INFLUENCE OF THE FILLING DEGREE OF MICROSPHERES ON THE BREAKDOWN VOLTAGE OF SYNTACTIC FOAM

C. Roggendorf[1*], A. Strauchs[1], A. Mashkin[1], A. Schnettler[1]
[1]Institute for High Voltage Technology, RWTH Aachen University,
Schinkelstraße 2, 52062 Aachen, Germany
*Email: Roggendorf@ifht.rwth-aachen.de

Abstract: Syntactic foam is a composite material consisting of a polymer matrix and hollow microspheres. In this paper a parameter study for different compounds of syntactic foam is presented. The short time breakdown voltage under electrical ac stress is investigated for different compounds. The parameter study lays its main focus on the variation of the filling degree of glass and polymeric microspheres. Moreover the influence of different diameters of the microspheres and the influence of additional silica particles on the short term breakdown voltage of syntactic foam is determined. All in all these investigations result in design criteria for a wide spectrum of syntactic foam compounds. This allows adjusting the material properties for each special application providing a high reliability and low costs.

1 INTRODUCTION

Insulation materials of the future are confronted more and more with a wide range of requirements. Beside good electrical properties, e.g. high electrical breakdown field strength, a compact design and low costs also play a major role. Syntactic foam represents an alternative to conventional insulation materials such as insulation oil or mineral filled polymers. It consists of a polymer matrix (called binder) and hollow spherical particles with a mean diameter of about 30 - 100 µm (microspheres), which are mixed into the binder. Syntactic foam features good electrical properties [1-3] and distinguishes itself with a low price. Due to its foam structure the insulation material features a very low density (down to approximately 0.65 g/cm³), which allows a very compact and lightweight design of high voltage components.

The name syntactic foam results from the microscopic structure of the material which is generated by the casting of hollow microspheres into the polymer matrix and strongly resembles a foam structure. Figure 1 shows a Scanning Electron Microscopy (SEM) picture of the material.

Ongoing investigations at the Institute for High Voltage Technology of RWTH Aachen University deal with the impact of different compounds of syntactic foam on the electrical, mechanical and thermal properties of this material. The variation of the filling degree and the kind of the microspheres provide the possibility to adapt a wide range of material properties for special applications. The present study focuses on the impact on the short-term breakdown field strength under electrical ac stress. Epoxy resin is used as binder filled with various hollow glass or polymeric microspheres with different diameters and filling degrees from 10 up to 50 % by volume. Materials with a lower filling degree have for example a lower viscosity, but materials with higher filling degrees a lower density and a lower price. Other properties including the mechanical flexibility of the material, the dielectric properties or the thermal conductivity can be modified by filling the syntactic foam additionally with silica particles. For each modification of the insulation compound it is important to have knowledge about the dielectric strength of the material to gain the optimal design of the insulation system.

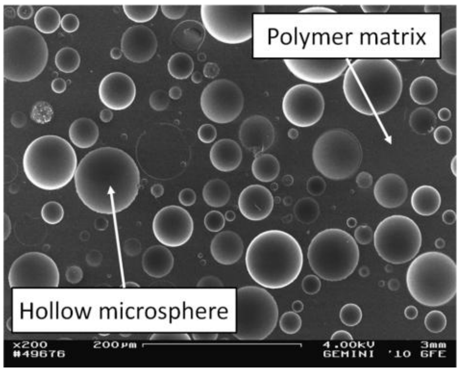

Figure 1: SEM-picture of the material structure of syntactic foam

2 DIFFERENT COMPOUNDS OF SYNTACTIC FOAM

By using different filling degrees and/or different fillers syntactic foam provides the possibility to adjust a wide range of material properties. The use of hollow microspheres realizes a material with a low density and low costs. Furthermore, the permittivity of the material is decreased by the gas inside the spheres. All of these properties are improved by increasing the filling degree. The density and the permittivity can also be improved by using microspheres with larger diameters due to a higher gas volume to wall ratio. The following investigations show on the contrary, that smaller spheres provide higher breakdown strength. The mechanical properties can be modified by different microsphere types. Glass microspheres feature a higher mechanical stability whereas polymeric spheres result in a higher flexibility of the material. In general, the thermal conductivity of syntactic foam is relatively low due to low thermal conductivity of the gas inside the hollow particles. It decreases with increasing filling degree of hollow microspheres. To improve the thermal conductivity of the material solid silica particles can be added to the foam.

3 MATERIAL CHARACTERIZATION

In the present study, the syntactic foam consists of a hot curing casting epoxy resin system filled with hollow microspheres. For filling degrees above 50 vol.-% the mixing viscosity of the material increases significantly and leads to a reduction in the material quality. For lower filling degrees below 30 vol.-% the benefits of syntactic foam, which are low costs and low weight, becomes less relevant. Hence, the investigated filling degrees are 30, 40 and 50 vol.-%, respectively. The microspheres vary in material and size. Table 1 gives an overview over the microspheres used in this investigation.

Table 1: Microsphere Parameters

Material	Mean Diameter	Filling Degree
Borosilicate glass	45 µm	30 vol.-% 40 vol.-% 50 vol.-%
	60 µm	
Acrylonitrile copolymer with $CaCO_3$ coating	40 µm	
	90 µm	

Furthermore, a mix of hollow polymer microspheres and solid silica particles are investigated. The resulting filling degree of the mix is constant and set to 50 vol.-%, whereas the ratio between hollow polymer microspheres and solid silica particles varies. For this investigation silanized silica particles with a mean particle size of 16 µm are used. Table 2 gives the information about the investigated compounds.

Table 2: Ratio between polymer microspheres and silica particles

Filling Degree Hollow Polymer Microspheres	Filling Degree Solid Silica Particles	Resulting Filling Degree
50 vol.-%	0 vol.-%	50 vol.-%
40 vol.-%	10 vol.-%	50 vol.-%
30 vol.-%	20 vol.-%	50 vol.-%

The components are mixed at a temperature of 60° C and afterwards degassed, before the mix is casted into a metallic mold. First the material is gelled in a rotating arrangement to avoid sedimentation of the filling materials. Afterwards the material is cured in a furnace. The correct order of the mixing process is shown in Figure 2.

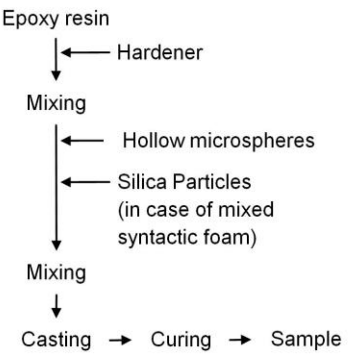

Figure 2: Preparation scheme for syntactic foam

4 EXPERIMENTS

4.1 Test Setup and Test Procedure

The electrical ac breakdown field strength is determined according to IEC 60243-1 [5]. During the test the voltage is increased stepwise until breakdown occurs. The voltage starts at 40 % of the expected breakdown voltage, and is increased every 20 s. The step size is a function of the start voltage and defined in [5]. Figure 3 shows the test setup. For the tests, the specimens are placed in a vessel filled with insulation oil to prevent surface discharges.

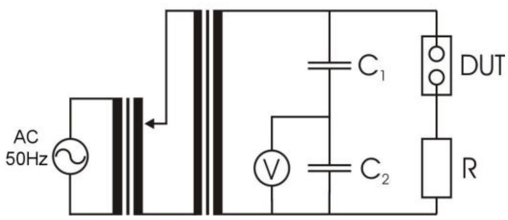

Figure 3: AC Measurement Setup

- C_1, C_2: capacitive divider
- R: current limiting resistor
- DUT: Device under test

4.2 Object Geometry

In order to determine the breakdown field strength, specimens with embedded sphere electrodes are manufactured (schematically shown in Figure 4). Steel electrodes of 12 mm diameter are used. The distance between the electrodes is set to 2 mm. This configuration provides a uniform field configuration with utilization factor of 0.865. The overall dimensions of the specimens are 3 cm x 3 cm x 6 cm. Five specimens per material are tested.

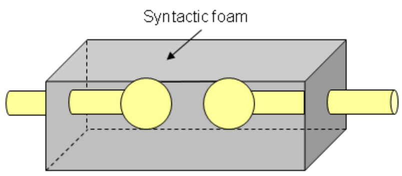

Figure 4: Specimen with embedded sphere electrodes

5 RESULTS AND DISCUSSION

5.1 Impact of microsphere size

The impact of the microsphere size on the electrical breakdown field strength (E_b) of syntactic foam filled with hollow glass and polymeric microspheres is presented in Figure 5 and Figure 6, respectively. The results are given as mean values with 95 % confidence intervals.

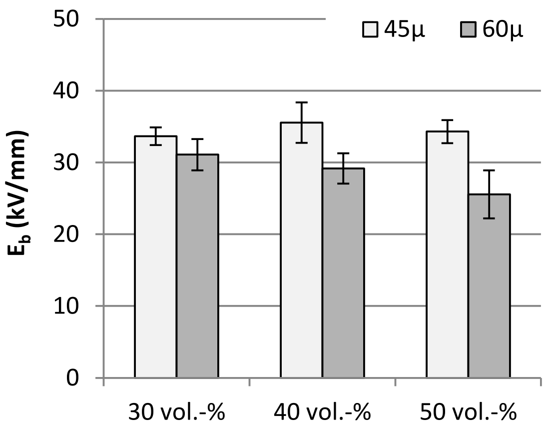

Figure 5: Specimens with glass microspheres (mean diameter of 45 and 60 µm)

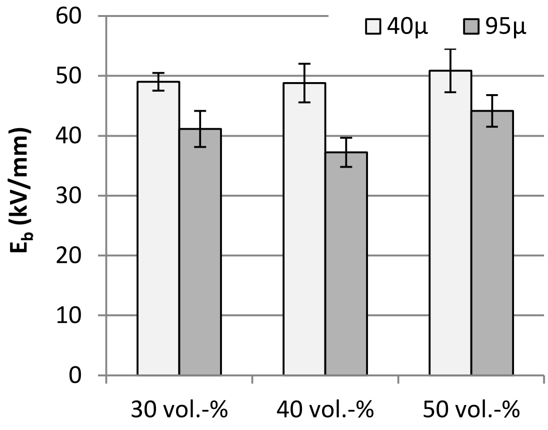

Figure 6: Specimens with polymeric microspheres (mean diameter of 40 and 95 µm)

Independent of the filling degree and microsphere type higher breakdown field strength can be observed for smaller microsphere diameters. This effect can be explained by the breakdown process in epoxy resin based syntactic foam under electrical ac stress. The breakdown is initiated by gas discharges inside the hollow microspheres [6]. For smaller gas volumes the probability for creating an electron to initiate the process decreases. Hence, the dielectric strength increases with smaller sphere diameters.

5.2 Impact of microsphere type

In the following, the impact of the hollow microspheres' type on the electrical breakdown field strength of syntactic foam is presented (Figure 7). The results are given as mean values with 95 % confidence intervals. Glass and polymeric microspheres with mean diameters of 45 µm and 40 µm are used as filler. It can be observed, that the specimens with polymeric microspheres feature higher breakdown field strength for all filling degrees than specimens with glass microspheres.

As mentioned above, the mean diameter of the microspheres has also a significant influence on the breakdown field strength. Nevertheless, due to the little difference in mean diameter (45 to 40 µm) it is expected, that this effect can be neglected and the impact of the sphere type is dominant. The polymeric sphere consists of a 0.1-1 µm polymeric wall with an approximately 5 µm $CaCO_3$ coating. In comparison the glass spheres consist of a 1 µm wall without any coating. As mentioned above, the breakdown is initiated by gas discharge activity inside the spheres, which results in erosion of the microspheres. Hence, the thicker sphere wall of the polymeric spheres features a higher resistivity against this erosion process.

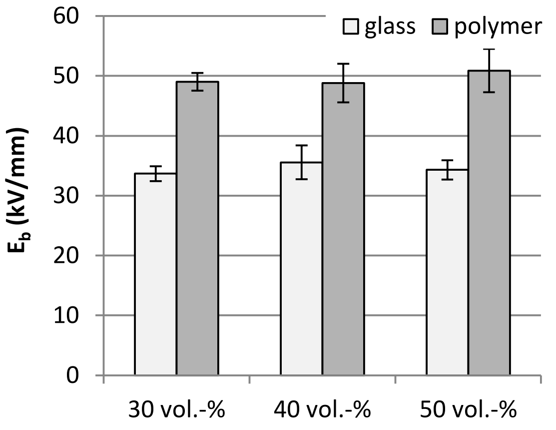

Figure 7: Specimens with different hollow microspheres' types (glass and polymer)

5.3 Impact of filling degree

All investigations presented above (Figure 5 - Figure 7) are carried out for different filling degrees. It can be observed that the filling degree of hollow microspheres has no significant influence on the dielectric strength of the material. This effect is independent of the other investigated parameters, which are the sphere diameter and the sphere type.

To explain this effect numerical field simulation are carried out for a typical syntactic foam arrangement. Figure 8 and Figure 9 show the results of the 3D field simulation in a sectional plane for filling degrees of 30 vol.-% and 50 vol.-%, respectively. The homogenous background field strength of the simulation is set to 25 kV/mm. This value represents the minimum breakdown field strength determined by the experimental investigations.

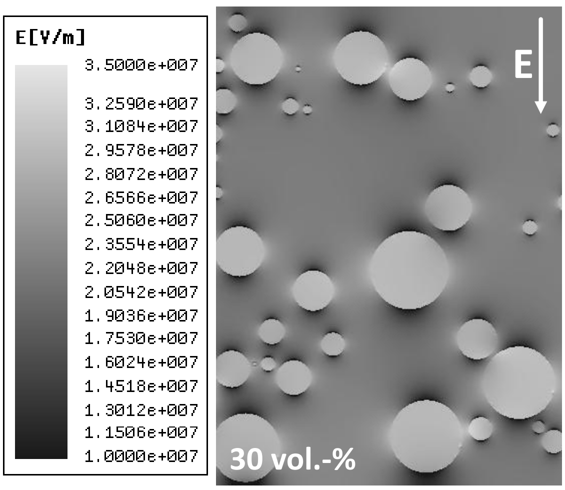

Figure 8: Field simulation of syntactic foam with 30 vol.-% filling degree of microspheres

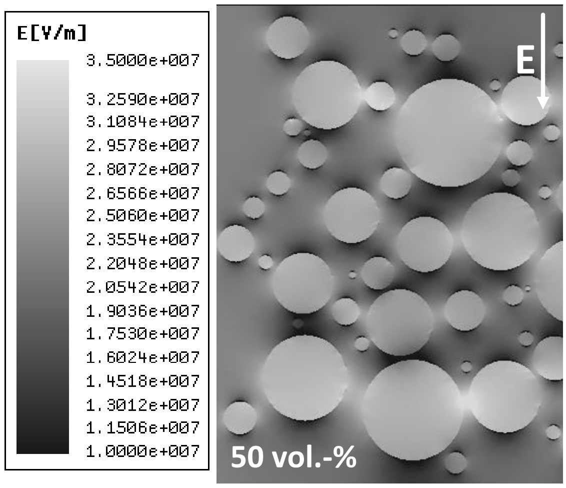

Figure 9: Field simulation of syntactic foam with 50 vol.-% filling degree of microspheres

The simulation shows for both filling degrees similar maximum field strength inside the microspheres. Therefore, it can be assumed, that the gas discharge activity starts at the same background field strength for different filling degrees. Hence, the dielectric strength of the material is independent from the filling degree of the microspheres.

5.4 Impact of additional silica microparticles

Figure 10 shows the influence of additional silica micro particles on the dielectric strength. The syntactic foam consists of a mix of hollow polymer microspheres (mean diameter 95 µm) and solid silica micro particles (mean particle size 16 µm). The material has a constant filling degree of 50 vol.-% for all specimens. However, the ratio between hollow polymer spheres and solid silica microparticles varies. The results are given as mean values with 95 % confidence intervals.

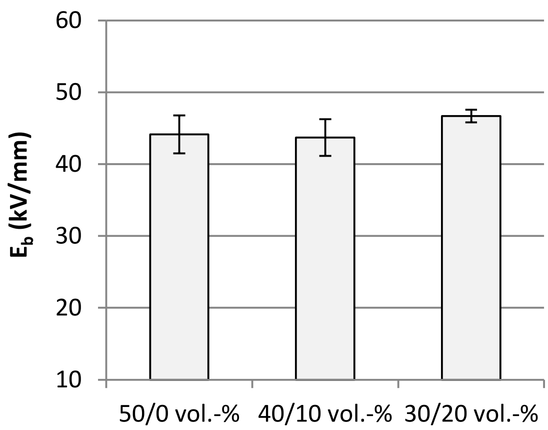

Figure 10: Specimens with additional silica particles (microspheres/silica particles vol.-%)

The results show no significant influence of the mix ratio between hollow micro spheres and silica particles. As shown before, the filling degree of the microspheres has no impact on the dielectric strength. Thus, it can concluded, that the use of additional silica particles also has no effect on the electrical breakdown strength under short-term ac stress.

6 CONCLUSION AND OUTLOOK

6.1 Conclusion

This study focused on the impact of different microspheres' diameters, types and filling degrees on the electrical breakdown field strength of syntactic foam based on epoxy resin under short-term ac stress.

Syntactic foam provides the possibility to adjust the material properties by varying the filling degree and the kind of fillers. For example silica microparticles can be added to increase the thermal conductivity. The type of sphere wall can be varied to influence the mechanical properties.

Short-term electrical breakdown test were performed for different material compounds and shows high values for all investigated material compounds. The results can be concluded by the following statements:

- The dielectric strength can be increases by using hollow microspheres with smaller diameters.
- The polymeric microspheres feature a higher dielectric strength compared to glass microspheres due to a thicker sphere wall.
- The dielectric strength is independent from the filling degree of microspheres. The effect was explained by the breakdown process in syntactic foam, which is initiated by gas discharges inside the spheres.
- Additional silica microparticles have no influence on the dielectric strength.

This parameter study provides the dielectric strength for a wide spectrum of syntactic foams, which is necessary for electrical design criteria for the application as insulation material for high voltage equipment. As main results of the parameter study it can be ascertained, that the filling degree of the filler has no significant impact on the dielectric strength under short-term ac stress. Thus, it is possible to design the epoxy resin based syntactic foam according to further criteria, e.g. mechanical and thermal properties.

6.2 Outlook

To design the syntactic foam for different applications a knowledge about the influence of the fillers for mechanical and thermal properties is also necessary. Therefore, further investigations concerning these parameters are planned. Aim of further investigations is to adjust the material properties for each special application, which leads to the best performance of the insulation materials to provide a high reliability and low costs.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] A. Strauchs et al.: "The Impact of Electrical Field Stress on the Volume Conductivity of Syntactic Foam", IEEE ISEI 2010, June 2010, San Diego, USA

[2] A. Mashkin et al.: "Investigation on Inverse Volume Effect of Syntactic Foam under Uniform dc Field Stress", IEEE ISEI 2010, June 2010, San Diego, USA

[3] M. Kessler; C. Roggendorf; A. Schnettler: "Behavior of elastic syntactic foams under impulse voltage stress", IEEE ISEI 2010, June 2010, San Diego, USA

[4] C. Roggendorf; M. Kessler; A. Schnettler: „Modification of the mechanical properties of epoxy resin with polymeric microspheres", ISH 2011, August 2011, Hanover, Germany

[5] IEC 60243-1: "Electrical strength of insulating materials - Test methods - Part 1: Tests at power frequencies", German version EN 60243-1: 1998.

[6] A. Troeger: "Analyse der elektrischen Durchschlagmechanismen in syntaktischen Schäumen", Dissertation, RWTH Aachen, 2009.