INVESTIGATIONS ON THE COMPRESSIBILITY AND THE DIELECTRIC BREAKDOWN STRENGTH OF HOLLOW MICROSPHERE FILLED SILICONE GEL UNDER ASPECTS OF HIGH VOLTAGE TECHNOLOGY

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Abstract: The attempt to use hollow microsphere filled silicone gels as insulation material in long-term stable and reliable applications requires a comprehensive and consolidated knowledge of their mechanical and electrical properties. The work presented deals with some fundamental investigations concerning the electrical and mechanical behavior of these materials.

The mechanical experiments are carried out with the help of different test setups to analyze in particular the short- and long-term compression performance of the materials during and after the vulcanization of the material. The investigations of the electrical properties primarily are performed by using dielectric breakdown tests on model insulations with a quasi-homogeneous field distribution.

The results show that hollow microsphere filled silicone gels provide a property profile which promises a good material performance for selected applications in the field of HV- and MV-insulation system technology.

1 INTRODUCTION

The use of novel insulating materials in medium and high voltage components requires a comprehensive and consolidated knowledge of their mechanical and electrical properties as well as their performance during prolonged electrical stress.

Hollow microsphere (HMS) filled silicone gels are such promising materials. They consist of a silicone gel as matrix material with mixed in gas-filled polymeric microspheres as filler, which show an average diameter of some 10 µm. Because of its structure the material is similar to foam (figure 1).

![Fig. 1: Light microscope image of the microstructure of a HMS-filled silicone gel [1]](image)

HMS-filled silicone gels are characterized by a low hardness, a high elasticity and stickiness. They present a solid and thus "dry" insulation material and show, due to the presence of the gas-filled cavities, a certain compression capability. This compression capability allows the material within limits to compensate inherent volume fluctuations caused by temperature. Due to these nearly unique mechanical properties these materials are interesting for the use in electrical insulation system technology [1]. In this field they are for example currently used in cable terminations [2].

The work presented deals with some fundamental investigations concerning the electrical and mechanical behavior of these materials. The main target of the tests carried out is to examine the short- and long-term compression performance of the materials during and after the vulcanization of the material as well as the electrical breakdown behavior influenced by different HMS-parameters and duration of electrical stress. The investigations are performed by using model insulations with a quasi-homogeneous field distribution at 50 Hz-AC voltage.

The used materials are commercially available silicone gel and different types of HMS.
2 EXPERIMENTAL PROCEDURES

2.1 Mechanical Investigation

In regard to use HMS-filled silicone gel as an insulating material for fully enclosed electric insulations the compression behavior of the materials is very important and it is absolutely essential to characterize it in a reproducible manner.

In the context of these studies the determination of the compression behavior of cross-linked samples is made with the help of force-distance-measurements by using a lever press [1]. Figure 2 exemplarily shows a force-distance-diagram obtained as result of such measurements.

![Force-distance-diagram of a compressibility test](image)

Fig. 2: Force-distance-diagram of a compressibility test

The estimation of the material compressibility exclusively takes place by using the compression phase of the recorded characteristic curve. To compare the compressibility of different materials the maximum volume-reduction at maximum force point $F_{\text{max}}$ is defined.

As test sample a cylindrical casting mould with a diameter of 50mm is used, in which the material is filled in. The volume of the sample equals to 107…127 ml. The compression is done with the help of a piston that completely covers the surface of the material sample and thus provides a hermetic closing. The maximum force applied to the piston is determined to $F_{\text{max}} = 1600$ N.

Furthermore, to improve the understanding of the material as well as for the manufacturing of technical insulations it is reasonable and necessary to know the compression behavior of non-cured material and the behavior during the curing-process.

As test sample to perform corresponding experiments a cylindrical vessel is used. With the help of two movable and fixable caps (bottom and cover plate of the test vessel) the volume of the material after potting can be decreased. The diameter is 50mm; the volume of the sample is in the range of 78 …98 ml. With this test-cell the development of the pressure can be measured during and after a reduction of the material volume.

2.2 Electric Breakdown Tests

A test-cell with two sphere electrodes – shown in figure 3 – was used for these investigations. The sphere diameter is chosen to $d_{K} = 20$ mm and the gap distance to $s = 2$ mm. The field distribution in the area between the electrodes is nearly homogeneous and can be characterized by the utilization factor $\eta$ (Schwaiger-factor). Thereby $\eta = 1$ defines a homogeneous field distribution. A decrease of $\eta$ correlates with an increase of the inhomogeneity of the electrical field. The utilization factor of the configuration used here is calculated to $\eta = 0.94$.

![Electrode configuration for the determination of the dielectric breakdown strength of HMS-filled silicone gel](image)

Fig. 3: Electrode configuration for the determination of the dielectric breakdown strength of HMS-filled silicone gel [3,4]

The manufacturing of the test samples is based on defined criteria, which have been determined in previous investigations [1].

For the determination of the AC breakdown voltage the samples were stored under dry conditions for 1000 hours (22 °C / r. h. < 10 %). During the test they are placed in an SF$_6$-environment to prevent external flashovers. The breakdown tests were carried out in accordance to IEC 60243 with 50 Hz AC voltage and a continuous voltage rise with a rate of 2 kV/s. A statistical evaluation is done with the help of the two-parametric form of the Weibull distribution. In order to get a sufficient level of statistical confidence, every test series consists of minimum five test samples [4-6].

2.3 Used HMS-Types

The HMS-types used for the investigations presented here are shown in Tab. 1 together with their relevant parameters.
The diameters and accordingly the particle sizes of the spheres of a HMS-type show a statistical distribution due to manufacturing. Therefore the term "average particle size" is used for the characterization of the spheres. Furthermore, the materials investigated contain two different filling gases and show only an insignificant difference in density.

**Tab. 1: Used HMS-types**

<table>
<thead>
<tr>
<th>HMS-type</th>
<th>Average particle size in µm</th>
<th>Density in g/l</th>
<th>Filling gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>40</td>
<td>30</td>
<td>Isopentane</td>
</tr>
<tr>
<td>B</td>
<td>80</td>
<td>30</td>
<td>Isopentane</td>
</tr>
<tr>
<td>C</td>
<td>40</td>
<td>25</td>
<td>Isobutane</td>
</tr>
<tr>
<td>D</td>
<td>80</td>
<td>25</td>
<td>Isobutane</td>
</tr>
</tbody>
</table>

**3 TEST RESULTS, EXAMINATION AND DISCUSSION**

### 3.1 Mechanical Tests

#### 3.1.1 Compression behavior of cross-linked samples

The measured force-distance-diagrams show for all the tested materials the same qualitative characteristics as illustrated in figure 2 exemplarily. This characteristic is reminiscent of a characteristic curve, which is shown by an ideal gas compressed in the same way. Therefore it is certainly the result of the adiabatic change of state of the filling gas of the HMS.

Thus, as expected, the maximum compressibility of the materials linearly increases with its filling degree, which can be approximately equated with a free gas volume in the material.

In this context figure 4 shows the compressibility of materials manufactured by using the HMS-type A at a force on the piston of $F_{\text{max}} = 1600\text{N}$ (see figure 2) in dependency of their filling degree.

As a particularly important finding, which is essential for the use of these materials in the area of high- and medium voltage insulation technology, is to be noted that the material always expands to its primary volume after compression. The deformation of the HMS during the compression shows up as fully reversible. Figure 5 shows a sketch of the sphere behavior during a compression cycle.

**Fig. 4: Maximum compression capacity of materials in dependency of their filling degree [1]**

**Fig. 5: Schematic illustration of HMS before, during and after a load of $P = 600\text{kPa}$ [7]**

#### 3.1.2 Long-term compression performance

For longer load durations, the material shows in cured as well as in the still uncured state an analog compression behavior. Figure 6 e.g. shows the characteristic of pressure in the volume of a material sample compressed during its curing process against time. The material used for this investigation is the HMS-type A and has filling degree of 40%.

**Fig. 6: Exemplary illustration of the characteristic of pressure in the volume of a material sample compressed during its curing process at $T = 23\text{°C}$**
It is evident that immediately after compression a decrease in pressure takes place in the sample volume, which attains a stationary final value after about 70 hours. This behavior is independent of the degree of compression. The final value depends on the used HMS-type and can be up to 50%, compared to the maximum pressure at the beginning of the compression. The reasons of the observed behavior could be caused by formation processes of the HMS or by a thermodynamic transition process of the filling gas [1].

As an important finding is to be noted again, that the pre-compressed material shows a fully reversible compression behavior and expands to its primary volume after the test. This was observed after a change of both the degree of compression and the material temperature. This behavior could be confirmed by further investigations on different gels.

3.2 Electrical Tests

The following chapter deals with the dielectric strength of HMS-filled silicone gels in a quasi-homogeneous electric field. In this context both, the influence of different HMS-parameters and the dependency of the dielectric breakdown strength are investigated.

3.2.1 Influence of the filling-degree on the dielectric breakdown strength

Figure 7 shows the dielectric breakdown strength of different materials manufactured by using the HMS-type A against their filling degree.

The result shows, that mixing in of HMS in silicone gel causes a significant decrease of the dielectric breakdown strength in comparison to unfilled gel. In this case the HMS are to be regarded as voids, which reduce the breakdown strength of the mixture compared to that of pure matrix material up to 65%. This behavior is, due to the significant overlapping of the confidence intervals, independent of the filling degree and thus the number of voids in the material.

Because of this independence the filling degree of the materials can be defined on the basis of other criteria, for example mechanical properties, to optimize it with respect to the particular application.

3.2.2 Influence of the average particle size and the filling gas of the used HMS-type on the dielectric breakdown strength

The following investigation was carried out by using four different materials with two different HMS-type-couples (figure 8):

Couple I: A and B: Filling gas Isopentan
Couple II: C and D: Filling gas Isobutan

The particle size is 40µm (A and C) and 80µm (B and D). The filling degree is 40% for all probes.

The result shows that the dielectric strength increases with a decrease of the average particle size. Furthermore, the filling gas Isobutane shows in contrast to the filling gas Isopentane a positive influence on the breakdown strength. Both results confirm that the gas-filled cavity of the HMS plays an important role in the breakdown process.

3.2.3 Influence of the increasing rate of the load voltage on the dielectric breakdown strength

A practice-orientated dimensioning of electrical insulation systems requires the knowledge of the breakdown strength together with the knowledge of the time- and load-dependent changes in the properties of the used insulating materials. This is crucially important for a long-term stable and reliable operation of the respective system.
A first estimation of the electrical long-term stability can be made by using tests with different rates of voltage rise. In this context a series of test results were initiated, which show the influence of the rate of voltage rise on the breakdown strength of a material manufactured by using the HMS-type A at a filling degree of 40%. The tests were carried out at a temperature of 22°C and a relative humidity of 37% ± 3%. The increasing rates of the load voltage are defined to:

\[
\begin{align*}
\nu_U &= 2 \text{ kV/s} \quad \text{(continuous voltage rise)} \\
\nu_U &= 2 \text{ kV/min} \quad \text{(stepwise voltage rise)} \\
\nu_U &= 2 \text{ kV/h} \quad \text{(stepwise voltage rise)} \\
\nu_U &= 2 \text{ kV/d} \quad \text{(stepwise voltage rise)} \\
\nu_U &= 2 \text{ kV/10d} \quad \text{(stepwise voltage rise)} \\
\nu_U &= 2 \text{ kV/48d} \quad \text{(stepwise voltage rise)}.
\end{align*}
\]

Unfilled silicone gels show no dependence of their dielectric breakdown strength on the rate of rise of the voltage and thus no detectable signs of electrical aging [3, 8]. Figure 9 shows that the breakdown strength of HMS-filled gels have a clear dependence up to a rate of about \( \nu_U = 2 \text{ kV/d} \). For lower increasing rates an influence is no longer detectable.

![Figure 9: 63%-quantiles with the 95%-confidence limit of the breakdown field strength (peak value) against the increasing rate of the load voltage](image)

It can be concluded that at a certain electrical load level the breakdown mechanism of the materials are subject to a change. In this context it can be assumed that the breakdown mechanism at high load voltages is based on partial discharges (PD): The longer the "effective duration time" of the PD, the lower the electrical breakdown strength of the material. Below a certain electrical load limit the material degradation seems to be very slow, the degradation mechanism changes. In that case the material "ageing" is much slower.

### 4 CONCLUSION

The results show that hollow microsphere (HMS) filled silicone gels provide a property profile which promises a good material performance for selected applications in the field of HV- and MV-insulation technology. The high compression capability that allows the material to compensate inherent temperature volume fluctuations sets the material apart from other insulating materials with solid character. The dielectric strength of the material shows a distinctive dependency on both the different micro-sphere parameters and the stress time.

Furthermore the results show that from an electrical point of view a material with small HMS-diameters and Isobutane as filling gas is preferable. However, a practice-orientated dimensioning of electrical insulation systems particularly requires the consideration of the electrical ageing performance. It should be based on an operating field strength which is far below the value determined with the help of short term tests.

### 5 REFERENCES


