THE USE OF MODEL CABLES FOR EVALUATION OF DC ELECTRICAL PROPERTIES OF POLYMERIC CABLE MATERIALS

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ABSTRACT

The possibility to use model cables with 1.5 mm insulation thickness for characterization of dc electrical properties of polymeric materials has been studied. Results from space charge measurements are presented and compared to those obtained from plaques (0.5 mm insulation) and full-sized cables (4.5 mm insulation). It is evident from PEA-measurements that the shape of the space charge distribution and the relative ranking of different insulation systems are basically equivalent among the different types of test specimens.

KEYWORDS

HVDC, power cables, polyethylene

INTRODUCTION

Model cables with insulation thickness 1.5 mm have been extensively used for evaluation of the wet ageing properties of insulating and semiconductive materials intended for crosslinked polyethylene (XLPE) ac power cables [1]. The main advantages with model cables compared to plaques and full-sized cables are ease of preparation, production (extrusion) under similar conditions as for full-sized cables, and the possibility to easily apply high stress levels.

The intention of the present study is to explore the possibilities to use model cables for characterization of the dc electrical properties. The focus of the paper is evaluation of the space charge accumulation process in XLPE insulation systems subjected to high dc electric stress. Will reproducible results be obtained in model cable measurements? Will the ranking of materials with respect to dc electrical performance be the same as in studies using plaques and full-sized cables?

SAMPLES

Three-layer model cables with insulation thickness 1.5 mm were extruded and dry-cured on a 1+2 pilot cable line, figure 1. The cables were thermally treated at 80°C and atmospheric pressure for five days to enable full comparison between the different material systems. This treatment ensured almost complete removal of the peroxide by-products: the levels were all below 100 ppm after the degassing step. However, one model cable and one full-sized cable were tested without previous degassing (figures 9 and 13).

The cables were cut into 1 meter long samples with 10 cm active length (with outer semicon) in the middle.

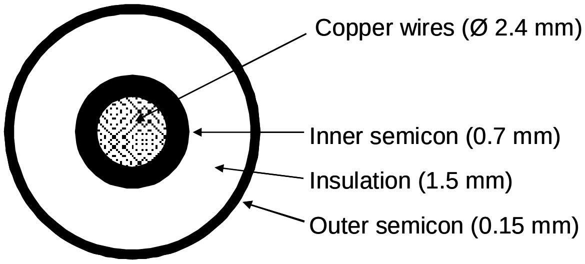

Figure 1: Three-layer model cables with insulation thickness 1.5 mm

The model cable results were compared to those obtained with plaque samples comprising a 0.50 mm insulation layer and a semiconductive layer on one side. Aluminium foil was used as electrode on the other side, this electrode was grounded during the measurements.

In addition, measurements were carried out on full-sized cables with insulation thickness 4.5 mm, a thickness corresponding to 15 kV ac power cables. A 50 mm^2 Al conductor was used in these cables.

Several different peroxide crosslinkable insulating and semiconductive materials were selected based on expected performance in dc electric field. The insulations were labeled INS1, INS2, INS3, and the semiconductive materials SC1 and SC2.

TEST METHODS

Space charge measurements were performed by the pulsed electro acoustic (PEA) technique in a controlled humidity and temperature environment. The model cables were submitted to dc poling voltages of 20 and 60 kV, corresponding to approximately 20 and 60 kV/mm electric field at conductor screen, while heated to 20 and 70°C uniform temperature in an oven. The space charge profiles were recorded regularly during the poling lasting for
10 000 s (3 hours) followed by a depolarization period lasting 2000 s (33 min) with the sample grounded. The voltage-on measurements shown here were obtained at the end of the poling, while the voltage-off profiles were recorded directly after removal of the high voltage.

Comparative space charge measurements were carried out on the plaque samples by applying electric fields in the range

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10 – 60 kV/mm at temperatures of 20, 45 and 70°C. The poling time was 10 000 s.

The full-sized cables were measured at voltage levels up to 150 kV (40 kV/mm conductor stress) and conductor temperatures up to 70°C. The poling time was extended to 20 000 s (5.6 hours).

For ranking purposes the parameter known as field enhancement factor (FEF) has been found to be useful. FEF is defined as the ratio between the actual electric field at the ground electrode and the Laplace field at the same position. It can be shown that FEF is easily calculated using the following relationship:

$$FEF = \frac{V_{peak}}{V_{peak,cal}} \cdot \frac{\mathrm{U}_{\mathrm{cal}}}{\mathrm{U}} \qquad [1]$$

where V_{peak} is the peak height of the ground electrode signal voltage (mV) at applied voltage U (kV) and $V_{peak,\ cal}$ is the peak height of the ground electrode signal voltage (mV) during a calibration measurement at such a low voltage U_{cal} (kV) that no space charges are present. A material with FEF = 1 is the preferred choice for dc applications. In case of heterocharges close to the ground electrode the electric field will be higher than the Laplace field resulting in FEF values > 1.

The space charge accumulation process depends in a complex way of the voltage, temperature, time and position why it is obvious that several parameters should be utilized for ranking. Therefore most voltage-on measurements are complemented with the internal stored charge density Q_m (C/m^3) equal to the average of the absolute charge density measured 2 s after removal of high voltage.

The horizontal axis in the graph shows the distance in mm from the ground electrode - in cables the outer semiconductive layer.

More information about the test methods are found in the references 2-8.

RESULTS AND DISCUSSION

Voltage and temperature dependence of space charge

The influence of the applied electric field is illustrated in figures 2 and 3 showing the charge density in voltage-on and voltage-off conditions, respectively.

The corresponding figures for the influence of the measurement temperature are numbered 4 and 5.

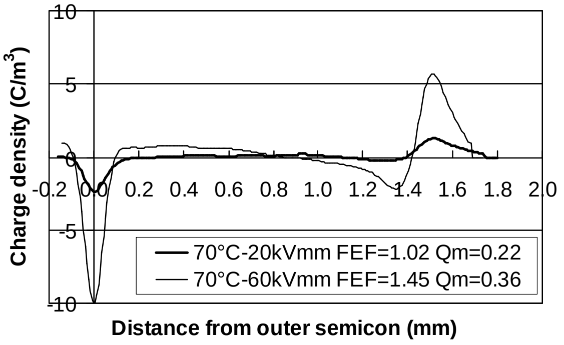

Figure 2: Voltage-on charge density in INS1/SC1 model cables poled at 20 and 60kV/mm for 10000 s at 70°C

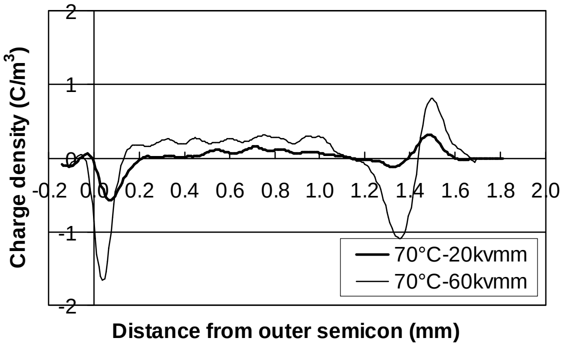

Figure 3: Voltage-off charge density in INS1/SC1 model cables poled at 20 and 60kV/mm for 10000 s at 70°C. The measurement is done 2 s after removal of high voltage.

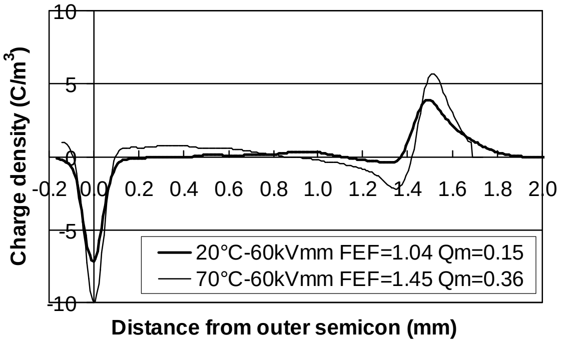

Figure 4: Voltage-on charge density at 20 and 70°C of INS1/SC1 model cables poled at 60 kV/mm for 10000 s

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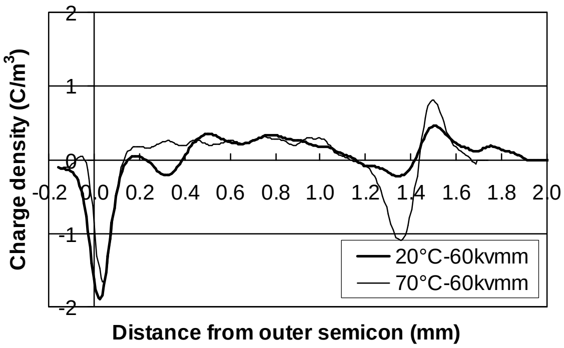

Figure 5: Voltage-off charge density at 20 and 70°C of INS1/SC1 model cables poled at 60 kV/mm for 10000 s. The measurement is done 2 s after removal of high voltage.

The results very clearly demonstrate that a combination of very high electric stress and temperatures is needed for significant accumulation of space charge, i.e. causing significant increase of the field enhancement, in the studied degassed model cables. The main part of the charges is heterocharges with resulting positive charges at cathode (the grounded outer semicon) and negative charges at anode (the conductor screen).

Experiments with cooling of the outer electrode (semicon) to give temperature gradients of 10 and 20°C through the insulation were carried out on model cables with conductor temperatures of 20 and 65°C. It was evident from space charge measurements that the temperature gradient as such was a factor of less importance than the applied voltage and the temperature of the outer semicon, once the applied field exceeds the threshold for space charge accumulation [9, 10].

Time dependence of charge accumulation

The time evolution of the space charge build-up process is described in plots of FEF versus poling time in figure 6. The field enhancement in the highly stressed (70°C, 60 kV/mm) sample quickly reaches values of 1.7 followed by a slow decrease due to reduction of positive heterocharges close to outer semicon.

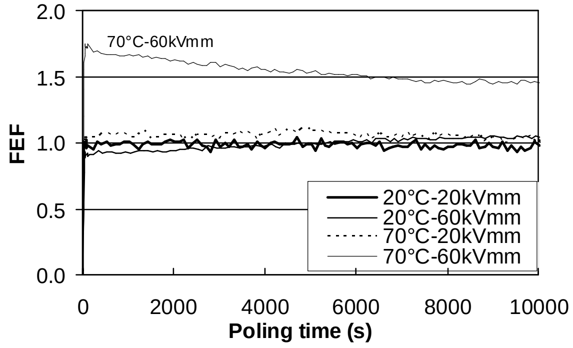

Figure 6: Time evolution of the field enhancement factor at outer semicon of model cable INS1/SC1

Comparison of different insulation systems

A useful test method must be able to differentiate between insulation systems and thus provide a ranking with respect to dc electrical performance.

A number of insulation systems with different insulating and semiconductive material were thus investigated. The space charge distributions are shown in figures 7 and 8.

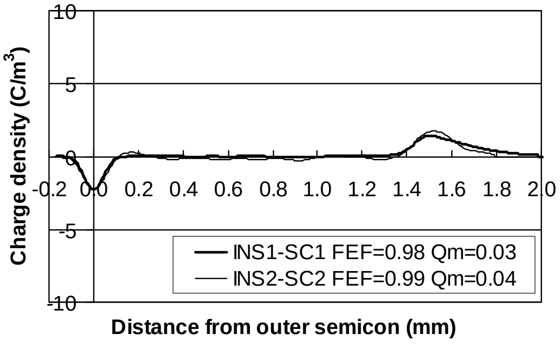

Figure 7: Voltage-on space charge profile of model cables comprising two different insulating systems at low temperature (20°C) and low stress (20 kV/mm).

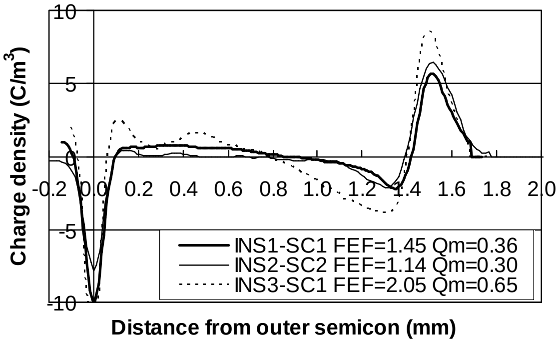

Figure 8: Voltage-on space charge profile of model cables comprising three insulating systems at high temperature (70°C) and high electric field (60 kV/mm).

It is obvious that the differences are small under low stress conditions; so a combination of high electric fields (60 kV/mm) and temperatures (70°C) is needed to achieve a straightforward differentiation between the systems and enable a performance ranking. System INS2/SC2 clearly exhibits less charge build-up than INS1/SC1 and especially INS3/SC1. These samples are, as previously described, fully degassed, but it is well known that by-products from the peroxide decomposition process are influencing the space charge accumulation. For comparison a model cable of INS3/SC1 was studied in non-degassed condition. The measurement, displayed in figure 9, reveals a more pronounced heterocharge accumulation in the outer part of the thermally untreated insulation; the FEF has thus increased from 2.05 to 3.15.

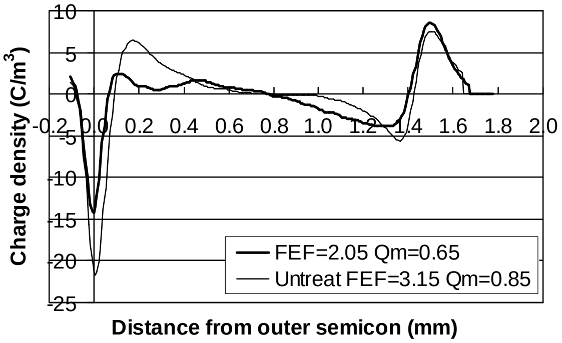

Figure 9: Voltage-on space charge profile of INS3/SC1, both not treated and thermally treated. Measurements at high temperature (70°C) and high electric field (60 kV/mm).

Comparisons with plaques and full-sized cables

The space charge distributions obtained from model cable measurement have been compared to those from 0.5 mm plaques (figures 10-11) and 4.5 mm cables (figures 12-13).

There are several similarities among the distributions from the three types of test specimen. One common feature is heterocharge accumulation in the outer part of the insulation, at least under high electric stress and temperature conditions. The ranking is basically the same with INS2/SC2 as the best material combination and INS3/SC1 as the system with the most pronounced charge build-up.

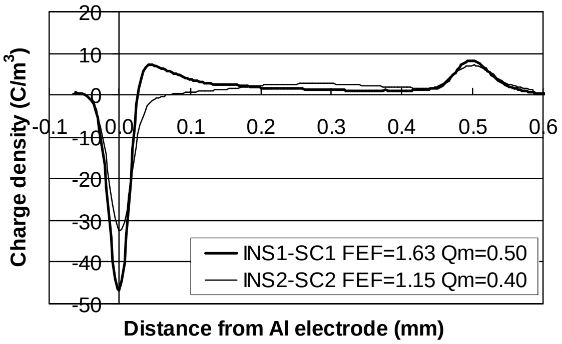

Figure 10: Voltage-on space charge profiles obtained on 0.5 mm plaques subjected to high temperature (70°C) and high electric field (40 kV/mm).

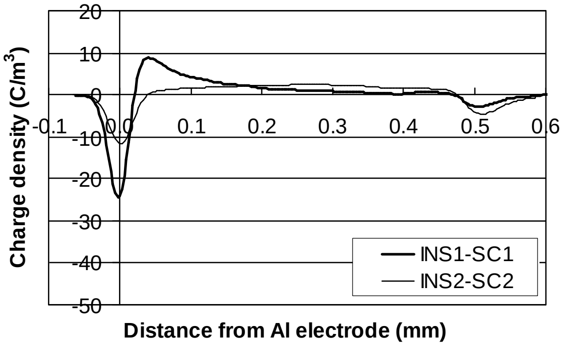

Figure 11: Voltage-off space charge profile of 0.5 mm plaques under the same conditions as in previous figure. The measurement is done 2 s after removal of high voltage.

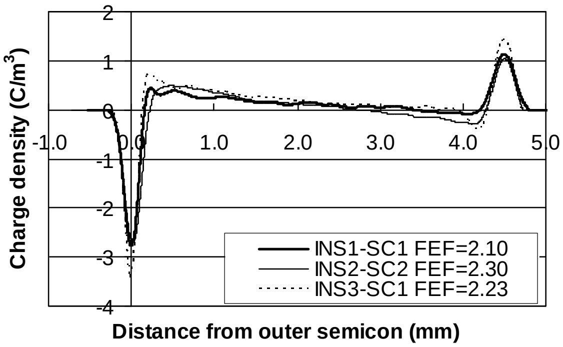

Figure 12: Voltage-on space charge profile of 4.5 mm cable samples at high conductor temperature (65°C) but low electric field (Emax 28 kV/mm). Poling time is 20000 s (5.6 hours). Surface temperature of the cable is 50°C.

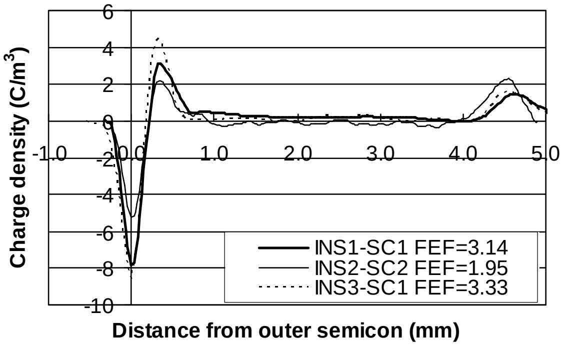

Figure 13: Voltage-on space charge profile of 4.5 mm cable samples at high conductor temperature (70°C) and high electric field (Emax 47 kV/mm). Poling time is 10 hours. Note that these cables have not been subjected to thermal pre-treatment.

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Dual-dielectric model cables

The dc electrical characteristics of dielectric-dielectric interfaces, relevant for cable accessories such as joints and terminations, have been studied using special type of model cables where the outer semiconductive has been replaced with an additional insulation layer. The space charge accumulation in such dual-dielectric EPR-XLPE model cables are reported by Bodega et al [6-8].

CONCLUSION

Three-layer model cable samples with an insulation thickness of 1.5 mm have been proven to be a versatile tool for cost- and time-efficient testing of the dc electrical properties of polymeric insulating and semiconductive materials. It has been shown that space charge measurements of these test specimens are capable of differentiation between insulation systems enabling a ranking of their dc properties. This method basically leads to similar results as the ranking process obtained from measurements on 0.5 mm plaques and 4.5 mm full-sized cables.

ACKNOWLEDGMENT

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