An investigation of dynamic mechanical, thermal, and electrical properties of housing materials for outdoor polymeric insulators

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Received 6 February 2004; received in revised form 12 March 2004; accepted 12 March 2004
Available online 11 September 2004

Abstract

The present paper reports the results about a study of mechanical, thermal, dynamic mechanical and electrical properties of housing (weather shed) materials for outdoor polymeric insulators. Silicone rubber, ethylene-propylene-diene monomer (EPDM) and alloys of silicon–EPDM are known polymers for use as housing in high voltage insulators. The result of dynamical mechanical measurement shows that the storage modulus of blends enhances with increase EPDM in formulation. It can be seen from the result of TGA measurement that initial thermal degradation of silicone rubber improves by the effect of EPDM in blends. The blends of silicone–EPDM show good breakdown voltage strength compared to silicone rubber. Surface and volume resistance of silicone rubber improve by EPDM content. The mechanical properties of EPDM such as strength, modulus and elongation at break improve by silicone.

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Keywords: Silicone rubber; EPDM; Dynamic mechanical thermal analysis; Breakdown strength; Initial decomposition temperature; Thermo-gravimetical analysis; Surface and volume resistance

1. Introduction

Polymeric insulators are widely as outdoor HV insulators, due to their superior service properties in the presence of heavy pollution and wet condition (high hydrophobicity, resulting in self-cleaning, so that it becomes unnecessary to wash insulators), resistance to vandalism, high electrical parameters (low dielectric permittivity, high breakdown voltage, high surface and volume resistance, etc.) and also very desirable characteristics from the observation point of transportation (no damage at transportation because of the absence of brittleness) and framing (lower weight) compared to the porcelain glass insulators [1–4]. In characteristic manner, composite polymer insulators are composed of three components, fiber glass reinforced resin rod system, metal end fittings, and polymeric weather sheds. The weather sheds are intended for protecting the fiber glass rod from the environment and electrical surface discharges. Weather sheds are usually polymeric or elastomeric materials that fabricated to provide an extended creepage distance while also presenting a low surface energy for water repellency [5]. Different polymers were used in the make up of composite insulators
weather-sheds. Non-ceramic insulators contained ethylene–propylene rubber (EPR) were made first by different companies in France and the USA (1975–1980). At 1976, Rosenthal in Germany and Reliable in the USA in 1983 presented silicone rubber (SIR) [6] and Ohio Brass introduced an alloy consisting of ethylene–propylene–diene rubber (EPDM) and silicone rubber produced in 1986. The alloys of EPDM and SIR make it possible to combine the properties of two materials [2]. 

Silicone rubbers (SIR) insulators present excellent hydrophobicity transference properties in operation. Consequently, the SIR insulators demonstrated excellent electrical performance under wet and contaminated environments, and are applied widely in polluted condition. But they suffer from price, mechanical properties and tracking resistance.

Ethylene–propylene–diene rubber (EPDM) due to its combination of superior electrical properties, its flexibility over a wide temperature range and its resistance to moisture and weather is used in HV insulators. EPDM endures from UV radiation and loss of hydrophobicity in operation. Properly, compounded alloys have excellent electrical and mechanical properties due to the presence of EPDM and are hydrophobic because of the silicone content. Surface energy of EPDM, silicone rubber, and their blend during aging was determined by contact angle measurement using water and formamide as the probe liquids and it was found that blending offers a good degree of protection toward aging of EPDM rubber [7]. Hydrothermal weathering study of the peroxide vulcanized specimens of silicone rubber, EPDM rubber, and their blend carried out for various durations at different temperatures reveals that silicone is very susceptible to degradation, while EPDM and the blend maintain more than 100% elongation at break during the times and temperatures [8].

In the work presented here mechanical, thermal, dynamic mechanical, and electrical measurements of silicone and EPDM and their different blends are introduced.

2. Experiments

2.1. Materials

All the materials used for this work were commercial products and they were used received without further treatments:

(a) Silicone rubber (SIR), type Elastosil R401/60, was obtained from Wacker Chemie, Germany. Fumed silica content 25%.

(b) Ethylene–propylene–diene rubber (EPDM), type Vistalon 7500, was prepared from Exxon Chemical, Belgium. Diene (ethylene norbornene) content 5.7%; ethylene content 55.5%; Mooney viscosity ML (1+8) at (125 °C) 82; density 0.86.

(c) The di cumyl peroxide (DCP) 98%; was produced by Hercules Inc., USA.

2.2. Mixing and molding

Several formulations containing silicone rubber and EPDM were prepared (Table 1). Silicone rubber was blended with EPDM at 130 °C in a Haake internal mixer, model Sys9000, Germany, for 10 min at a rotor speed of 100 rpm for preparation alloys of SIR–EPDM. The individual elastomers and the blends were compounded with peroxide in a roll mill at room temperature. Vulcanization was done in hydraulically operated press at 170 °C and 15 bar for 10 min.

2.3. Mechanical properties

The mechanical properties of samples were determined according to ASTM D 412 by MTS System Cooperation MTS10/M testing machine. The tensile strength, elongation at break and modulus were measured by using a 500 mm/min cross-head speed. The dumbbell-shaped specimens were obtained from vulcanized sheet. Five specimens are measured for each composition.

2.4. Dynamic mechanical thermo-analysis (DMTA)

The ability of a polymeric material to withstand loads at elevated temperatures is one of the key aspects of engineering performance to be studied. Dynamic mechanical analysis is a method that measures the stiffness (shear, tensile, flexile modulus) and mechanical damping (internal friction or dissipation (loss) factor tan 𝜂) as a function of temperature. In particular, changes in these parameters can be measured as a function of temperature and/or as a function of impressed frequency. The technique has high sensitivity for detecting changes in internal molecular mobility and morphology. In particular, the mechanical dissipation factor, acting together with the dielectric tan 𝜂, may contribute significantly to heat generation in the materials. These dynamic mechanical parameters, on the
other hand, are known to be extremely sensitive to structural changes in polymeric materials [9].

The thermal mechanical properties of the samples were determined by dynamic mechanical thermal analysis (DMTA), using a DMTA 983 (TA Instrument, Inc., USA) to determine the viscoelastic properties in the bending mode. Rectangular bar specimens of dimension 30×10×2 mm³ were used for the study. Samples were heated from -150 to 100 °C at a heating rate 4 °C/min at a frequency of 1 Hz. The samples were scanned for their viscoelastic responses including, storage modulus ($E'$) and loss factor (tan δ). Four specimens are measured for each composition.

2.5. Thermo-gravimetical analysis (TGA)

Thermo-gravimetical analysis is an instrument simply measures weight change vs. temperature. It is a very effective technique to study chemical and physical phenomena as a function of temperature. TGA provides definitive data for materials and product design and aging stability information with short test times (<60 min). For TGA measurement, specimens were cut from the samples as small pieces (10 mg). The specimen is heated from 40 to 600 °C at a constant rise of temperature (10 °C/min) in nitrogen atmosphere, while the sample weight is continuously monitored by computer screen. The equipment from Perkin Elmer was used to test the samples. Three specimens are measured for each composition.

2.6. Dielectric breakdown strength

The dielectric strength of an insulating material can be defined as the voltage gradient or dielectric stress through the material at which electrical failure or breakdown occurs. The total breakdown voltage is determined by placing electrodes on opposite surfaces of a specimen disc or plaque, and increasing the potential difference between the electrodes until the material can no longer resist the flow of current. Test specimens should be in the form of a sheet or a plaque and their standard thickness is 1 mm. In this study, the composition of electrodes was a sphere of 20 mm in diameter on high voltage side and a sphere of 20 mm in diameter on low voltage side. An insulating oil was used as embedding medium for the measurement at room temperature. Imposed voltage is AC 50 Hz with increasing rate of 2 kV/s (Fig. 1). Specified test method was according to IEC 60156. Ten specimens are measured for each composition.

2.7. Resistivity

The surface resistivity is defined as the electrical resistance of the surface of an insulator material. It is measured between two electrodes mounted on the surface of the sample. Since the surface length is fixed, the measurement is independent of the physical dimensions (i.e., thickness and diameter) of the insulator sample. The resistivity of an insulator is measured by using a known voltage, measuring the resulting current, and calculating the resistance using Ohm’s Law. The resistivity is dependent on several factors. First, it is a function of the applied voltage. Environmental factors also affect an insulator’s resistivity. In general, with increasing humidity, the resistivity decreases. To make accurate comparisons to a specific test, the applied voltage, electrification time, and environmental conditions should be kept constant. Depending upon the application, the volume or the surface resistivity, or both, are measured.

Surface resistivity is measured by applying a voltage across the surface of the insulator sample and measuring the resultant current as shown in Fig. 2.

Surface resistivity ($\rho_s$) measurements (Eq. (1)) assume the applicability of Ohm’s law [10]:

$$\rho_s = \frac{R}{P/g}$$

where $\rho_s$ is the surface resistivity, $R$ the resistance, $P$ the effective perimeter of the guarded electrode, $g$ the width of the gap.

A schematic of the resistivity test setup, as specified in IEC 60093, is shown in Figs. 2 and 3.
Volume resistivity is defined as the electrical resistance through a cube of insulating material. When expressed in ohm-centimeters, it would be the electrical resistance through a 1 cm cube of insulating material. In volume resistivity measurements, the test specimen is placed between the two electrodes, one of them is guarded to prevent surface leakage around the edges. In most cases, readings are taken 1 min after application of 500 or 1000 V DC. The resulting current through the bulk of the specimen is measured by a bridge circuit, using a DC amplifier. The volume resistivity \( \rho_v \) calculation assumes the simple applicability of Ohm’s law, and is stated in (Eq. (2)) [10]:

\[
\rho_v = \frac{R}{A/d}
\]  

(2)

where \( \rho_v \) is the volume resistivity, \( R \) the measured resistance, \( A \) the area of the smaller electrode; \( d \) the thickness of the specimen.

In this study, the equipment from LEM CO (Insulation Tester ISO 5kV) was used. Five specimens are measured for each composition.

### 3. Results and discussion

#### 3.1. Mechanical properties

The mechanical properties such as tensile strength, elongation at break and modulus of samples are presented in Table 2. It indicates that with increase EPDM content in blends tensile strength, modulus and elongation decreased. It can be seen from Fig. 4 that samples B (EPDM), E, and F have no modulus at 300% elongation and with silicone content, the modulus improves (samples C and D). Furthermore, the tensile strength of samples increases with silicone content.

#### 3.2. Dynamic mechanical thermo-analysis study

The commonly used dynamic mechanical instruments measure the formation of a material in response to vibrational forces. The technique gives information about elastic modulus (storage modulus) that defines the energy stored in a specimen due to an applied strain. In a dynamic experiment, when equilibrium is reached and viscoelastic behavior is linear, both stress and strain vary sinusoidally, but strain lags behind stress. The storage modulus \( E' \) is in phase with the strain, whereas, the loss modulus \( E'' \) is \( 90^\circ \) out of phase with the strain and is related to dissipation of energy. The ratio of loss modulus to storage modulus is referred to as internal damping or the loss tangent (\( \tan \delta \)). Some important data representing the dynamic mechanical behavior of the investigated materials are listed in Table 3. The dynamic mechanical spectra (\( E' \) and \( \tan \delta \) as function of temperature) for samples are shown in Figs. 5 and 7, respectively.

The value of storage modulus for samples decreases at the glass transition (Fig. 5). The decrease of storage modulus in the transition zone is very noticeable. The decrease in the value of storage modulus for EPDM occurs only at the transition zone. It can be seen from Fig. 6 that the value of storage modulus of silicone rubber (A) improved with EPDM content and reaches its maximum with sample C. Glass transition temperature and the loss tangent (\( \tan \delta \)) values of samples at 1 Hz as a function of temperature (\(-150 \) to \( 100^\circ \)C) are presented in Fig. 7. Silicone rubber shows two peaks, one is at a temperature of about \((-94^\circ \)C) due to glass transition temperature, and other at about \((-22^\circ \)C).
corresponding to crystalline melting point [11]. The tan δ peak value relating to the low temperature peak is 0.09 and for other peak it is 0.14. A single mechanical transition has been observed in temperature range studied and is recognized as the α-relaxation or the glass transition peak for EPDM (Fig. 7). The α-relaxation is related to the Brownian motion of the main chain associated with the glass transition and the relaxation of segments associated with it [9]. Onset of glass transition of EPDM is marked by a sharp decrease in its storage modulus, as shown in Fig. 5.

Sample B (EPDM) shows a prominent peak at the temperature of (−23°C) and the peak tan δ value is 0.45. Samples C–F show two peaks in the tan δ plots (Fig. 7 and Table 3). The low temperature peak is due to silicone and it is not very noticeable. The other peak that occurs at a higher temperature and more prominently is caused by glass transition of EPDM and crystalline melting of silicone. In blends (C, D, E, F), the glass transition of the silicone component occurs at a lower temperature than that of pure silicone. The peak tan δ value is also higher for the blends at the second peak (Fig. 7) and the value of tan δ increases with EPDM content (Table 3).

On the other hand, at the first peak, the value of tan δ decreases with EPDM content. It can be seen from Table 3 and Fig. 7 that sample F has the lowest value of tan δ at first peak in comparison to other samples.

3.3. Thermo-gravimetrical analysis (TGA) measurements

Tracking and erosion of polymeric materials occur with thermal degradation as a result of high temperatures caused by dry band arcing. Thermal degradation
behavior under elevated temperature may be closely
related to the resistance to tracking and erosion and our
previous study confirms this hypothesis [12].

TGA spectra of the virgin samples are shown in Fig.
8. It can be seen from Fig. 8 and Table 4 that the range
of temperature from 30 to 300 °C did not affect signifi-
cantly the change of weight of all samples. It means that
all samples provides stability up to 300 °C. The initial
degradation temperature corresponding to 1% decom-
position for neat materials, shifts towards higher tem-
perature for blends C to F. It can be seen from Table 4
that the initial degradation temperature corresponding
to silicone rubber (A), EPDM (B), and blends of C, D,
E, and F are found to be 317, 362, 333, 340, 378, and 400
°C, respectively.

Silicone rubber (A) shows an initial degradation
temperature at 317 °C which is the lowest of all inves-
tigated samples. It can be due to lower bond energy of
Si–C bonds (Si–C bond dissociation energy 306 kJ/mol)
in silicone rubber compare to bond energy of C–C (346
kJ/mol) in other polymers [13].

It can be seen that sample F has a higher thermal
stability than A (SIR), B (EPDM) and other samples.
This can be due to reduction of Si–C bonds compared to
A and existing of Si–O–Si bonds (Si–O–Si bond disso-
ciation energy 447 kJ/mol) [13] compared to B in sample
F. Table 4 shows the percentage of residue weight of the
blends as a function of temperature (°C).

Fig. 9 shows the histogram of initial degradation
temperature for blends. It can be seen that with the in-
crease EPDM content in blends the initial degradation
temperature increases. The lower initial degradation of
silicone rubber compared to other samples can be the
result of decomposition of cyclic silicone oligomers and
also lower bond energy (Si–C). It is shown from gas
chromatography–mass spectroscopy measurements [14]
and also there have been description in the literature of
the thermal degradation of PDMS that silicone rubber

has cyclic dimethylsiloxane (DMS) together with a small
amount of linear DMS (≈1 wt%). The molecular units
of most formed cyclic DMS (≈90 wt%) are 3–6 (D3–D6)
[13–17]. Low unit silicone oligomers dominate low
boiling temperatures, with those of D2–D6 ranging from
173 to 245 °C. Therefore, these oligomers are volatilized
due to thermal effects.

It can be also seen from Table 4 that above the
temperature of 500 °C, the thermal stability of blends
decreases with EPDM content. It is due to the exist-
ence of bond Si–O–Si (Si–O–Si bond dissociation
energy 447 kJ/mol) [13] and fumed silica in blends, in
this case permanence of blends improves with silicone
content.
3.4. Dielectric breakdown strength measurements

Low level conduction in insulating materials can be attributed to impurities that provide small concentrations of charge carriers in the form of ions and/or electrons. At high fields, the electrodes may also inject new carriers into the polymer, causing the current to increase more rapidly with voltage than one would expect from Ohm’s law. At very high fields, these and other processes, often involving conduction over a surface, inevitably lead to complete failure of the polymer as a dielectric. This phenomena is also known as the dielectric breakdown [18].

Table 5 shows the dielectric breakdown strength of samples unaged and after thermal aging at 100 °C for 600 h (the thickness of samples was 1 mm). It can be seen that dielectric strength of EPDM (B) is higher than other samples in virgin case, but it has the highest breakdown loss after thermal aging.

Fig. 10 shows a histogram of breakdown strength for different samples. The dielectric strength of silicone (A) improves after blending with EPDM (samples C–F). As the result of high content silicone and its thermal stability in polymers (C and D), compared to samples (E and F), the breakdown strength increases with content of silicone rubber after thermal aging.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>BS₁ (kV/mm)</th>
<th>BS₂ (kV/mm)</th>
<th>Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>29</td>
<td>27</td>
<td>6.8</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>32</td>
<td>28.8</td>
</tr>
<tr>
<td>C</td>
<td>31</td>
<td>29</td>
<td>6.45</td>
</tr>
<tr>
<td>D</td>
<td>32</td>
<td>28</td>
<td>12.5</td>
</tr>
<tr>
<td>E</td>
<td>34</td>
<td>25</td>
<td>26.4</td>
</tr>
<tr>
<td>F</td>
<td>35.5</td>
<td>24.3</td>
<td>31.54</td>
</tr>
</tbody>
</table>

BS₁: Breakdown strength for unaged samples; BS₂: breakdown strength for thermal aged samples.

Table 6 shows the surface resistance of silicone rubber and other polymers in virgin case and after different aging. The samples were exposed to 90–95% humidity for 1200 h, and thermal aging was performed in an oven at 100 °C for 600 h. It can be seen from Table 6 that silicone shows some decrease in resistivity after humidity aging. The decrease in resistivity of silicone can be attributed to the absorption of humidity. Blends (C–F) also show some decrease in resistivity after humidity aging. It can be associated with the diffusion of the vapor to the bulk of samples.

Thermal aging is reducing the resistivity of EPDM and the blends. It means that thermal stress deteriorates EPDM and their blends with silicone rubber during the aging. Fig. 11 shows a histogram of the comparison of the surface resistance of polymers before and after different aging.

The volume resistivity of polymers was measured at 25 °C, 45% humidity, and the applied DC voltage was 5 kV.

Table 7 shows volume resistivity of samples in unaged, after humidity aging (1200 h at 90–95% humidity) and after thermal aging (100 °C at for 600 h). It can be seen from Table 7 that value of volume resistance of silicone increases after humidity aging. The increase in volume resistivity can be attributed only to the removal of charge carriers from the vulcanisate by the distilled water or the condensing steam during weathering with a diffusion mechanism. Blends also show some increase in resistivity after humidity aging. It can be associated with the rejection of the charge carriers to the liquid medium.

Fig. 12 shows a histogram of the comparison of the volume resistance of polymers before and after different aging.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>SR₁ (TΩ)</th>
<th>SR₂ (TΩ)</th>
<th>SR₃ (TΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>160</td>
<td>140</td>
<td>80</td>
</tr>
<tr>
<td>B</td>
<td>330</td>
<td>8</td>
<td>90</td>
</tr>
<tr>
<td>C</td>
<td>200</td>
<td>160</td>
<td>92</td>
</tr>
<tr>
<td>D</td>
<td>220</td>
<td>180</td>
<td>100</td>
</tr>
<tr>
<td>E</td>
<td>240</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>F</td>
<td>250</td>
<td>21</td>
<td>110</td>
</tr>
</tbody>
</table>

SR₁: Surface resistance of samples in virgin case; SR₂: surface resistance of samples after heat aging; SR₃: surface resistance of samples after humidity.
aging. It can be seen from Table 7 and Fig. 12 that the volume resistance of samples decreases with thermal aging and the loss of volume resistance increases with EPDM content.

4. Conclusion

The mechanical, thermal, dynamical mechanical, and electrical properties of polymeric insulators such as silicone rubber, EPDM, and different blends of them have been investigated.

- Mechanical properties of EPDM such as tensile strength, modulus, and elongation at break improve by silicone content.
- Results of DMTA show that storage modulus of silicone rubber and EPDM are enhanced by blending of them.
- Initial temperature decomposition of silicone rubber increases by blending of EPDM.
- Breakdown strength of silicone rubber is improved by EPDM.
- Surface and volume resistance of silicone rubber increase by EPDM.
- Humidity stress decreases surface resistivity of samples and increases volume resistivity in the effect of the rejection of the charge carriers in the samples.
- Electrical properties of EPDM and different alloys of silicone–EPDM are susceptible to heat aging.

Acknowledgements

The authors thank the Ministry of Energy of Iran for supporting this project. We thank also the companies Wacker, Exxon, Hercules for supplying raw materials.

References


