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Partial Discharge Characteristics in LLDPE-Natural Rubber Blends: Correlating Electrical Quantities with Surface Degradation

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Abstract – Partial discharges (PD) lead to the degradation of high voltage cables and accessories. PD activities occur due to the existence of impurities, voids, contaminants, defects and protrusions during the manufacture and installation of power cables. Commonly, insulation failures occur at cable joints and terminations, caused by inhomogeneous electric field distributions. In this work, a blend of natural rubber (NR) and linear low density polyethylene (LLDPE) was investigated, and the optimal formulation of the blend that could resist PD was discussed. The experiments were conducted under a constant high voltage stress test of 6.5 kV AC and the magnitude of partial discharge activities was recorded using the CIGRE method II. Pattern analysis of PD signals was performed along with the interpretation of morphological changes. The results showed that the addition of 10 wt% of NR and 5 wt% of Alumina Trihydrate (ATH) provided promising results in resisting PD activities. However, as the NR content increased, more micropores existed, thus resulting in increased PD activities within the samples.

Keywords: Partial discharge, Natural rubber, PD pattern, Linear low density polyethylene

1. Introduction

Partial discharge phenomenon is a pre-breakdown phenomenon that arises due to the presence of imperfections in an insulator. Imperfections such as contaminants and impurities in an insulator diverges the electric field across the insulator, resulting in a local stress enhancement at the imperfection sites. This leads to performance deterioration of the insulator [1-4].

Partial discharges commonly occur in power cables such as those made from cross-linked polyethylene (XLPE) [5-8]. Therefore, analyses of partial discharge activities within power cables have to be carried out periodically to monitor the insulation performance of the cables. These include partial discharge analyses for cable terminations, which are often considered as weak insulation points with the highest partial discharge activities [9].

Recently, the use polymer blends and composites have drawn increasing interests from the dielectrics community for enhancing partial discharge performance of insulators. With an appropriate combination of different materials, the resulting materials are expected to offer better insulation performance than the conventional XLPE systems. Although lots of analyses on chemical, mechanical and electrical characteristics of polymer blends and nanocomposites have been carried out [10, 11], analyses on partial discharge characteristics of polymer blends and composites were scarce. Specifically, partial discharge characteristics of linear low density polyethylene-natural rubber (LLDPE/NR) blends were less discussed in the literature.

From the work of Makmud et al. [12, 13], partial discharge characteristics of LLDPE/NR blend, investigated using CIGRE method II, were found to depend on the ratio of the blend. Furthermore, polymer nanocomposites are fabricated by adding uniformly dispersed nanosized filler into the polymer matrix. The nanosized filler is typically added to the matrix in small quantity which is less than 10 wt%. Adding more than 10 wt% of nanofiller is considered uneconomical for mass production since the commercial nanofillers are very expensive [14]. Also, at higher weight percentage of nanofiller amount, they tend to be agglomerated thereby nullifying the beneficial effect of nanoparticles [15]. In this work, partial discharge patterns of LLDPE/NR filled with 5 wt% of ATH nanofiller were analyzed along with morphological analyses using a scanning electron microscope (SEM). When the electric field was increased from zero to a maximum value, phase position changes of partial discharge events around the zero area were discussed.

2. Experimental Procedure

2.1 Sample preparation

The compositions of the prepared samples are tabulated

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Table 1. Sample composition in weight percentage (wt%)

Sample Name	LLDPE	NR	ATH
A	100	0	5
B	90	10	5
C	80	20	5
D	70	30	5

in Table 1. The LLDPE/NR blends were made up of NR with different compositions, ranging 0 wt% - 30 wt%. 5 wt% of alumina trihydrate was added to the blends for enhancing surface tracking resistance [16]. The samples were blended using a two-roll mill mixer for 15 minutes at a temperature of 180 °C. Each sample was then molded by using a melt compression method at 160 °C, prior to cooling down at room temperature.

2.2 Experimental setup

Fig. 1 illustrates the experimental setup for partial discharge testing. A CIGRE method II standard test cell (as also shown in Fig. 2) was used to house a test sample. A current transducer was used to detect partial discharge activities within a frequency range of 20 kHz to 80 kHz.

A picoscope was used to acquire partial discharge and power supply signals. The output of the picoscope was connected to a netbook via a USB port using the LabVIEW interface. The main function of the netbook was for logging partial discharge monitoring data. Partial discharge data were then captured, saved and analyzed using a program developed based on the LabVIEW software. For safety purposes, a high voltage (HV) resistor and a sphere gap were used to protect the HV transformer and the measuring equipment (the picoscope and the netbook) respectively

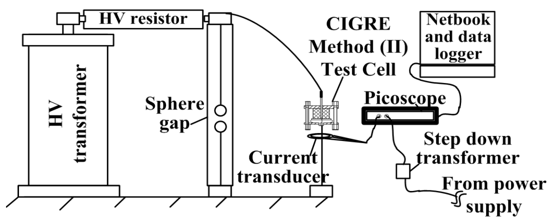


Fig. 1. Circuit arrangement for partial discharge measurement

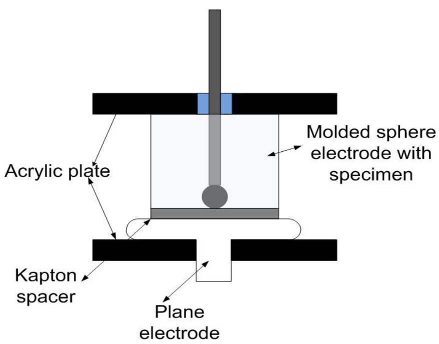


Fig. 2. CIGRE Method (II) Test Cell

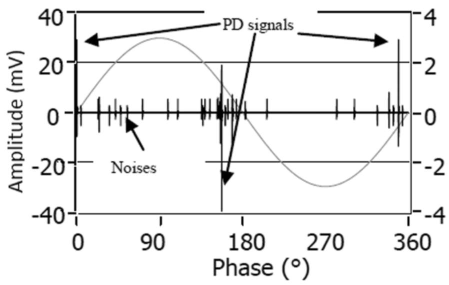


Fig. 3. Partial discharge waveform with noise

from over-current in case of breakdown during testing.

For the LabVIEW software, a sampling rate of 125 kS/s was used and data were saved if a threshold voltage of 20 mV was recorded. Each partial discharge file contains 2500 data sets, equivalent to 20 ms recorded data that represents a full cycle of a 50 Hz sinusoidal waveform.

The first 625 data sets represent the phase angle between 0-90°, the second subsequent 1250 data sets represent the phase angle between 90° – 180°, the third subsequent 1875 data sets represent the phase angle between 180° – 270°, and the final subsequent 2500 data sets represent the phase angle between 270° – 360°. Partial discharge signals were recorded continuously for one hour at 6.5 kV AC applied voltage. Analysis for partial discharge patterns was done after the experiment via the LabVIEW block program that had taken a highest value between the 1st data set and the 626th data sets, and also between the 1875th data sets and 2500th data set. Other highest values were taken between the 626th and 1875th data sets, as shown in Fig. 3.

2.3 Partial discharge calibration

To obtain exact values of charges from partial discharge testing, partial discharge equipment needs to be calibrated. In this work, the calibration was performed using the Partial Discharge Charge Calibrator Type 450 manufactured by Haefely. The Picoscope was calibrated by injecting the point of measurement with five different pulse charges, i.e., 5 pC, 10 pC, 20 pC, 50 pC and 100 pC, and the results were compared with the literature [12]. For example, a partial discharge magnitude of 200 mV was found to be equivalent to 20 pC. The ratio between the reading in mV and pC was maintained at a ratio 10:1. It is noteworthy that the charge sensitivity of the partial discharge detection system is 2 pC, based on a fixed threshold voltage of 20 mV. Therefore, signals with charges above 2 pC are considered as partial discharge signals.

3. Results and Discussion

3.1 Partial discharge trend

Partial discharge number and magnitude characteristics of samples A, B, C and D were shown from Fig. 4 until Fig. 7, respectively. The partial discharge data were collected and plotted at a time interval of 10 minutes. From the obtained results, the highest partial discharge numbers were recorded for sample C during the first 10-minute interval. This was followed by samples A, D and B. In other words, among all investigated samples, sample B had the lowest partial discharge magnitudes and partial discharge numbers, and is therefore a sample with optimum partial discharge resistance characteristics. It should be noted that the partial discharge behaviours represent a transition time between zero crossings of the electric field inside a void into a certain amount of electric field. Also, it can represent physical processes inside a void. In the CIGRE method II test cell configuration shown in Fig. 2, there is a space or void of 0.1 mm between the high voltage electrode and the insulation layer. When a high voltage is applied to the electrode, the void, which is usually filled with normal air, is bombarded by electrons, causing the void to be filled with new gases with a higher pressure, causing the breakdown threshold voltage within the void to increase. This reduces the discharge rate inside the void. Also, different materials will generate different gases and different pressures inside a void [17].

Moreover, it was noticed that, positive partial discharge magnitudes and positive partial discharge numbers exhibited

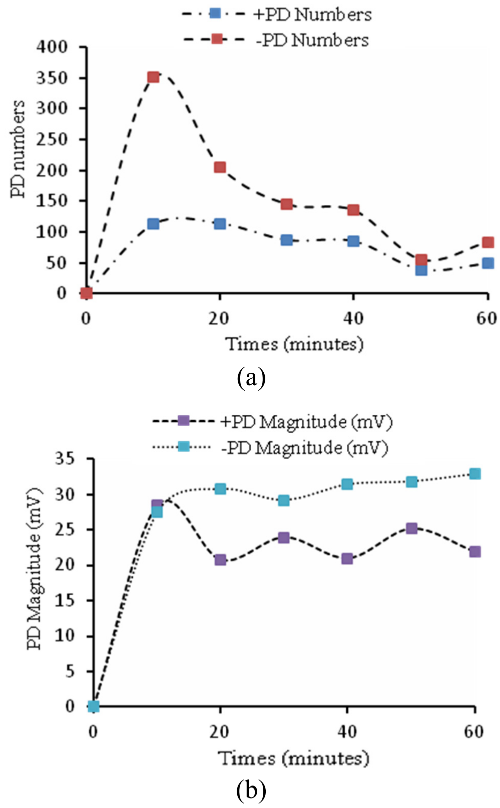


Fig. 5. PD characteristics of sample B; (a) PD number, (b) PD magnitude

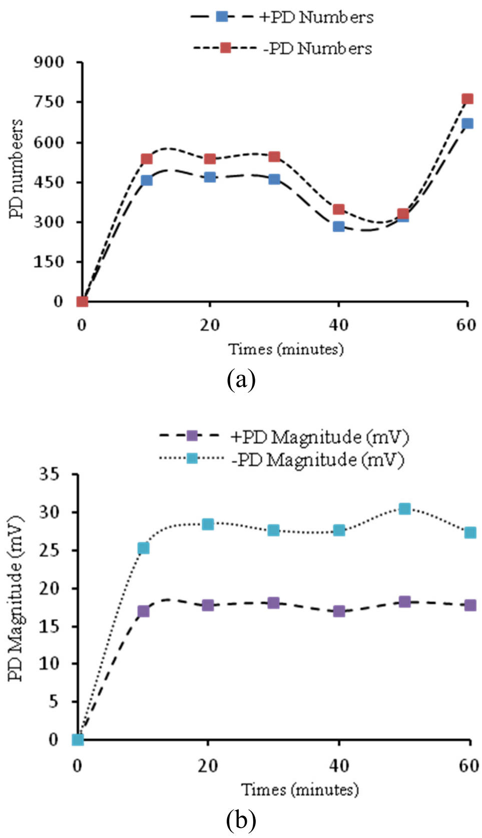


Fig. 4. PD characteristics of sample A; (a) PD number, (b) PD magnitude

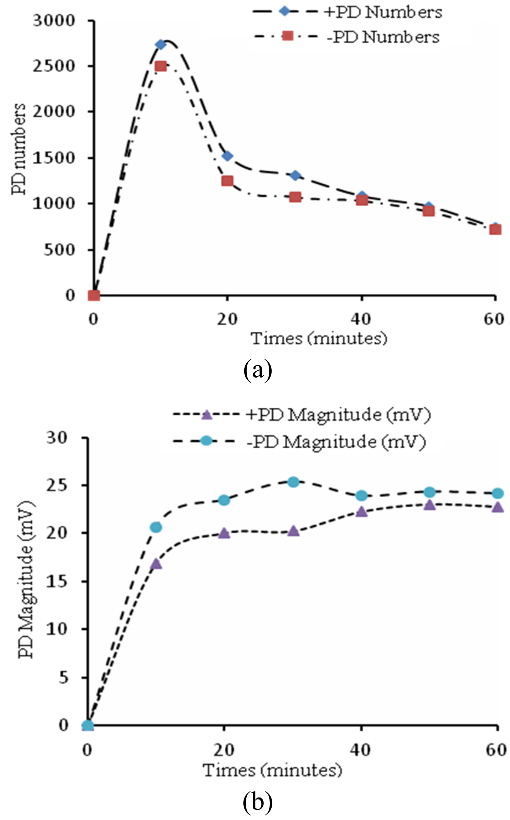


Fig. 6. PD characteristics of sample C; (a) PD number, (b) PD magnitude

small changes or almost constant values in almost all samples. This constant condition could be due to the insufficient electric field that was needed to create new discharges. However, the negative partial discharge magnitudes and partial discharge numbers depicted a reduction as a function of time. This condition could be elucidated by referring to the material composition effects. In sample B specifically, the addition of 10% of NR and 5% of ATH filler contributed to the enhancement of partial discharge resistance due to its stiffness and elasticity characteristics which help to trap the charge and filled in the void gaps. However, when the number of NR increased, it seems to attract more partial discharge activities due to an increase in the number of pores that could be a major drawback for insulating materials.

In case of partial discharge magnitudes, sample C had the highest total partial discharge magnitudes, followed by samples A, D and B. The higher PD magnitude was contributed by the partially high gas pressure and high temperature produced by partial discharges inside the void, thereby leading to a high magnitude of partial discharge. Also, partial discharges produced space charges that strengthen the local electric field in the voids, thus maintaining a continuous development of partial discharge

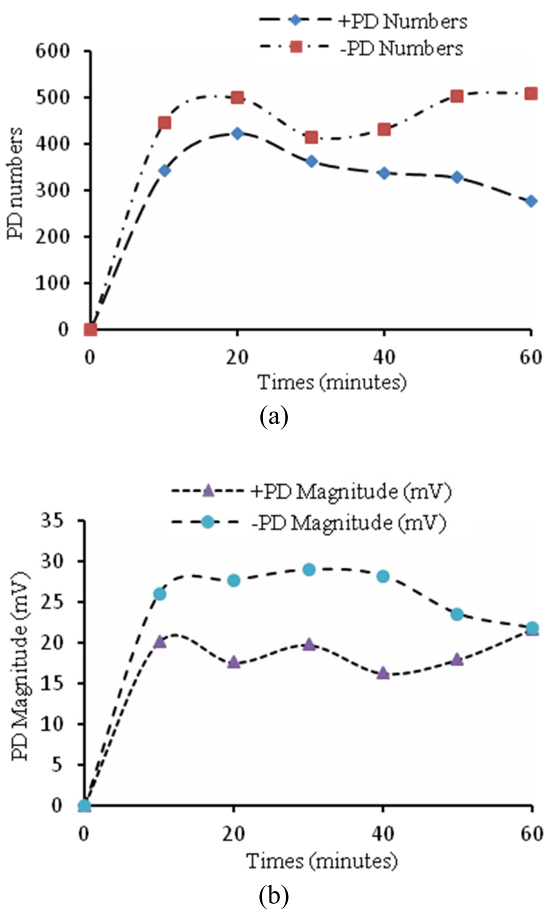


Fig. 7. PD characteristics of sample D; (a) PD number, (b) PD magnitude

to form more abrupt and partially changes of partial discharge patterns [18].

3.2. Phase-resolved partial discharge patterns

Partial discharge characteristics of the investigated samples were further analyzed by taking into account the respective phase resolved partial discharge patterns. Fig. 8

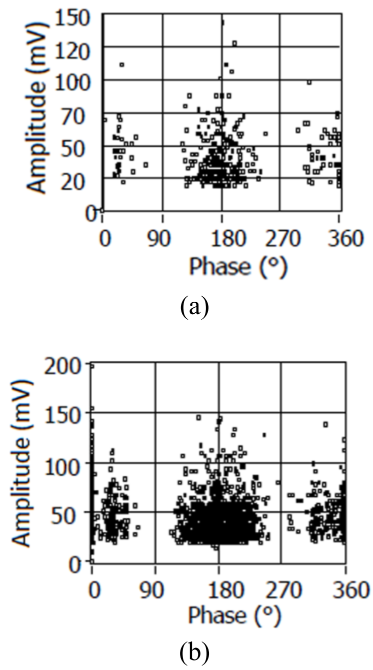


Fig. 8. PD pattern of sample A (a) after 10 minutes, (b) after 60 minutes

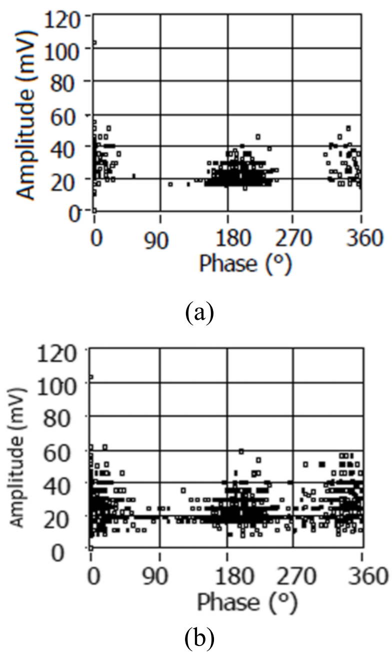
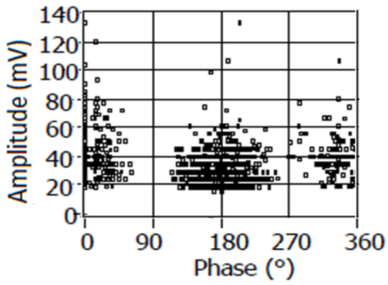
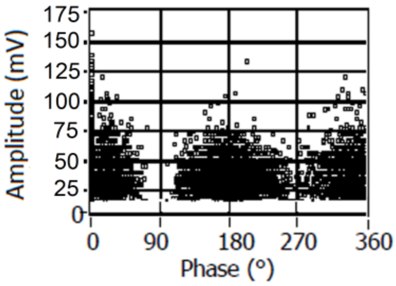


Fig. 9. PD pattern of sample B (a) after 1 minutes, (b) after 60 minutes

to Fig. 11 illustrate the phase-resolved partial discharge patterns of samples A, B, C and D, respectively at the first 10 minutes and at the maximum test duration of 60 minutes. All the highest magnitude is located at the zero crossing area where the partial discharge events take place. In the first 10 minutes, all partial discharge magnitudes were below 60 mV, and the highest partial discharge magnitude was about 160 mV (see Fig. 11(a)). The phase positions of

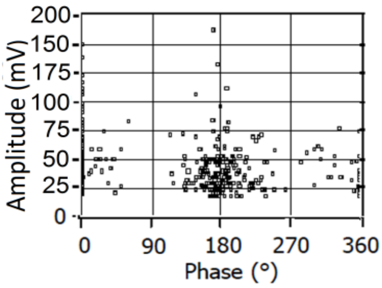


(a)

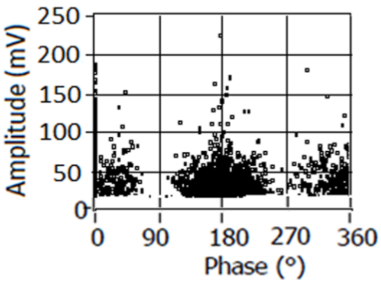


(b)

Fig. 10. PD pattern of sample C (a) after 10 minutes, (b) after 60 minutes



(a)



(b)

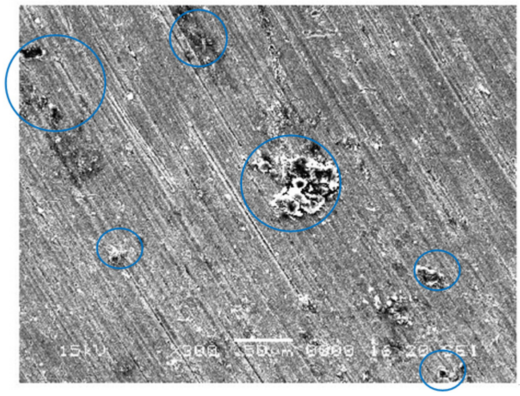
Fig. 11. PD pattern of sample D (a) after 10 minutes, (b) after 60 minutes

partial discharge events were located around zero area where the electric field changed from zero and reached its maximum value fetching.

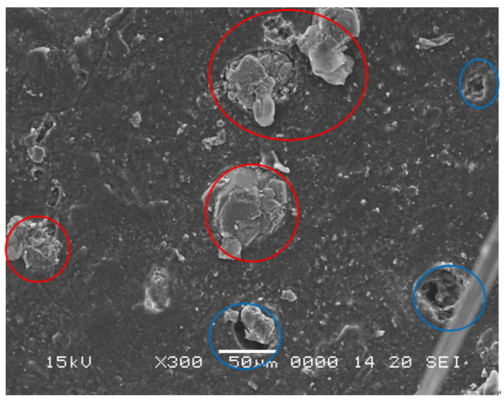
At 60 minutes of partial discharge measurement, partial discharge activities were dense especially in sample C, thereby showing the relationship between PD and aging times. Therefore, it can be interpreted that partial discharge activities degraded an insulating material, resulting in more micropores, oxidative decomposition, by-products deposition, and uneven congregating state caused by partially hot temperature and high pressure produced from PD thereby causing the wall of the micropores to be softened and created the burst between those walls [18, 19].

3.3. Scanning electron microscopy analysis

Scanning electron micrographs of the investigated samples before and after partial discharge testing are shown from Fig. 12 until Fig. 14. It is understood that the surface of the material is affected by partial discharge activities during the testing. Some microsized damages caused by partial discharge activities were found and it was identified as by-products due to material decomposition. This is shown as red circled regions of Fig. 12(b), Fig. 13(b) and Fig. 14(b). Under an applied voltage, partial

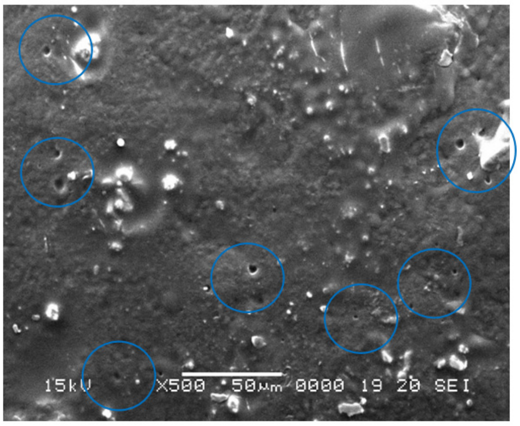


(a)

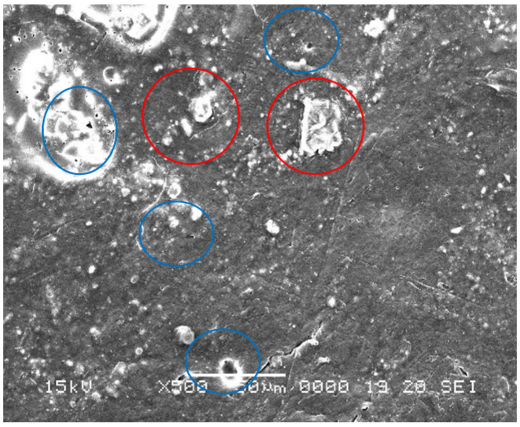


(b)

Fig. 12. Sample B (a) before PD test, (b) after PD test

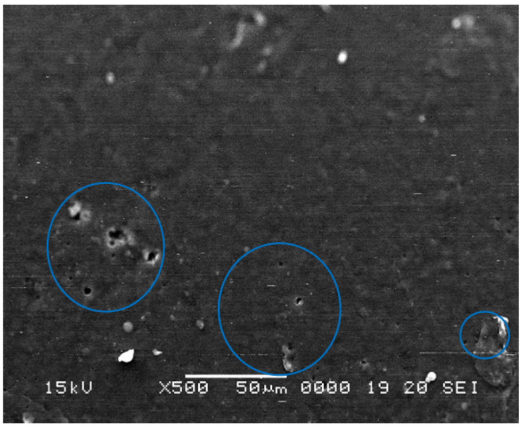


(a)

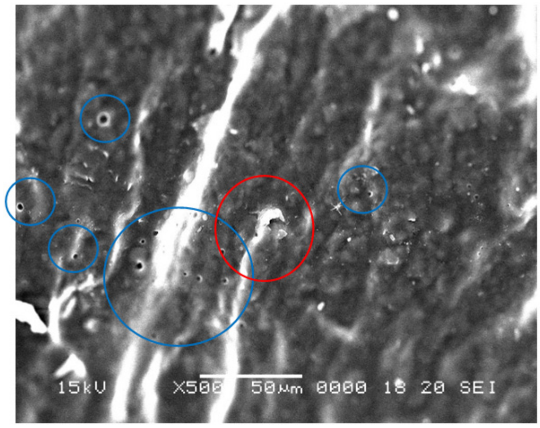


(b)

Fig. 13. Sample C (a) before PD test, (b) after PD test



(a)



(b)

Fig. 14. Sample D (a) before PD test, (b) after PD test

discharges induce gas pressure centralization and increase the temperature process. Thus, promoting the existence of by-products by decomposition of polymer chain due to partial high pressure and hot temperature [7, 20, 21].

Furthermore, an increased amount of micropores was found in samples with higher content of NR. The micropores attracted more PD activities. Likewise, after some of the micropores are broken through, the macrospores are created and thereby increasing the number of PD activities inside the NR vicinity. Micropores could therefore be one of the primary factors that weaken the insulating material, resulting in the working electric field to become maximal, which eventually lead to the complete breakdown of insulation [18].

It can be seen that micropores increased in sample D (Fig. 14) which had more NR content compared to sample B (Fig. 12). The micropores were circled in blue in Fig. 12, Fig. 13 and Fig. 14. The micropores might increase the gas pressure in the NR vicinity. Under an applied voltage, discharges that occur inside micropores may induced ionization, resulting in a high temperature and a high pressure at the pores' vicinity, thus softening and weakening the insulation. On the other hand, the area around the high voltage tip of electrode suffers more damages compared to the area outside the electrode in the same sample.

4. Conclusion

The results showed that different weight percentages of an NR addition to LLDPE had effects on the partial discharge resistance of the resulting material. Specifically, the test sample B, i.e., LLDPE with 10 wt% of NR showed improved partial discharge resistance. Each material composition responded differently to high electric field stresses, and the partial discharge pattern analysis showed that there was no significant effect in terms of partial discharge phase of occurrences. In addition, the test sample B showed the lowest PD values for the first 10 minutes and the PD reading taken after 60 minutes. Morphological studies using SEM showed that an increase in the NR weight percentage improved surface roughness of the resulting material, but some porosity was detected. The differences between the samples' surfaces before and after partial discharge testing indicated damages on the sample's surface caused by the tip electrode.

Acknowledgements

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