The Influence of Residue on Space Charge Accumulation in Purposely Modified Thick Plaque XLPE Sample for DC Application

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Abstract: Effects residues (cross-linking by-products and additives) in polyethylene on space charge accumulation and decay have been investigated using the pulsed electro-acoustic technique. Space charge profiles have shown a great variation both in the charge initiation during the voltage ramping-up process and during long term stressing and decay (volts off). Samples were subjected to different conditioning processes, resulting in different proportions of residues (fresh, 0.5% residue and thoroughly degassed). The results show that residual impurities, including the by-products of cross-linking, play a key role in the space charge accumulation in cross-linked polyethylene. On the removal of impurities by degassing, a small homocharge build up was found in the vicinity of the electrode. It is concluded that space charge accumulation is governed by the charge injection through dielectric/electrode interface when the sample is thoroughly degassed.
Key Words: Space charge; Cross-linking by-products; XLPE and PEA.

INTRODUCTION

HVDC cable systems require materials that inhibit space charge accumulation. This paper presents space charge characteristics on plaques made from these materials using the pulsed electroacoustic (PEA) method [1]. The plaques needed to be thicker (~2 mm) than normal film sample so high voltages application was required in order to obtain adequate electric fields for space charge measurement. The acoustic attenuation and dispersion had to be considered carefully in analyzing the space charge distribution [2, 3]. Some points on electrode design and data processing in respect of thick samples have been addressed in this paper. Samples subjected to different degassing treatments, i.e. under conditions of fresh (not degassed), partially degassed (0.5% residue) and thoroughly degassed were studied in terms of space charge accumulation and decay. For the reference, charging and discharging behavior was also investigated in thermally pressed low density polyethylene (LDPE), which was regarded as residue free specimen.

EXPERIMENTAL

PEA system for thick plaque samples

For the relatively high voltages required, a voltage bushing is used on the high voltage electrode and an adequate flashover distance is required along its sample surface between the high voltage and ground electrodes (Fig 1). This big size requirement both for the sample and top electrode make it difficult to maintain an even contact between the sample and the electrode insulator surfaces; some air gaps inevitably formed between them. Smearing silicone grease around the embedded semiconducting electrode of the sample successfully blocked the discharge path at the voltages up to 100kV.

Fig. 1 Photograph of PEA electrodes system for thick plaque samples

The acoustically lossy and dispersive properties of the polymeric material cause significant deteriorations in the sensitivity and spatial resolution as the distance from the transducer increases. A data compensation algorithm was developed to correct for this [2, 3].

Samples

Fig. 2 shows the press-molded sample's dimensions and its cross-section. The semiconducting electrodes were embedded by cross-linking to the planar sample on both sides. The residue concentration in the sample was controlled by a degassing treatment: "fully degassed" (90^{o}C in an oven for three days) "partially degassed" samples retained 0.5% of impurities and "fresh" (no thermal treatment). An additive free low-density polyethylene (LDPE) sample was also studied for comparison.

Measurement procedure

An initial voltage ramp-up test was done in which the magnitudes of the induced electrode charges were recorded as a function of applied field. A threshold electric field was found above which space charge started to accumulate. This experiment was then followed by space charge distribution measurement at

40kV/mm for a period sufficient of equilibration of the space charge. Finally a decay test was used to study the depolarization characteristics of the material with the removal of external stressing voltage.

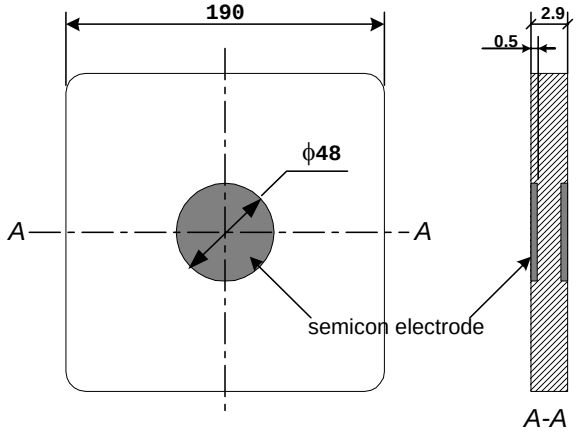


Fig. 2 Sample dimension and cross-section

RESULTS

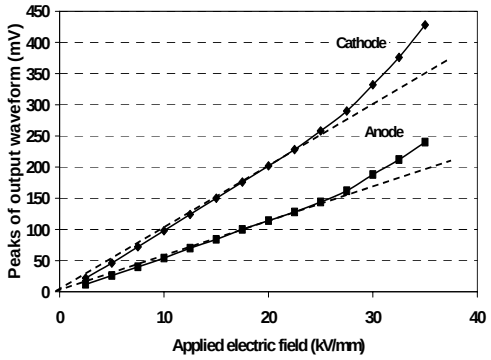
Threshold field for space charge generation

As seen in Fig. 3, there is a linear correlation between the induced surface charges on the electrodes at lower external stressing fields for all three samples; this is expected for a classical capacitor:

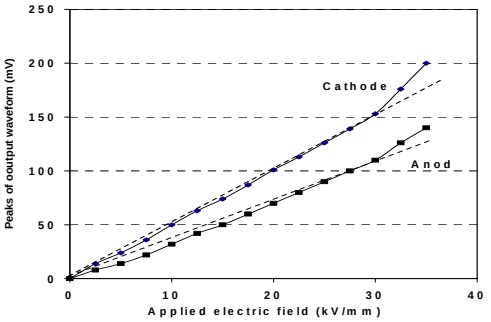
$$\sigma = \varepsilon_0 \varepsilon_r E$$

where σ is charge density on electrode, $\varepsilon_0\varepsilon_r$ is the dielectric permittivity and E the electric field strength. A linear relationship suggests that no space charge was formed within the bulk of material at lower fields. For fully-degassed samples no space charge was found up to 35kV/mm, Fig 3(c). For the other samples "threshold field" were found (25kV/mm for fresh samples, 30kV/mm for partially degassed samples) from where the curves start to deviate from linearity by bending upwards, like the results Fig. 3 (a) and (b). This extra induced charge is attributed to heterocharge accumulation close to two electrodes, which would be observed in following charge distribution measurement.

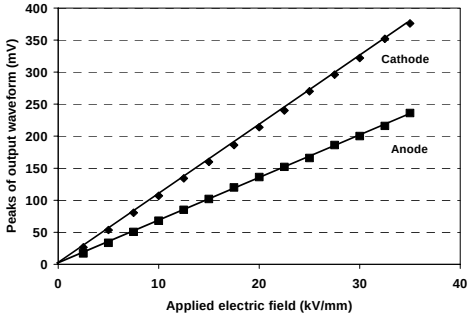
In order to get rid of the influence of stressing time on charge formation, the measurement at each field was carried out quickly within a time less than 10 seconds. For this reason the peak heights of the induced surface charges at the upper and the ground electrodes need to be read directly from the oscilloscope in units of voltage. Due to the attenuation of the acoustic signal across the sample, the reading of the upper electrode (away from the transducer) is lower than an equivalent reading from the ground electrode.



(a) Fresh (not degassed) sample



(b) Partially degassed sample (0.5% residue)

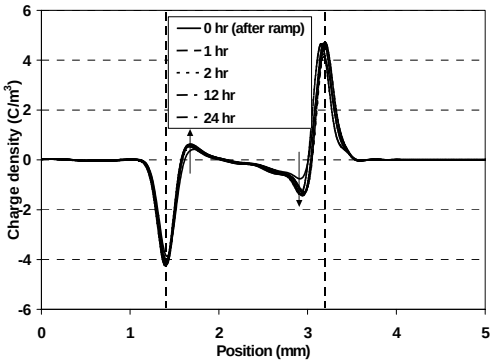


(c) Fully degassed sample

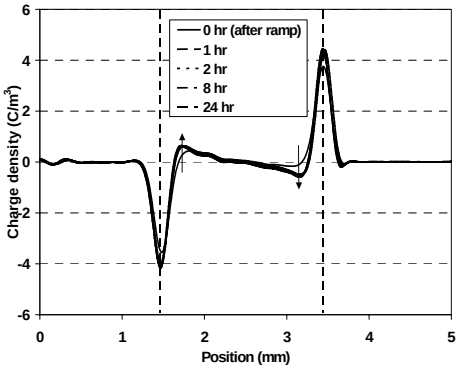
Fig 3. Relationship between the induced charges on electrode and applied field

Space charge development

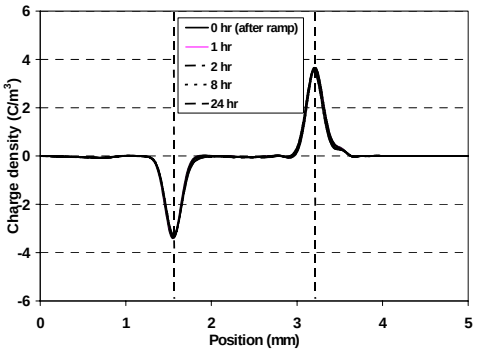
Subsequent space charge profiles, measured at 40kV/mm, are shown in Fig. 4. Space charge in the fresh and partially degassed samples appears to accumulate very quickly. It is evident that a considerable amount of heterocharge accumulated during the voltage ramp up test, as shown by profiles of 0 hr in Fig. 4 (a) and (b). The charge distribution quickly reaches equilibrium within the first hour, which can be evidenced by the little change over the following 23 hours. The fresh sample shows a slightly higher charge density than the sample with 0.5% residue. For the fully degassed sample, it is hard to discern any charge formation over the stressing term from results in Fig. 4 (c).



(a) Fresh sample



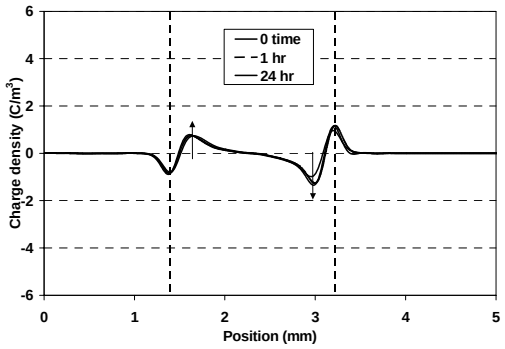
(b) Partially degassed sample



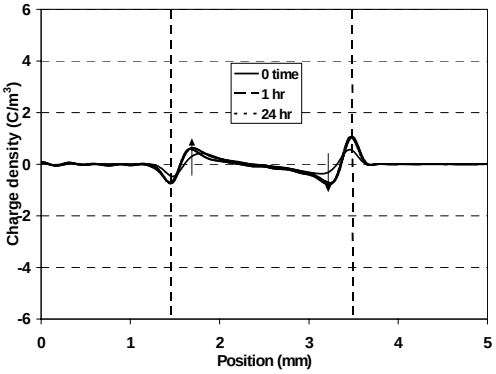
(c) Fully degassed sample

Fig. 4 Space charge development in XLPE with voltage application

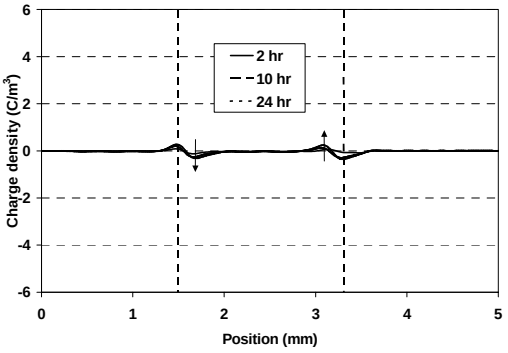
To check whether homocharge has been obscured by electrode/dielectric interface injection, measurements were also conducted under open-circuit conditions (voltage off) at different times over the whole stressing period. A part from the heterocharges shown in Fig 5 (a) and (b) within fresh and partially degassed samples, small homocharges are clearly revealed in Fig. 5 (c) in the degassed sample, both at anode and cathode. These charges show a slow and but constant build up rate over the whole stressing time.



(a) Fresh sample



(b) Partially degassed sample

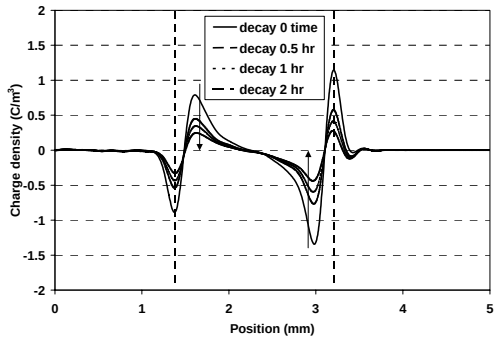


(c) Fully degassed sample

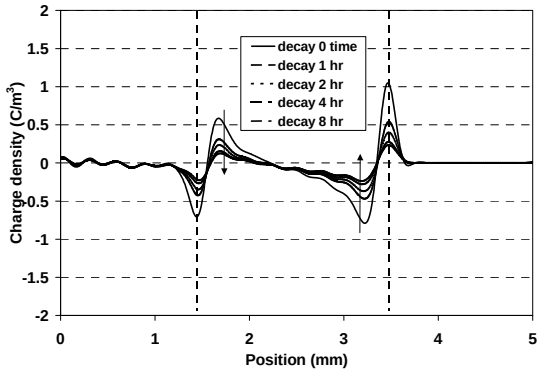
Fig. 5 Space charge development in XLPE, under open circuit

Space charge decay

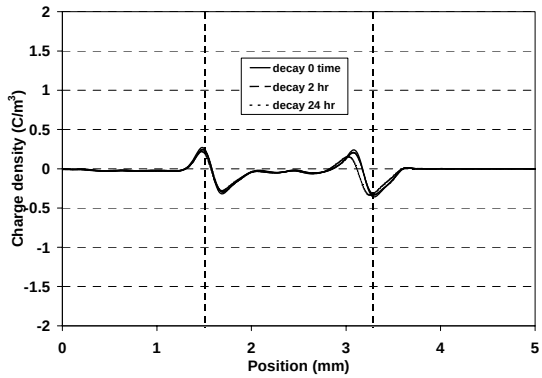
The space charge decay observations are shown in Fig. 6. Both the fresh and the partially degassed sample exhibit a fairly high decay speed, as seen in the profiles in figures (a) and (b), whereas the homocharge generated in the degassed sample possesses a high stability after the external stressing voltage was removed. No significant difference could be observed among charge distributions obtained in 24 hour-long decay tests in Fig. 6 (c).



(a) Fresh sample



(b) Partially degassed sample

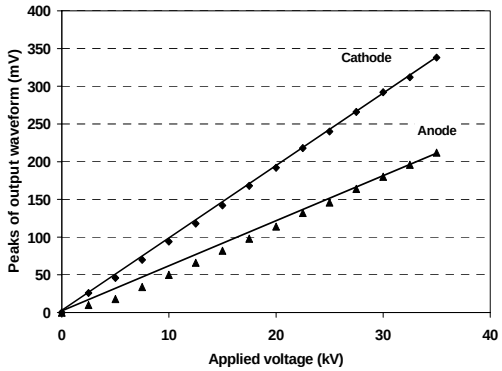


(c) Fully degassed sample

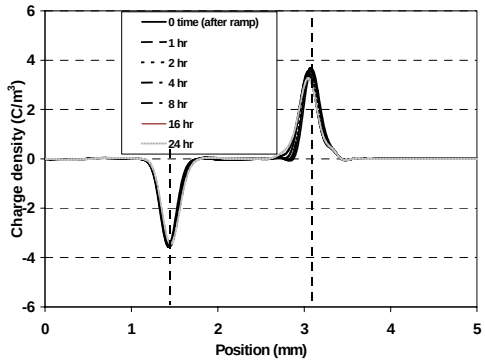
Fig. 6 Space charge decay profiles, under electrode short-circuited

Results of LDPE sample

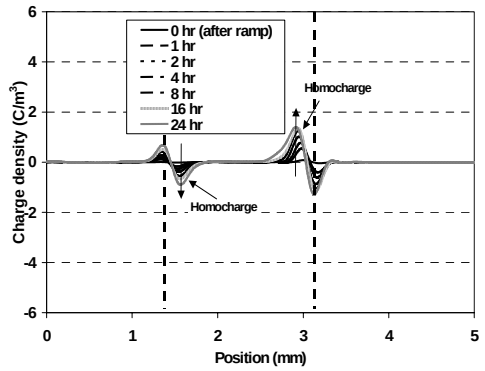
The ramp test on the LDPE sample, Fig. 7 (a), revealed a linear relationship between the induced electrode charge and external voltage, suggesting no space charge was formed. During the following ageing period, homocharges gradually accumulated close to the electrodes, Fig. 7 (b) and (c), the latter clearly showing the presence of homocharge under open circuit conditions. Like all the homocharges observed in the degassed XLPE sample, the homocharge in this LDPE sample also showed a very slow decay speed, Fig. 7 (d).



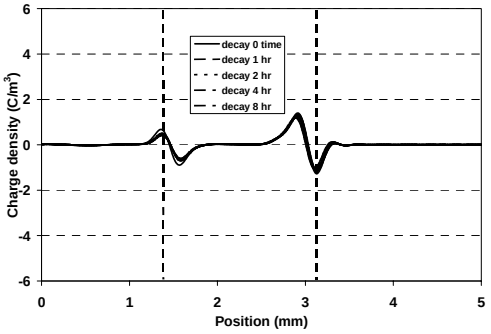
(a) Voltage ramping test



(b) Space charge development with voltage application



(c) Space charge development under open circuit



(d) Space charge decay under electrode short-circuited

Fig. 7 Space charge behavior within LDPE sample

DISCUSSION

Threshold field for charge formation and charge polarity after long term stressing

The non-linear relationships between the induced surface charge and the value of applied field in Fig. 3 (a) and (b) indicate that the undegassed and partially degassed XLPE samples appear to have heterocharge accumulation during the voltage ramp process. Impurities within XLPE appear to be the main source of the heterocharge generation due to the field assisted ionization [4]. As residues were removed by degassing, the threshold voltage for space charge formation increases with the fully-degassed XLPE and the LDPE samples showing no space charge effects, see Table 1. As the PEA system has measuring sensitivity limitation, the fresh sample with higher impurities concentration is therefore likely to show a notable amount of charge at lower field (threshold) in comparison with partially degassed sample. In the degassed XLPE and pure LDPE, no evidence of charge formation within the sample could be found in ramp test at the field value below 35kV/mm. Moreover, no heterocharge and only small homocharge were observed in the following long term stressing process. It is generally believed that this charging progression is dominated by interface injection, which is mainly controlled by electric field at a given electrode and dielectric materials. With the homocharge accumulation, the interfacial stress declines gradually thus the space charge generation in this case is long but constant process. The results may also suggest that homocharge formation in these samples is more difficult than heterocharge in sample containing residues, the former requires higher stress and longer times [5, 6].

All measurements reveal that samples with and without residues may not only have different charging abilities (threshold field), but also possess utterly different charging mechanisms, which lead to the formation of space charge being of opposite polarities in the volume of the polymer adjacent to the electrode.

Table 1. Threshold stress (kV/mm) of space charge formation and charge polarity

	Un-degassed	0.5% residue	Degassed
XLPE	25 (hetero)	30 (hetero)	>35 (homo)
LDPE	>35 (hetero)		

Space charge building up and decay speed

The time for the space charge to reach its saturation is a metric for the speed of charge formation. Fig. 4, 5 and 7 (c) reveal that for the samples having residual impurities (normally developing heterocharges) show a faster charge accumulation compared with the degassed XLPE or LDPE sample (where homocharges appears). In fresh sample and sample with 0.5% residues, the space charge reached its saturation distribution within 1 hour, whereas homocharge in degassed XLPE and LDPE held a continuous accumulating process.

By inspecting the space charge measurements of all other modified XLPE samples (some of these are not shown here for reasons of commercial confidentiality), it is normally found that the space charge decay speed closely corresponds to its building up speed. Typical results that lead to this conclusion are presented in Fig. 8 in which two XLPEs are regarded as typical fast charging and slow charging examples respectively. Similar conclusions can be drawn from heterocharge in sample with residual impurities and homocharge in residue free XLPE or LDPE sample, Fig. 9.

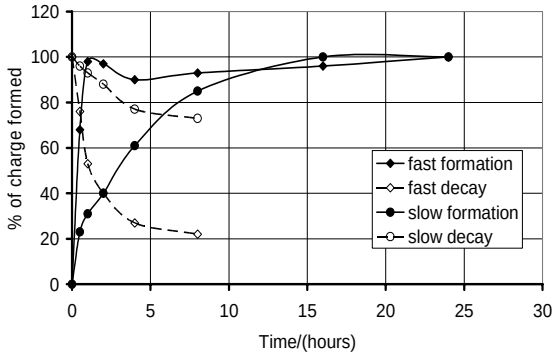


Fig. 8 Space charge accumulation rate in accordance with decay rate

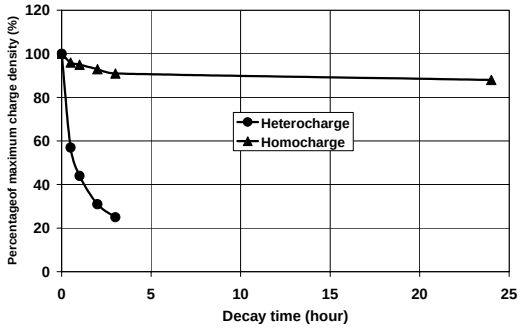


Fig. 9 Comparison of homo and hetero charge decay speed in XLPE

CONCLUSIONS

The PEA system introduced here is ideal for measuring space charge in thick plaque samples.

Residual impurities, e.g. the by-products of cross-linking and additives in material manufacturing play a key role in heterocharge accumulation in XLPE. In fully degassed samples, small homocharges are formed. Fast heterocharge formation has been observed in all the samples with residues. However, the homocharge,

which appeared in all degassed samples and LDPE, showed a slower formation speed.

The space charge accumulation speed corresponds well with the decay speed. In other words, the faster the space charge accumulates, the quicker it decays. It is also found that homocharge in degassed material decays much more slowly than the heterocharge in the same undegassed material.

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