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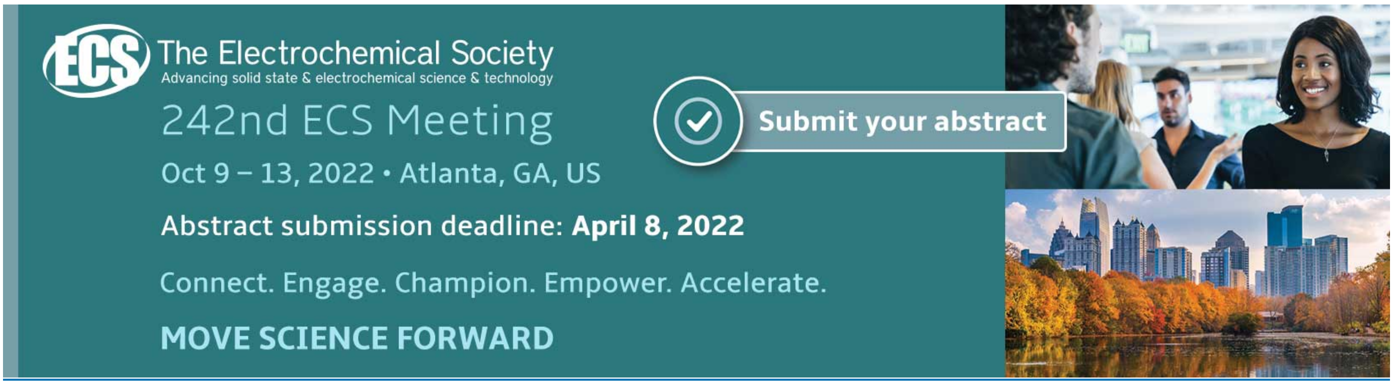

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# Influence of corona discharge on the hydrophobic behaviour of nano/micro filler based silicone rubber insulators

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## Abstract

Silicone rubber is one of the most used outdoor insulation materials in the last few decades due to its improved performance in contaminated and humid conditions. The improved performance of silicone rubber insulators is due to their hydrophobic nature, however, the organic nature of silicone molecules makes them vulnerable to ageing and degradation. This paper aims at investigating the loss and recovery of hydrophobicity of four different silicone rubber micro/nanocomposites exposed to corona discharge. The samples were exposed to corona discharge generated by pin-plate electrode configuration under AC stress. A series of tests were performed to observe the impact of different electrode-sample gaps and for various periods of corona exposure. The hydrophobicity of samples was measured pre and post corona exposures at various intervals up to 72 h. This time could confirm the hydrophobicity recovery process. Numerical simulations were also performed in COMSOL Multi-physics to investigate the electric fields along the sample surface at different electrode gaps. Experimental results showed that samples recovery time was proportional to the duration of exposure to corona discharge and inversely proportional to the electrode-sample gap. Among all, samples with 2.5% nano-silica as additive showed better hydrophobicity recovery. Simulation results showed that an increase in electrode gap resulted in decreased electric field intensity, hence supporting the experimental outcomes.

## 1. Introduction

Generally, ceramic and glass insulators are used for outdoor high voltage insulation due to their high mechanical strength and non-organic nature [1, 2]. These insulators have been the extensive materials of choice for high voltage insulators and lightning arresters, offering adequate resistance to electrical stresses and outdoor contacts without noteworthy wearying. Yet, they do have certain shortcomings such as hydrophilic nature, low performance in polluted environmental surroundings initiating flashovers and regular tripping, inclination to punctures, cement growth on the surface, prone to vandalism and relative higher installation cost [3].

Polymeric insulators were introduced, in the 1960s, to overcome the deficiencies of ceramic and glass insulators. These insulators have definite leads over traditional insulators [3, 4]. One of the major advantages of polymeric insulators is of being naturally hydrophobic which make them repellent against the formation of conductive layer [5]. However, this hydrophobicity is reduced or lost if the polymeric insulator is subjected continuously to electrical stress [6]. Among these electrical stresses, the corona discharge has been declared as a key player in causing the loss of polymeric insulator hydrophobicity [7]. However, when corona stress is removed and insulators are provided enough time, they recover their hydrophobicity.

The inception of the corona discharge at the electrodes is dependent on their material type as well as on electric field intensity at their tip [8]. For instance, sharp edges of pointy electrodes result in high electric field

**Table 1.** Composition of test samples.

| Sample number | Sample | Filler concentration |
|---|---|---|
| Sample 1 | SNC-2.5-$SiO_2$ | 2.5% Nano Silica |
| Sample 2 | SNC-5-$SiO_2$ | 5% Nano Silica |
| Sample 3 | Silicone Rubber | Neat Silicone Rubber |
| Sample 4 | SMNC-10$\mu SiO_2$–2n$SiO_2$ | 10% micro, 2% Nano silica |

intensity and resultant corona inception [9]. This high electric field intensity results in ionizing the surrounding air generating ions and electrons moving in the direction of applied electric field stress [10].

Yong Zhu *et al* observed that hydrophobicity of silicone insulating rubber (SIR), a polymeric insulator, declined over time under corona discharge as it decreased the ratio of water repellent C–H, Si–$CH_3$ and Si–O bonds and develops hydrophilic O–H groups and C=O bonds [11]. This breakage in hydrophobes is the result of photons, generated due to corona stress, which possesses more energy than the binding energy of these bonds [7].

H Hillborg *et al* reported that this water repellency will recover with time if the applied external field is removed. It was believed that lower molecular weight (LMW) species movement from bulk to surface make this recovery possible [12]. Owen *et al* describe the relocation of LMW molecules to the surface as well as the reorientation of polar groups at the surface as probable mechanisms of recovery of SIR hydrophobicity after corona stress [13].

For increasing the resistance against hydrophobicity loss and to pace up its recovery, composites of silicone rubber are prepared by adding fillers of different types and sizes of micro and nanometers [14–17]. Though contact angle decreases and cracks appear on the surface of SIR composites, however, the performance of nano-filler based silicone composite is better than pure SIR [18].

Most of the previous work is focused on the loss of hydrophobicity recovery of SIR under constant stress, at fixed electrode gap and for some specific time [7, 11, 19–24]. In this paper, four samples of silicone insulating rubber having four different sizes and the ratios of silica fillers are experimented with corona discharge using pin-plate electrode configuration at various gaps and for various exposure times. The loss and recovery of hydrophobicity of these samples were investigated along with electric field intensity was simulated on finite element method-based software, COMSOL Multiphysics.

## 2. Materials and method

### 2.1. Sample specification

In this research, four SIR composites incorporated with different amounts of micro and nano Silica as fillers were used. The samples composition is detailed in table 1. These samples were circular in shape with a thickness of 5 mm and a diameter of 86 mm.

### 2.2. Hardware setup

For the generation of corona discharge, a pin-plate electrode configuration with an AC voltage supply of 7.5 kV was used. In total, six copper electrodes with sharp edges were utilized. AC voltage was supplied to the electrodes while a copper plate, with a sample on top of it, was grounded. The schematic diagram of the test setup is shown in figure 1. Test specifications are listed in table 2.

Figure 2 shows the glow due to corona discharge between electrode pins and SIR specimen.

### 2.3. Hydrophobicity measurement

Using the setup shown in figure 1, each sample was exposed to corona discharge at distances of 10, 15 and 20 mm between electrodes-tip and sample-surface. At each distance, all samples were exposed to corona for different duration (i.e., for 10, 20 and 30 minutes). Hydrophobicity was measured using the method proposed by Sweden Transmission Research Institute (STRI), 92/1, Hydrophobicity Classification (HC) Guide [25]. This method is convenient for finding an insulating surface hydrophobicity and is considered an authoritative standard [26]. As per guidelines of the STRI method, a fine mist of water was sprayed from 25 cm and, within 10 seconds of spraying, based on drops appearance hydrophobicity was judged among seven classes of hydrophobicity from HC-1 to HC-7. According to STRI, HC-1 corresponds to an exclusive hydrophobic surface while HC-7 represents a completely hydrophilic surface. These classifications offer a rough value of the wetting grade and are appropriate for a fast and easy check of insulators in the field. This procedure of hydrophobicity measurement

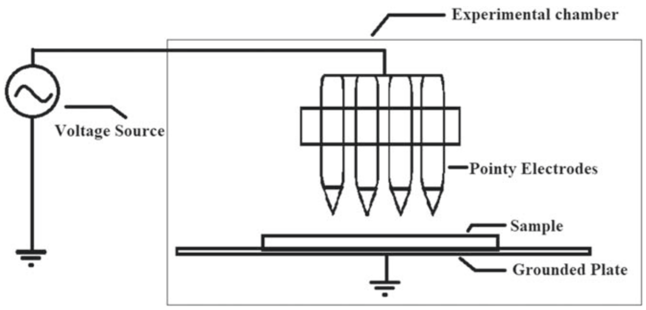

**Figure 1.** Schematic diagram of the test setup.

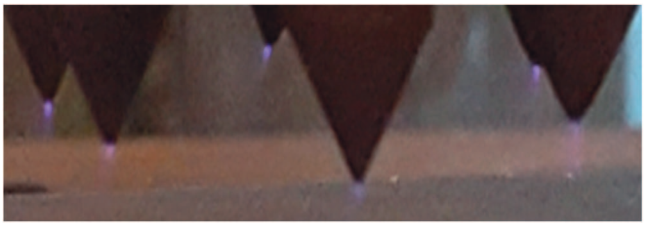

**Figure 2.** Corona discharge between electrode tips and specimen.

**Table 2.** Specification of the experimental setup.

| Element | Specification |
|---|---|
| Chamber Size | 45 × 45 × 45 cm |
| Chamber wall diameter | 4 mm |
| No. of rods (positive electrodes) | 6 |
| Rods Diameter | 12 mm |
| Rods length | 78 mm |
| Rod tip radius | 0.18 mm |
| Grounded/Negative plate size | 26 × 26 × 0.1 cm |
| Voltage supplied | 7.5 kV |

was repeated on each sample before and after corona testing, and for 2 to 3 days to observe their recovery. The hydrophobicity of each sample was measured on a plane surface.

### 2.4. Simulation model

A model of the experimental setup was designed, simulated, and analysed in finite element method (FEM) based software named COMSOL Multiphysics to visualize electric field distribution over the insulators at various distances. Dimensions of the models were kept identical to the experimental setup. Meshed model of the simulation is shown in figure 3. Overall, four electrodes gaps configurations (5, 10, 15, 20 mm) were simulated.

## 3. Experimental results and discussion

After performing the experiments on all the insulators and examination of their hydrophobicity according to STRI, 92/1, HC Guide, graphs of all information were plotted for comparisons. The following figure 4 shows the initial hydrophobicity of test samples before application of corona discharge upon them. All samples showed exclusive hydrophobic behaviour i.e. HC-1.

Figures 5–13 compares the HC class of all four samples when exposed to corona discharge from an electrode-sample gap of 10, 15 and 20 mm (each for 10, 20 and 30 minutes) respectively. All samples lost their hydrophobicity level to HC 6 at a lower distance of 10 mm irrespective of time length, as shown in figure 14, while with an increased electrode-sample gap this loss was significant only when samples were exposed to corona

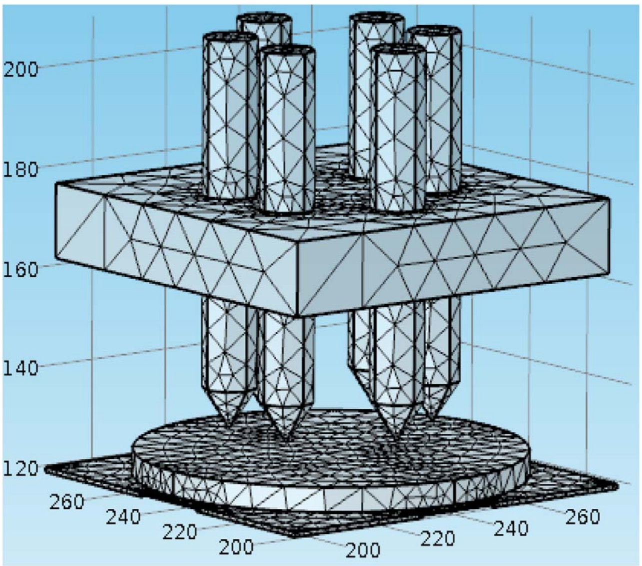

**Figure 3.** Meshed model of electrodes and sample geometry.

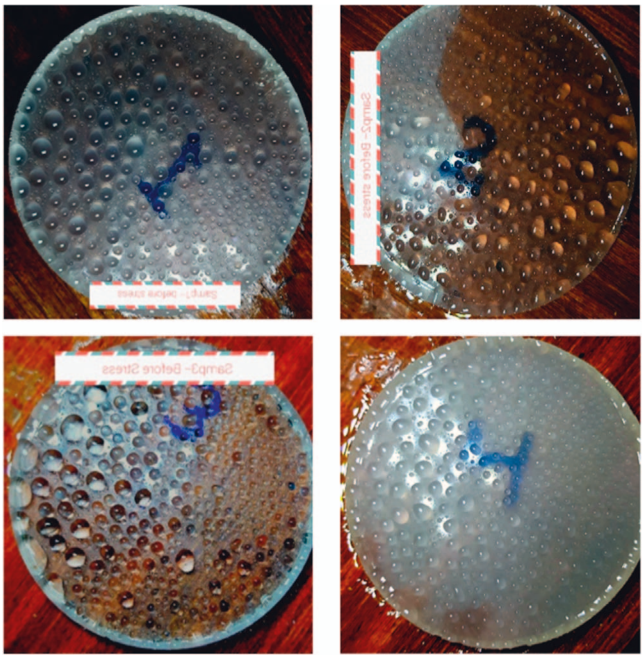

**Figure 4.** Initial hydrophobicity of samples before application of corona discharge.

for a long duration but still it did not lead them towards complete hydrophobicity loss, an image of the experiment is shown in figure 15.

The recovery process was different for all four samples and among them, nano-silica based composites exhibited fast recovery when exposed to corona from an electrode-sample gap of 10 mm as shown in figure 16. Figures 5–13 also verify that doubling the time of corona exposure lessened the recovery process while nano filled samples took days to recover their hydrophobicity. It was also observed that samples, upon exposure to corona, for half an hour, from an electrode-sample gap of 10 mm, as illustrated in figure 7, despite the passage of 72 hours, could not fully recover their hydrophobic level. This is due to the permanent damage caused to hydrophobic methyl group molecules, due to extended corona exposure, as these groups possess low surface energy [27].

The obtained results for tests at an electrode-sample gap of 20 mm are presented in figures 11–13. With an increased electrode-sample gap, the loss and recovery process of hydrophobicity was significantly affected. This

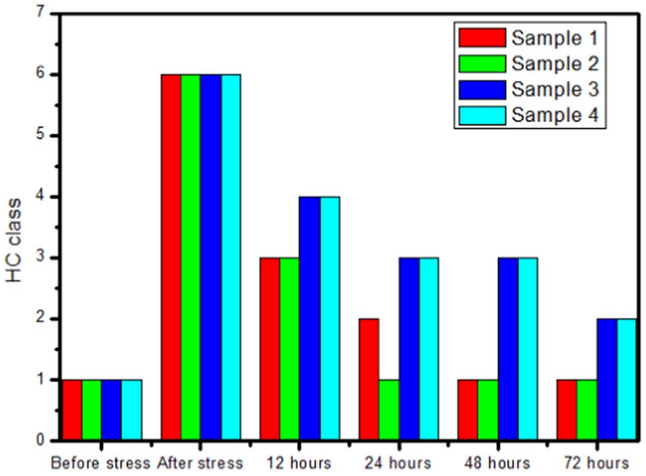

**Figure 5.** HC variation due to 10-minute exposure at 10 mm electrode-sample gap.

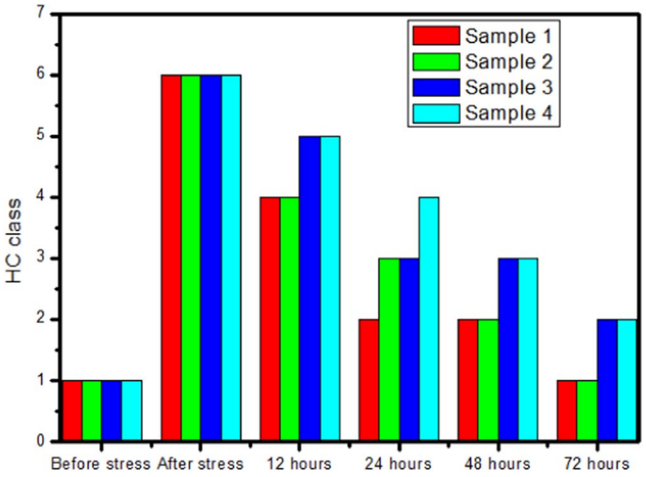

**Figure 6.** HC variation due to 20-minute exposure at 10 mm electrode-sample gap.

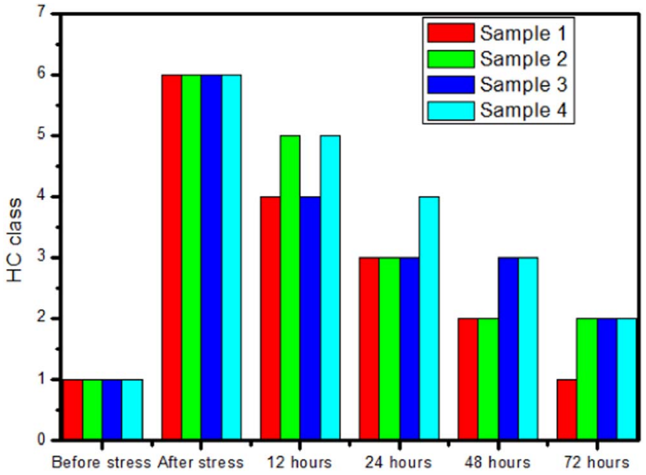

**Figure 7.** HC variation due to 30-minute exposure at 10 mm electrode-sample gap.

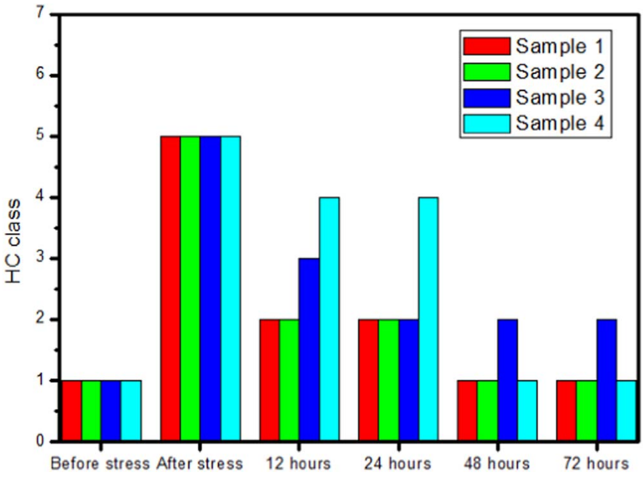

**Figure 8.** HC variation due to 10-minute exposure at 15 mm electrode-sample gap.

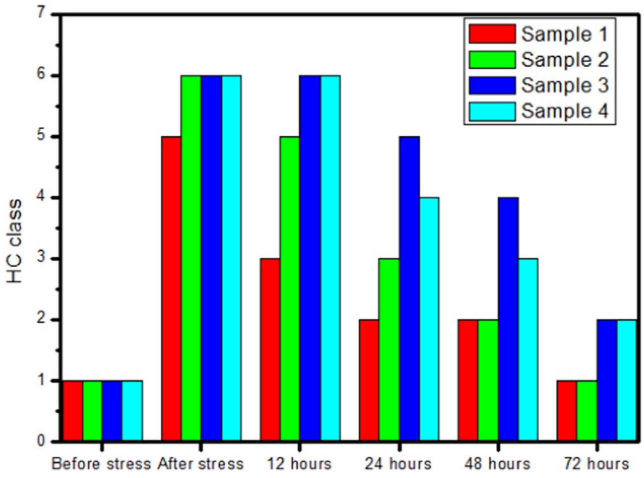

**Figure 9.** HC variation due to 20-minute exposure at 15 mm electrode-sample gap.

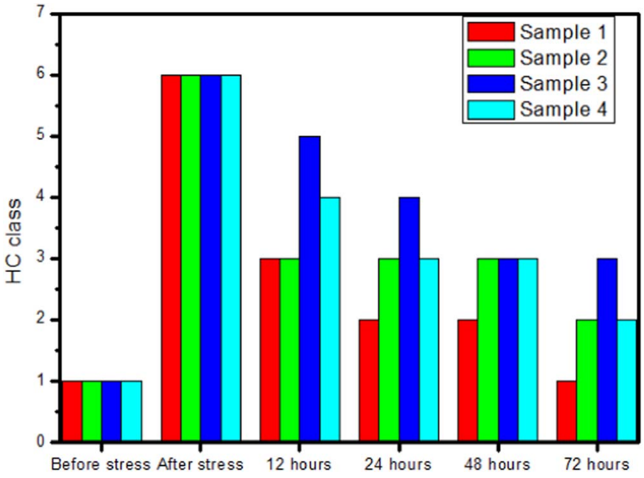

**Figure 10.** HC variation due to 30-minute exposure at 15 mm electrode-sample gap.

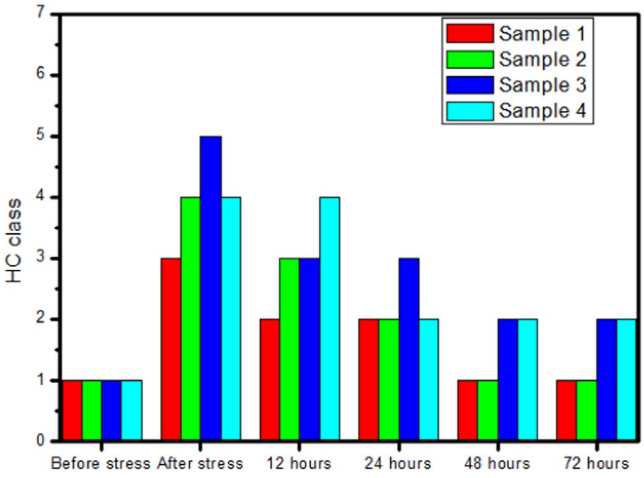

**Figure 11.** HC variation due to 10-minute exposure at 20 mm electrode-sample gap.

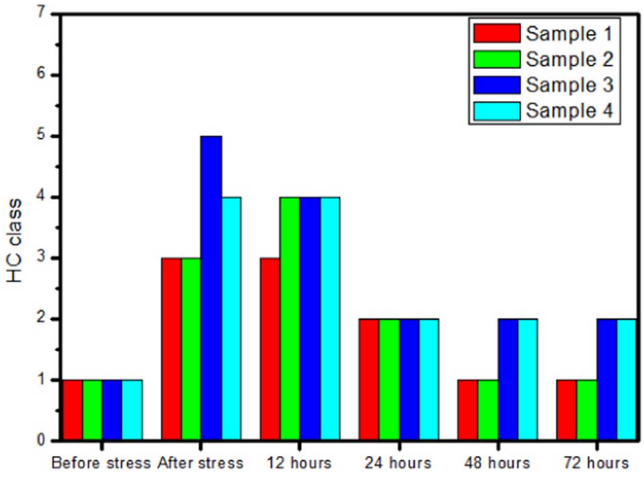

**Figure 12.** HC variation due to 20-minute exposure at 20 mm electrode-sample gap.

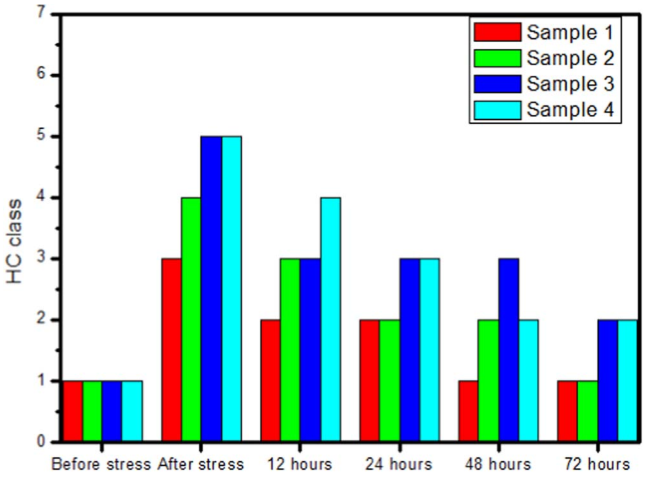

**Figure 13.** HC variation due to 30-minute exposure at 20 mm electrode-sample gap.

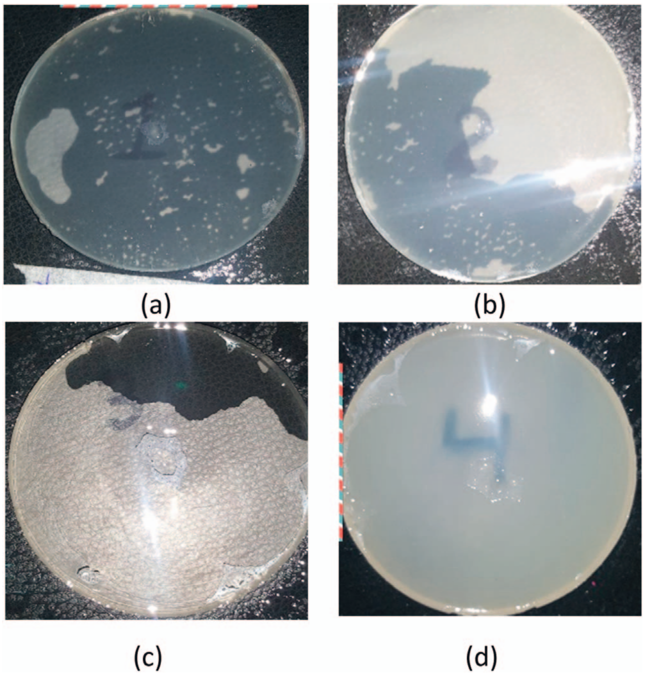

**Figure 14.** Hydrophobicity of sample after exposure to corona for 10 minutes from electrode sample gap of 10 mm (a) sample 1 (b) sample 2 (c) sample 3 (d) sample 4.

**Figure 15.** Sample 1 after 30 minutes under corona stress from an electrode-sample gap of 20 mm.

time the hydrophobicity loss was not as severe as in the case of other electrode-sample gaps. The HC of samples 1 and 2 improved to HC-3 just within 12 hours of the test which is better for the same samples from the 10 mm and 15 mm electrode gap.

Figure 17 shows that hydrophobicity is lost first beneath the electrode tips and spreads to the adjacent area towards the outer boundary. Detailed examination of all samples revealed that irrespective of sample composition and filler size, samples lose their hydrophobicity after exposure to corona discharge. However, the recovery process was highly influenced by filler size and concentration. The gap between the high voltage electrode tip and insulator sample defined the loss in hydrophobicity. For the low electrode gap, hydrophobicity was lost quicker and took more time to recover as compared to tests where the electrode gap was larger.

This hydrophobicity degradation can be associated with the consequence of a chemical reaction, triggered by the combined action of ions, electrons, ozone, and UV irradiations produced by corona discharge. The reaction resulted in depletion of water repellent silicon-methyl and silicon-oxygen-silicon bonds whereas growth of water-loving (hydrophilic) free radicals of hydroxyl (OH) groups and oxidation on the surface. Fillers enhanced the performance of polymer by providing reinforcement. Silicone insulating rubbers with nano-sized filler particles of 2% and 5% by weight had low hydrophobicity damage and their pace for regaining pre-testing state

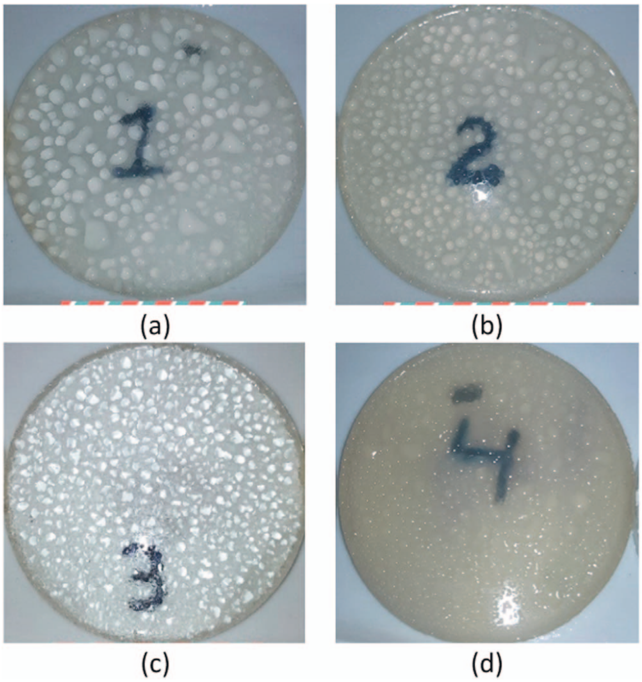

**Figure 16.** Hydrophobicity recovery of the sample after 24 h post corona exposure for 10 minutes from electrode sample gap of 10 mm (a) sample 1 (b) sample 2 (c) sample 3 (d) sample 4.

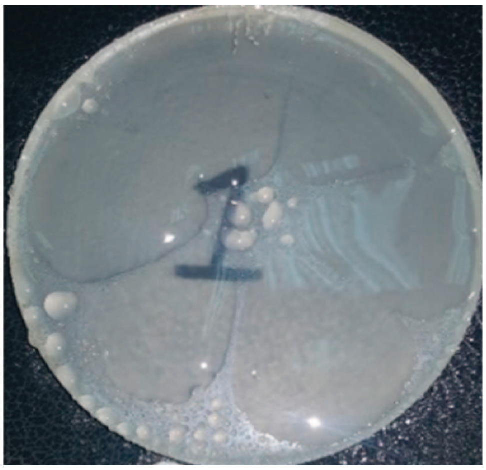

**Figure 17.** The pattern of hydrophobicity loss.

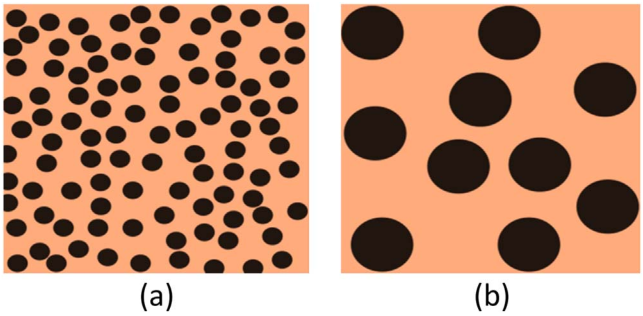

**Figure 18.** (a) Composition of nanoparticles (b) Composition of microparticles.

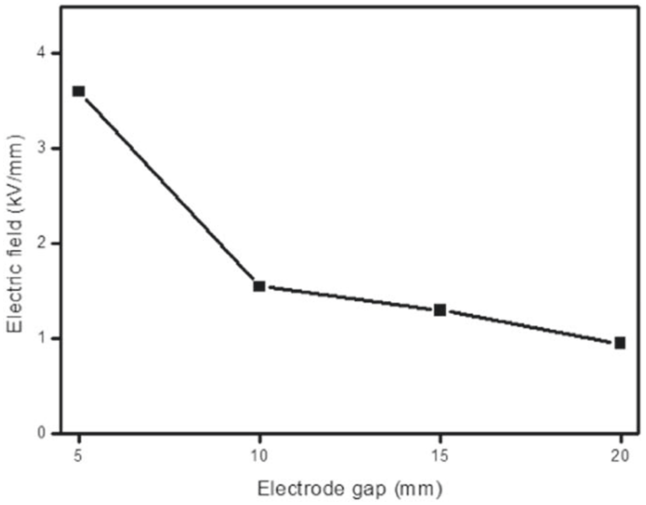

**Figure 19.** The electric field strength at different electrode-sample gaps.

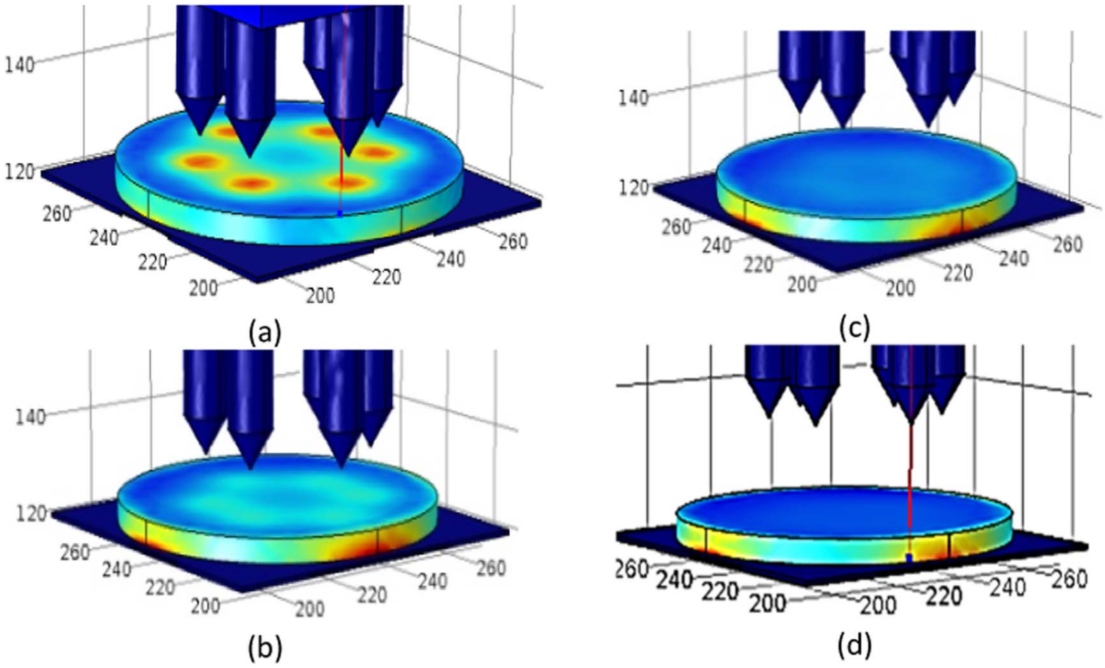

**Figure 20.** Electrical field stress at electrode-sample gap of (a) 5 mm (b) 10 mm (c) 15 mm (d) 20 mm.

was way superior to the micro-nano composite and pure silicones. This is because nano-fillers form a large surface area. Normally, size and surface area have opposite relations i.e. nanofillers have more surface because particles are more closely packed in and form a smoother surface than micro-fillers as shown in figure 18 [10]. Between nanocomposites, recovering speed of silicone rubber with 2.5% silica filler by weight was superior to the silicone rubber with 5% silica filler by weight.

When samples were removed, they started regaining their hydrophobicity to a pre-discharge state. Experiment duration and hydrophobicity recovery displayed a direct relation. When a sample was placed under corona discharge for a longer time, the response took a long time to recover back. This is due to the relocation of LMW fluid to the surface from the bulk material and the reorientation of the polar group at the surface [12, 13].

At higher distances of 15–20 mm, hydrophobicity loss was severe due to long time exposure instead of electrode gap. From the outcomes of the experiment that hydrophobicity loss is lower if the distance between electrode tip and samples is increased and the time duration of exposure to corona is decreased. This is because the power of corona generated by sharp electrodes lessens with the increase in gap.

## 4. Simulation results and discussion

Based on the simulations of four different electrodes configuration models, points, where the electric field was maximum, is determinable which subsequently depicts parts of samples, vulnerable to corona discharge. Figure 19 illustrated the summary of maximum electric field stresses observed at different electrode gaps.

Simulations result back the outcomes of the experiment that at shorter gaps sample experiences high stress and losses hydrophobicity significantly, due to corona and in that too in a fairly short time than the larger gaps. Figure 20 illustrates the change in electric field stress as the electrode gap is increased and support the patterns observed in figure 17.

## 5. Conclusions

One of the major advantages of polymeric insulators is of being naturally hydrophobic which make them repellent against the formation of the conductive layer. In this paper, a series of experiments were performed on four different nano/micro silica-based silicone insulators to observe their hydrophobicity loss and recovery behaviour under and after exposure to corona stress. STRI hydrophobicity guide 92/1 was used to analyze the hydrophobicity of the samples. The results presented in this paper show that the distance and exposure time of corona discharge upon samples significantly impacts the hydrophobicity loss and recovery pattern of hydrophobicity. Filler size and their concentration have a role in the loss and recovery of hydrophobicity as well. Based on the results of the experiment some concluding points are:

- Hydrophobicity recovery was better for nano and micro-based silicone than pure silicone rubber.
- Nanocomposites have better performance when compared to micro and amalgam of micro-nano composites because of their large surface area which makes particles packed closely and form a smoother surface than micro-fillers.
- At a low electrode distance, such as 10 mm, the loss of hydrophobicity was faster, and recovery was slower due to the damage caused by high corona discharge intensity (as visualized in simulations) to LMW molecules.
- Samples exposed for a longer duration of 20 to 30 min took longer time of up to 1 to 2 days to recover their hydrophobicity.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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