

Aging Performance of Low-Density Polyethylene/Silicone Rubber Blends Insulators Under Contaminated Conditions

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Abstract- Insulation materials are a vital part of the electrical system in all kinds of high voltage (HV) Transmission lines. Environmental stresses affect the performance of all types of insulation materials over time. Dielectric breakdown strength (DBS), Hydrophobicity, Leakage current (LC), internal partial discharge and volume resistivity are important parameters that degraded in the service environment. The materials stand best in outdoor insulation, with the lowest partial discharge, highest breakdown strength, high hydrophobic, Lowest Leakage current, and highest volume resistivity. Enhancement of these parameters is a potential avenue for many researchers over the period. In this study various Polythene/Silicone rubber blends were prepared and aged for 1000 hours in an accelerated environment to investigate the enhancement in their outdoor performance.

Index Terms-- Dielectric breakdown strength (DBS), Hydrophobicity, Internal partial discharge (PD), Leakage Current (LC), Low-density polyethylene (LDPE), Service aging.

I. INTRODUCTION

High voltage (HV) insulating materials have been evolved for over 100 years. At the commencement of the 20th century, HV insulating materials were mainly natural fabrics such as rubber, pitch, marble, and mica. The study by Alwaan et al. (2015), Ameli et al. (2014) and Zhang et al. (2015) found that insulating materials were extricated directly from oils, natural minerals, plants, etc., and these materials were contemplated the 1st generation of insulating materials[1-3]. These materials possess limited electrical properties like resistivity and breakdown strength.

Polyethylene has long been utilized as a high-voltage cable insulation material due to its excellent physical, chemical, and electrical characteristics. Because of their minute size, in addition to surface effect, inorganic nanoparticles can amend polyethylene's electrical and mechanical properties, like dielectric breakdown strength (DBS), volume resistivity (VR), tensile strength (TS), permittivity, space charge, and dielectric loss (DL) properties. Polyethylene nanocomposites are considered an auspicious contender for high voltage direct current (HVDC) applications.

The study by S. Li et al. (2010) found that consistently incrementing demand for electrical power, leading to expeditious growth in high voltage insulating materials [4]. With the evolution of polymers, the insulator market was immersed with artificial materials such as insulating varnishes, composites, and adhesive substances. Hence, these polymer materials are considered as the 2nd generation of high voltage insulating

materials. Moreover, polymer substances exhibit more remarkable electrical properties than the 1st generation of insulating materials (natural materials). Meanwhile, in the commencement of the 21st century, the caliber of electrical power systems perpetuated to expand.

The study by Soundarajan et al. (2003) found that thermoplastic elastomer (TPE) is considered as 3rd generation polymeric material that is anticipated most of the benchmarks of high-voltage outdoor insulation, it offers advantages over silicone rubber and other thermoset polymers in terms of processing speed, efficiency, and cost as a thermoplastic. Furthermore, it is 100% recyclable and reusable, making it ecologically beneficial [5].

The study by Soundarajan et al. (2007) evaluated 28-kV, environmentally friendly, thermoplastic elastomeric (TPE) insulators for long-term performance under faintly modified IEC-1109 5,000-hrs conditions[6]. He made changes that comparably resembled the physical environment to the IEC test conditions. Uniform Ultraviolet (UV) radiation, rain, heat, salt fog, and humidity, as well as electrical (HV) stresses, are all used. There was discoloration, hydrophobicity loss, and hydrocarbon bond loss after 5000 hours of age. Despite the molecular and microstructural alterations, the insulators appeared to be in good condition.

The study by Jana et al. (2003) found that Polyethylene/silicone rubber combination is one kind of thermoplastic elastomer (TPE) mixture that has been detailed studied due to the perspective of silicone rubber (SR) and

Polyethylene (PE) as high voltage insulating materials [7]. For low and high-temperature cable applications, silicone rubber (SR) produces remarkable results. Because of silicone rubber's (SR) superior properties in outdoor insulations, humid and very polluted environments are suitable for its applications.

Matsunaga and Whitney (2000) suggested that Fourier-transform infrared spectroscopy (FTIR) techniques and dihydrogen monoxide (H₂O) as a method of determining low-density polyethylene (LDPE) [8]. In this study, they found that corona activity can expedite the slow process of the microbiological defile. It was additionally visually examined that ultraviolet (UV) light was a significant degradation aspect compared to biological defile and corona discharge.

The study by Vadahanambi et al. (2009) discussed the example of polythene, which is non-polar [9]. The easing is not resulting from dipole directions. However, on the addition of silicone rubber (SR), the introduction of dipoles results from the presence of nano-fillers within the silicone rubber (SR) phase; As a result, the orientation of dipoles was delayed with the application of an electric field. Thus, the tan δ incremented as silicone rubber (SR) content increased.

The study by Reid et al. (2011) Electric charges that partially bridge the insulation between electrodes are called partial discharges (PD) [10]. They can be categorized as internal and external partial discharges. Corona discharges and surface discharges are examples of shallow partial discharges. Air voids (known as holes in solid insulation and bubbles in liquid insulation) within insulation materials cause internal partial discharges.

Singha and Thomas (2008) studied the dielectric breakdown strength (DBS), volume resistivity (VR), and permittivity of epoxy nanocomposites using TiO₂, ZnO, and Al₂O₃ nanofillers [11]. The dielectric breakdown strength (DBS) increased significantly with TiO₂ filler loadings of 0.2wt% and 0.5wt% in comparison to raw epoxy. However, with 1wt% & 5wt% TiO₂ filler loadings, the dielectric breakdown strength (DBS) was reduced compared to natural epoxy. In comparison to natural epoxy, ZnO loading up to 1wt% results in lower permittivity values. The permittivity values for ZnO loading up to 5wt% were compared to natural epoxy higher. A decrease in volume resistivity (VR) is seen for both ZnO and TiO₂ nanocomposites up to a certain filler level, but then a rise is observed beyond that level. For Al₂O₃ with filler loading, volume resistivity (VR) values were high until 1wt%, then gradually decreased. The enhanced characteristics of nanocomposites have been steadily identified and understood by numerous theoretical models, according to current research on polyethylene/TiO₂ nanocomposites. These characteristics are only true of nanocomposites that are not aged. Aged nanocomposites retain unclear properties. According to studies, cable insulation operates at a maximum temperature of 90 degrees Celsius. The study by Dalal et al. (2005) found that insulation material's strong dielectric characteristics may cause undesirable

disadvantages in its performance at high-temperature conditions [12]. As a result, more study into the thermal aging characteristics of polyethylene/TiO₂ nanocomposites is required.

Most researchers have evaluated the electrical properties of virgin samples using different materials and nanofillers with different weight percentages. This study evaluated virgin samples with aged LDPE/SiR blends samples using three different nanofillers such as SiO₂, TiO₂ and TiO₂@SiO₂ under contaminated conditions in a specially fabricated weathering chamber for 1000 hours. Electrical properties (Dielectric breakdown strength, Leakage Current and hydrophobicity) have been evaluated before and after aging

II. MATERIALS AND METHODOLOGY

A. MATERIALS

Based on this study, LDPE was used as the base polymer. Plastic LDPE has a density of 910 ~ 0.925 g/cm³ and a melting point of 108°C. Among the nanofillers used are titanium dioxide (TiO₂), silicon dioxide (SiO₂), and titanium dioxide coated with silicon dioxide (TiO₂@SiO₂). Table I summarizes the physical properties of individual nanofillers.

TABLE I
CHARACTERISTICS OF NANOFILLERS

Properties	SiO ₂	TiO ₂	TiO ₂ @SiO ₂
Size of Particles	28 nm	30-50 nm	15-25 nm
Density (g/cm ³)	2.44	4.23	4.24
Surface Area (m ² /g)	158	67.66	40-60
Purity (%)	99.50	99.50	99.50
Melting Point (°C)	1600	1844	2791
Boiling Point (°C)	2230	2973	1841
PH	3.70 ~ 4.70	6.10	4.60 ~ 5.50

B. PREPARATION OF MATERIALS

By using the direct dissemination method (solution mixing method), we incorporated LDPE and nanofillers into our formulation. The study by Kalaitzidou et al. (2007), Kim et al. (2006) & Yang and Nelson (2006) studied Mixing melts (Kalaitzidou et al., 2007; Kim et al., 2006; Yang & Nelson, 2006) or mixing solutions [13-15] are two methods of direct dissemination. To remove any residue of moisture from the surface of the nanofillers, the samples were first heated at 100°C for 5 minutes. After adding the nanofillers to ethyl acetate, the mixture was stirred by a magnetic stirrer for 15 minutes before ultrasonically sonicating for 20 minutes to give the final formulation. In the Ethyl Acetate/Nano Filler solution, weighted quantities of LDPE (base matrix) were added and ultrasonically sonicating for 20 minutes, followed by 15 minutes of magnetic stirring at 60°C and 700 rpm. A nanofiller matrix integrated with LDPE nanocomposites was eventually formed after ethyl acetate evaporated from the solution. After mixing the LDPE and nanocomposite, stainless

steel molds were then used to melt the mixed material for 20 minutes at 125°C. For the next 20 minutes at 30 ° C, the samples were put in an oven. During the experiment, 60 mm-diameter circular samples with a thickness of 2 mm were created. For various filler loadings, the prepared nanocomposites are listed in Table II. Figure 1 and 2 shows the experimental setup.

TABLE II
NANO FILLER CONCENTRATION

Sample	Nomenclature		
LDPE (Raw)	L01		
% of Nanofillers	0.25%	0.5%	0.8%
LDPE/TiO2	LT01	LT02	LT03
LDPE/SiO2	LS01	LS02	LS03
LDPE/TiO2@SiO2	LTS01	LTS02	LTS03

C. METHODOLOGY

Step 1: Sample Preparation

Step 2: 1000 hours Experiment (Under Multi Stresses: High Voltage, UV Radiation, Humidity, Heat and Acid rain)

Step 3: Characterization of Parameters (Dielectric Breakdown Strength, Leakage Current & Hydrophobicity)

Step 4: Results and Discussion



FIGURE 1. Experimental Setup



FIGURE 2. Equipment inside Chamber

III. RESULTS AND DISCUSSION

A. DIELECTRIC BREAKDOWN STRENGTH

The study by Wels et al. (2018) defined that an insulating material's dielectric strength is the voltage required to cause a dielectric breakdown of the material [16]. Dielectric Breakdown Strength (DBS) variations of LDPE base material with different nanocomposites of LDPE/TiO₂, LDPE/SiO₂ and LDPE/TiO₂@SiO₂ are given as follows.

Least Variation of 10.62 KV was observed in LDPE/0.5%TiO₂ from virgin to 1000 hours under accelerated stresses. Highest Variation of 32.25 KV was observed in LDPE/0.25%TiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 23.18 KV was observed in LDPE after 1000 hours under accelerated stresses. Highest Value 53.40 KV was observed in LDPE/0.5%TiO₂ after 1000 hours under accelerated stresses as shown in Fig. 3.

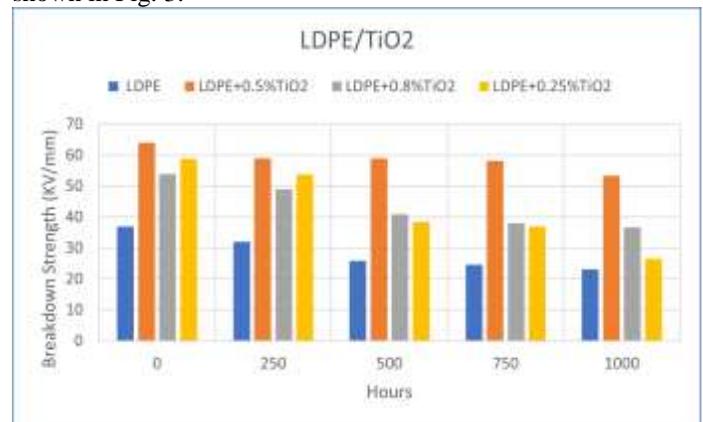


FIGURE 3. Change in Breakdown Strength (KV/mm) of LDPE/TiO₂ nanocomposites with aging

Least Variation of 13.82 KV was observed in LDPE from virgin to 1000 hours under accelerated stresses. Highest Variation of 33.48 KV was observed in LDPE/0.8%SiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 25.00 KV was observed in LDPE/0.5%SiO₂ after 1000 hours under accelerated stresses. Highest Value 46.46 KV was observed in LDPE/0.25%SiO₂ after 1000 hours under accelerated stresses as shown in Fig. 4.



FIGURE 4. Change in Breakdown Strength (KV/mm) of LDPE/SiO₂ nanocomposites with aging

Least Variation of 8.20 KV was observed in LDPE/0.5%TiO₂@SiO₂ from virgin to 1000 hours under

accelerated stresses. Highest Variation of 13.82 KV was observed in LDPE/0.25%TiO₂@SiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 22.80 KV was observed in LDPE/0.8%TiO₂@SiO₂ after 1000 hours under accelerated stresses. Highest Value 24.26 KV was observed in LDPE/0.25%TiO₂@SiO₂ after 1000 hours under accelerated stresses as shown in Fig. 5.



FIGURE 5. Change in Breakdown Strength (KV/mm) of LDPE/TiO₂@SiO₂ nanocomposites with aging

B. LEAKAGE CURRENT

The study by Amin et al. (2009) defined that an electric current flowing from the surface of the insulation even when it is in good condition is known as leakage current [17]. Blackburn (1992) found that if the leakage current (LC) value exceeds a certain threshold point, it causes an insulation material to degrade more rapidly [18]. Leakage Current variations of LDPE base material with different nanocomposites of LDPE/TiO₂, LDPE/SiO₂ and LDPE/TiO₂@SiO₂ are given as follows.

Least Variation of 8.20 mA was observed in LDPE/0.8%TiO₂ from virgin to 1000 hours under accelerated stresses. Highest Variation of 18.74 mA was observed in LDPE/0.25%TiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 9.63 mA was observed in LDPE/0.5%TiO₂ after 1000 hours under accelerated stresses. Highest Value 38.72 mA was observed in LDPE/0.25%TiO₂ after 1000 hours under accelerated stresses as shown in Fig. 6.

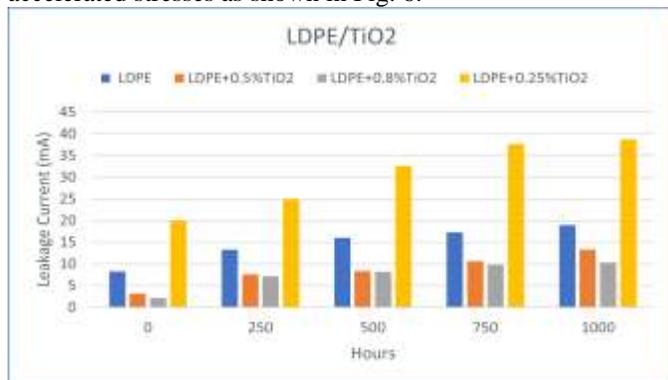


FIGURE 6. Change in Leakage Current (mA) of LDPE/TiO₂ nanocomposites with aging

Least Variation of 8.00 mA was observed in LDPE/0.5%SiO₂ from virgin to 1000 hours under accelerated stresses. Highest

Variation of 14.00 mA was observed in LDPE/0.25%SiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 11.32 mA was observed in LDPE/0.5%SiO₂ after 1000 hours under accelerated stresses. Highest Value 17.53 mA was observed in LDPE/0.25%SiO₂ after 1000 hours under accelerated stresses as shown in Fig. 7.

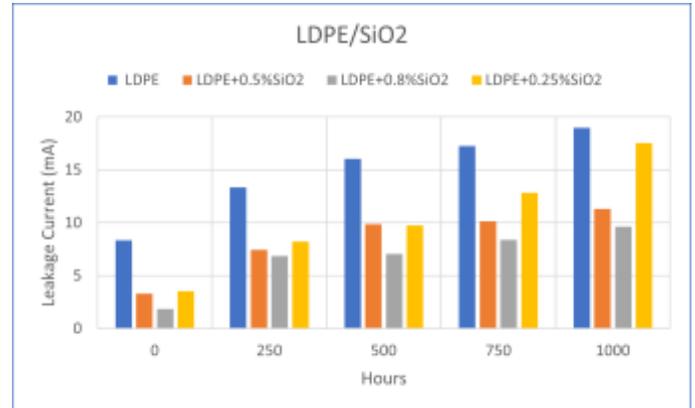


FIGURE 7. Change in Leakage Current (mA) of LDPE/SiO₂ nanocomposites with aging

Least Variation of 1.12 mA was observed in LDPE/0.5%TiO₂@SiO₂ from virgin to 1000 hours under accelerated stresses. Highest Variation of 4.18 mA was observed in LDPE/0.25%TiO₂@SiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 3.88 mA was observed in LDPE/0.5%TiO₂@SiO₂ after 1000 hours under accelerated stresses. Highest Value 6.50 mA was observed in LDPE/0.25%TiO₂@SiO₂ after 1000 hours under accelerated stresses as shown in Fig. 8.

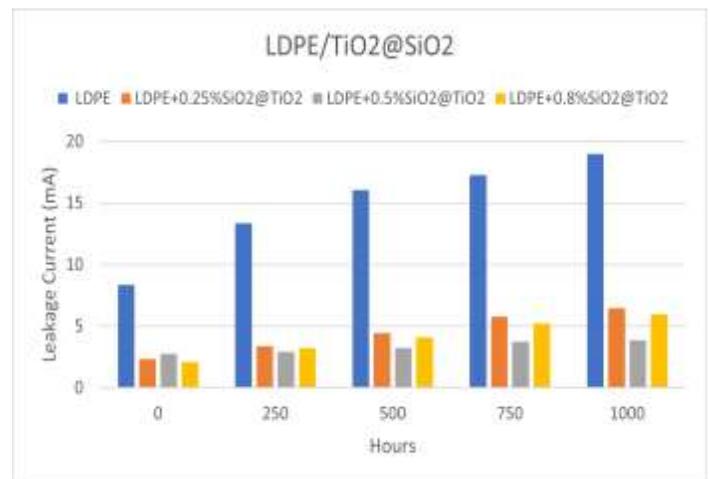


FIGURE 8. Change in Leakage Current (mA) of LDPE/TiO₂@SiO₂ nanocomposites with aging

C. HYDROPHOBICITY (CONTACT ANGLE)

A property of the materials to repel water from its surface called hydrophobicity. In other words, lacks affinity for water, and tends to repel or not absorb water. Sessile drop Technique was adopted while measuring the contact angle (Θ_c) and STRI hydrophobicity classification method was adopted while identifying the drop

patterns. Hydrophobicity of LDPE base material with different nanocomposites of LDPE/TiO₂, LDPE/SiO₂ and LDPE/TiO₂@SiO₂ from virgin sample to 1000 hours as follows: Least Variation of 13° was observed in LDPE/0.25%TiO₂ from virgin to 1000 hours under accelerated stresses. Highest Variation of 18° was observed in LDPE/0.8%TiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 53° was observed in LDPE/0.5%TiO₂ after 1000 hours under accelerated stresses. Highest Value 56° was observed in LDPE/0.8%TiO₂ after 1000 hours under accelerated stresses as shown in Fig. 9.

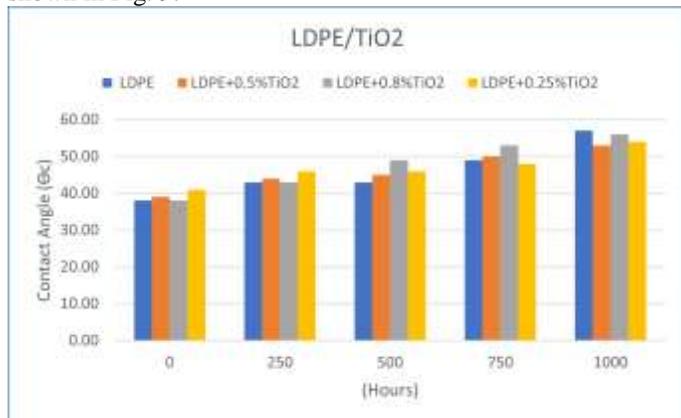


FIGURE 9. Change in Contact Angle (θ_c) of LDPE/TiO₂ nanocomposites with aging

Least Variation of 16° was observed in LDPE/0.5%SiO₂ from virgin to 1000 hours under accelerated stresses. Highest Variation of 27° was observed in LDPE/0.8%SiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 39° was observed in LDPE/0.5%SiO₂ after 1000 hours under accelerated stresses. Highest Value 69° was observed in LDPE/0.8%SiO₂ after 1000 hours under accelerated stresses as shown in Fig. 10.

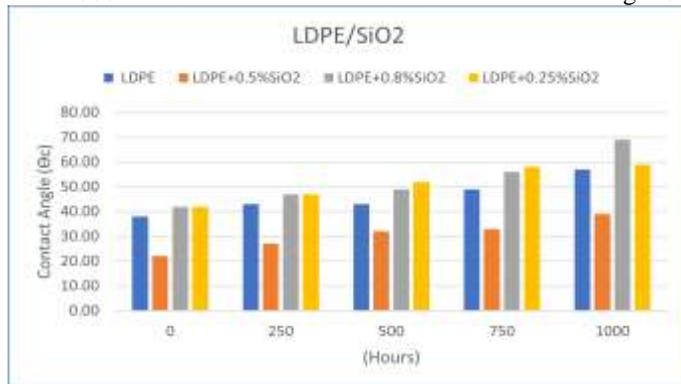


FIGURE 10. Change in Contact Angle (θ_c) of LDPE/SiO₂ nanocomposites with aging

Least Variation of 8° was observed in LDPE/0.5%TiO₂@SiO₂ from virgin to 1000 hours under accelerated stresses. Highest Variation of 22° was observed in LDPE/0.25%TiO₂@SiO₂ from virgin to 1000 hours under accelerated stresses. Least Value 49° was observed in LDPE/0.5%TiO₂@SiO₂ after 1000 hours under accelerated stresses. Highest Value 63° was observed in LDPE/0.25%TiO₂@SiO₂ after 1000 hours under accelerated stresses as shown in Fig. 11.

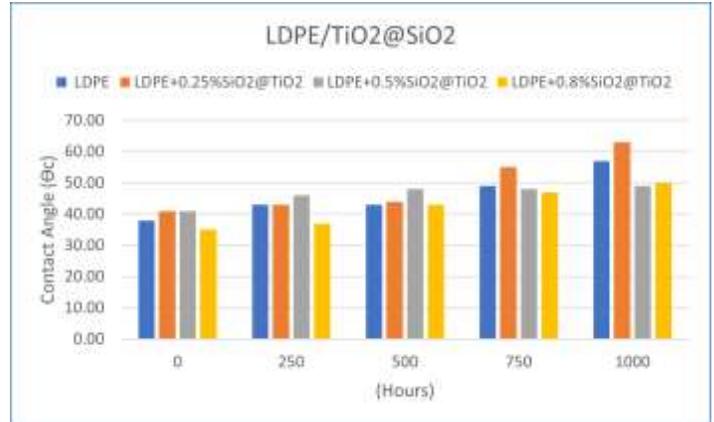


FIGURE 11. Change in Contact Angle (θ_c) of LDPE/TiO₂@SiO₂ nanocomposites with aging

IV. CONCLUSION

As compared to all three LDPE nanocomposites investigated, LDPE/TiO₂@SiO₂ nanocomposites exhibit the minimum variations in breakdown strength (BDS), hydrophobicity (Contact angle), and leakage current (LC) at 0.5% filler loading from virgin sample to 1000-hours aged sample. Insulating polymers conduct due to the intramolecular band conduction and intramolecular hopping of mobile electrons. Due to the semiconductive nature of TiO₂, the conduction barrier is reduced. Higher filler concentrations result in a lower resistance and conduction barrier. High voltage stresses facilitate the transition of insulators to conductors easier. TiO₂@SiO₂ nanoparticles are good hydrophobic by nature which enhance the hydrophobicity of the material. Nano fillers with core shells perform much better than ordinary nano fillers when it comes to improving all the dielectric properties of insulating materials.

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