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Effect of silica nanofiller in cross-linked polyethylene as electrical tree growth inhibitor

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ABSTRACT

One of the main phenomena that contributes to the non-success of cable insulation made of cross-linked polyethylene (XLPE) is electrical treeing. To improve the XPLE cable insulation, the use of nanofiller has been introduced. Adding the nanofiller in the based composite offers better cable lifetime and resistance to deal with the cable failure. One of the potential nanofillers that can increase the insulation performance of XLPE cable is silica nanofiller. To this extent, the studies on silica nanofiller in XLPE are focusing on the impulse breakdown strength, dielectric loss, permittivity, space charge, alternating current (AC), and partial discharge. The studies reveal that the dielectric properties of the XLPE nanocomposite have significant improvement. Therefore, this work investigates the effect of various concentrations of silica nanofiller in XLPE composite as electrical tree inhibitor. The concentrations of silica nanofiller in XLPE were 0.25 wt%, 0.5 wt%, 0.75 wt%, 1.0 wt%, 1.25 wt%, 1.5 wt%, and 1.75 wt%. The silica nanofillers have 96%-99% purity, 20-30 nm sizes and the shapes are spherical. As a result, the XLPE composite containing 1.5 wt% silica nanofiller demonstrate higher tree inception voltage and detaining the tree propagation speed, which could be considered as an inhibitor medium of electrical tree growth.

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1. INTRODUCTION

Cross-linked polyethylene (XLPE) has been extensively applied in high voltage (HV) cable insulation owing to the outstanding mechanical and dielectric properties. Nevertheless, the application of XLPE as the underground distribution cables and insulating material is more likely prone to the unforeseen weather and uncontrolled contaminations which may initiate and develop water trees in the power cable under high electric field with the presence of residual moisture [1]–[4]. The water tree developments in certain circumstances may generate electrical trees and ultimately cause power cables insulation breakdown. The electrical tree growth occurs in three stages: initiation/inception, propagation, and breakdown [5]–[10]. Recently, with the rapid nanotechnologies development, the nanofiller addition in polymeric material gains attention owing to their outstanding performance in improving tree inception voltage (TIV) and inhibiting fast tree growth. To date, there are few studies on the electrical tree behaviour on polymeric material containing nanofiller such as ZnO, Al_2O_3 and SiO_2 nanofillers [9]–[14]. However, most of the studies are focusing on the polymeric materials such as LDPE, epoxy resin, SiR, and polyethylene [15]–[22].

Thus, it is apparent that the study of electrical tree behaviour in XLPE composite containing silica nanofiller yet to be explored and the understanding of the fundamental characteristics are essential. Therefore, this article reporting on the investigation of the effect of various concentrations of silica nanofiller in XLPE composite. The concentrations of the silica nanofiller were 0.25 wt%, 0.5 wt%, 0.75 wt%, 1.0 wt%, 1.25 wt%, 1.5 wt%, and 1.75 wt%. The silica nanofillers have 96%-99% purity, 20-30 nm sizes and the shapes are spherical. The TIV and growth profiles of electrical tree in the XLPE nanocomposite for each concentration were also identified. In addition, the morphology analysis was also performed in this work.

2. METHOD

2.1. Sample preparation

The pure XLPE was supplied by Borealis AG with a density of 0.922 g/cm^3. The silica nanofiller of 96%-99% purity was supplied by US Nano Inc. with the size of 20-30 nm for spherical-shaped nanofiller. The preparation of pure XLPE and XLPE with silica nanofiller were carried out by melting the pellets at a temperature of 115 °C, 50 rpm speed for 6 minutes using the Haake internal mixer. When the XLPE was melted, various concentrations of silica nanofiller (0.25 wt%, 0.5 wt%, 0.75 wt%, 1.0 wt%, 1.25 wt%, 1.5 wt%, and 1.75 wt%) were mixed at similar conditions for 7 minutes. Using temperature of 160°C, the samples were then press-moulded for 6 minutes prior to cross-linking at the same pressure for only 3 minutes using hot press at pressure of 1,000 psi. At similar conditions, the cooling process was performed for 2 minutes.

The sample was prepared in rectangular-shaped with the dimension of 15×25×2 mm. Figure 1 shows the schematic diagram and the photograph of the prepared sample. Prior to thrusting the needle made of tungsten into the sample, the sample was placed in the oven for 2 minutes at a temperature of 120 °C. The tungsten needle with a diameter of 1 mm and tip angle of 30° was steadily trusted into each of the rectangular-shape sample. The gap between the tip of the tungsten needle and ground electrodes was set at 2 mm.

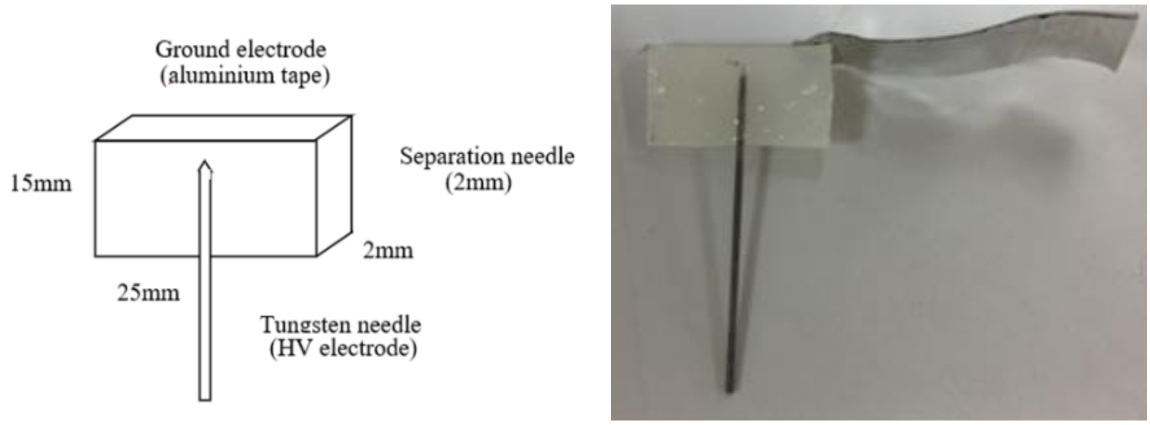


Figure 1. Schematic diagram and photograph of sample

2.2. Electrical treeing experimental setup

Figure 2 exhibits the electrical tree experimental setup consisting of high voltage transformer ($50\ Hz\ 240\ V/100\ kV$), limiting resistor (10 MΩ) and capacitive divider (1,000:1). The experiment was carried out using the voltage at 1 kV/sec rate until the TIV detection occurred. The TIV was defined after the length of the tree inception reached 10 µm [23]. The voltage applied rate was remained constant at the TIV in order to examine the propagation of electrical tree in each sample. The electrical tree propagation was examined until it reached 1 mm starting from the tip of the needle. The sample was placed below the microscopes and the electrical tree development was observed using the charge-coupled device (CCD) through the monitor. The image of the electrical tree was recorded occasionally. The source of high voltage was attached to the needle electrode, while the plane electrode (aluminum tape) was attached to the ground. The tank contained mineral oil to prevent surface flashover and external discharge throughout the experiment. All the experiment was conducted on ten samples for each filler concentration.

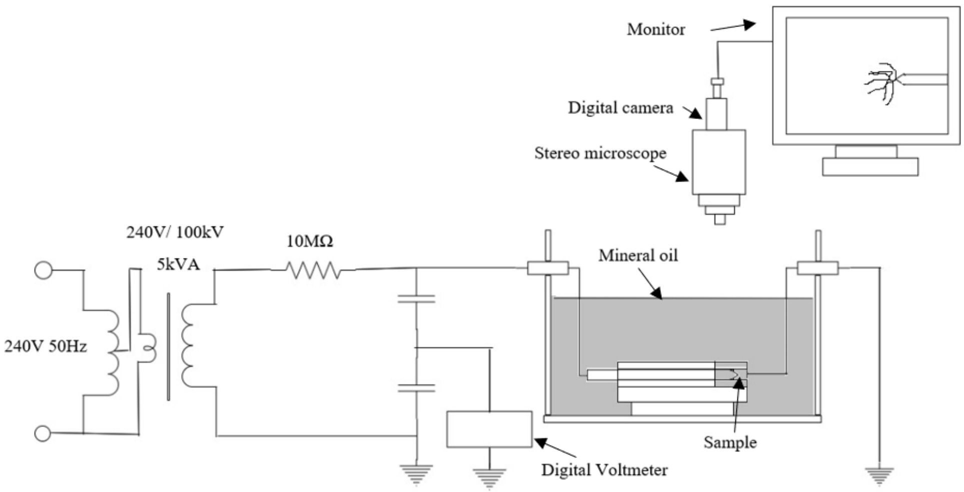


Figure 2. Experimental setup of electrical treeing

3. RESULTS AND DISCUSSION

3.1. Tree inception voltage

Figure 3 shows the TIV at various silica nanofiller concentrations in XLPE. Based on Weibull distribution, the TIV probability was referred at 63.2%. Table 1 shows the distributions of shape (*b*) and scale (*h*) where *b* represented the data dispersion and *h* represented the TIV. The XLPE composite containing 0.25 wt%, 0.5 wt% and 0.75 wt% silica nanofiller exhibits slightly lower TIV values than the pure XLPE. While the TIV for the XLPE containing 1 wt%, 1.25 wt%, 1.5 wt% and 1.75 wt% silica nanofiller were greater than the pure XLPE.

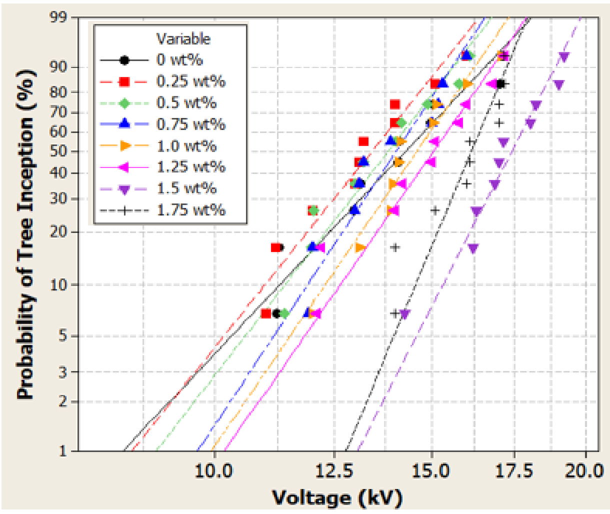


Figure 3. Weibull distribution of tree inception voltage at various concentrations of silica nanofiller

Table 1. Distributions of *b* and *h* relative to Figure 3

Sample	Shape, *b*	Scale, *h* (kV)
XLPE	8.031	14.95
0.25 wt% XLPE/silica	9.453	13.95
0.5 wt% XLPE/silica	9.789	14.35
0.75 wt% XLPE/silica	11.44	14.49
1 wt% XLPE/silica	11.05	15.08
1.25 wt% XLPE/silica	10.87	15.56
1.5 wt% XLPE/silica	14.69	17.86
1.75 wt% XLPE/silica	18.10	16.48

3.2. Electrical treeing propagation in XLPE nanocomposite

Figure 4 shows the images of electrical treeing propagation captured by CCD camera. The images of electrical tree were captured at 1 mm length after TIV. The images of the electrical tree displayed the formation of bush tree types in pure XLPE and XLPE containing silica nanofiller for all concentrations. The time duration of the electrical tree propagation in pure XLPE composite to reach 1 mm was 75 minutes as shown in Figure 4(a). By adding silica nanofiller in XLPE, the electrical tree propagation can be detained which escalated the duration time of electrical tree growth. However, it is limited to the silica nanofiller concentration up to 1.5 wt% as shown in Figure 4(b) to Figure 4(g). The propagation time of electrical tree in XLPE containing 1.5 wt% silica nanofiller to reach 1 mm from the tip of needle electrode is 146 minutes. In contrary, the duration time for electrical tree propagation in XLPE containing 1.75 wt% silica nanofiller was slightly decreased has shown in Figure 4(h).

Figure 5 shows the propagation of the electrical tree length in 60 minutes after TIV for all concentrations of silica nanofiller in XLPE compared to pure XLPE. The results indicate that the electrical tree propagation length reached 801 µm in pure XLPE (0.07 min/µm) within 60 minutes after TIV. Meanwhile, the propagation of electrical tree lengths for XLPE containing 0.25 wt%, 0.5 wt%, 0.75 wt%, 1.0 wt%, 1.25 wt%, 1.5 wt%, and 1.75 wt% silica nanofiller were 780 µm (0.08 min/µm), 720 µm (0.08 min/µm), 709 µm (0.08 min/µm), 690 µm (0.09 min/µm), 667 µm (0.09 min/µm), 603 µm (0.10 min/µm) and 655 µm (0.09 min/µm), respectively. This has proven that the electrical tree propagation has been impeded in XLPE containing silica nanofiller compared to that of pure XLPE composite. According to the dual-layer model theory, the silica nanofiller acts as obstruction to tree growth speed in XLPE composite [24], [25].

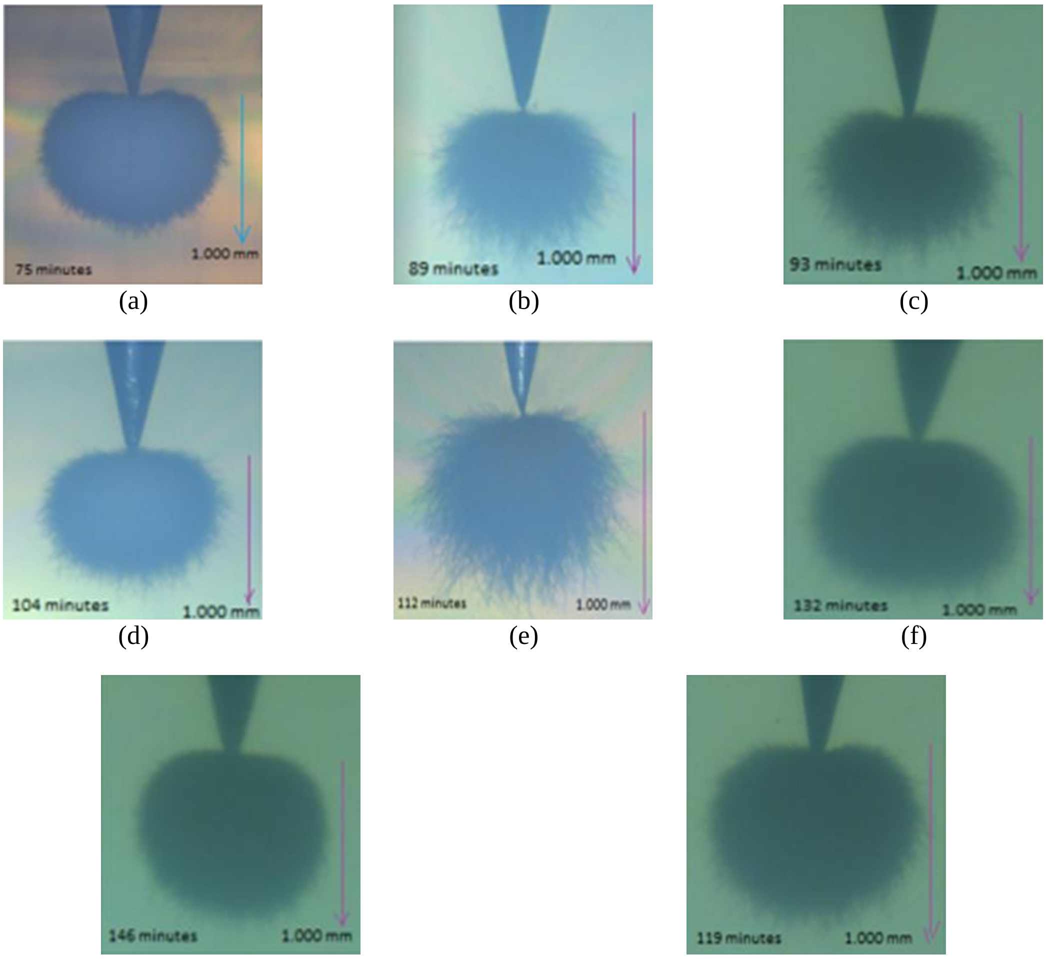


Figure 4. Images of electrical tree growth with respect to time in pure XLPE and XLPE/silica nanocomposites, (a) pure XLPE, (b) 0.25 wt% XLPE/silica, (c) 0.5 wt% XLPE/silica, (d) 0.75 wt% XLPE/silica, (e) 1 wt% XLPE/silica, (f) 1.25 wt% XLPE/silica, (g) 1.5 wt% XLPE/silica, and (h) 1.75 wt% XLPE/silica

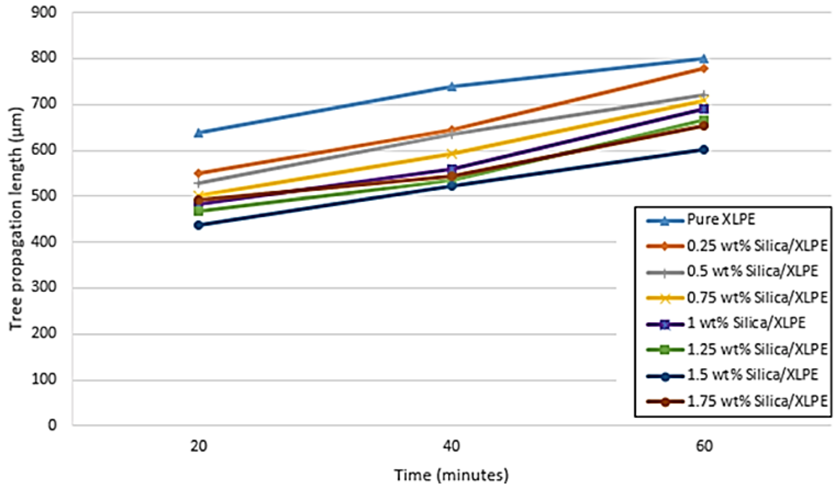
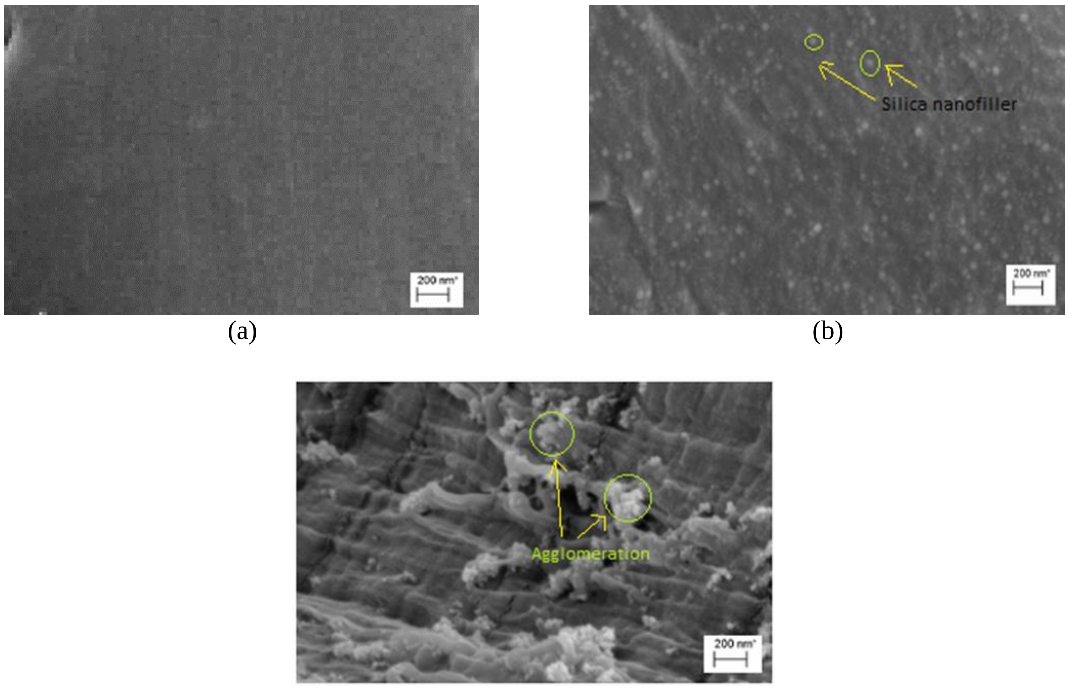


Figure 5. Electrical tree propagation length

Figure 6 shows the morphologies analysis at 30K magnification of pure XLPE and XLPE containing silica nanofiller. Figure 6(a) exhibits the clear image of pure XLPE without the presence of silica. Figures 6(b) and 6(c) show the morphology images for XLPE/silica nanocomposites. Homogeneous dispersion of silica nanofiller in XLPE can be seen at the 1.5 wt% concentration as shown in Figure 6(b). The homogenous dispersion of nanofiller in XLPE composite may affect to the higher TIV and obstructed the growth of the electrical treeing in the nanocomposites [15]–[19]. Thus, the homogeneous dispersion of silica nanofiller in XLPE prolongs the electrical tree growth propagation. Figure 6(c) depicts the morphologies of XLPE containing 1.75 wt% silica nanofiller. This image obviously showed that by adding 1.75 wt% silica nanofiller into XLPE composited may yield to the agglomeration and overlapping of the silica nanofiller. This probably contribute to the void formation between nanofiller and XLPE interface, providing effortless paths to extract the charges throughout the propagation of electrical tree [9].



(a) (b)

(c)

Figure 6. Morphologies of pure XLPE and XLPE containing silica nanofiller at 30K magnification, (a) pure XLPE, (b) 1.5 wt% XLPE/silica, and (c) 1.75 wt% XLPE/silica

Moreover, XLPE containing silica nanofiller introduce the dual-layer model theory [24], [25] which consists of tightly and loosely bound region. Figure 7 shows that the tightly bound (inner layer) and loosely bound (outer layer). The tight bound behaves as charge traps to obstruct the electrical tree growth, while the loosely bound region has more conductivity than other layers of the nanocomposites. After the tree has initiated, it begins to grow through the XLPE and silica nanofiller. The silica nanofiller would obstruct the propagation and behave as trapping sites to the growth of electrical tree and also avoid tree from growing straight into the XLPE/silica nanocomposite. The tree showed to zigzag pattern which reduced the propagation time of the tree, generating several tree branches and eventually forming a bush type tree. It is believed that the presence of silica nanofiller in XLPE hindering the discharge avalanche in the nanocomposite which delays the electrical tree propagation [21]. It has been experimentally proven that the XLPE/silica nanocomposite has delayed the propagation time of the electrical tree in comparison to that of pure XLPE as shown in Figure 4.

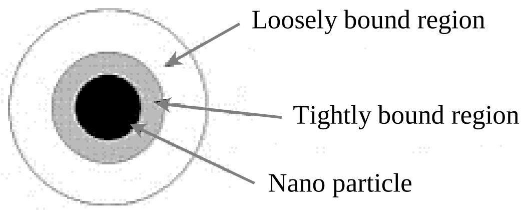


Figure 7. Dual-layer model [24], [25]

4. CONCLUSION

The TIV and electrical tree propagation in pure XLPE and XLPE containing various concentrations of silica nanofiller have been studied. The XLPE containing silica nanofiller of 1 wt% to 1.75 wt% exhibit higher TIV (0.87% to 10.23% higher) compare than pure XLPE. The 1.5 wt% silica nanofiller in XLPE has the highest TIV value and significantly obstructs electrical tree propagation speed, which could be potentially implemented in XLPE cable insulation as electrical tree growth inhibitor.

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