BEHAVIOR OF CROSSLINKED POLYETHYLENE INSULATION OF MEDIUM AND HIGH VOLTAGE POWER CABLES UNDER UV RADIATIONS

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Abstract: *In this study, an experimental investigation of ultraviolet (UV) radiations effects on the high voltage cable crosslinked polyethylene (XLPE) insulation characteristics is presented. Measurements of mechanical, physical and electrical properties are also performed. In order to highlight the surface damages after ageing, different complementary techniques such as attenuated total reflectance - Fourier transformer infrared spectroscopy) and scanning electron microscopy are conducted. Obtained results show that several of the XPLE insulation properties are affected by exposition to UV radiations. Moreover, a correlation between mechanical, electrical and physical properties, and physico-chemical alterations was noticed. Furthermore, our study displayed prominently that there was a concurrence between crosslinking and chain breaking.*

Key words: *Ultraviolet (UV) radiations, Crosslinked polyethylene (XLPE), Insulation.*

1. Introduction

Owing to their excellent properties, polymeric insulating materials are widely used in electrical power equipment [1]. With age, like all materials, devices made of polymers undergo dramatic effects on their properties [2]. Actually, it is well known that the most significant degradation occurs during exposure to an aggressive environment. This will result in several modifications of polymer mechanical, physical and chemical properties.

Generally, polymers which are extensively used in outdoor applications are exposed to solar ultraviolet (UV) [3]. Radiation reaching the earth surface is characterized by wavelengths ranging from approximately 295 nm up to 2500 nm. The actinic range of solar UV radiation representing UV-A and UV-B is about 6% of the total radiation [4]. Previous studies have shown that UV radiations involve crucial degradations in the properties of polymer materials [5]. The recent studies have adopted several methods to monitor the aging condition of cable materials. They have reported that UV radiations can cause several evolutions in physical properties of polymers, like hydrophobic stability [6] or weight loss [7], and mechanical characteristics [8]. It has also demonstrated that all these changes are a consequence of material chemical modifications, such as chain scission and crosslinking [8].

Polyethylene in its crosslinked form (XLPE) is widely used as an electrical insulation in extruded power cables [9] and preferred by utilities worldwide [10]. It is gradually replacing other types of polyethylenes due to its greater mechanical and thermal stability [11]. The effect of the environmental constraints (temperature, humidity and pressure) on the XPLE characteristics has received considerable attention and several studies have been carried out on this topic. However, few works are dedicated to its photodegradation phenomenon [11], [12], [13]. Gulmine and Akcelrud [11] have evaluated the effect of UV-ageing in its appearance and chemical properties. Wu et al. [12] have shown that the products of XLPE photooxidation are mainly hydroperoxides and various carbonyl groups. The authors in [13] demonstrated that the kind of crosslinking agent (silane and peroxide) influences the XLPE’s degradation mechanism under UV.

The focus of this work is to investigate the possible changes in the properties of XLPE insulation subjected to UV. These changes are investigated using mechanical tests (tensile strength, elongation at break and surface hardness), physical experiments (surface wettability and water retention), electrical surface resistivity and Physico-chemical characterizations using attenuated total reflectance - Fourier transformer infrared spectroscopy (ATR-FTIR) and scanning electron microscopy (SEM).

2. Experimental Setup

2.1. Samples and UV Ageing Conditions

Square plates of 130 mm x 130 mm and 2 ± 0.2 mm thickness were moulded and crosslinked at 180°C under a pressure of 300 bars from granules of Borealis natural crosslinkable polyethylene compound HFDE LE4201R, using pressurized heat press. This material, in its granule form, contains polyethylene blended with 2% of dicumyl peroxide (DCP) as cross-linking agent and an antioxidant. The studied material is used as high voltage cable insulation. Artificial UV ageing undergone by the XLPE samples was carried out in an accelerated UV-aging chamber, designed and built specially for this investigation. The samples irradiation is accomplished using ten low-pressure vapor fluorescent lamps of 36 Watts characterized by wavelength irradiation ranging mostly (98%) from 350 nm to 400 nm. The lamps were placed 10 cm above the XLPE's top surface. The samples are subjected to the various experiments after each 20 hours of exposure. The maximum aging time is 240 hours. The ageing is performed under a temperature of 55±5°C without controlling the humidity.

2.2. Mechanical Properties

Mechanical tests were carried out to determine the evolution of the elongation at break, tensile strength and surface hardness as well to assess the general relaxation behaviour of the material under mechanical load. According to IEC 60811.1.1 (International Electrotechnic Committee) standard, the elongation at break and tensile strength tests are performed on samples having a dumbbell shape of 5 cm length, cut from the obtained plates. After each 20 h aging time, 7 samples were taken, the first five are intended for testing elongation at break and the tensile strength, and the two others are reserved for measuring the surface hardness.

2.2.1. Elongation at Break and tensile strength

Tensile testing (elongation at break and tensile strength), was carried out on a Schnek-Trebel testing machine. The experiments consist in breaking the sample, at ambient temperature, using a dynamometer which moves with speed of 50 mm/min. Elongation at break and tensile strength were measured simultaneously.

2.2.2. Surface Hardness

Surface hardness is a versatile tool for evaluating the mechanical properties of polymers [14]. It is a property directly related to the efficiency of polymerization and to the mechanical transitions, for instance, glass transition [15]. In our study, the measurement of this property was performed using an Amsler hardness tester.

2.3. Physical Properties

From the obtained plates, specimens in square form (6cm × 6cm) were cut. After each 20 hours of UV-exposure ten samples were removed from the UV-irradiation chamber. The first five are intended for evaluating the water absorption and the others five for measuring contact angle and work of water adhesion to XLPE surface evolutions.

2.3.1. Water Contact Angle and Work of Water Adhesion

The water contact angle measurement and work of water adhesion evaluation are frequently used in characterizing surface hydrophobic properties of various materials. Static contact angle is the equilibrium angle at which a liquid interface meets at the solids surface. Usually, the concept is illustrated with a small liquid droplet resting on a flat horizontal solid surface, which can identify the surface hydrophobicity (water repellant) and surface hydrophilicity (water attraction) of the materials [16].

In order to study the UV radiation effect on the hydrophobicity, a test ring was carried out. It comprises a micro-syringe, a torch, a samples holder and a high-resolution camera. An experimental procedure was thus followed to determine the contact angle value: it is to take pictures using the digital camera for a droplet of 10 ml of distilled water, deposited on the solid insulation surface. Contact angles are then determined. The measurement procedure with this device complies with the operation principle of a goniometer. The total water adhesion (W_A) calculation is related to the contact angle measurement, it is given by the following equation:

$$W_A = \gamma_W . (1 + cos\theta_W) \qquad (1)$$

Where $\gamma_{W=}$72.8 mJ/mm^2 is the surface tension of water and Θ_W is the contact angle.

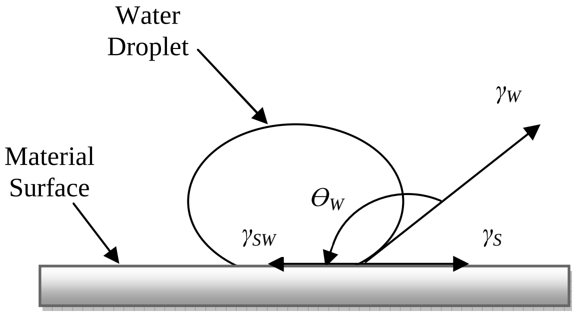


Fig.1 Contact angle of water droplet on the material surface

2.3.2. Water Absorption

The UV-exposed and Unexposed samples to UV were immersed into distilled water for 24 h to be saturated, and then dried in an oven for 2 hours at 105 °C. Because the samples had different volumes and weights, water absorbance, W_r (%) was adopted to quantify the amount of absorbed water. The weights of the samples before and after drying were recorded using an electronic balance. Water absorption is calculated using the formula:

$$W_r\,(\%) = (W_2 - W_1/W_1).100 \qquad (2)$$

Where W_1 and W_1 are, respectively, the mass of wet sample and the mass of dry sample.

2.4. Electrical Surface Resistivity

Surface resistance was measured according to IEC 60093 standard, using a Teraohmmeter and a resistivity measurement cell (three electrode method) as shown in Fig.2. Fig.3 is a sketch of the surface resistivity measurement cell; it is containing a guarded or measuring electrode (diameter, D_1=50 mm), a ring electrode (inner diameter, D_2=60 mm) and a counter electrode (diameter, D_3= 110 mm).

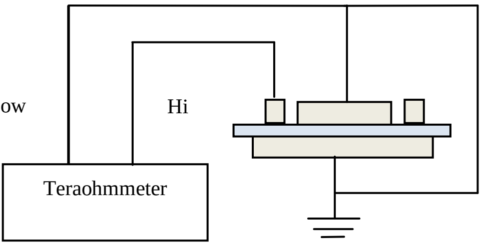


Fig.2 Experimental configuration for surface resistivity measurement according to CEI 60093

Surface resistance measurement was carried out at ambient conditions. It was obtained by applying a DC voltage of 500 V between the guarded electrode and the ring electrode. The value obtained after 60s of voltage application was recorded as the suitable resistance. Surface resistivity is related to the configurations and dimensions of the used electrodes. It is calculated by:

$$\rho_s = R_s.\frac{P}{g} \tag{3}$$

Where R_s is the measured resistance in ohm, P is the effective perimeter ($P = \pi\,(D_1 + D_2) / 2$) of the guarded electrode and g ($(D_2 - D_1) / 2)$) is the distance between the guarded and ring electrode.

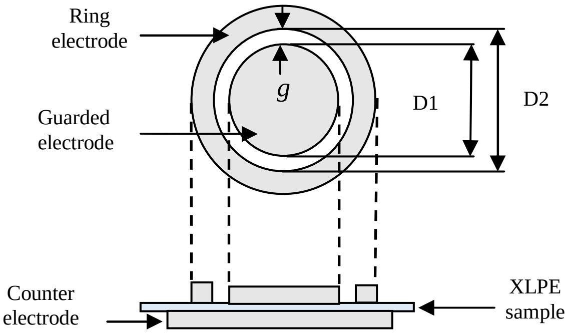


Fig.3 Electrode assembly for surface resistivity measurement

2.5. Attenuated Total Reflectance (ATR) Characterization

Recently, various techniques have been used to disclose the chemical changes underwent by polymers during and after degradation originated by several stresses [11]. ATR-FTIR is a widely-used technique for the analysis of polymer degradation. It is suited for sample surface analysis that is otherwise not accessible by transmission spectroscopy [17]. This technique allows for the assessment of the making and breaking of chemical bonds, one can gain insight into the degradation mechanisms present during the different aging process [18].

In our study, the chemical changes induced by UV radiations on the XLPE insulation have been evaluated using this technique. Hence, a JASCO FTIR-4200 spectrometer has been used for this purpose.

2.6. Scanning Electron Microscopy (SEM)

In order to study, the changes in morphology of UV- aged XLPE; micrographs of samples in different aging states were investigated on the surfaces by scanning electron microscopy (SEM). SEM has become a powerful technique in materials research [7]; it is based on the principle of electron interaction with matter. It allows obtaining images of the sample surface with high resolution and providing information about the morphology and the chemical composition of a solid material. In our work, the exposed XLPE's surfaces morphology were studied using Scanning Electron Microscope (SEM, Phillips XL30-type) operating at 20 kV in high vacuum.

3. Experimental Results and Discussions

3.1. Mechanical Properties

3.1.1. Elongation at Break and Tensile Strength

In general, the mechanical properties (elongation at break and tensile strength) of the polymers depend on their molecular weight, the presence of branches, crosslinks [19], crystallite thickness and crystalline – amorphous ratio [20]. These properties are controlled more by the changes occurring in the amorphous phase (phase that chains are in messy) [19]. Many authors have demonstrated that the changes of mechanical characteristics under several constraints are a consequence of chemical changes. However, a correlation between the evolution of elongation at break and tensile strength has been often excluded.

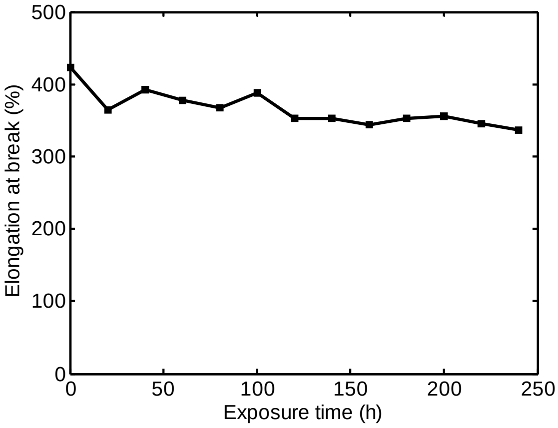


Fig.4 Evolution of elongation at break according to aging time

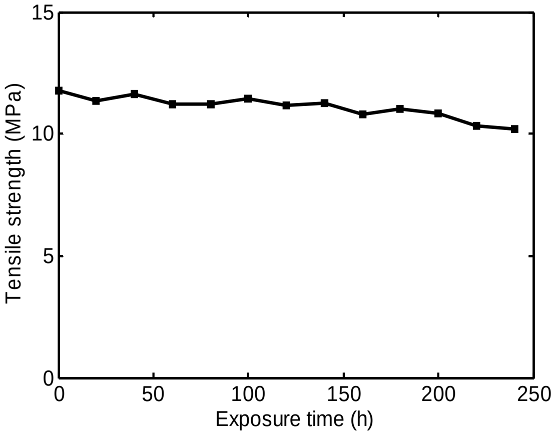


Fig.5 Evolution of tensile strength according to aging time

Figs 4 and 5 depict respectively the elongation at break and tensile strength evolutions. As it can be seen in these figures, the mechanical properties of XLPE insulation decrease with UV-exposure time. The elongation at break dropped from 423% to 350% after 120 hours of UV-exposure and reaches 336% at the aging end. For tensile strength, the decrease is slighter, so it decreases from 11.77 MPa 11.5 MPa after 120 hours and close the value of 10.20 MPa at the experiment end.

According to the literature [21], [22], [23], [24], [25], the observed facts can be attributed to the XLPE insulation photodegradation which is followed by chemical changes such as chain scission. These alterations lead to the decrease of both amorphous region size and molecular weight which lead to weakness and embrittlement of the material, to which can be attributed the decrease in the elongation at break and tensile strength. Kaczmarek et al. [21] have shown that the mechanical properties deterioration of polypropylene after UV irradiation is a consequence of main chain scission, which takes place mainly in its amorphous phase. Jin et al. [22] have proved that the reduction of mechanical properties can be attributed to the combination of growth in crystallinity and chain scission which gives rise to the stress concentration and crack propagation in material. Eve and Mohr [23] have correlated the mechanical parameters decrease to the reduction of the molecular weight of the polymer material, resulting from the photo-induced chain breaking. Cui et al. [24] have concluded that the embrittlement caused by chemical evolutions is a factor which affects the tensile properties. Al-Salem et al. [25] have deduced that the loss of amorphous regions due to the chemical alterations leads to the change in mechanical characteristics of polymers.

3.1.2. Surface hardness

Generally, surface hardness evolutions are often correlated to degradation. Under UV exposure, it was observed that this characteristic is sensitive to UV-induced degradation [26]. Considering this fact the hardness studies of the UV-exposed and unexposed samples were carried out. Fig.6 represents the XLPE insulation hardness evolution. As it can be seen in this figure, the surface hardness increases slightly. It grows from 54 shD to reaches 58 shD after 100 hours of UV-exposure and remains relatively constant after this period.

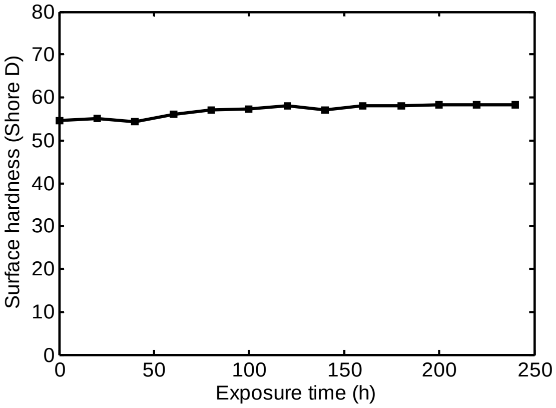


Fig. 6 Change of hardness according to aging time

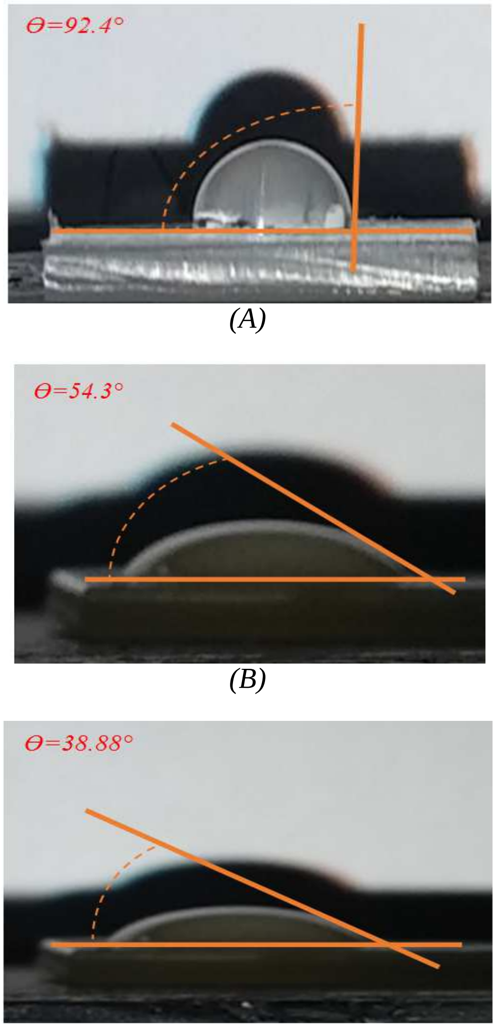
The obtained results show that chain breaking processes are not the predominant pathway of UV-degradation as always reported in several theories. Thereby, other phenomena such as crosslinking and end-linking that can affect the XLPE insulation mechanical properties (essentially hardness) may arise. Although, these two phenomena differ in their processes when polymers are subjected to ionising radiations, they lead to polymers having the same physical properties (high molecular weight, crystallinity….). The crosslinking mechanism consists in creating links between the molecules to form a network. While the end-linking process involves the linking of fragments to the main chain of a neighboring molecule to give a branched one with a higher molecular Weight [27].

3.2. Physical Properties

3.2.1. Water contact angle and work of water adhesion

The contact angle measurement indicates that UV exposure increases the wettability (Fig.7) of the XLPE insulation. Fig.8 shows that the contact angle decrease (wettability increase) is dramatic at the beginning of exposure, it decreased from 92.4° to 54.3° in the first 120 hours of treatment. After this phase, the decrease becomes less marked by increasing the length of UV exposure. The contact angle reaches the value of 38.88° at the end of UV-aging. Identical wettability behaviour was observed by many authors. Waddell et al. [28] have shown that the wettability of UV-Irradiated polydimethylsiloxane elastomer increased with an increase in exposure time until the angle reached a plateau; in which no significant changes in wettability were observed. Gaubner et al. [29] have also noticed a substantial increase in wettability polydimethylsiloxane irradiated at 172 nm.

The contact angle decrease can be assigned to the creation of new polar groups and to the increase of surface roughness. The contact angle measurements results are in good agreement with those reported in previous works. Jofre-Reche et al. [30] ascribed the contact angle decrease to the creation of carbon–oxygen groups and to surface morphology changes (roughness). O'Connell et al. [31] have shown that both polar and non-polar group's rise leads to the decrease of contact angle in non-polar polymers. Fig.9 shows that the work of water adhesion behaviour correlates with the wettability increase. So, it increased considerably at the beginning of ageing and slowed thereafter. The rise of work adhesion can be attributed to the photooxidation phenomenon which leads to the increase of surface free energy and polar contents.



(A)

(B)

(C)

Fig.7 Water contact angle values of XLPE samples at: - (A): 0h, (B):120h, (C) 240h of UV exposure. Surface hydrophobicity of samples was reduced after UV exposure

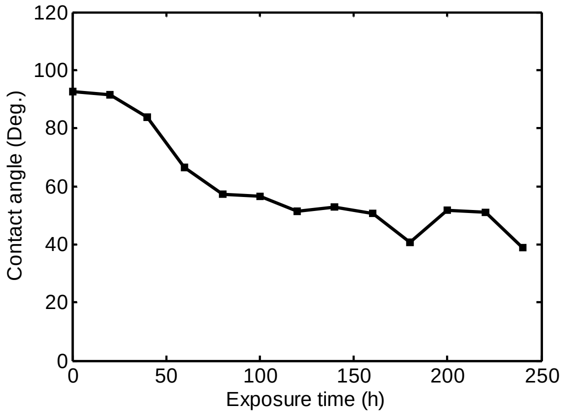


Fig. 8 Change in contact angle as a function of UV aging time

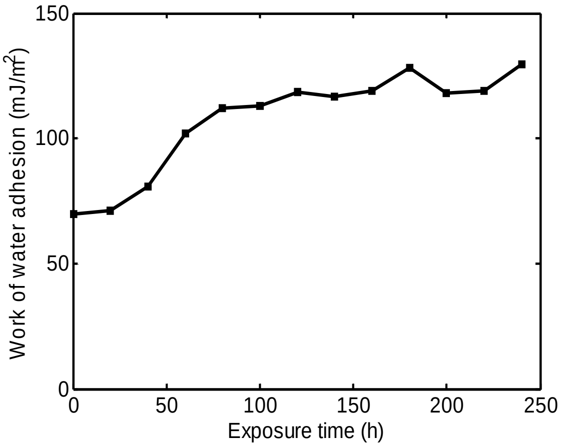


Fig. 9 Change in work of water adhesion as a function of UV aging time

2.2.2. *Water absorption*

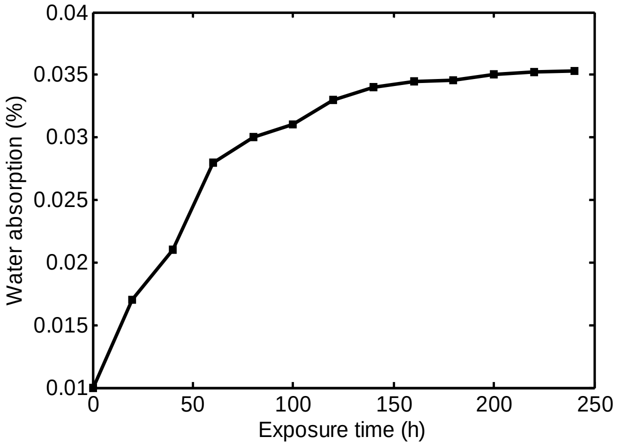


Fig. 10 Change in water retention as a function of UV aging time

Fig.10 displays the evolution of retained water with irradiation time. As it can be seen in this figure, the water content increased rapidly at the beginning of treatment and after that, the absorption process inside the XLPE insulation becomes less important. This behaviour is normal; it has been noted and explained by several authors. Asmatulu et al. [32] have attributed the increase of polymer coating water retention under UV to the increase of wettability (decrease of contact angle), which lead to water spread on the coating surface. Rosu et al. [33] have assigned the increase of water retained amount to the formation of chemical structures with high polarity as a result of photochemical and photo-oxidation processes.

3.3. Electrical surface resistivity

Surface resistivity or conductivity is one of properties that represent significantly the insulation state. It is frequently used as a diagnostic tool for characterizing aging of polymers under several constraints, in particular under UV radiations [34]. The change of this property is an indication of the physical and chemical properties evolutions.

Qualitatively, we notice that surface resistivity underwent variations with respect to UV-exposure time. Globally, the surface resistivity of XLPE decreases with exposure time. This decrease can be correlated with the decrease of hydrophobicity and the change in the surface chemical structure. Indeed, the photooxidation phenomenon leads to change in the surface chemical structure and to creation and accumulation of surface charges. These charges could lead to an increase of both wettability and surface conductivity.

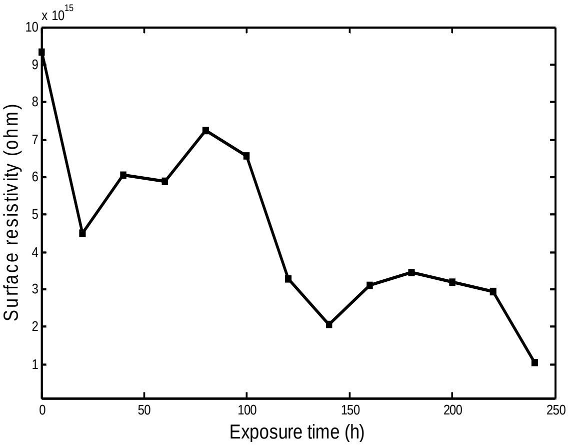


Fig. 11 Evolution of surface resistivity with UV aging time

3.4. Attenuated Total Reflectance (ATR)

In order to identify and to understand the structure changes of XPLE induced by the UV radiations, infrared spectroscopy ATR-FTIR investigations are conducted. Figure 12 shows the transmittance FTIR spectra of unaged and UV-aged XPLE. Globally, spectra of virgin and irradiated samples display similar characteristics, but indicate changes in the intensities of several peaks. The main results are summarized as follow:

a. The observed peaks at 721, 2847 and 2915 cm^{-1} assigned to the methylene CH_2 of polyethylene [35], and the CH_3 peak at 1369 cm^{-1} decrease,
b. The intensities of the small peaks at 1186, 1264 and 1315 cm^{-1} assigned, respectively, to C=C bond, Mehyl group and Acetophenone group decrease and then disappear for higher expose time,
c. The small peak corresponding to antioxidant at 1129 cm^{-1} decreases then disappear for higher expose time. Indeed, the antioxidant loss may be responsible of the polymer degradation,
d. The peak at 2361 cm^{-1} assigned to CO_2 increases with exposure time. This increase indicates an increase in the photo oxidation activity.
e. The two narrow and weak absorption peaks at 3600 and 3626 cm^{-1} are attributed to non-hydrogen-bonded alcohols and hydroperoxides [12].

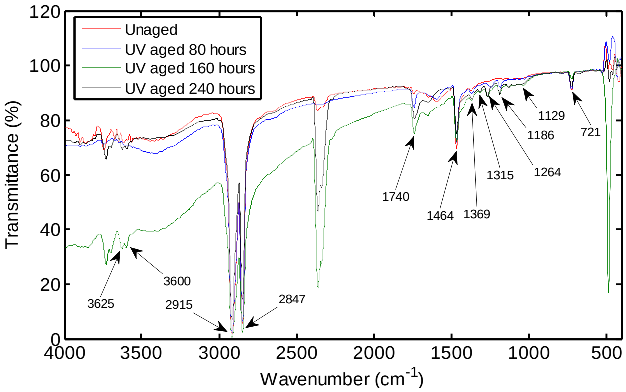


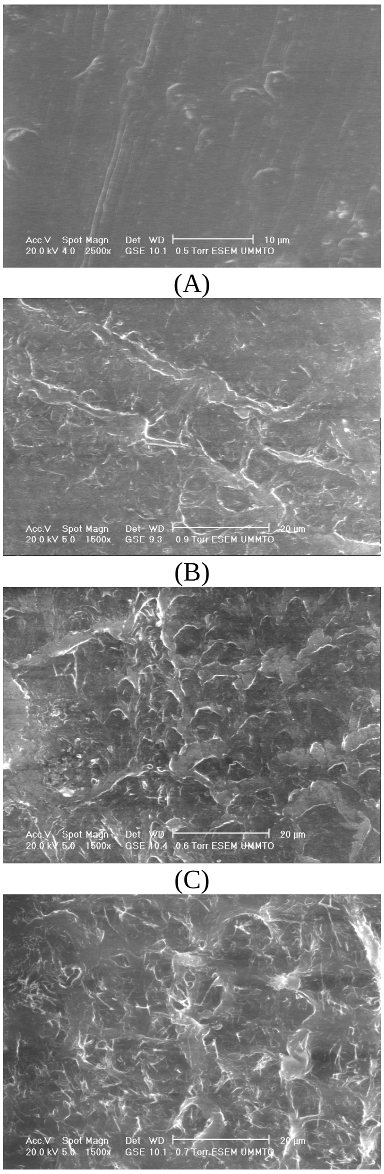
Fig. 12 FTIR- ATR Spectrum of aged and ungaed XLPE under UV radiations

These changes in peaks intensities and the scission of several bonds reveal a degradation of the XPLE after irradiation. Indeed, the chains scission leads to the diminution of the mechanical properties (elongation-at-break and tensile strength). On the other hand, chains scission reactions contribute to the formation of vinylidene and vinyl groups and other unsaturated groups in XLPE chains. These groups are responsible for the color changes of the material.

3.5. Scanning Electron Microscopy (SEM)

Fig.13. (A-D) shows the micrographs of aged and unaged XLPE samples. As it is observed, no significant changes in surface morphology of the sample are observed. Thus, the surface appearance of all the samples is almost identical. By comparing these micrographs, it is observed that UV-exposed samples showed neither pores nor cracks, but with less smooth and homogenous surfaces than the exposed one. So, the aged samples exhibit slight changes of roughness and color. For longer exposure time, oxidation induced by UV may take place in the amorphous region of the semi-crystalline studied material (XLPE), because the

crystalline region is impermeable to oxygen. On the other hand, the superficial layer crystallizes and shrinks, inducing craters which lead to the material weakness and fragility.



(A)

(B)

(C)

(D)

Fig. 13 SEM micrographs of the samples: -(A): Unaged, (B): Aged 80h, (C): Aged 160h, (D) Aged 240h.

The results are in good accordance with those reported previously [36]-[37]-[38]. Many works have shown that no significant changes in occurs in the UV-aged insulators morphology [36]. Venkatesulu and Thomas [37] noticed that UV radiations lead to the roughness increase of the polymeric insulators. Woo et al. [38], when studying the UV-ageing of certain composites, have shown that microcracks started to appear on the material surface after about 300 hours under UV-exposure.

4. Conclusions

In this work, the XLPE insulation behaviour under UV irradiation has been studied. Typical mechanical parameters (elongation at break, tensile strength and surface hardness), electrical surface resistivity and physical properties (water retention, contact angle and work of water adhesion) have been determined for the high voltage cable insulation. The evolution of these properties has been correlated to the physico-chemical photo-degradation of the insulating polymer. Also, it has been shown that UV exposure of XLPE insulation leads to evolutions in the mechanical properties. The contact angle and work of water adhesion measurements show that UV irradiation increases the wettability of the XLPE insulation. The reduced hydrophobicity is supported by a decrease in the contact angle and an increase of the total water adhesion. The physical evolutions lead to the rise of retained water amount inside the material and to the decrease of electrical resistivity. The surface morphology changes (increase of roughness) showed by SEM micrographs and chemical alterations confirmed by ATR analysis substantiate the mechanical (decrease of elongation at break and tensile strength and increase of surface hardness) and physical (increase of wettability and water absorption) behaviors. Generally, it was showed that UV irradiation leads to an increase of some of the XLPE insulation properties, associated with deterioration of others.

References

1. Sekii, Y. *Degradation of low-density polyethylene and cross-linked polyethylene by partial discharge,* IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 17, No. 1, pp. 116-124, 2010.
2. Bouguedad, D., Jbara, O., Rondot, S., Mekhaldi, A., Hadjadj, A. Investigation of accelerated thermal aging of EPDM polymer by electric tests in air and by means of a SEM technique in high vacuum, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.19, No. 3, pp. 981-989, 2012.
3. Ramanujam, M., Wachtendorf, V., Purohit, P.J., Mix, R., Schönhals, A., Friedrich, J.F. *A detailed dielectric relaxation spectroscopy study of artificial UV weathered low density polyethylene*, Thermochimica Acta, Vol. 530, pp. 73-78, 2011.
4. Feldman, D. *Polymer weathering: Photo-Oxidation*, Journal of Polymers and the Environment, Vol. 10, No. 4, pp. 163-713, 2002.
5. Doumingue, L., Mallarino, S., Cohendoz, S., Feaugas, X., Bernard, J. *Extrinsic fluorescence as a sensitive method for studying photo-degradation of high density polyethylene: Part I,* Current Applied Physics, Vol. 10, No. 4, pp. 1211-1215, 2010.
6. Youn, B.H., Huh, C.S. *Surface degradation of HTV silicone rubber and EPDM used for outdoor insulators under accelerated ultraviolet weathering condition,* IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 12, No. 5, pp. 1015-1024, 2005.
7. Vanga Bouanga, C., Couderc, H., Fréchette, M.F., Savoie, S., Malucelli, G., Camino, G., Castellon, J., Bannet, L., Toureille, A. *Dielectric study of low glass transition temperature cycloaliphatic UV-curable epoxy networks*, IEEE Transactions on Dielectrics and

Electrical Insulation, Vol. 19, No. 4, pp. 1269-1282, 2012.

8. Boubakri, A., Guermazi, N., Elleuch, K. Ayedi, H.F. *Study of UV-aging of thermoplastic polyurethane material*, Materials Science and Engineering: A, Vol. 527, No. 7-8, pp. 1649-1654, 2010.
9. Fothergill, J.C., Dodd, S.J., Dissado, L.A., Liu, T., Nilsson, U.H. *The measurement of very low conductivity and dielectric loss in XLPE Cables: A possible method to detect degradation due to thermal aging*, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 18, No. 5, pp. 1544-1553, 2011.
10. Al-Arainy, A., Malik, N.H., Qureshi, M.I., Al-Saati, M.N. *The performance of strippable and bonded screened medium-voltage XLPE-insulated cables under long-term accelerated aging*, IEEE Transactions on Power Delivery, Vol. 22, No. pp. 2, 744-751, 2007.
11. Gulmine, J.V., *Akcelrud, L. Correlations between Structure and Accelerated Artificial Ageing of XLPE*, European Polymer Journal, Vol. 42, No. 3, pp. 553-562, 2006.
12. Wu, Q., Qu, B., Xu, Y., Wu, Q. *Surface photo-oxidation and photostabilization of photo cross-linked polyethylene*, Polymer Degradation and Stability, Vol. 68, No. 1, pp. 97-102, 2000.
13. Celina, M., George, G.A. *Characterisation and degradation studies of peroxide and silane crosslinked polyethylene*, Polymer Degradation and Stability, Vol. 48, No. 2, pp. 297-312, 1995.
14. Larché, J.F., Bussiere, P.O., Thérias, S. J., Gardette, L. *Photooxidation of polymers: Relating material properties to chemical changes*, Polymer Degradation and Stability, Vol. 97, No. 1, pp. 25-34, 2012.
15. Bardi, M.A.G., Machado, L.D.B. *Accompanying of parameters of color, gloss and hardness on polymeric films coated with pigmented inks cured by different radiation doses of ultraviolet light*, Radiation Physics and Chemistry, Vol. 81, No. 9, pp. 1332-1335, 2012.
16. Yasuda, T., Okuno, T., Yasuda, H. *Contact angle of water on polymer surfaces*, Langmuir, Vol. 10, No. 7, pp. 2435-2439, 1994.
17. Kupper, L., Gulmine, J.V., Janissek, P.R., Heise, H.M. *Attenuated total reflection infrared spectroscopy for micro-domain analysis of polyethylene samples after accelerated ageing within weathering chambers*, Vibrational Spectroscopy, Vol. 34, No. 1, pp. 63-72, 2004.
18. Bhargava, S., Kubota, M., Lewis, R.D., Advani, S. G., Prasad, A.K., Deitzel, J.M. *Ultraviolet, water, and thermal aging studies of a waterborne polyurethane elastomers based high reflectivity coating*, Progress in Organic Coatings, Vol. 79, pp. 75-82, 2015.
19. Briassoulis, D., Aristopoulou, A., Bonora, M., Verlodt, I. *Degradation Characterisation of agricultural low-density polyethylene Films*, Biosystems Engineering, Vol. 88, No. 2, pp. 131-143, 2004.
20. Boukezzi, L., Boubakeur, A. *Prediction of mechanical properties of XLPE cable insulation under thermal aging*, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 20, No. 6, pp. 2125-2134, 2013.
21. Kaczmarek, H., O1dak, D., Malanowski, P., Chaberska, H. *Effect of short wavelength UV-irradiation on ageing of polypropylene/cellulose compositions*, Polymer Degradation and Stability, Vol. 88, No. 2, pp. 189-198, 2015.
22. Jin, J., Chen, S., Zhang, J. *UV aging behaviour of ethylene-vinyl acetate copolymers (EVA) with different vinyl acetate contents*, Polymer Degradation and Stability, Vol. 95, No. 5, pp. 725-732, 2010.
23. Eve, S., Mohr, J. *Effects of UV-irradiation on the thermo-mechanical properties of optical grade poly (methyl methacrylate)*, Applied Surface Science, Vol. 256, No. 9, pp. 2927-2933, 2010.
24. Cui, H., Hanus, R., Kessler, M.R. Degradation of ROMP-based bio-renewable polymers by UV radiation, Polymer Degradation and Stability, Vol. 98, No. 11, pp. 2357-2365, 2013.
25. Al-Salem, S.M., Abraham, G. Al-Qabandi, O.A., Dashti, A.M. *Investigating the effect of accelerated weathering on the mechanical and physical properties of high content plastic solid waste (PSW) blends with virgin linear low density polyethylene (LLDPE)*, Polymer Testing, Vol. 46, pp. 116- 121, 2015.
26. Bartolommeo, P., Irgoyen, M., Aragon, E., Frizzi, M.A., Perrin, F.X. *Dynamic mechanical analysis and Vickers micro hardness correlation of polymer coating UV ageing characterisation*, Polymer Degradation and Stability, Vol. 72, No. 1, pp. 63-68, 2001.
27. Mujahid, M., Singh, P., Srivastava, D.S., Gupta, S., Avasthi, D.K., Kanjilal, D., *Study of chain scission versus crosslinking in MeV ion-irradiated polycarbonate using dielectric constant measurements and UV spectroscopy*, Radiation Measurements, Vol. 38, No. 2, pp. 197-203, 2004.
28. Waddell, E.A., Schreeves, S., Carrell, H., Perry, C., Reid, B.A., McKee, J. *Surface modification of Sylgard 184 polydimethylsiloxane by 254 nm excimer radiation and characterization by contact angle goniometry, infrared spectroscopy*, Applied Surface Science, Vol. 254, No. 17, pp. 5314-5318, 2008.
29. Graubner, V., Jordan, R., Nuyken, O., Kötz, R., Lippert, I., Schnyder, B., Wokaun, A. *Wettability and surface composition of poly (dimethylsiloxane) irradiated at 172 nm*, Polymeric Materials: Science & Engineering, Vol. 88, pp. 488-489, 2003.
30. Jofre-Reche, J.A., Martin-Martinez, J.M. *Selective surface modification of ethylene-vinyl acetate and ethylene polymer blend by UV–ozone treatment*, International Journal of Adhesives and Adhesion, Vol. 43, pp. 42-53, 2013.
31. O'Connell, C., Sherlock, R., Ball, M.D., Aszalós-Kiss, B., Prendergast, U., Glynn, T.G. *Investigation of the hydrophobic recovery of various polymeric biomaterials after 172 nm UV treatment using contact angle, surface free energy and XPS measurements*, Applied Surface Science, vol. 255, No. 8, pp. 4405-4413, 2009.
32. Asmatulu, R., Mahmud, G.A., Zhang, B., Ahmed, I. *Effects of UV Light on water contact angles of nanocomposite coatings*, In: SAMPE Fall Technical Conference, Salt Lake City, 2010.
33. Rosu, D., Rosu, L., Mustata, F., Varganici, C-D. *Effect of UV radiation on some semi-interpenetrating polymer networks based on polyurethane and epoxy resin*, Polymer Degradation and Stability, Vol. 97, No. 8, pp. 1261-1269, 2012.
34. Gao, Y., Du, B.X., Zhang, J.W. *Measurement of surface resistivity on gamma-ray irradiated polymer insulating materials*, Conference Proceedings of ISEIM, pp. 161-

164, Kyoto, 2011.

35. Shimada, A., Sugimoto, M., Kudoh, H., Tamura, K., Segushi, T., *Degradation distribution in insulation materials of cables by accelerated thermal and radiation ageing*, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 20, No. 6, pp. 2107-2116, 2013.
36. Farhadinejad, Z., Ehsani, M., Ahmadi-Joneidi, I., Shayegani, A.A., Mohseni, H. *Effects of UVc radiation on thermal, electrical and morphological behavior of silicone rubber insulators*, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 19, No. 5, pp. 1740-1749, 2012.
37. Venkatesulu, B., Thomas, M.J. *Long–term accelerated weathering of outdoor silicone rubber insulators*, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 18, No. 2, pp. 418-424, 2011.
38. Woo, R.S.C., Chen, Y., Zhu, H., Li, J., Kim, J., Leung, C.K.Y., *Environmental degradation of epoxy–organoclay nanocomposites due to UV exposure. Part I: Photo-degradation*, Composites Science and Technology, Vol. 67, No. 15-16, pp. 3448-3456, 2007.