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Influence of AC ageing on space charge dynamics in LDPE

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Abstract

In the present work efforts have been made to investigate the influence of ac ageing on space charge dynamics in low-density polyethylene (LDPE). LDPE films with 200μm were aged at 50 kV/mm at 50 Hz for various times at ambient temperature. Space charge dynamics in the samples after ageing were monitored using the pulsed electroacoustic (PEA) technique. The results indicate that there is a significant amount of negative charge accumulation in the aged sample due to charge injection. These injected charges are captured by the deep traps originated from the interface between crystalline and amorphous regions in LDPE. The total amount of charge increases with the ageing time. Chemical analysis by infrared spectroscope (FTIR) and Raman microscope reveals little changes taken place in the bulk of the material after ac ageing. The consequence of the accumulation of space charge under ac conditions on the lifetime of the material has been discussed.

1. Introduction

Solid extruded polymeric materials such as crosslinked polyethylene (XLPE) and uncrosslinked polyolefins are used widely for underground high-voltage power transmission cables. The advantages of such materials are their excellent electrical properties combined with good physical properties. However, under certain high voltage operating conditions, trapped or low mobility electrically charged species within the bulk can give rise to space charge, resulting in localised electric stress enhancement which may lead to premature failure of the cable well below the anticipated and designed values.

In the past two decades, numerous studies have been carried out to develop further a better understanding of the build up of trapped space charge within solid dielectric materials [1-9] which has resulted in a better understanding of charge dynamics and their effect on material selection and processing. However, majority of the work has been carried out under dc conditions, little attention has been given to the effect of ac ageing on space charge formation in the bulk insulation. Work on the dynamics and the role of space charge on electrical breakdown under 50 Hz ac conditions has only received limited attention [6-12]. However, there is an increasing body of opinion that space charge build up can, under certain conditions, be a contributing factor to electrical tree initiation of high voltage insulation. As the majority of XLPE HV cables will be operating under ac conditions in the immediate future, it is appropriate to investigate charge trapping and mobility under such conditions. It is believed that under ac conditions the changes in polarity every half cycle limits the time charge can accumulate when ac frequency is greater than 0.1 Hz [10]. Recent work using other techniques [6-8, 11, 12] demonstrated that the presence of space charge in polymeric cable insulation materials under ac conditions. However, no quantitative charge distributions were presented.

This paper reports on space charge measurements on 200 μm thick LDPE using the pulsed electroacoustic (PEA) system. Samples were subjected to 50 Hz ac electric stresses in the region of 50 kV/mm at room temperature for a period of more than 20 hours. The accumulation of space charge at various times after ac ageing was monitored. The possible influence of the accumulated charge on the long term performance of the material has been discussed.

2. Experimental Details

Sample details

LDPE was chosen initially because of its relatively simple chemical structure and its wide applications in cable insulation. Space charge formation in a material is greatly affected by the presence of impurities and additives as they can act either as ionisable centres under a high electric stress or as trapping sites. In order to reduce the influence of the impurities, additive-free low-density polyethylene (LDPE) was selected for the present study. The thickness of the sample was typically ~200 μm thick. The diameter of the sample is 50 mm.

AC electrical ageing

AC ageing was carried out at ambient temperature for various times at an applied electric stress of 50 kV/mm. In order to prevent from flashover the top brass electrode was cast in epoxy resin and the bottom electrode was semicon. A typical sample and ac ageing testing circuit is shown in Fig. 1.

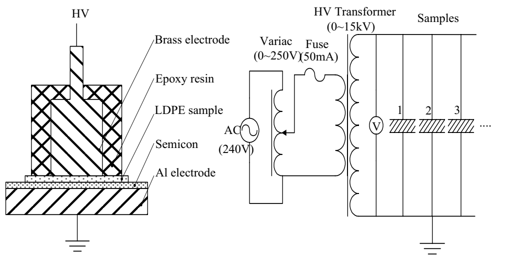

Fig.1 Schematic diagram of sample and testing circuit.

PEA technique

The space charge measurements were taken using the PEA system, which has a pulse width of 5ns. The sensor used was a 9 μm thick $LiNbO_3$ material that enables the system to be heated up to 90°C although this was not utilised in the present study. A constant pressure was maintained during the measurements. The principle of the PEA technique is shown in Fig. 2. Acoustic waves are produced at charge layers at both electrodes and internal charge when an electrical pulse is applied to a sample. The acoustic signals are detected by a piezo-electric sensor. The spatial resolution the system is determined by the pulse width and sensor thickness. In our system the resolution is less than 10 μm which is considered adequate in the present study. The details about the PEA technique can be found in [10].

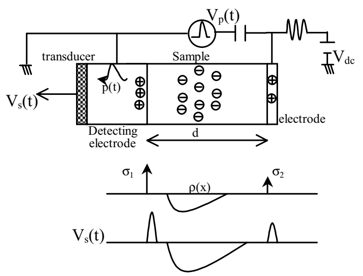

Fig.2 Schematic diagram of PEA system.

When an acoustic pulse travels through a material it will interact with the material. The absorption and dissipation of the acoustic energy into heat or other forms of energy are the major reasons causing attenuation. On the other hand the dispersion may be caused by the scattering of the acoustic waves (due to densely distributed inhomogeneities and frequency dependence of material constants such as elastic modulus). As a result the pulse will decrease in magnitude and broaden in width. This effect cannot be neglected if a thick sample is in question. A signal processing algorithm has been employed to recover the signal.

Chemical analysis

It is well known that long term ageing can cause chemical changes which subsequently deteriorate electrical performance of the material. High electric stress can accelerate the processes of deterioration. Infrared (IR) and Raman spectra are very sensitive to the chemical changes. They have been used extensively to examine chemical changes caused by electrical ageing. In the present study, theses techniques have been used to monitor any chemical changes taken place in the aged sample.

3. Experimental Results

Charge formation during ac ageing

Once the samples were removed from the ageing at various ageing times, space charge formed was examined prior to the application of dc stress. The charge distributions for various ageing times are shown in Fig. 3.

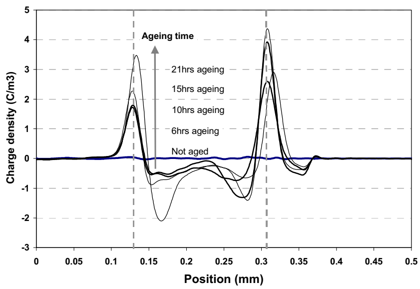

Fig.3 Charge distribution in LDPE aged for various times at 50 kV/mm.

It is noticed that negative charge was formed in all the samples aged. Although the negative charge tends to spread across the sample, more charge can be found in the region adjacent to the electrodes.

The total amount of charge accumulated in the samples can be calculated based on the charge density distribution given in Fig. 3.

$$Q = \int_0^d \rho(x) S dx \qquad (1)$$

where ρ is the charge density S the electrode area and d the thickness of the sample.

The relationship between the total amount of charge accumulated and the ageing time at 50 kV/mm is shown in Fig. 4.

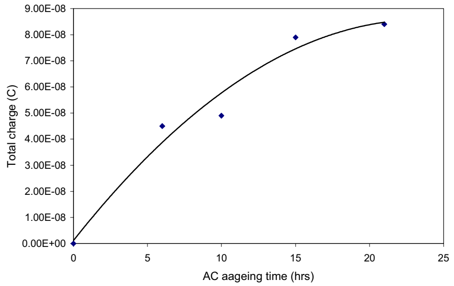

Fig. 4 Relationship between the total charge and ageing time at 50 kV/mm.

From this figure it is clear that the total amount of charge accumulated in the bulk of the material increases with the ageing time. It seems that the total amount of charge may reach to saturation at a longer ageing time. The long term influence of charge presence on the electrical performance is often related to how deep the charges are trapped. This can be estimated by measuring the change in charge profile after a period of time. Fig. 5 shows the charge distributions immediately after ageing and 24 hours later in the sample aged for 15 hours at 50 kV/mm. It can be seen that there is no significant change in distribution although the amount of charge is slightly less after 24 hours. This indicates the charge decay rate is very slow, suggesting deep trapped charge.

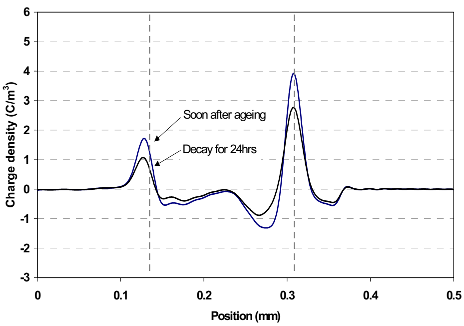

Fig. 5 Change in charge distribution after 24 hours in the aged sample.

Chemical analysis

Under the influence of electric stress, chemical changes may take place. Both infrared (IR) and Raman spectra have been used to measure chemical changes in LDPE. Figs. 6 and 7 depict the IR and Raman spectra of LDPE prior to and after ageing tests.

There is no significant changes occurred in the sample aged for 56 hours. The possible explanation is that the period of stressing time is too short. However, in Raman spectra before and after ageing, there is a slightly rise in background which is caused by fluorescence. Recent investigation into electrical tree in polyethylene [13] reveals that the fluorescence is due to partial degradation of the polymer. It must be stated that the rise in background is no way near to those observed in a treeing region.

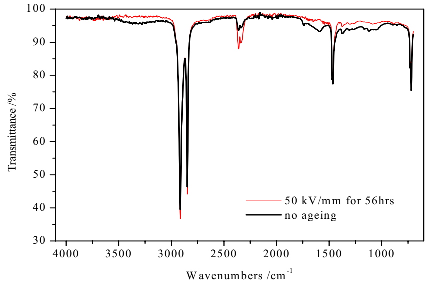

Fig. 6 IR spectra of LDPE prior to and after ageing (50 kV/mm for 56 hours).

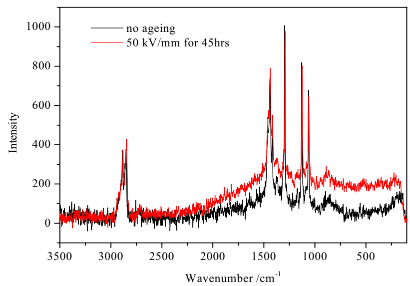

Fig. 7 Raman spectra of LDPE prior to and after ageing (50 kV/mm for 45 hours).

4. Discussion

According to the band theory based on the quantum mechanics, a large amount of traps exist in a semi-crystalline material. They mainly locate at the interfaces between crystalline regions and amorphous regions. Extra traps can be caused by the fold at the surface in the long molecular chains. The depth of these traps varies depending on the nature of the traps. It has been reported to be in the range of 0.3eV to 3eV. When a high voltage is applied to the material, the Fermi level in the material will be lowered down so the electrons and holes can be injected from the electrodes into the material. Consequently, the traps in the material will be filled up. Of course the amount of trapped charge in the bulk depends on the duration of the voltage application and the magnitude of the voltage. These trapped charge carriers will then cause the distortion of the original field distribution.

Charges formed in the material can be classified into fast and slow charge depending on their mobility. In most of cases it is the slow charge (or trapped charges) which may cause some adverse effect on the performance of the insulation, such as lifetime reduction of insulation due to local electric stress enhancement. The electric stress caused by space charge can be calculated using

$$E(x) = \int_0^x \frac{\rho(x)}{\varepsilon_0 \varepsilon_r} dx \qquad 0 \le x \le d \quad (2)$$

Based on the charge distribution shown in Fig. 3, the maximum stress for the sample aged for 21 hours occurs at the interfaces. The estimated field is ~20 kV/mm, comparable with the ageing stress (50 kV/mm). This has a significant implication for insulation systems. A high local electric field can lead to partial discharge activity, resulting in degradation of the material and possibly premature failure of the system.

An estimate can be made of the consequence of such stress enhancement (due to presence of space charge) on the material life using the inverse power law

$$E^n t = \text{constant} \qquad (3)$$

where E is the electric stress applied to the material, t the expected life time of the material and n is a constant. For example, in view of the above estimation the electric stress increasing by 40%, hence the lifetime is reduced to 6.8% of the original (1pu) with a conservative value n=8. This is a significant reduction in lifetime for the insulation. Further research is under way to examine the effect of lower ageing stress on the lifetime of the material.

5. Conclusions

In this paper the presence of space charge in LDPE after ac ageing at 50 Hz has been investigated. It has been experimentally demonstrated the presence of space charge under ac ageing conditions at an applied electric stress of 50 kV/mm. Following conclusions may be drawn from the study.

Negative space charge is present in the bulk of the material and the total amount of charge increases with the ageing time. Decay test indicates that the charges are captured in deep traps. These deep traps are attributed to defects at the interfaces between the amorphous and crystalline regions.

Chemical analysis shows no significant changes taken place in the bulk. This may suggest that the space charge measurement is a very sensitive technique which can reveal minor physical and chemical changes in the aged material.

The presence of space charge lead to an electric stress enhancement which may shorten the lifetime of the insulation system.

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