discrete droplets fall from the peristaltic pump. The dripping droplets flow down along the inclined sample and get into area that was pre-soaked.

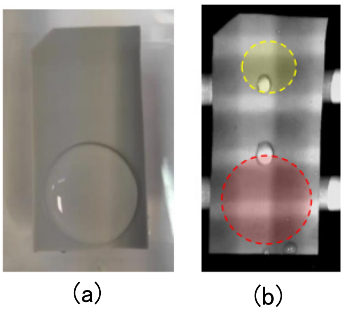


Fig. 6. (a) The region of preliminary soaking of the sample with a large droplet. After the soaking, the large droplet is removed, the soaking area is shown with a red circle in (b). The yellow area shows the place where the small dripping droplets fall, which then flow down along the sample.

Figs. 7−9 show frames from the video sequence for undamaged and damaged (pre-soaked) samples, each figure corresponding to a type of rubber. The grid on the surface of the samples is connected to the shadow of the metal grid. A metal mesh protects the cameras from high voltage near the setup. Each figure is analyzed separately further.

Fig. 7 shows the behavior of droplet flow from Silfor rubber. A droplet from an undamaged sample flows smoothly and uniformly in 0.3 seconds. The red dashed line indicates the position of the droplet at each moment in time. In the case of a damaged sample, the droplet is decelerated at the boundary of the wetted zone in 0.2 seconds and slowly begins to flow. At 0.4 seconds, it comes to a complete stop, and the next droplet washes it away.

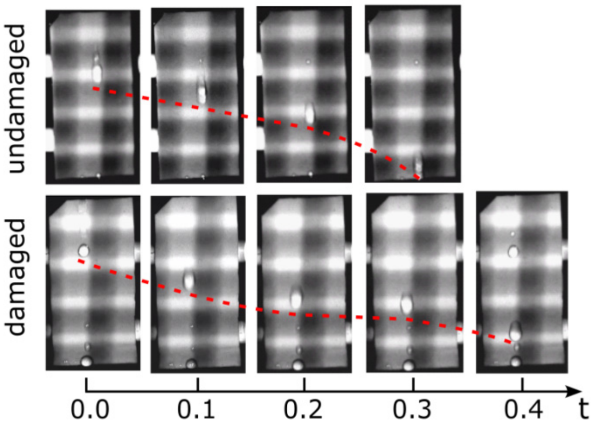


Fig. 7. The behavior of rolling droplets for damaged (pre-soaked) and undamaged samples of Silfor rubber.

Fig. 8 shows the behavior of droplet flow from RTV rubber. The droplet from an undamaged sample flows smoothly and uniformly in 0.8 seconds. The red dashed line indicates the position of the droplet at each moment in time. In the case of a damaged sample, the droplet is decelerated at the boundary of the damaged area and stops (it can be seen from the first frame in Fig. 8 for damaged sample). The next droplet drips onto the stationary one, they merge and quickly flow under the influence of gravity. It can be seen how a water trail forms in the damaged area, it appears as a shiny strip at the 0.4-second mark in Fig. 8.

It is noteworthy that the static angle does not fall below 90° in the damaged area (Fig. 5), indicating that the static hydrophobicity remains unaffected in the damaged area. That is, such a water trail is not lost static hydrophobicity, as is commonly believed.

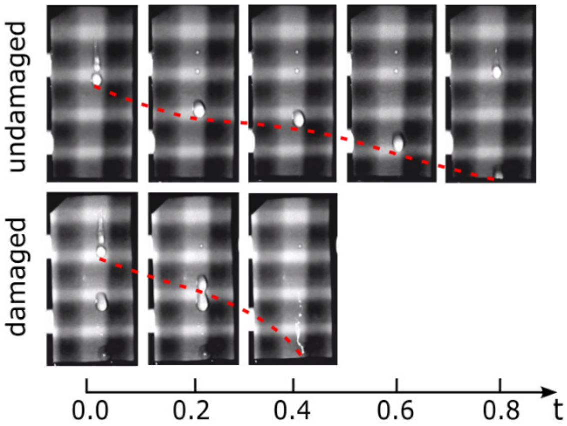


Fig. 8. The behavior of rolling droplets for pre-soaked (damaged) and undamaged samples of RTV rubber.

Fig. 9 shows the behavior of droplet flow from Powersil rubber. The first and second lines depict two different flow patterns for an undamaged sample. In addition to uniform rolling down, dripping from an undamaged sample can also be non-uniform. This is related to the surface characteristics of the undamaged sample. In the case of a moisture-damaged sample, water flows similarly to how it does for RTV rubber. The droplet is decelerated in the damaged area, and the subsequent incoming droplet merges with it. For Powersil rubber, the behaviors of the droplets in undamaged samples (second type of flow, second line in Fig. 9) are similar to those in damaged samples (third line in Fig. 9). It is assumed that this similarity is linked to the minimal impact of moisture on Powersil rubber. Consequently, the nature of droplet flow remains consistent after soaking the sample. This is particularly worth noting, as it will be consistent with the occurrence of discharge activity in the next section.

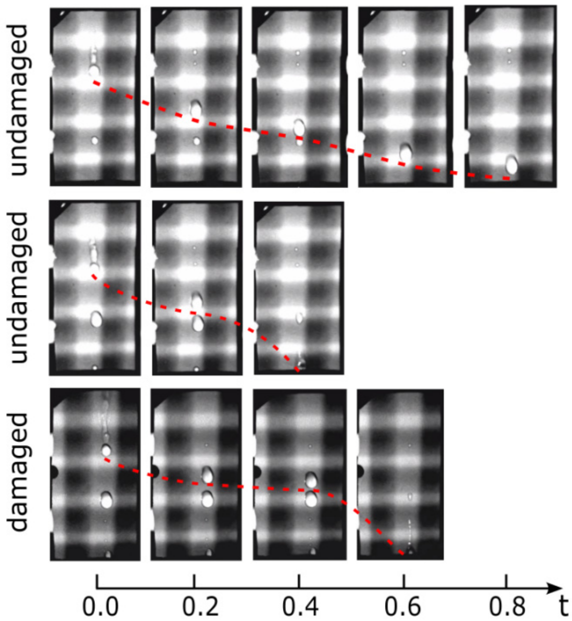


Fig. 9. The behavior of rolling droplets for pre-soaked (damaged) and undamaged samples of Powersil rubber. The first and second lines show two different flow patterns for an undamaged sample.

3.4 Discharge activities on rubber before and after water exposure

Voltage is applied to the samples pre-soaked with water droplets. The droplets continue to roll down from the inclined sample; however, due to the intensified strength of the electric field at the edges of the droplets, partial discharges occur. Typically, these discharges happen when several droplets merge. These discharges occur and reduce hydrophobicity along the drip path from the sample. After a while, the drip path becomes entirely hydrophilic, and at this point, the voltage is turned off.

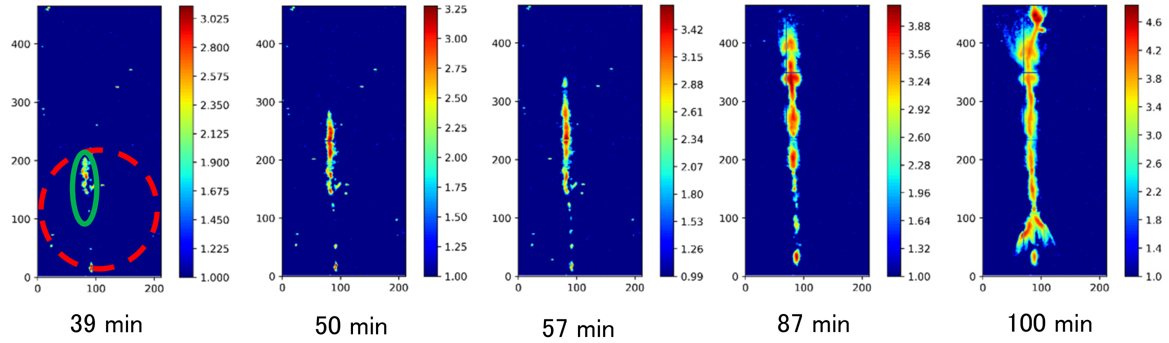
Fig. 10 shows frames with accumulated discharge intensity at different moments during the experiment for three types of rubber. Each frame is the sum of previous frames with partial discharges from the beginning of the experiment up to that frame. The last frame represents the cumulative discharge intensity over the entire duration of the experiment. The time between frames varies to visually illustrate the development of discharge activity.

It is worth separately analyzing the very beginning of discharge activity (the first column of frames in Fig. 10). For all three types of rubber, discharges start in the wetted area (the red dashed line marks the area of preliminary soaking, the green line marks the place of the first discharges). This occurs because, as the droplet flows down, it slows down in this area, and the subsequent droplet flows onto it, resulting in the discharge.

It is important to note that for all rubbers, discharge activity initiates in the upper part of the soaked area. Subsequently, discharges move higher, indicating the growth of the hydrophilic area upwards. Over time, discharges emerge across the entire droplet-flow area, including within the soaked region. This indicates that the soaked area was not fully hydrophilic, as discharges arise in this area.

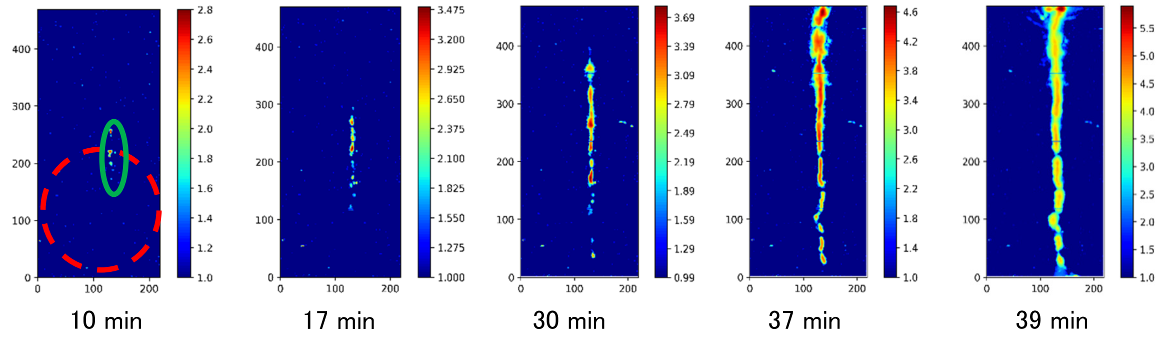
Comparing the initiation of discharge activity between pre-soaked samples (the first column of frames in Fig. 10) and undamaged samples (Fig. 11) reveals the following observations:

1) for Silfor and RTV rubbers discharges start in different positions, namely, the lower region of the sample in the case of a moisture-damaged sample, and in the upper part of the sample in the case of an undamaged sample;
2) for Powersil rubber discharges appear in the same lower area for both undamaged and moisture-damaged samples. This fact is consistent with the dripping behavior observed from the surface sample.



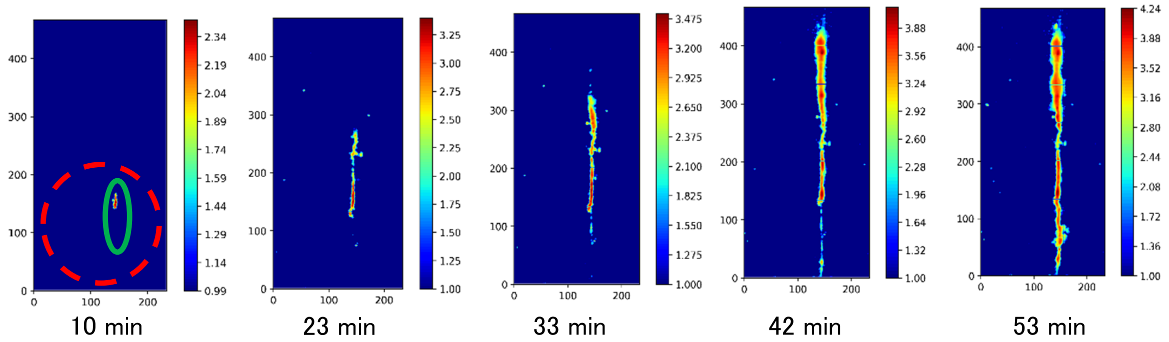
39 min 50 min 57 min 87 min 100 min

Silfor



10 min 17 min 30 min 37 min 39 min

RTV

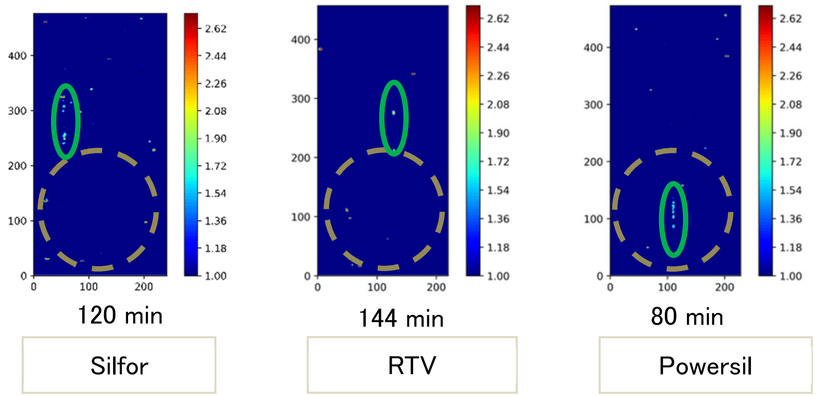


10 min 23 min 33 min 42 min 53 min

Powersil

Fig. 10. Frames with accumulated discharge intensity during the hydrophobicity loss experiment for pre-soaked samples. The soaked area is shown by red dashed lines in the first frames on the first summary frame for each rubber. The green line shows the region where the first discharges occur. The color legend indicates the intensity of the discharge in relative units.

Soaked area affects total loss of hydrophobicity time. The time for complete loss of hydrophobicity for pre-soaked Silfor sample was 100 minutes, RTV — 39 minutes, for Powersil — 53 minutes. The time for complete loss of hydrophobicity is longer for undamaged samples: Silfor lasted for 120 minutes, RTV— 144 minutes, Powersil — 80 minutes. The difference in times for the three types of rubber is due to the chemical composition and manufacturing process. What matters is that soaked areas decrease the time until complete loss of hydrophobicity in all cases.



120 min 144 min 80 min

Silfor RTV Powersil

Fig. 11. The position of the first discharges for undamaged samples. The gray dashed lines shows the area from Fig. 10, but this area has not been soaked. The green line shows the region where the first discharges occur. The color legend indicates the intensity of the discharge in relative units.

4. Conclusion

The study examines how preliminary soaking of a silicone rubber sample influences the behavior of water runoff, contact angle, and the duration of hydrophobicity loss due to discharges. All factors, except for the static angle, demonstrate that sample pre-soaking significantly affects the sample's characteristics. This holds true for three rubber types: Silfor, RTV, and Powersil. The main conclusions are as follows:

(1) The surface of the rubber sample changes due to the soaking of droplets of saline solution, specifically, water takes longer time to flow down from this area. Such an effect can become critical in the operation of insulators. Insulators exposed to rain and fog have moisture on their surface. This kind of soaking affects how droplets subsequently roll from the insulator and how discharge activity occurs.

(2) The pre-soaked area of the sample influences the onset of discharge activity. Discharges occur in the soaked area. This occurs because the rolling droplets are decelerated in this area, the next droplet flow onto them, and discharges occur between them.

(3) The duration of the loss of hydrophobicity in the case of a pre-soaked area is shorter than for an undamaged sample.

In light of the obtained results, it is proposed to include preliminary soaking in the test program to assess the resistance of insulators to loss of hydrophobicity.

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