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Polymer Testing 22 (2003) 313–318

POLYMER TESTING

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Investigation into the failure of XLPE cables due to electrical treeing: a physico chemical approach

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Received 17 June 2002; accepted 13 August 2002

Abstract

In the present work, electrical trees in XLPE cables were experimentally generated under AC voltages. The formation of a tree-like structure and a bush type of tree structure was observed in the samples. The causes for variation in the shape of the tree structure are detailed. The importance of Weibull parameters for the present study is emphasized. Furthermore, physicochemical analysis by wide angle X-ray diffraction studies (WAXD), differential scanning calorimeter analysis (DSC), and emission spectroscopy were used to understand the characteristic variation in the material and to diagnose the state of the insulation structure.

Keywords: Treeing; XLPE; Weibull; WAXD; DSC; Emission; Fluorescence; Phosphorescence

1. Introduction

The life expectancy of high voltage power cables is adversely affected by 'electrical treeing', a pre-breakdown phenomenon, which accounts for premature failure of cables in service. Under normal operating voltage stress, a series of partial pre-breakdown channels emanates from a region of existing defect sites, in the form of gas cavities or conducting inclusions or intrusions, in the insulation structure. These pre-breakdown channels formed around the defect site in the dielectric structure resemble branches of a tree and, hence, the name 'treeing' is given to the deleterious process. Since such an occurrence is purely due to electrical stress, the mechanism is termed electrical treeing [1].

With the advancement of power transmission capacity, it has become necessary to design and develop a compact, cost effective and reliable insulation structure for underground cables. A survey of earlier work in the area of failure of underground cables in service indicates that a large body of literature is available on water treeing, however information on the inception, propagation and termination of electrical trees under different voltages appears to be scanty [2,3,4]. Failure of insulation due to treeing at operating voltage level is a matter of great concern and the power supply utilities the world over are trying to investigate the situation. Hence, a credible database has to be generated in order to understand the mechanism of failure of insulation structure due to electrical trees, which adversely affect the life of the insulation structure.

With all this known, in the present work experimental studies were carried out to understand the process of failure of the insulation structure due to electrical treeing, especially under AC voltages. The propagation characteristics of electrical trees under AC voltages have been studied by adopting Weibull distribution parameters. In addition, the physico-chemical changes in the tree following the breakdown zone are analysed using wide angle X-ray diffraction (WAXD), differential scanning calorimetry (DSC), and by emission spectroscopy, to diagnose the characteristic changes in the virgin material.

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0142-9418/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0142-9418(02)00106-X

2. Experimental

The experimental setup for generating trees under AC voltage has been designed in such a way as to obtain the required database in a short time. For this purpose, the point from which a tree can originate has been predetermined by implementing defects of known geometry into the body. The specimens used for generation of electrical trees in the laboratory were obtained from a 33 kV XLPE cable. The outer semi-conducting layer of the cables was pealed off after applying a heat pad over the surface. The samples of 2 cm length were cut from long lengths of cable. The specimens were stabilised by heating them at about 90 °C for 90 h. A conducting defect was simulated by inserting a sharp metallic needle into the dielectric body. The trees were expected to initiate from this point. The needle used had a nominal tip radius of curvature of 5 μm. The selected pins were inserted into the insulation at 130 °C and annealed for half an hour to relieve the residual strain at the tip of the needle. The effective thickness between the central conductor and the tip of the electrode was maintained between 3 and 5 mm. The space between the pin and the dielectric was effectively sealed with cold setting araldite and the specimens were immersed in filtered, degassed mineral transformer oil ready for voltage application. The needle was connected to the high voltage source and the conductor of the cable was grounded.

3. High voltage source

The high AC voltage of power frequency was produced from a transformer rated at 20 KVA, 50 Hz, 20 KV unit. The AC voltage was measured using a capacitance divider.

4. Physico-chemical analysis

4.1. Wide angle X-ray diffraction (WAXD)

This study helps in identifying any variation in percentage crystallinity of the material or addition of new phases in the tree following the breakdown zone. Loss of crystallinity peaks is an indication of variation in the material. In the present work, WAXD measurements were done with a Philips X-ray diffractometer. A scan rate of 2°/min at 2000 cycles using Cu Kα radiation of wavelength 1.596 Å was applied. A radial scan of Bragg angle (2θ) vs. intensity was obtained with an accuracy of ±0.25° at the location of the peak.

4.2. Differential scanning calorimetry (DSC)

This technique involves the measurement of energy necessary to establish zero temperature difference between specimen and a reference material when the two specimens are subjected to heating to identify thermal degradation. The melting behavior of the specimens was observed using a Perkin Elmer model DSC-2C apparatus. The experiments were performed under a nitrogen atmosphere, at a heating rate of 10 °C/min. Alumina was used as a standard.

4.3. Emission measurements

Emission measurements were performed on a Hitachi F-4500 spectro fluorimeter. The excitation wavelength was 344 nm and the emission spectrum was recorded in the range of 354–600 nm with the excitation and emission slit width of 5 nm, maintained at a PMT voltage of 700 V and the scan speed at 2400 nm/s.

5. Results and discussion

Fig. 1 shows the optical photographs of different types of electrical trees formed in the XLPE cable specimen under AC voltages. It is observed that a bush type of tree (Fig. 1a) and a tree-like tree (Fig. 1b) structure are formed at the tip of the needle electrode which is connected to high voltage. Fig. 1c shows a typical breakdown path formed in the insulation structure due to propagation of an electrical tree and terminating at the ground electrode. When high voltage is connected to the needle electrode, the local electrical field near the needle tip is enhanced and if the order of magnitude exceeds the maximum electric field of the material, causes incipient damage to the insulation structure. Further, the injection of charges from the high voltage electrode to the insulation structure were trapped near the defect site formed, and the charges get deposited on the surface of the damaged zone causing local reaction with the applied field, reducing the electric field in the zone. Also, the decomposition products of the insulating materials subject to discharges are mainly gaseous but unsaturated hydrocarbons and conducting carbons are produced [5]. In general, depending on the electro negativity and the chemical reactivity of the gas contained in the microvoids, it can retard or accelerate the tree growth. Sometimes, the charges are also injected into the insulation structure through the defect formed zone-enhancing field at one point, causing further enlargement of the channel resulting in a '*tree-like tree*' structure. Otherwise, local discharges will occur causing increased diameter of the damage zone forming a '*bush type*' of electrical tree. Some authors suggest that channel propagation will continue provided there is a critical energy stored at the tip

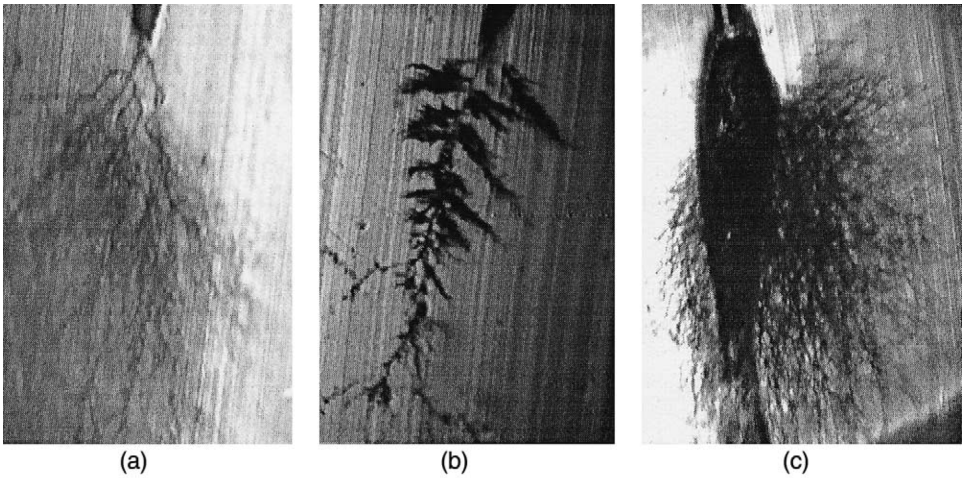

Fig. 1. Electrical trees under AC voltage: (a) bush type tree; (b) tree-like tree; (c) tree followed with breakdown.

of the channel, allowing degradation of the material by discharges. If there is not sufficient energy, the channel will stop growing and discharge will recur in the main branches forming a bush type tree structure [6].

In the experimental run, 20 identical samples were used for the study and the needle electrodes were connected to the high AC voltage. The study was carried out at different voltage levels. On application of the voltage, the points in time of breakdown of specimens were noted. In the present study, censored data analysis was used. Only 10 failure times were noted and the remaining samples were cut and examined visually for any tree structure formation. It was noticed that the samples that did not fail were found with tree structures (especially in the samples stressed at lower voltage magnitudes), whereas in the specimens stressed at high voltage magnitude, no clear-cut tree structures were noticed. The reason for this is that the injected charges cause reaction at some point surrounding the pin electrode, initiating the tree to form quickly and reach the ground electrode, causing breakdown, whereas at the low voltage magnitude, the injected electrons will not attain sufficient energy to cause cleavage of material and only local damage will occur, increasing the diameter of the defect. This allows us to conclude that the bush type of tree structure is less dangerous compared to tree-like tree structures, where the rate of tree propagation is aided by the applied voltage.

Even though the samples are identical, the scatter in the failure times of the specimens is large. It is essential to utilise statistical tools to understand the severity due to electrical stress. The cumulative Weibull distribution function is given by

$$F(t) = 1-\exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right] \tag{1}$$

where α is the scale parameter, β is the shape parameter, γ is the location parameter and t is the random variable, usually time to breakdown. $F(t)$ indicates the proportion of specimens tested which will fail by time t. The scale parameter represents the time required for 63.2% of tested units to fail. The shape parameter is a measure of dispersion of failure times for $t = \alpha$. The parameter γ indicates the time from voltage application in which failure of any unit is not possible. Therefore, Eq. (1) is written for $t > \gamma$ and $F(t) = 0$ for $0 < t \leq \gamma$ [7].

The values of α and γ are represented in time whereas β is a dimensionless number. The location parameter is normally taken as zero, which we call a two-parameter Weibull distribution. The life of an insulation material could be assessed by a life estimation test in which the solid dielectric is subjected to a constant high voltage stress until failure. Repeating the test several times on identical specimens usually yields greatly varying values of time. These values can be represented statistically by the Weibull distribution [7]. The experimental data are used to estimate the parameters of the distribution. Fig. 2 shows the Weibull plot for the failure times of the insulation structure due to electrical trees, operated at different voltage levels. Table 1 shows the variation in the characteristic life of the insulation material and the shape parameter for the failure data caused due to electrical treeing, at different voltage levels. It is observed very clearly that increase in magnitude of applied voltage shows a reduction in the characteristics life of the insulation structure. In addition, it is noticed that the slope parameter (β) obtained under different electrical stress is varying. It is clear that if the β value is more than one, which is an indication that the failure of the insulation material is due to local erosion causing failure of insulation structure. When the electrical stress is high, the

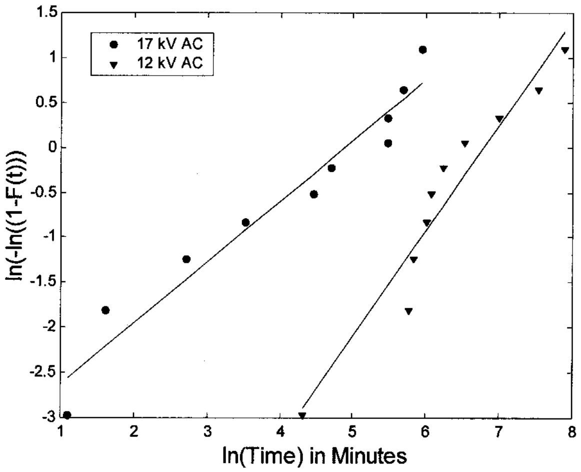

Fig. 2. Weibull plot of times to failure of XLPE specimen due to electrical tree under AC voltages.

Table 1
Variation in characteristic life and shape parameter at different voltage levels

Voltage magnitude	Characteristic life time (min)	Shape parameter (β)
12 kV AC	890	1.167
17 kV AC	131	0.677

value of β is less than one, indicating that the failure causes intrinsic failure (puncture) of the insulation structure. At lower voltage magnitudes, it is noticed that, initially, with a certain number of samples, the slope parameter is greater than one and as and when the number of failed samples increases, the value of β is reduced, as shown in Fig. 3. Similar characteristics were observed by Bozzo et al., showing a reduction in the β values with respect to time [8]. This clearly indicates that, in the specimen which is stressed for a long time, especially in electrical tree formation studies, the failure of the specimen is not only by the electrical stress but also by any local condition formed, which alters the failure rate. This means that the local conditions aid the process of failure and cause failure of the materials at an early stage.

Carrying out experimental studies and understanding the failure times alone is not sufficient. It is essential to understand the physico-chemical changes that would occur in treeing following the breakdown zone. The local electric discharges cause considerable changes in the structure of the surrounding material. Among other things, carbonisation, chain scission and conversion of amorphous to crystalline phase are known to occur. The X-ray diffraction pattern of virgin XLPE material and the treeing following the breakdown zone are very similar and for the sake of brevity only the virgin XLPE sample WAXD is shown in Fig. 4. The WAXD plot of the XLPE specimen showed two peaks at 21.5 and at 23.9° which are characteristics of 110 and 220 lattice planes [9]. The percentage crystallinity of the material was calculated using the Hinrichsens method [10] and for XLPE material it is calculated as 56. The WAXD spectrum does not appear to show any change in the position of the peaks or their splitting throughout the scan range. This means that hardly any change has occurred in the crystallinity of the material or any new phase in the material.

Examination of a tree following the breakdown region has been made with a DSC. The DSC thermograms of the virgin material and the material in the tree following the breakdown path are shown in Fig. 5. A reduction in the melting point of the material is observed in the treed

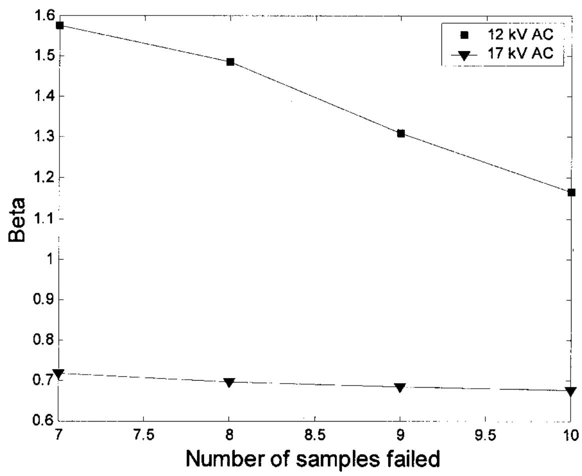

Fig. 3. Variation in the shape parameter (β) with number of samples failed in an experimental run.

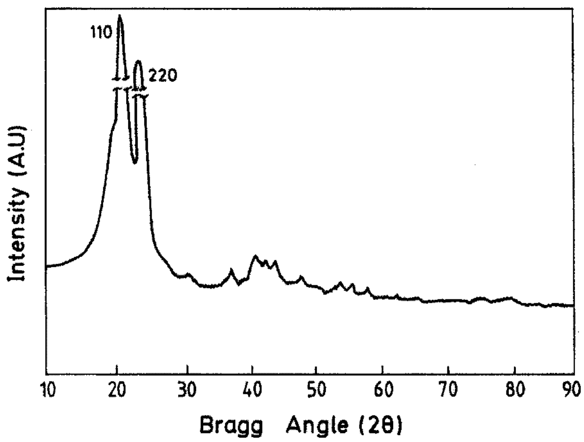

Fig. 4. Wide angle X-ray diffraction pattern of XLPE specimen.

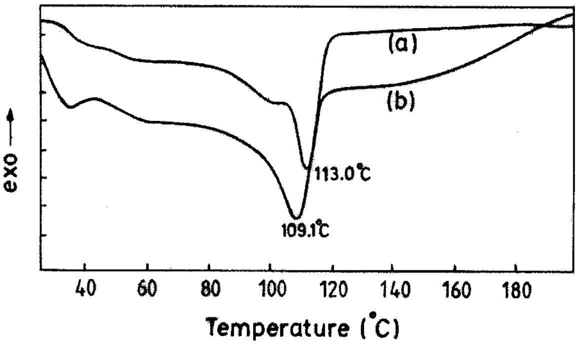

Fig. 5. DSC thermogram: (a) virgin sample; (b) tree followed with breakdown zone sample.

zone. No new phase has been observed in the treed zone, which was confirmed by similar thermograms for the virgin and the degraded samples. It is well known that the tree formation is due to degradation of materials forming free radicals in the zone.

The reaction kinetics responsible for the formation of free radicals is as follows and the process confirms that the treeing process is a degradation process.

$$RH \xrightarrow{\text{Homolytic cleavage}} R* + H*(\text{free radical}) \quad (2)$$

$$R*O_2 \xrightarrow{\text{Oxidation}} ROO*(\text{alkylperoxyradical}) \quad (3)$$

$$ROO* + RH \rightarrow ROOH + R*(\text{free radical}) \quad (4)$$

Fig. 6 shows the fluorescence spectra of the virgin XLPE and the treeing following the breakdown path. Normalization of the emission spectra was made, since for powder samples the intensities of emission spectra of different samples are unrelated to each other and cannot be compared. It is only the relative intensities of different bands within the same spectrum that is of experimental significance. The emission spectrum of the virgin sample shows an intense structured emission at around 375–400 nm when excited at 344 nm. The emission spectrum of the tree sample, in addition to the band at 375–400 nm, shows a new red shifted emission band appearing as a prominent shoulder at around 470–500 nm, at the same excitation wave length. For the specific material chosen, this characteristic feature was observed for every degraded sample. Thus, we believe that the appearance of this band can be used as an indicator of degradation of the polymer. In order to understand whether the emissive chromophores are a covalently bonded part of the polymer or are free molecules incorporated in the polymer matrix during their manufacture from hydrocarbon sources, a solvent extraction study was done.

Equal amounts (200 mg) of the virgin material and the sample from the tree area were extracted with 10 ml of diethyl ether. The emission spectra for the extracted samples are given in Fig. 7a and b. It is seen that the emission from both the ether-extracted solutions are very similarly structured. Observation of this intense emission

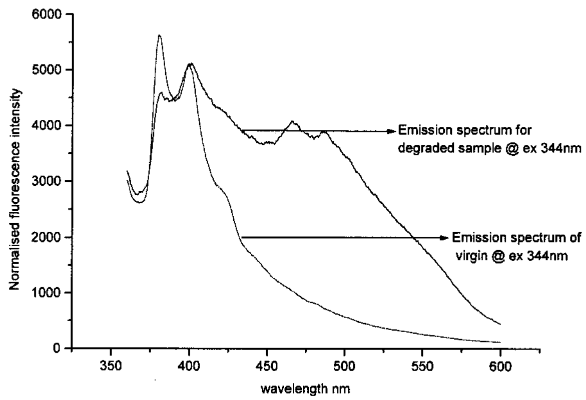

Fig. 6. Normalised emission spectrum of the degraded polymer.

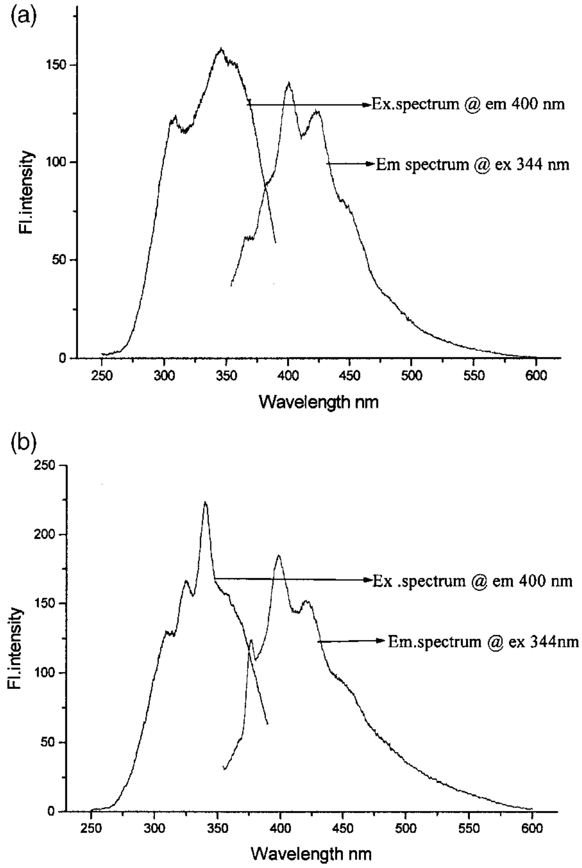

Fig. 7. Excitation emission spectrum of specimen after extraction with ether: (a) virgin sample; (b) tree followed with breakdown zone.

in a solution medium confirms that this emission is due to fluorescence, as phosphorescence is rarely observed in fluid media at room temperature. The fluorescence peaks are highly structured in both spectra with well-marked vibrational structuring at ~1350 cm^{-1}. The structuring corresponds to aromatic ring C–C stretching frequency [11]; it is possible that the fluorophores could be some polycyclic aromatics which may be present during polymer processing. The close similarity of the fluorescence in extracted solutions of both virgin and degraded samples and the absence of the band at 470–500 nm suggest that the fluorophores responsible for the emission are unaffected by the degradation process.

Since our studies in solution have already indicated that the band at 375–400 nm is due to fluorescence, the origin of only the 470–500 nm band was yet to be found. If this band were due to phosphorescence, a phosphorescence spectrum taken at 77 K would have been conclusive. However, access to this temperature was not possible in the existing fluorimeter setup. An attempt was made to record room temperature phosphorescence spectra of both the virgin and degraded sample powders. No observable emission was detected and it cannot be conclusively inferred whether the band at 470–500 nm is due to fluorescence or phosphorescence. In a study of ageing of HDPE and LLDPE grade polyethylenes, a system similar to the one under study, Allen et al., [12], have shown that the characteristic emission in the degraded polyolefin is due to the presence of low levels of cyclic α,β-unsaturated carbonyl compounds of the enone and the enal type. Molecules with carbonyl groups are known to easily undergo an inter-system crossing process, thereby facilitating phosphorescence from the triplet state. One reason why we did not observe this emission under room temperature phosphorescence measurement conditions may be due to shortening of phosphorescence lifetime at room temperature.

6. Conclusions

Electrical treeing causes early failure of electrical insulation structures under normal operating conditions. A tree-like tree structure or a bush type tree structure can form from the defect site. It is noticed in the experimental study that an increase in the applied voltage magnitude shows reduction in characteristic life of the insulation material. In a Weibull distribution parameter study, estimation of beta factor indicates that at higher voltage magnitude the values of beta are less than one, indicating that failure of insulation is of intrinsic type. The physicochemical analysis, especially the WAXD and DSC results, indicate no additional phases are formed in the tree following the breakdown path. A slight reduction in the melting point of the insulation structure is observed in the treed zone. The reaction kinetics show the formation of free radicals in XLPE specimens from the treed zone, suggesting that treeing is a degradation process. Emission spectral studies show the appearance of a new emission band at 470–500 nm range in samples from the treed zone of the degraded XLPE. The emission is fairly strong and can be used for monitoring polymer degradation.

Acknowledgements

R.S. wishes to thank Dr S.R. Chakravarthy for helping him to take the optical pictures of the electrical tree structure.

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