

Solid particle erosion of electrically insulating silicon and EPDM rubber compounds

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Summary

Jet erosion tests of outdoor insulating silicone and EPDM rubbers were carried out by means of a modified sandblasting equipment. The presence of relatively large, non-reinforcing filler particles increased the erosion rate of the silicone rubber compounds. The erosive wear of highly filled compounds strongly depended on the incident angle of the eroding particles. Rubbers with low amount or very finely dispersed reinforcing filler showed a good resistance to solid particle erosion. The mechanisms of material removal were studied by scanning electron microscopy and discussed.

Introduction

Polymer materials such as silicone rubber and ethylene/propylene/diene rubber (EPDM) are widely used as weathershed materials of outdoor insulators. Because of their original surface hydrophobicity, these polymers are used to replace traditional insulating materials under extreme pollution conditions. In windy places and deserts, fast moving solid particles can cause erosive wear of the surface of the polymer housing. Deteriorated polymer surfaces tend to collect more contamination under certain conditions that can lead to a decrease of the measured flashover voltage. (1,2)

The objective of this work was to compare the resistance of different polymer insulation materials to solid particle erosion. Accelerated mechanical erosion (jet erosion) was achieved by exposing the materials to a high-speed sandblasting process. The measured erosion rates were used to evaluate the resistance of the different compounds to the effects of sandstorms and other forms of solid particle erosion.

Experimental

All the erosion tests were performed in a commercial sandblasting chamber. The equipment was modified for carrying out measurements according to industrial standards (3,4). A sample holder is used to position the sample inside the chamber. The working distance and the impact angle are adjusted by moving the nozzle holder and turning the sample holder. The speed of the erodent particles was adjusted by modifying the air pressure of the nozzle.

The speed of the erodent particles was measured by the "rotating-disks method". Two parallel disks were mounted on the shaft of an electric motor. A part of the erodent bundle is directed to the first wheel through a mask. The particle that can get through a gap of the first wheel impacts the rear wheel where the wearing of the surface of the disk indicates the location of impingement. The speed can be calculated from the angle of the impact

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center and the gap using the speed of the rotation. The mass flow of the erodent material was measured by collecting and measuring the weight of erosive material gone through the mask. The eroded surfaces were studied with a JEOL scanning electron microscope. Secondary electron imaging was used at 20 kV acceleration voltage. The samples were coated with gold in order to reduce charge accumulation on the surface. Contact angles were measured using a Ramé-Hart contact angle goniometer. Surface roughness parameters were measured with an UBM scanning laser profilometer. The erodent material used in the erosion measurements was corundum (Particle size: 0.06-0.12 mm, specific density: 4 g/cm³). The shape of the corundum particles was irregular with relatively sharp edges. This represents the most erosive particles that can be found under natural conditions.

Notation	ATH [phr]	Tensile strength [N/mm ²]	Tear resistance [N/mm]	Hardness [Shore A]
S0	0	3.29	18	43
S1	50	3.32	13	51
S2	120	2.32	7.5	58
EPDM	120	4.91	30.2	64

Table 1. Composition and mechanical properties of LSR materials

The base of the silicone rubber compounds (denoted by S0, S1 and S2) was a commercially available LSR (Liquid Silicone Rubber) material. This contains about 20 wt % of an Aerosil type silica. Aerosil is a very finely dispersed amorphous material with very large specific surface. A series of compounds was produced by filling the base compound with alumina-trihydrate (ATH; $d_{95\%} = 4 \mu\text{m}$). The alumina-trihydrate was surface treated by trimethyl-methoxy-silane. In order to make the processing of the compounds easier, 5 phr (parts pro hundred resin, where resin is the basic LSR compound) of trimethyl-siloxy terminated poly-dimethyl-siloxane oil (viscosity of 350 mPas) was added to all compounds.

A commercial EPDM compound was also involved to the experiments. Table 1. shows the composition and physical properties of each insulating rubbers.

Results and discussion

Mechanical erosion tests

The resistance of the insulator materials to erosive wear was compared by subjecting them to a relatively high speed, erosive sand-blasting treatment. The material samples were covered with an iron mask having a circular hole with a diameter of 30 mm. The bundle of erosive material was directed to the center of the exposed sample surface at 90° (normal to the surface). The working distance was 160 mm in each experiment. The

maximal speed of corundum particles was about 120 m/s. At this erodent speed relatively high erosion rates can be observed.

The erosive wear was monitored by measuring the weight loss of the samples. In the following charts, weight loss was plotted against the mass of erodent that impacted the surface. Erosion rate is defined as the slope of the linear part of these curves. The dimension of the erosion rate is *g/kg of erodent* (weight loss pro mass of erodent).

Figure 1 shows the kinetics of material removal from the different samples. At the beginning of the erosion process, the unfilled silicone rubber, S0, showed an incubation period when no material removal was observed. After the incubation period, a continuous material removal occurred that is reflected in the linear section of the erosion curve. The behavior of the ATH filled compounds was similar with a much shorter incubation period. The silicone rubber without ATH and the mechanically strong EPDM rubber showed good resistance to erosive wear. Increasing the amount of added ATH filler significantly increased the rate of the erosion.

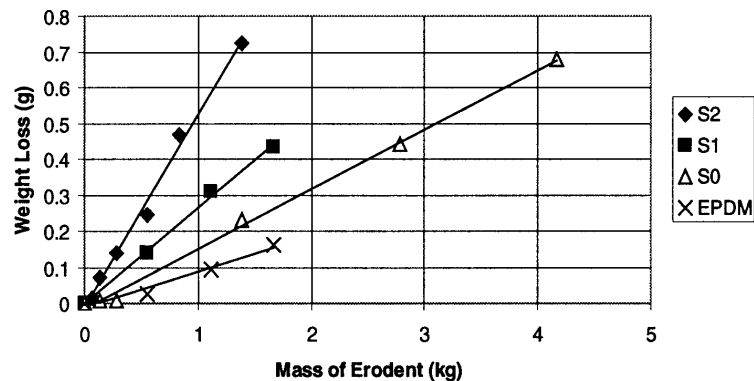


Figure 1. Erosive wear of different polymer insulating materials

Erosive wear was also studied at incident angles different from 90°. Figure 2 summarizes the dependence of the erosion on the impact angle. Treatment times were set to provide 0.45 kg of erodent material reaching the surface. The weight loss caused by such a constant amount of erodent was in the linear period, so the weight loss values plotted against the impact angles in Figure 2 represent the observable erosion rates.

The highly filled S2 and EPDM materials exhibited much higher material loss at oblique impact angles than at perpendicular erosive bundle. The silicone rubber containing no ATH was not sensitive to the impact angle changes. The weight loss at 30° was slightly larger than at 90° but it was significantly smaller than that of the ATH filled versions.

The erosion rates were measured, also at 30°. The results are compared with those obtained for 90° impact angle in Figure 3.

The erosion rates show the same tendency as the material loss due to a certain amount of impacting erodent material. The unfilled silicone rubber shows the best overall

performance though its tensile strength and tear resistance is lower than those of the EPDM compound.

Note that the speed of the particles in the presented accelerated tests is much higher than the wind speed in sand storms. Therefore measurements were carried out to check the effect of the particle speed on the length of the incubation periods and the erosion rates. S0, the silicone rubber with no added filler, was tested at different particle speeds and 90° impact angle. Table 2 shows the results of these experiments.

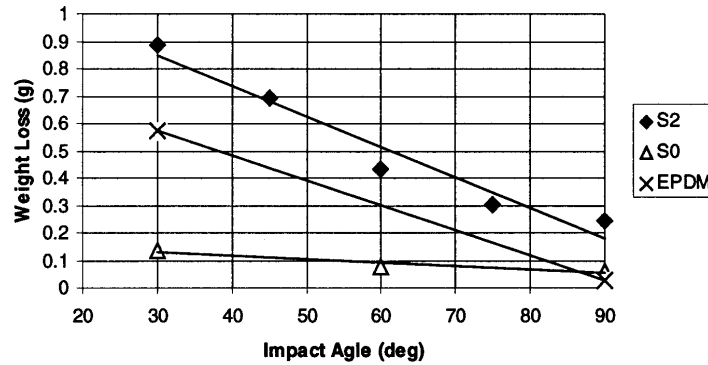


Figure 2. Effect of impact angle on the weight loss of insulating materials

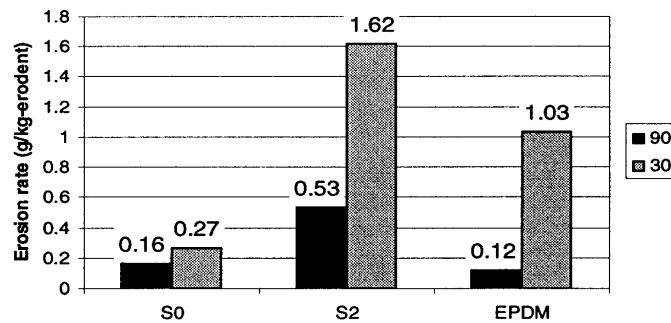


Figure 3. Erosion rates of insulating materials at two different impact angles. The labels show the actual value of the erosion rate

Particle speed (m/s)	Incubation period (min)	Rate of erosion (g/kg _{erodent})
27	∞	0
48	25	0.015
71	3	0.048
111	0.2	0.16

Table 2. Incubation period and erosion rate for different particle speeds. S0 silicone rubber, 90° impingement angle

Both incubation period and steady state erosion rate were found to be strongly dependent on particle speed. As it was expected, incubation periods were longer and erosion rates

were lower with decreasing particle speed. In fact, at 27 m/s no material removal was observed within a reasonable test time for the unfilled S0 silicone rubber compound. This suggests that a not highly filled silicone rubber can withstand a long-term exposure to severe sandstorms.

The mechanism of erosion

Rubbers are known to have excellent resistance to erosive wear. The theoretical models of erosive wear of unfilled rubber at normal impact angles was presented earlier (5). In the proposed mechanism, material is removed from the surface by propagation of subsurface fatigue cracks caused by solid particle impactation. Where the dense network of subsurface fatigue cracks intersect, chunks of material can be detached.

The mechanism of the erosion of silicone rubber materials is similar to that presented in the literature. Figure 4 shows a scanning electron micrograph of the sandblasted S0 material surface from the incubation period. The surface of the silicone rubber is intact, no surface or subsurface cracks can be observed. The erodent material is deposited on the surface. In the constant wear interval of the high-speed sand-blasting process, some cracks occur in the layer deposited on the surface and in the silicone rubber layer itself that favors to material removal.

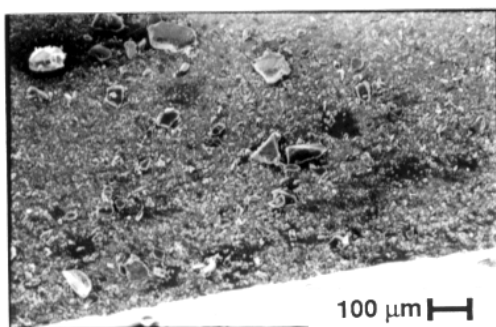


Figure 4. Sandblasted surface of S0 silicone rubber. Impact angle: 90°, incubation period

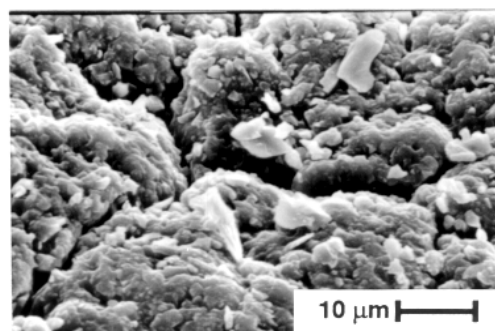


Figure 5. Sandblasted surface of S2 silicone rubber. Impact angle: 90°, material removal period

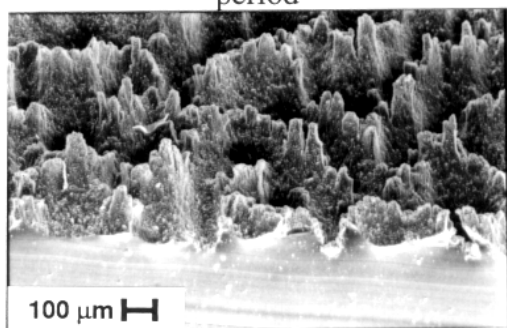


Figure 6. Sandblasted surface of S0 silicone rubber, impact angle: 30°

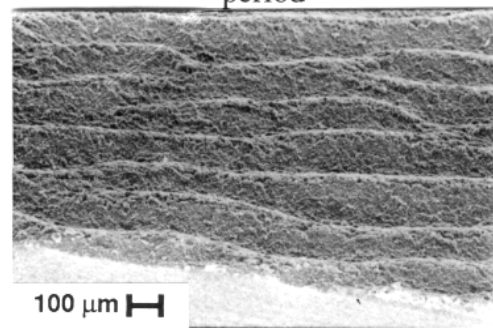


Figure 7. Sandblasted surface of S2 silicone rubber, impact angle: 30°

Figure 5 shows the SEM picture of the highly filled S2 silicone rubber material form the steady-state material removal period. More and larger cracks can be observed on the surface than in the case of the unfilled silicone rubber.

Figure 6 shows the scanning electron microscopic images of slantwise eroded S0 silicone rubber. A series of ridges, running perpendicularly to the direction of erosion, is formed on the surface. This corresponds to the mechanism proposed in the literature (6). According to the proposed scheme, erosion occurs by the progressive growth of fatigue cracks from the bases of the ridges into the bulk. Figure 6 shows large, deep cuts at the top of the ridges. In the case of the silicone rubber material without added filler the mechanism proposed by (6) must be completed by the fact that fatigue cracks occur not only at the base of the ridges but material can be cut out from the top of the ridges too.

The highly filled silicone rubber exhibits quite different picture than that of S0 (Figure 7). There are no cuts on the ridges and the valleys are much shallower than on S0 surface. Instead of fatigue cracks or cuts in the polymer matrix, the material removal is accelerated by the filler-matrix interfaces in the rubber. In the case of EPDM, which is also a highly filled material, the shape of the erosion is similar but the valleys are even shallower than on S2.

Introduction of filler particles accelerates the mechanical erosion of rubber compounds at both normal and oblique impact angles. Interfaces of matrix and filler are good promoters of subsurface crack propagation that leads to fast material removal in solid particle erosion processes.

Wettability of the sandblasted silicone rubber surfaces

Wetting properties of eroded and contaminated surface of insulation materials play a key role in outdoors electrical applications. At the beginning of the incubation period, a relatively large amount of erodent material is deposited on the surface of silicone rubber resulting in a thick contamination layer. The wettability of these contamination layers was assessed by measuring advancing and receding contact angles immediately after the sand blasting treatment.

It was expected that the surface of the samples should have lost its original hydrophobicity because of the introduced wettable contamination onto the surface. Instead of that, advancing contact angles of 120-130° and receding contact angles of 10-15° were measured. Contact angle hysteresis, the difference between advancing and receding contact angles, was very high and it was found to be dependent on the kinetics of contamination layer formation.

The possible sources of contact angle hysteresis in the case of silicone rubber are: molecular rearrangement of polysiloxane chains, energetic inhomogeneity and surface roughness.(7) Figure 8 shows the effect of the latter which seems to be the major variable. The contact angle hysteresis changes parallel with the maximum peak-to-valley distance measured at different phases of the contamination layer formation.

Changes in surface roughness can be explained by the mechanism of the contamination layer formation. First, some erodent material is deposited on the surface resulting in high

surface roughness and contact angle hysteresis. Further impingement of solid particles sweeps the larger particles away from the surface and form a layer consisting of small erodent particles. This leads to a decrease of surface roughness. When this layer starts to break apart (phase of material removing) hysteresis begins to grow again.

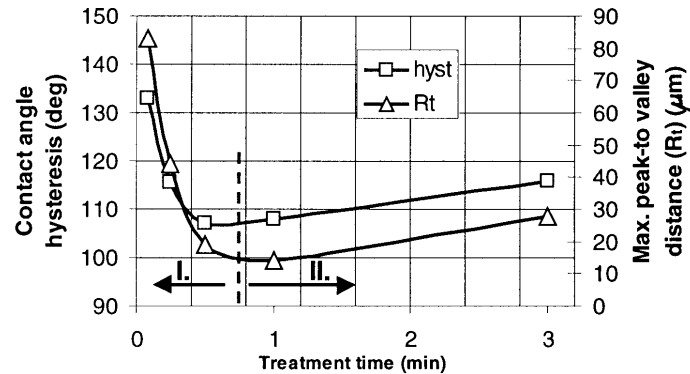


Figure 8. Correlation of contact angle hysteresis and surface roughness on sand-blasted silicone rubber. I. contamination deposition, II. material removal period

High advancing contact angles imply that all the particles deposited on the surface were completely covered by silicone oligomers migrating out from the bulk of the material. Silicone compounds contain silicone oligomers that are not linked to the polymer network. The amount of these oligomers was increased when compounding oil was added to the materials. Wetting of a rough non-wettable surface can result in the formation of an air-solid composite interface between the wetting liquid and the solid surface.(7) The extremely high advancing contact angles can be explained by the presence of a composite interface on the wetted contaminated silicone rubber surface. However, the very low receding contact angles exclude the presence of a composite interface when retracting water from the surface. This difference in the two wetting processes can be explained by the unusually high contact angle hysteresis (30-35°) measured on smooth and clean silicone rubber surfaces.(8) The large hysteresis allows to form a composite interface for advancing and a non-composite fully wetted interface for receding wetting processes.

Conclusions

Based on this study performed on the particle jet erosion behavior of outdoor insulating silicone and EPDM rubber compounds the following conclusions can be drawn:

Effect of impact angle

- At 90° impact angle, the silicone rubber compound with only Aerosil filler and the EPDM compound showed the highest resistance to erosion. The mechanism of material removal in this case seemed to be controlled by surface and subsurface crack propagation.

- At oblique impact angles the Aerosil-filled silicone rubber outperformed all the materials with higher amount of added alumina trihydrate (ATH) filler. Material removal was observed to occur from the top of the slantwise ridges formed during solid particle erosion.

It can be thus stated that the relatively soft and resilient Aerosil-filled silicone rubber shows good resistance to the erosive wear regardless to the direction of the solid particle impingement.

Effect of the amount of non-reinforcing filler

Increasing amount of ATH strongly increased the sensitivity to erosive wear in both normal and oblique impact directions. The weak interfaces between matrix and ATH filler favoured the subsurface crack propagation that directly led to material removal from the surface.

Wettability of contaminated silicone surfaces in the incubation period

Contamination layers were found to be hydrophobic immediately after the deposition process. This can be explained by the presence of free silicone oligomers on the surface of silicone rubber samples that can fully cover the contaminant particles. An unusually high contact angle hysteresis occurs due to possible differences between advancing and receding wetting mechanisms.

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References

1. Arafá, B.A., Hamed, H., Sedeek, A. ElGendy, O.A., Awad, M.M., Nosseir, A., "Aging of Polymer Insulator Surface Under the Effect of Sand Storms", *9th International Symposium on High Voltage Engineering*, Graz, Austria, 1995, #3185. (1-4)
2. Rizk, M.S., Nosseir, A., Arafá, B.A., ElGendy, O.A., Awad, M.M., "Effect of Desert Environment on the Electrical Performance of Silicone Rubber Insulators", *10th International Symposium on High Voltage Engineering*, Montreal, Canada, 1997 #3069-1
3. ASTM G76-83 "*Standard Practice for Conducting Tests by Solid Particle Impingement Using Gas Jets*" (Reapproved 1989)
4. DIN 50 332 "Strahlverschleiß-Prüfung"
5. Arnold, J.C., Hutchings, I.M.: "Erosive Wear of Rubber by Solid Particles at Normal Incidence", *Wear*, **161** (1993) 213-221
6. Arnold, J.C., Hutchings, I.M.: "A Model for the Erosive Wear of Rubber at Oblique Impact Angles", *J. Phys. D: Appl. Phys.* **25** (1992) A222-A229
7. Garbassi, F., Morra, M., Occhiello, E.: "Polymer Surfaces", John Wiley & Sons, England, 1994 pp.: 161-199
8. Bognár, A., Besztercey Gy., Bánhegyi, Gy., Kimata, R., Szaplóczay, P., "*Study of Surface Properties of Silicone Rubber Compounds for Composite Insulators*", SEE Workshop on Non-Ceramic Outdoor Insulation, Paris, 1994