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Influence of MgO nanofillers on a novel LLDPE/HDPE compound's resistivity for HVDC usage

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ABSTRACT

One important consideration for high-voltage direct current (HVDC) cable insulation systems is the resistivity level. Researchers have looked into using polymer nanocomposites as insulators in order to address this. The electrical qualities of HVDC cable insulation are significantly improved by these nanocomposites. The resistivity level of a compound made of linear low-density polyethylene (LLDPE) and high-density polyethylene (HDPE) filled with different amounts of magnesium oxide (MgO) nanofiller was investigated experimentally in this work. The Design of Experiment (DOE) method was utilized in conjunction with a running test setup to design the 4-point probe measuring technique. The basic polymer composition was made up of 70:30 LLDPE to HDPE ratios. Finding the best sample with the fewest error fluctuations and a favourable resistivity pattern was the aim. Notably, under some circumstances, the addition of 5 weight percent MgO filler produced higher resistance than the 1 weight percent MgO filler. Our investigation leads us to the conclusion that a higher proportion of MgO nanofiller is associated with a higher resistivity, suggesting that this is a promising way to improve the insulating qualities of HVDC cables.

Keywords: *Polymer blends, Resistivity, Nanofiller*

1. INTRODUCTION

The next development in filled resins is polymer nanocomposites, in which micron-sized inorganic fillers (usually approximately 50 weight percent) are injected into polymers. More moderate amounts of nano-fillers are incorporated into recently created polymer nanocomposites. When compared to micro-fillers, nano-fillers have substantially larger surface areas, even if their quantity is much lower (few weight percent). It is essential to comprehend these nano-fillers' interactions with polymer matrices in order to understand the qualities that come from nano-structuration. Manufacturers have to finish extensive analysis and development testing before they can start prequalification testing. The manufacturer will determine the specifics of this development work and the related analyses, which may include evaluations of electrical resistivity, breakdown strength, and space charge behaviour [1].

Examining the mechanisms of electrical resistance in thin polymer films is the focus of several reviewed publications [2]. These scientists discovered that dopant impurities can induce what is known as "residual resistivity" in highly insulating polymers (such as polyethylene or polystyrene). It is widely acknowledged that a polymer's electrical resistivity can vary when 'dopant' molecules that can oxidize or reduce connections between polymer chains are present. Scientific study has been interested in the impact of impurities acting as dopants on the electrical resistivity of thin polymer films 1. More specifically, these impurities can cause residual resistance in highly insulating polymers like polyethylene or polystyrene.

The electrical resistance that persists in materials that are otherwise very insulating is referred to as "residual resistivity." The interactions between polymer chains can change with the introduction of dopant molecules. While some dopants might oxidize these interactions, others might lessen them. This has an impact on the polymer's overall electrical resistance [3].

Optimizing the performance of insulating materials, particularly in applications such as high-voltage direct current (HVDC) insulation, requires an understanding of the principles underlying residual resistivity. Researchers hope to improve the stability and dependability of polymer-based insulation systems for a range of technical and industrial uses by examining these impacts. The synergic stress dependence of the insulation's dc resistivity is the cause of the intrinsic thermal stability limit of HVDC cable that results from this criticality [4].

Limitations in the insulation's DC and heat resistance lead to this kind of stability. One important factor is the insulating material's DC conductivity. Temperature and stress both have an impact on it. Within the DC wires, there is a connection between the resistively graded electric field distribution and temperature distribution. Although it was previously thought that dynamic contact with the environment caused the excessive sheath temperature, new study identifies other important variables that contribute to thermal runaway. Thermal instability can be caused solely by multi-factor dependent DC conductivity, with the boundary conditions at the sheath having just a minor effect [5].

It is essential to comprehend the connection between resistivity, temperature, and electric field while developing HVDC insulation materials. Engineers can utilize experimental models to optimize insulating materials for a given material based on the substance's resistivity behaviour. The distribution of the electric field inside the insulation layer of HVDC cables can be computed with accuracy relate to modelling. In summary, complicated models that take into account temperature, electric field, and material properties are involved in the link between resistivity and HVDC insulation. Practical applications in HVDC systems require more investigation and analysis [6].

It has been investigated [2] how electrical dielectrics function in thin polymer films. These researchers found that impurities, such as polyethylene or polystyrene, can act as dopants in highly insulating polymers, producing so-called residual conductivity. The electrical conductivity of a polymer can be altered by the presence of "dopant" molecules, which have the ability to oxidize or decrease bonds with polymer chains. This criticality leads to the intrinsic thermal stability limit of HVDC cable because of the synergistic stress dependency of the insulation's dc conductivity [4].

In this paper, property of Linear Low-Density Polyethylene (LLDPE)/High-Density Polyethylene (HDPE) blend with magnesium oxide (MgO) nano-filler at 1% and 5% weight percentage are investigated. A comparison was made and provided between the resistivity value and the compound weight percentage for a sample that was produced at two different temperatures and screw speeds.

2. NANOFILLERS IN HVDC CABLE

The size of the filler material has a major influence on the properties of the composite, according to research on fiber (particle) reinforced composites. This is due to the fact that adhesion, dispersion, bonding, and surface interactions with the matrix are all greatly influenced by the size of the filler particle. These effects have a larger influence on nanoscale features because some of them become more noticeable as the filler size gets smaller. Nanoscale fillers have a very large surface to volume ratio because properties like as adhesion, electrical resistivity, catalytic reactivity, gas storage, and chemical reactivity depend on the interface's structure. On the other hand, at the nanoscale, quantum confinement, energy quantization, molecular mobility, and electromagnetic forces become more active. The activities lead to increased surface energy, magnetism, hydrophobic effect, hydrogen bonding, van der Waals, intermolecular bonding, catalysis, and other effects. The basis for nanotechnology and nanostructured materials is this broadening rise in effects [7].

Nanofillers can have two uses in polymer mixtures. Enhancing mechanical, barrier, thermal, flame retardant, and electrical characteristics comes first. The second is changing the morphology and miscibility/compatibility of polymer mixes. The position, interactions with blended components, and dispersion of these additives in the polymer blend determine how well nanoparticles can modify the morphology, interfacial properties, and performance of immiscible polymer blends [8]. For more than 20 years, people have been interested in nanotechnology all across the world. The advent of nanocomposites and nanofillers in both academic and commercial contexts adds to this enthusiasm. Over the years, numerous researchers have become interested in the nanosized particles because they exhibit an improvement in the properties of polymer composites. However, there seem to be a number of misconceptions and misinterpretations about definitions and understanding, suggesting that the terminology surrounding nanoparticles is crucial. It indirectly calls attention to the possibility of progress in the creation of new standards for materials. Electrical engineering is not lagging behind; nanocomposites are being used to enhance materials that already exist, such insulators. Numerous varieties of nanofillers have been investigated thus far [9].

3. DESIGN OF EXPERIMENT (DOE) APPROACH

The design of experiment approach for this project used the two-level factorial designs, to ascertain if certain variables affect the response by assessing the degree to certain combinations of two or more variables have an effect. This section is devoted to this topic. The designs require an experiment with all possible mixtures for each of the levels of the k components that are being considered. The trials are referred to as runs or treatments. The latter statement is derived from agronomy, which is the field that originated many of the methods employed in experimental design. Consider researching how increasing phosphorus and nitrogen could affect a crops output.

Two-level three-factor design trials, of which there are eight tests, can also be taken into consideration, as Figure 1 illustrates 8(3^2). Generally, if there are k items, then two experiments are required. Consequently, a two-level factor design is described using a complete 2 level factorial design [10, 11].

4. METHODOLOGY

4.1. Material

The linear low-density polyethylene (LLDPE) injection molding grade used in this study has a density of 0.9170 g/cm³ and a melt flow index of 2 g/10 min. This material was initially supplied as extruded pellets by Itochu Chemicals America Inc. The high-density polyethylene (HDPE) injection molding grade with a density of 0.956 g/cm³ and a melt flow index of 10 g/10 min. This material was initially sold by Lotte Chemical Titan (M) Sdn Bhd as extruded pellets. Magnesium oxide (MgO), a nanofiller that compounds to the polymer blend, is produced in China and has a particle size of about 50 nm.

4.2. Compounding of Polymer Nanocomposite Using Design of Experiment (DOE) Approach

The Design of Experiment approach (DOE) is used to evaluate and optimize products, processes, and services. It facilitates the methodical planning and selection of parameters so that things can be studied in more detail using the information gathered from the process operating in the altered circumstances [4]. Through simultaneous manipulation of several inputs, DOE is able to detect significant interactions that can go unnoticed when examining one component at a time (OFAT). The 2-level factorial approach was the design experiment method applied in this project. The approach was used to figure out whether specific factors or the interplay of two or more factors alter the answer [12].

The blends consist of a mixture of nanofiller and 70 percent LLDPE and 30 percent HDPE in a 70:30 ratio. We employed 1 weight percent and 5 weight percent of MgO to adjust the mixing nanofiller. In a 70:30:5 ratio, 700 g of LLDPE, 300 g of HDPE, and 50 g of MgO make up 1 kg. The formulation of several ratios is the same in different combinations [13]. Because the composition results in blending to generate electrostatic blends, the composition of 70LLDPE:30HDPE is chosen as the foundation polymer [14]. Moreover, in contrast to other thermoplastics, it has great mechanical and electrical properties [15]. Table 1 illustrates how the Design of Experiment (DOE) method was used to arrange the composition formulation and study designation.

4.3. Blending the Polymer Blends Using Twin Screw Extruder

Developed in Italy in the late 1930s by [6], a twin-screw extruder is a device with two single screws that addresses the tryer of mixing cellulose acetate without the solvent. Colombo came up with a technique for intermeshing co-rotating screws that worked as well as a mixer [8]. Extruders with twin screws are more effective than those with single screws at mixing different materials (additives, fillers, and liquids) uniformly. With conical or parallel screws that can rotate either way (corotating or counter-rotating) and with different levels of intermeshing, Numerous designs are available for twin screw extruders. [9]. This twin screw extruder machine's experiment setup involves creating a range of sample categories for testing. The machine was assembled to the cutting palletizing for finalizing the product. The variable screw speed options are 65 rpm and 75 rpm, and the temperature settings are 170°C and 180°C were displays in Table 1 and the final product produce as seen in Figure 2.

Table 1. Composition and identification of compounds

LLDPE (%)	HDPE (%)	Nanofiller (%)	Screw Speed	Temperature	Designation
70	30	1	60	170	B1
70	30	1	75	170	B2
70	30	1	60	180	B3
70	30	1	75	180	B4
70	30	5	60	170	B5
70	30	5	75	170	B6
70	30	5	60	180	B7
70	30	5	75	180	B8

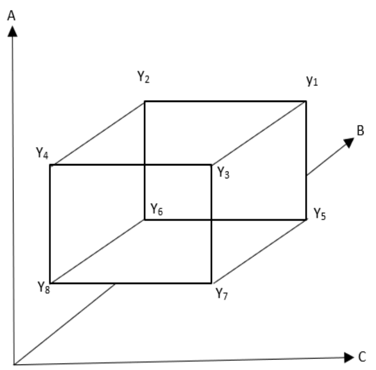

Figure 1. Three-factor design for Two-Level Factorial Method with A, B and C factors

Figure 2. Granules from twin-screw extruders

4.4. Moulding using Heat-press

The output blending pellets from the twin screw extruder was heat-pressed at temperatures between 170 and 180°C to form square samples. As seen in Figure 3, square samples were made utilizing a mould in 1 mm and 3 mm of thickness. The square sample was cut into small samples with a diameter of 2.8 cm that is shown in Figure 4. This sample was prepared to be tested in the resistivity test.

5. RESULTS AND ANALYSIS

This section discusses the results and analysis that was done in this research. After samples were prepared, the test took place to check the resistivity value of the sample with the resistivity test.

5.1. Resistivity Measurement

Resistivity is one of the key factors for HVDC cable insulation design, the resistivity is required to be high enough to reduce thermal runaway. In this study, the resistivity of LLDPE/HDPE/MgO blend was investigated.

The resistivity test setup is shown in Figure 5. The resistivity of LLDPE/HDPE-MgO samples can be determined using a straightforward instrument called a four-point probe. By detecting voltage through the inner probes and running current through the two outer probes, the substrate resistivity may be calculated. The sheet resistivity of the top emitter layer can be readily determined experimentally with a "four-point probe." The current passing through the outer probes induces a voltage in the inner voltage probes. The cell needs to be kept dark because the connection between the n and p-type materials functions like an insulator. In this investigation, the resistivity of the samples was measured with a probe, and the K16220 program was used to record the data (ASTM-F43-99) [16]. The impedance was measured for every operational frequency. Figure 5 shows the setup and arrangements for the test. Every sample measured 2.8 cm in diameter and 1 millimetre in thickness.

5.1.1. Repeatability

Three samples were examined using three distinct line areas for each compounded sample in the resistivity measurement utilizing a 4-point probe and K16220 software. The results were shown in Figure 6, and Table 2 contained the average value calculations for each compounding sample. Based on the graph, it can be inferred that the resistivity values obtained from the three tests consistently display an error of less than 5%. B7 has the least error, which is 0.38%, while B4 has the worst error, which is 1.59%.

Analysis was done on the resistivity strength's temperature dependence. The sample in B1–B4 has 1 weight percent MgO nanofiller, whereas B5–B8 contains 5 weight percent MgO nanofiller. The results indicate that samples B5, B6, and B7 exhibited an increase in their group sample while

Figure 3. Molding sample from hydraulic press

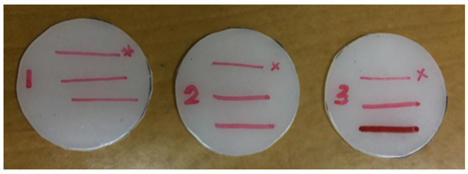

Figure 4. Small sample in diameter of 2.8 cm

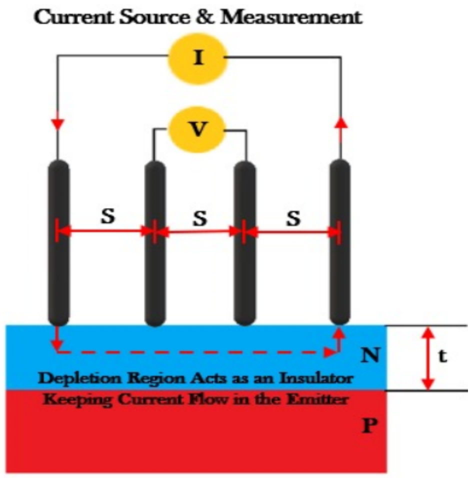

Figure 5. Resistivity Test setup

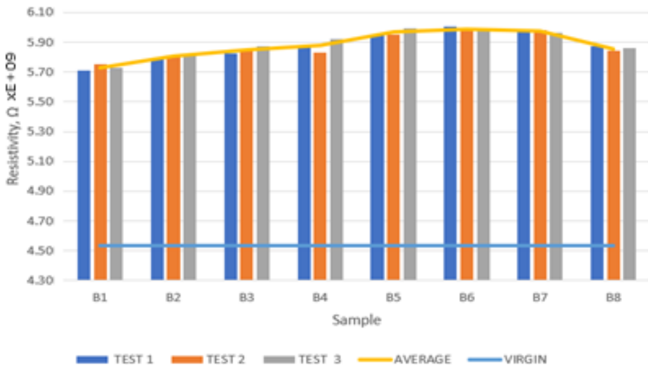

Figure 6. Resistivity of MgO

Table 2. Error percentage of sample tested

Sample	Error
B1	0.75
B2	0.62
B3	0.82
B4	1.59
B5	0.95
B6	0.54
B7	0.38
B8	0.55

using a 5 weight percent MgO filler. As a result, resistance strength rises as temperature rises. The MgO filler particles are typically embedded in the polymer matrix, creating a physical barrier to the movement of free charge carriers. This acts as a form of electrical shielding, preventing charge from flowing freely through the material. As a result, the composites materials resistance increases [17].

The volume electrical resistivity of the insulation used in HVDC cables is shown on the graph. Data for eight samples, designated B1 through B8, are included. There are five data sets in each sample. Resistivity is plotted on the y-axis and ranges from 4.30×10^9 to 6.10×10^9 (Ω). The resistivity changes throughout many tests and averages are displayed by the data points. The volume electrical resistivity of HVDC cable insulation determines the electric field. Consequently, experimentally-derived relationships indicating resistivity's dependency on temperature and electric field have an impact on the DC field profiles. Various experimental models for electrical conductivity in HVDC cable insulation have been investigated by researchers. These models take into account variables such as electric field intensity and temperature. The exponential dependence of electrical conductivity on temperature (T) and electric field (E) is described by one such model, which is known as Klein's formula. The field coefficient of conductivity is represented by a constant in the expression.

5.1.2. Optimum Value

As can be seen in Figure 6, the greatest resistivity was measured for B6 at a temperature of 170°C and a screw speed of 75 rpm, with a 5-weight percent MgO composition. B1, which has the lowest resistance at 170°C and 60 rpm screw speed and a 1-weight percent MgO composition, has the lowest temperature. According to the graph, resistivity rises from B1 to B6 and then starts to fall toward B8. It has been discovered that the ideal composition for LLDPE/HDPE-MgO polymer to raise the material's resistivity is 5 wtg% MgO. The outcome shows that the sample's dielectric can vary depending on the quantity of nanofiller injected. When 5 wt% of MgO nanofillers are added at 170°C and 75 rpm screw speed, the resistivity percentage can be improved by 32% in comparison to the virgin polymer-blend depicted in Figure 6.

In order to provide the optimum insulation at high voltage, the composites' increased resistivity results in the sample having the lowest conductivity. Polymer nanocomposites, or NCs, are composites of organic polymers and evenly distributed nanoscale inorganic fillers that are gaining significant interest as novel materials with enhanced characteristics across multiple applications. According to a number of studies published recently, polymers with nanofillers added to them exhibit better dielectric characteristics like resistivity, space charge behaviour, breakdown strength, and partial discharge resistance [18]. Since MgO has a higher thermal conductivity property by nature, a higher amount of MgO aids in heat dissipation and lowers the dissipation factor [13]. Combining nano-fillers with polymers including polyethylene (PE), polyamide (PA), and polypropylene (PP) have been shown to improve electrical properties, resilience to high voltage environments, and thermal endurance [19].

The resistance versus screw-speed graph and the associated values for the testing sample's weight and temperature are displayed in Figure 7. Based on the observation, it shows an increment from 60 rpm to 75 rpm screw-speed for 1 wtg%-170°C, 1 wtg%-180°C and 5 wtg%-170°C while decrement for 5 wtg%-180°C. The difference was calculated with 1.22% for 1 wtg%-170°C, 0.5% for 1 wtg%-180°C, 0.3% for 5 wtg%-170°C and 2.05% for 5 wtg%-180°C. For 60 rpm screw-speed dependence on the temperature, the value of the resistance is increasing from 170°C to 180°C for 1 wtg% and 5 wtg% with 1.9% and 0.2%. For 75 rpm screw-speed dependence on the temperature, the value of the resistance increases for 1 wtg% from 170°C to 180°C with 1.2% while decrease for 5 wtg% with 2.2%. The study found that adding 5 wtg% MgO to the LLDPE/HDPE polymer yields the ideal mixture for increasing the material's resistivity. The chemical properties of the filler surface and the interfacial region between the two dictates how the matrix and filler interact.

The material's free zone had been filled with nanofiller. MgO nanofillers have dielectric properties due to its higher resistivity value [20].

6. CONCLUSION

The resistivity characteristics of polymer-blend LLDPE/HDPE-MgO were examined in the section above using various compounding techniques, varying the amount

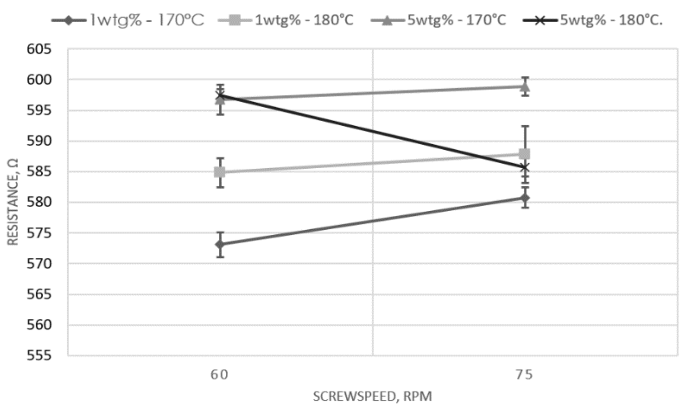

Figure 7. Resistivity dependence on screw-speed, temperature and weightage of the polymer blend LLDPE/HDPE-MgO

of nanofiller, screw-speed, and sample temperature. Consequently, it was discovered that the blend's resistivity differed slightly from the others. The dielectric characteristics of LLDPE/HDPE-MgO will be improved by adding MgO in a specific percentage that corresponds with temperature and screw-speed, based on the results of the resistivity test. With a greater resistivity, the LLDPE/HDPE-MgO combination at 5 weight percent MgO nanofiller has been determined to be optimal for HV insulation. The variable of the composition is an additional component that enhances the dielectric characteristics. Based on the observed results, the blending composition grows more dependable at 170°C and 60 rpm screw-speed. The sample's increased resistivity will enhance the electrical characteristics of insulating materials intended for high-voltage uses.

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