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EFFECT OF ATH FILLER ON THE ELECTRICAL TRACKING AND EROSION PROPERTIES OF NATURAL RUBBER-LLDPE BLENDS UNDER WET CONTAMINATED CONDITIONS

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ABSTRAK: *Penebat polimer semakin diterima oleh utiliti elektrik di seluruh dunia. Perkembangan yang hebat dalam penggunaan penebat berpolimer adalah disebabkan oleh kebaikannya yang banyak jika dibandingkan dengan penebat-penebat porselain dan kaca. Kertas kerja ini menjelaskan kelakuan jejakan permukaan elektrik dan hakisan daripada bahan formulasi baru termoplastik elastomer (TPE) dengan aras kandungan alumina trihydrate (ATH) yang berlainan. Getah asli yang dicampurkan dengan poliethylena berketumpatan rendah linar pada nisbah berat yang berlainan telah digunakan sebagai polimer asas daripada bahan TPE. Satu ujian jejakan elektrik dan hakisan mengikut IEC 587 atau ASTM D2303 telah dilakukan untuk mengkaji ciri-ciri arus bocor ke atas permukaan bahan di bawah keadaan pencemaran basah dan tegasan elektrik. Analisa morfologi telah dilaksanakan untuk menghubungkan sifat-sifat jejakan permukaan dengan morfologi permukaan sebelum dan selepas ujian jejakan. Ciri-ciri tertentu discas elektrik menyumbang kepada fenomena jejakan. Keputusan eksperimen menunjukkan campuran yang mengandungi berlainan aras ATH mempengaruhi dengan ketara sifat-sifat jejakan permukaan dan hakisan. Kandungan daripada 50 pph ATH telah didapati memperbaiki rintangan jejakan permukaan dan hakisan sebatian.*

ABSTRACT: Polymeric insulators are increasingly being accepted by electric utilities worldwide. The tremendous growth in the application of polymeric insulators is due to their substantial advantages compared to porcelain and glass insulators. This paper describes the electrical surface tracking and erosion behaviour of newly formulated thermoplastic elastomer (TPE) materials with different levels of alumina trihydrate (ATH) content. Natural rubbers blended with linear low-density polyethylene (LLDPE) at different weight ratios were used as base polymer of the TPE materials. An electrical tracking and erosion test according to IEC 587 or ASTM D2303 was conducted to study the characteristics of leakage current on the material surface under wet-contaminated and electrical stress conditions. Morphological analysis was carried out to relate the surface tracking properties with the surface morphology before and after the tracking test. Certain characteristics of the electrical discharge contributed to the tracking phenomenon. Experimental results showed the blends filled with different levels of ATH significantly influenced the surface tracking and erosion properties. ATH content of 50 pph was found to improve the surface tracking and erosion resistance of the compounds.

KEYWORDS: Tracking, leakage current, polymer, insulator, surface morphology.

INTRODUCTION

Composite polymeric insulators (PIs) are increasingly being accepted by electric utilities worldwide. During the past five decades, PIs are widely used in place of traditional porcelain and glass for high voltage insulating applications in electrical power systems (Kikuchi *et.al.*, 1999). The tremendous growth in the applications of PIs is due to their advantages such as lightweight, higher mechanical strength to weight ratio, low surface energy, resistance to vandalism and better performance in the presence of wet contaminated conditions (Mackevich, 1997). Polymeric outdoor insulators such as silicone rubber (SR), ethylene propylene rubber (EPR) and ethylene vinyl acetate (EVA) filled with silica and alumina trihydrate (ATH) fillers are currently used in high voltage engineering (Hackam, 1999). The use of such fillers has been proven to improve the surface tracking and erosion properties of most PIs in high voltage applications (Sundhar *et.al*, 1992; Mackevich and Simmons, 1997).

Despite the fact that the existing polymeric materials have been proven to be viable, research and development for new formulation of thermoplastic elastomer (TPE) material is still being conducted in order to make them more competitive. No single base polymer alone has all the necessary properties for high voltage insulating material. During service, insulation materials are subjected to environmental and electrical stresses, which lead to their degradation. Appropriate formulations of selected polymer materials offer alternatives for high voltage applications in the future.

Environmental and electrical aging stresses on PIs in service cause their performance to deteriorate. It is well known that electrical tracking has been the most common cause of insulation failure. Tracking is developed from the electrical surface discharge activity due to the flow of leakage current (LC) on the energised insulator surface under wet-contaminated conditions. Arcs created from this surface discharge phenomenon burn the insulator material and create the carbonised track. In order to minimise the degradation process by the surface-tracking phenomenon, suitable fillers are added to the base polymer material. In high voltage polymeric materials, the ATH fillers impart high electrical tracking and fire retardance as well as reinforced the physical strength (Hackam, 1998). Previous works have shown that compounds filled with optimum amount of fillers could enhance the resistance to tracking (Kim *et.al.*, 1992; Xuguang, 2000), improve mechanical performance (Besztercey *et.al*, 1999) and reduce flammability as well (Yeh *et.al.*, 1995). ATH plays an important role in improving surface tracking and erosion resistance. It reduces the polymer content, which then decreases thermal decomposition products caused by endothermic dehydration (Kumagai and Yoshimura, 2001).

This paper reports the influence of ATH fillers on the tracking performance of newly formulated TPE materials. The effects of accelerated aging from environmental and electrical stresses are studied by measuring the LC on the material surface. A surface tracking and erosion test based on IEC 587 or ASTM D2303 test procedures is conducted to evaluate resistance to tracking and erosion of electrical insulating materials used under severe ambient conditions.

EXPERIMENTAL SET-UP AND TEST PROCEDURES

Materials Preparation

Three different weight ratios of base polymer with different loadings of ATH were used throughout this study. The LLDPE injection moulding grade with specific melt flow index of 50 g/10 min, manufactured by Titan (M) Sdn Bhd and natural rubber (NR) of SMR-CV grade, obtained from Rubber Research Institute of Malaysia (RRIM) were used as base polymer. Powder grade ATH filler produced by BDH Ltd was used. This filler was mixed with the base polymer to improve electrical surface tracking and erosion resistance. Table 1 shows the formulation of the compounds for the tracking test.

The NR and LLDPE with ATH were blended in a Brabander Plasti-Corder at 160°C for 13 minutes at a rotor speed of 40 rpm. Samples of the blends were then compression-moulded into slab shapes of dimension 120 x 50 x 6 mm in an electrically heated hydraulic press at 160°C. The total moulding time was 15 minutes at a pressure of 100-120 kg/cm^2.

Table 1. Material composition of polymeric insulators

Sample	Base Polymer Ratio (%)		ATH (pph of base polymer)
	NR	LLDPE	
R4PE1A0 R4PE1A50 R4PE1A100 R4PE1A150	80	20	0 50 100 150
R3PE2A0 R3PE2A50 R3PE2A100 R3PE2A150	60	40	0 50 100 150
R2PE3A0 R2PE3A50 R2PE3A100 R2PE3A150	40	60	0 50 100 150

Hardwear Set-up and Procedures

The system for evaluating the surface tracking and erosion resistance of solid polymer insulating material is shown in Figure 1. The test is based on IEC 587 or ASTM D2303 standard methods and popularly known as Inclined-Plane Tracking (IPT) test.

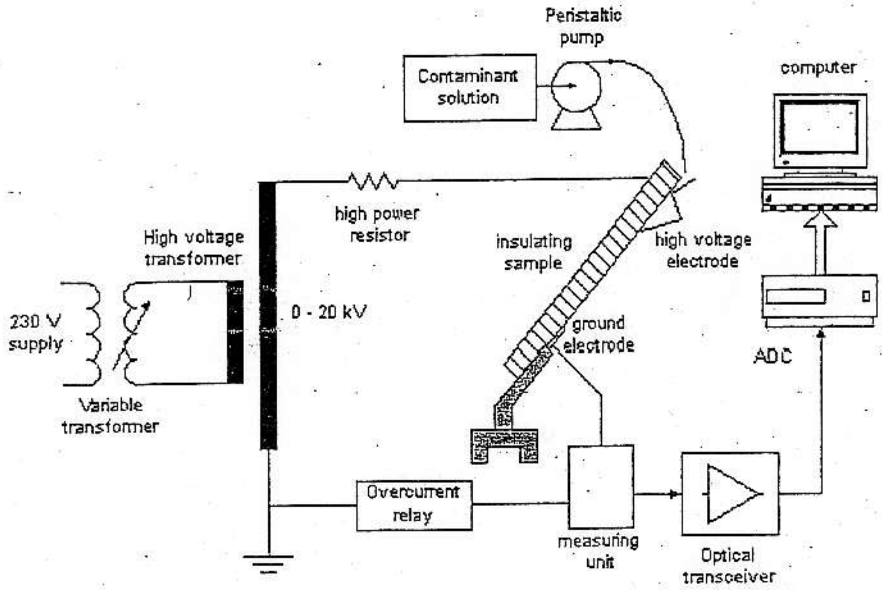


Figure 1. *Experimental set-up for surface tracking test*

A 1.0 kVA, 0-20 kV high voltage transformer was used to supply a high voltage stress across the sample. The sample was wet-contaminated by a continuous flow of the contaminant solution at the top of the sample through a PVC tube. A 0.1% by mass of ammonium chloride solution with a non-ionic wetting agent was used as a contaminant electrolyte. The flow of the electrolyte was controlled at the required value by using a peristaltic pump. The sample was mounted with the flat test surface on the underside, at an angle of 45º from the horizontal with the stainless steel electrodes 50 mm apart. Eight layers of filter paper were clamped between the high voltage electrode and the sample in order to get the proper flow of the contaminant electrolyte. The details of the test are described in the standard procedures (IEC 587, 1984: ASTM D2303, 1990). Basically the test is successfully conducted when the effective scintillation is observed, which means the existence of small yellow to white arcs just above the teeth of the ground electrode.

The test was conducted for 5 hours under contaminated and wet conditions. A 2.5 kV test voltage with electrolyte flow-rate of 0.15 ml/min was used throughout the experiment. The resistivity of the contaminant solution was maintained between 370 - 400 Ω-cm. The test set-up was placed inside a Faraday cage to avoid any outside noise or disturbance that could affect the test measurement. All the high voltage equipment and the cage were properly grounded for safety purpose. Surface tracking was monitored by measuring the surface LC that flows on the material surface. An on-line LC monitoring system is developed to monitor the progress of the test. For data analysis, a LabVIEW programme was written to communicate with the analog to digital converter (ADC) to sort out the LC signal and display it on the computer screen. In order to capture a full screen of the LC waveform patterns, the sampling rate of data acquisition was set to 2440 samples per second.

Morphological Study

The surface morphology of the compound was investigated by using a scanning electron microscope (SEM) of model JEOL JSM-5610. Before scanning, the samples were sputter-coated with platinum to minimise charging effect. A 20 mA sputtering current and 70 seconds coating time was used to obtain a 6 nm film thickness of deposited platinum. The electron gun of the SEM was energised at 10 kV in order to avoid possible damage to the material surface if a higher voltage is used. The micrograph of the compound surface was recorded at 200 magnifications for clearer observation.

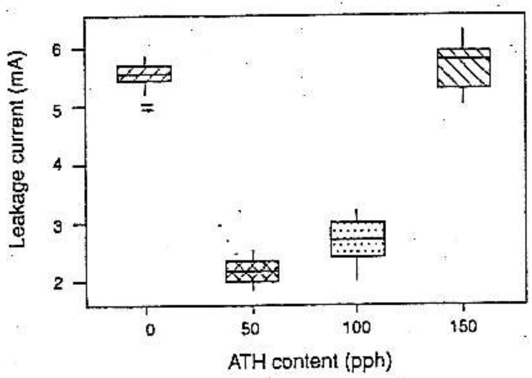
RESULTS AND DISCUSSION

The surface tracking and erosion properties of the insulating material are very much related to the development of LC. The levels and the characteristics of the LC significantly influence the carbon tracks development from the electrical discharge activity. For this reason, the observation on LC was taken into consideration when analysing the surface tracking and erosion properties. The LC properties could provide useful information that determine the performance of polymer insulating materials.

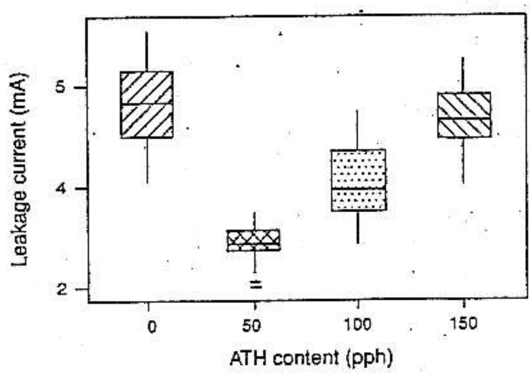
Effect of ATH on LC development

Figure 2 shows the box-plot of LC data for each composition, which was recorded every minute until the end of the experiment. The rms value of LC within the box-plot shows that the data lies between the first and third quartile of a set of data collected. For all blend formulations, a range of 2-6 mA of LC was observed throughout the experiment. The same results are also found in the case of silicone rubber, polyethylene vinyl acetate and polyolefin (Chang and Mazeika, 2000: Gorur *et.al,* 1997). The low-level of measured LC indicates that the compounds of NR/LLDPE have a mechanism to suppress the LC development. It is likely the blends have acquired good hydrophobicity due to the lower LC flow.

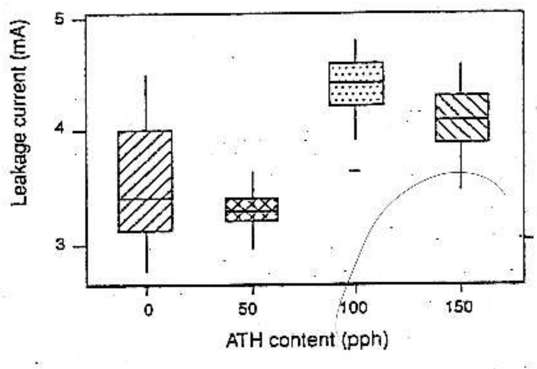
Figure 2 shows that at 50 pph ATH loading for each compound, the surface tracking and erosion properties improved in relation to the lowest LC value but started to decrease in the tracking resistance at higher levels of ATH. Concentrations lower or greater than 50 pph ATH will both decrease the surface tracking and erosion capability. Another study on EPDM compound has also shown that with the presence of 40-80 pph ATH, the erosion of the surface sample is minimised (Costa *et.al.*, 1991). Xuguang *et.al.* (2000) has reported that the capability of tracking and erosion resistance of high temperature vulcanized silicone rubber is optimised with approximately 50 pph ATH filler content.



a) Compound of 80% NR and 20% LLDPE (R4PE1)



b) Compound of 60% NR and 40% LLDPE (R3PE2)



c) Compound of 40% NR and 60% LLDPE (R2PE3)

***Figure 2.** Leakage current magnitude of blends at different concentrations of ATH*

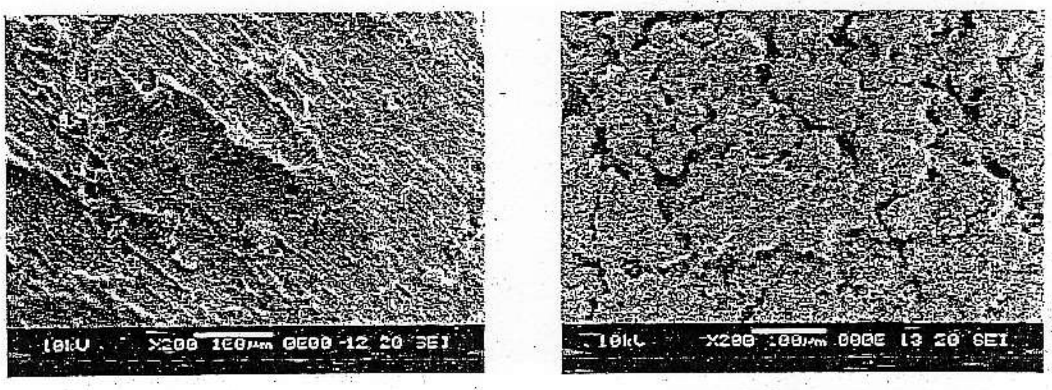
The ATH filler plays an important role in improving surface tracking by allowing an endothermic reaction that results in the release of water vapour when heated by a discharge arc. The released water vapour then cools the surface, thus limiting the thermal degradation and prevents the formation of a continuous carbon track (Kumagai *et.al.*, 1998; Kumagai & Yoshimura, 2001). At very high levels of ATH, the fillers are difficult to blend and produce a uniform dispersion. This results in a rougher surface, which leads to an increase in the surface LC. Meanwhile with small amount of ATH (< 50 pph), the filler does not give sufficient protection against damage during surface discharge and tracking activity.

Morphological Analysis

To study the blends compatibility under different levels of ATH contents as well as the effect of the surface tracking phenomena on surface degradation, the surface micrographs of 60% NR and 40% LLDPE compounds are selected for discussion. Figure 3(a) and Figure 4(a) exhibit the surface morphology for the virgin compounds without and filled with low level of ATH respectively, while Figure 6(a) shows the surface morphology of the compound with high content of ATH loading. The effects of electrical surface tracking on surface degradation are shown in Figure 3(b), Figure 4(b), Figure 5(b) and Figure 6(b).

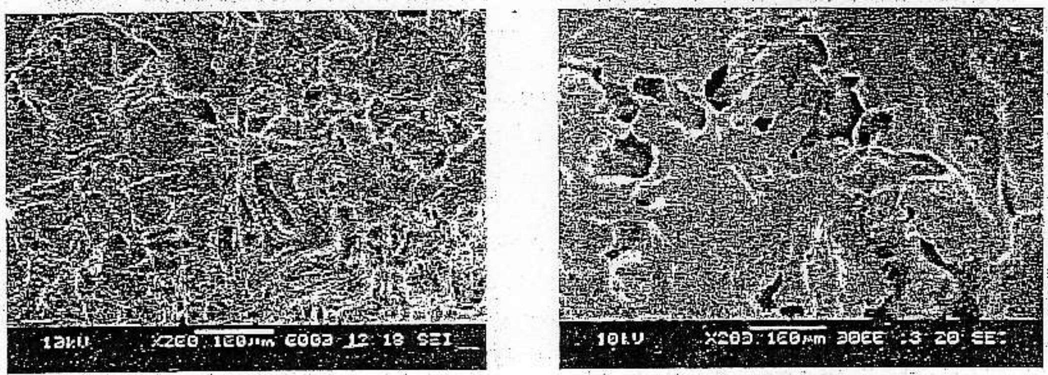
The inspection of the micrographs of virgin compounds with no ATH (Figure 3(a) and the compound with lower content of ATH (Figure 4(a)) reveals that the NR and LLDPE components are compatible and well mixed. The existence of tiny holes in the compound of Figure 4(a) is due to the air traps formed during the moulding process. The compatibility of NR/LLDPE can be improved if suitable additives such as liquid natural rubber (Dahlan *et.al.*, 2000) and crosslinking agent of dicumyl peroxide (Tanrattanakul & Udomkichdecha, 2001) are used. It is also observed that for compounds filled with low and moderate amount of ATH as shown in Figure 4(a) and Figure 5(a), the basic components in the compound are homogeneously dispersed and only small agglomerates of the fillers occur. This shows that the interaction between fillers and the polymer matrix is strong as well as possessing good adhesion property.

However for compounds with higher content of ATH fillers (Figure 6(a), the material surface was rougher due to difficulty in dispersing it uniformly in the compound, where the particles of ATH filler appeared on the surface. The ATH filler used in this compound seemed to be irregular in size. Some particles diameter reached up to 100 μm and these bigger size particles could have decreased the surface tracking and erosion resistance and contributed to a less smooth surface. Previous works have shown that the size of ATH particles play an important role on surface tracking properties. It is found that the ATH particles sizes of 4.5-13 μm offered the best electrical tracking properties and resisted failure over the longest period of time (Deng *et.al.*, 1995).



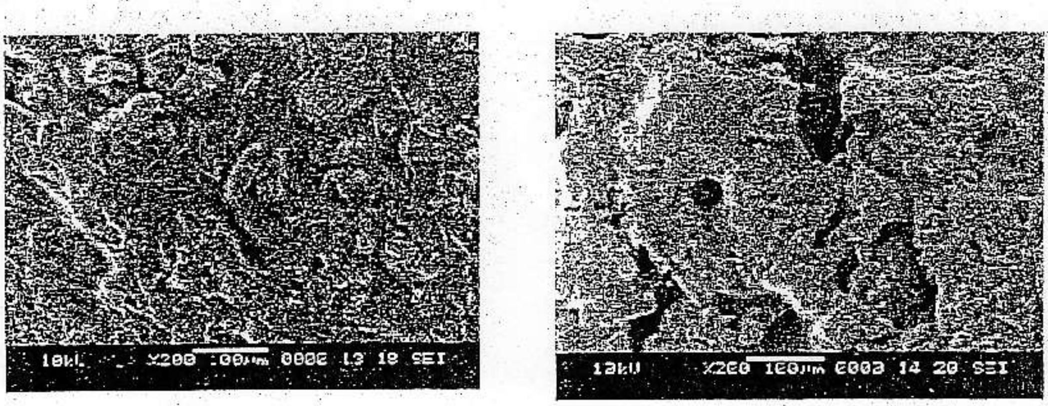
a) Before test b) After test

Figure 3. SEM micrograph of compound R3PE2 with ATH of 0 pph



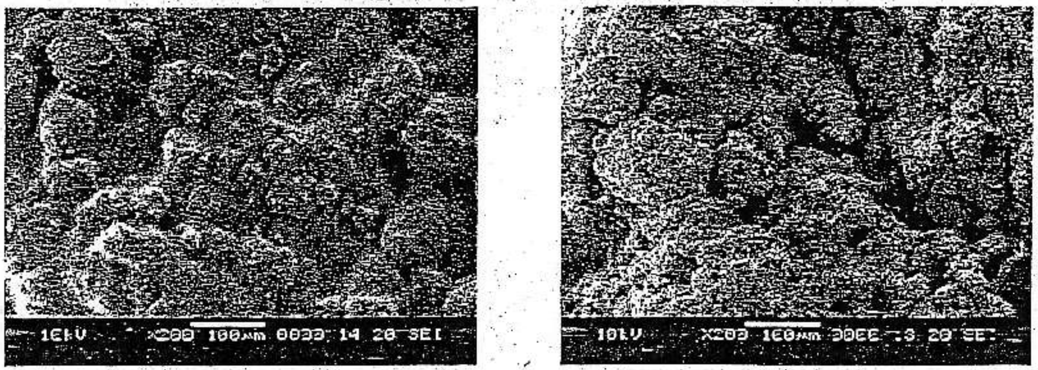
a) Before test b) After test

Figure 4. SEM micrograph of compound R3PE2 with ATH of 50 pph



a) Before test b) After test

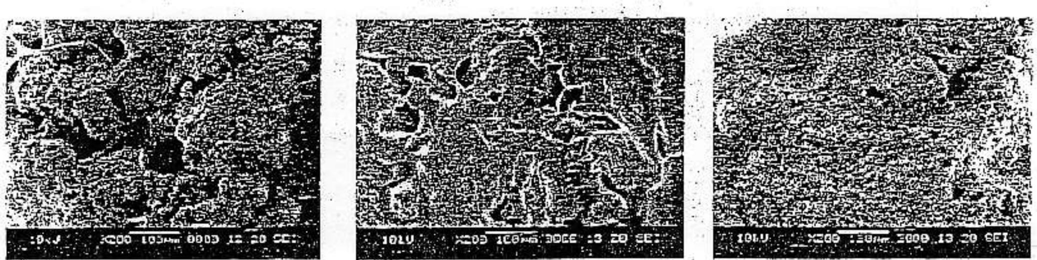
Figure 5. SEM micrograph of compound R3PE2 with ATH of 100 pph



a) Before test b) After test

Figure 6. *SEM micrograph of compound R3PE2 with ATH of 150 pph*

When the compounds are subjected to high voltage stress, the surface structure is damaged due to dry-band arcing. The SEM micrographs of Figure 3(b), Figure 4(b), Figure 5(b) and Figure 6(b) show that the material surface is porous and some cracks appear. The degree of surface damage depends on the level of LC as well as the characteristics of electrical discharge. By comparing the different groups of base polymer weight ratio, it is observed that the compound with 40% NR and 60% LLDPE (R2PE3) showed the lowest range of LC flow. Physical inspection on the material surface also showed less damage on sample R2PE3 compared to the other formulations (R4PE1 and R3PE2). The compounds with higher LLDPE to NR content ratio (40% NR/ 60% LLDPE) exhibit minor cracking, whereas compounds with less LLDPE to NR content ratio (80% NR/ 20% LLDPE and 60% NR/ 40% LLDPE) experienced major cracking as shown by their surface morphology in Figure 7.



a) R4PE1A50 b) R3PE2A50 c) R2PE3A50

Figure 7. *Surface morphology after tracking test for different compound formulations*

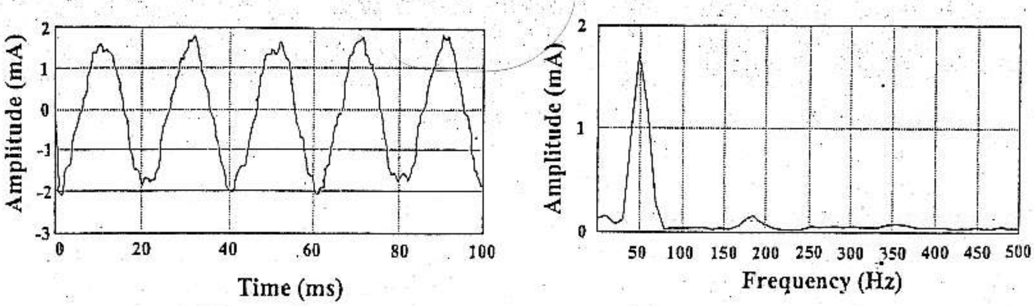
During the electrical discharge activity, the temperature of a thermal spot was found to be more than 200°C (Kumagai & Yoshimura, 2001). This high temperature is sufficient to melt or dissolve the base polymer especially on the NR component, which is known to have a lower melting temperature. It is believed that most of the thermal decomposition products are derived from the degradation of NR component rather than LLDPE component. This shows that the use of higher content LLDPE of fire-retardant grade, incorporated with the optimised content of ATH filler could improve the surface tracking and erosion properties of the blends.

Characteristics of LC Waveform Patterns

When the insulating material is wet, a resistive LC flows which is generally many orders of magnitude higher than the capacitive current of a dry insulator. The LC results in non-uniform heating of the contaminated layer that eventually causes dry-band to be formed at the narrow sections where the LC density is highest. The voltage across the insulator appears across the high resistivity dry-band and can result in a breakdown of the air above the dry-band. The electrical discharges will cause the high thermal spots to be developed at the arc root thus leading to gradual erosion of the insulator surface. These repeated discharges burn the insulator surface to create carbonised regions, referred to as "*surface tracking*".

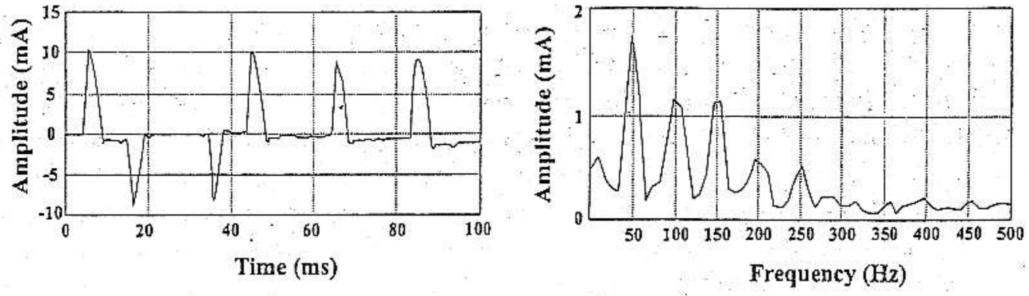
Likewise the LC level, the electrical discharge characteristics also affect the degradation of the sample. These discharge characteristics can be identified from the inspection of the LC waveform pattern. Analysis of LC through observation of different waveshapes and frequency spectrum characteristic could indicate the condition of the insulator surface during the test. Fernando & Gubanski (1999) and Suda (2001) have classified the transition of LC waveforms into different stages when describing the discharge characteristics. They also discussed the possible causes of this LC behaviour and its relation to surface hydrophobicity.

During the test, the different stages of the LC behaviour are identified based on the waveform patterns, as illustrated in Figure 8, Figure 9 and Figure 10. When a weak dry-band activity or the partial lost of hydrophobicity occur, the LC waveform has a distortion at the crests of the waveform. Small spikes observed at the peak of the waveform are due to the corona effect as depicted in Figure 8(a). The frequency spectrum of the waveform in Figure 8(b) indicates slight increase in the harmonic components with a total harmonic distortion (*THD*) of 8.04%.



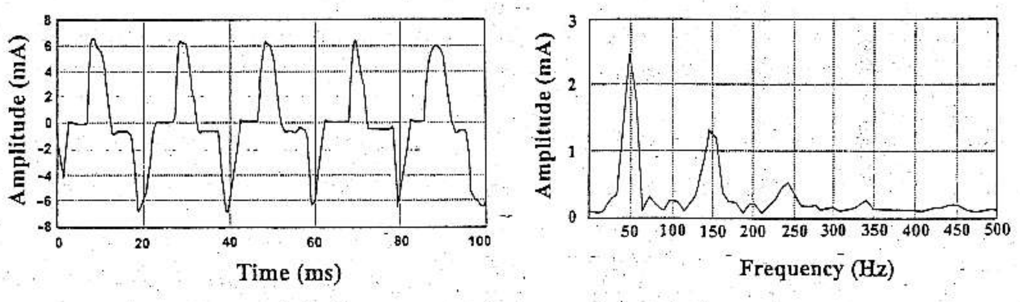
a) LC waveform b) Frequency spectrum

Figure 8. *LC waveform and frequency spectrum during weak dry-band formation*



a) LC waveform b) Frequency spectrum

***Figure 9.** LC waveform and frequency spectrum during short and random discharges*



a) LC waveform b) Frequency spectrum

***Figure 10.** LC waveform and frequency spectrum during continuous local discharges*

The waveform pattern in Figure 9(a) indicates the existence of several random short discharges. These discharges are less energetic and move rapidly from one location to another location without causing any degradation. The non-symmetrical pattern shows all harmonic components as revealed in Figure 9(b) with a recorded *THD* of 109.48%. In the presence of intermittent, strong as well as continuous local arc, the recorded LC waveform is shown in Figure 10(a) with a *THD* of 57.5%. The stable and continuous discharge results in the waveform pattern that is symmetric and contains odd harmonic components as depicted in Figure 10(b). During this phenomenon, it was observed that the electrical discharge stay rooted in a particular spot much longer and initiated degradation of the insulating sample. This localised and persistent discharge activity can raise the temperature to cause degradation.

CONCLUSION

The electrical tracking and erosion properties of natural rubber-linear low density polyethylene blends filled with different levels of ATH were investigated by analysing leakage current under the inclined-plane tracking test method. Experimental results showed that surface tracking depends on the presence of ATH filler and blend formulations. Based on the compositions investigated, it is found that 50 pph of ATH offers the optimum surface tracking and erosion resistance. The role of ATH in the leakage current suppression mechanism was discussed in relation to the endothermic reaction. Surface morphology of the compounds shows that the degree of surface damage is related to the level of leakage current as well as the characteristics of the electrical discharges. The electrical discharge activity also contributed to the variation of the electrical tracking and erosion properties of the blends and this observation can be identified from the LC waveform pattern.

REFERENCES

ASTM D2303. (1990). *Standard Test Methods for Liquid-Contaminant, Inclined-Plane Tracking and Erosion of Insulating Materials.* The American Society for Testing and Materials.

Besztercey, G.,Karger-Kocsis, J., Szaplonczay, P. and Kimata, R. (1999). Erosive Wear of Electrically Insulating Rubber Compounds by Solid Particles. *High Voltage Engineering Symposium,* **1(4)**: pp 176-179.

Chang, R.J., and Mazeika, L. (2000). Analysis of Electical Activity Associated with Inclined-Plane Tracking and Erosion of Insulating Materials. *IEEE Trans on Dielectrics and Electrical Insulation.* **7(3)**: pp 394-400.

Costa, R.A., Hattori, R.S. and Redondo, E.G. (1991). Optimisation of EPDM Compounds for Resistance Insulators to Electrical Tracking. *Int Conf on Properties and Applications of Dielectric Materials,* pp 300-304.

Dahlan, H.M., Khairul Zaman, M.D. and Ibrahim, A. (2000). Liquid Natural Rubber (LNR) as a Compatibiliser in NR/LLDPE Blends. *J. App. Polymer Science.* **78**: pp 1776-1782.

Deng, H., Hackam, R. and Cherney, E.A. (1995). Role of the Size of Particles of Alumina Trihydrate Filler on The Life of RTV Silicone Rubber Coating. *IEEE Trans. Power Delivery.* **10(2)**: pp 1012-1024.

Fernando, M.A.R.M. and Gubanski, S.M. (1999). Leakage Current Patterns on Contaminated Polymeric Surfaces. *IEEE Trans on Dielectrics and Electrical Insulation.* **6(5)**: pp 688-694.

Gorur, R.S., Montesinos, J., Varadadesikan, L., Simmons, S. and Shah, M. (1997). A Laboratory Test for Tracking and Erosion Resistance of HV Outdoor Insulation. *IEEE Trans on Dielectrics and Electrical Insulation.* **4(6)**: pp 767-774.

Hackam, R. (1998). Outdoor High Voltage Polymeric Insulators. *Int. Symposium on Electrical Insulating Materials.* Toyohashi, Japan. pp 1-16.

Hackam, R. (1999). Outdoor HV Composite Polymeric Insulators. *IEEE Trans on Dielectrics and Electrical Insulation.* **6(5)**: pp 557-585.

IEC 587. (1984). *Evaluating Resistance to Tracking and Erosion of Electrical Insulating Materials Used Under Severe Ambient Conditions.* British Standards Institution.

Kikuchi, T., Nishimura, S., Nagao. M., Izumi, K., Kubota, Y. and Sakata, M. (1999). Survey on The Use of Non-ceramic composite insulators. *IEEE Trans on Dielectrics and Electrical Insulation.* **6(5)**: pp 548-556.

Kim, S.H., Cherney, E.A. and Hackam, R. (1992). Effect of Filler Level in RTV Silicone Rubber Coatings Used in HV Insulators. *IEEE Trans on Electrical Insulation.* **27(6)**: pp 1065-1072.

Kumagai, S., Wang, X. and Yoshimura, N. (1998). Solid Residue Formation of RTV Silicone Rubber due to Dry-band Arcing and Thermal Decomposition. *IEEE Trans. Dielectrics and Electrical Insulation.* 5 No. 2: pp 281-289.

Kumagai, S., and Yoshimura, N. (2001). Tracking and Erosion of HTV Silicone Rubber and Suppression Mechanism of ATH. *IEEE Trans on Dielectrics and Electrical Insulation.* 8(2): pp 203-211.

Mackevich, J. and Simmons, S. (1997). Polymer Outdoor Insulating Materials Part II: Material Considerations. *IEEE Electrical Insulation Magazine.* **13(4)**: pp 10-16.

Mackevich, J. and Shah, M. (1997). Polymer Outdoor Insulating Materials Part I: Comparison of Porcelain and Polymer Electrical Insulation. *IEEE Electrical Insulation Magazine.* **13(3)**: pp 5-12.

Suda, T. (2001). Frequency Characteristics of Leakage Current Waveforms of an Artificially Polluted Suspension Insulator. *IEEE Trans on Dielectrics and Electrical Insulation.* **8(4)**: pp 705-709.

Sundhar, S., Bernstof, A., Goch, W., Linson, D. and Huntsman, L. (1992). Polymer Insulating Materials and Insulators for High Voltage Outdoor Applications. *IEEE Int Symposium on Electrical Insulation.* Baltimore USA. pp 222-228.

Tanrattanakul, V. and Udomkichdecha, W. (2001). Development of Novel Elastomeric Blends Containing Natural Rubber and Ultra-low-density Polyethylene. *J. App. Polymer Science.* **82**: pp 650-660.

Xuguang, L.,Yougong, W. and Fuyi, L. (2000). Study on Improving the Tracking and Erosion Resistance of Silicone Rubber. *The 6th. Int Conf on Properties and Applications of Dielectric Materials*. Xi'an, China. pp 342-345.

Yeh, J.T., Yang, H.M. and Huang, S.S. (1995). Combustion of Polyethylene Filled with Metallic Hydroxides and Crosslinkable Polyethylene. *J. Polymer Degradation and Stability*, **50:** pp 229-234.