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Original Research Article

Electrical and Mechanical Performances for Low-Density Polyethylene Nano Composite Insulators

Eman El_Sherkawy[1*], Loai S. Nasrat[2], Mahmoud Rihan[3]

[1]Electrical Engineering Department, The High Institute of Engineering and Technology- Tod, Luxor, Egypt
[2]Electrical Engineering Department, Faculty of Engineering, Aswan University, Aswan, Egypt
[3]Electrical Engineering Department, Faculty of Engineering, South Valley University, Qena, Egypt

***Corresponding Author:** Eman El_Sherkawy
Electrical Engineering Department, The High Institute of Engineering and Technology- Tod, Luxor, Egypt

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Abstract: Low-density polyethylene (LDPE) metal oxide nanocomposites are used as high-voltage insulation in AC cables to reduce space charging and other issues. Nanoparticles such as SiO_2, MgO, and ZnO are used as fillers in polyethylene matrix to achieve good electrical, thermal, and mechanical properties such as space charge reduction, increased surface and volume resistance, and high dielectric stress bearing capabilities. LDPE/Al_2O_3 compounds are prepared at concentrations of 1%, 3%, 5%, and 7% for nanofillers and at concentrations of 10%, 20%, 30%, and 40% for micro fillers. The dielectric strength of the LDPE/Al_2O_3 sample was measured at different temperatures to determine the effect of temperature on the dielectric strength value. To check the various properties of the samples, the tensile strength test has been applied. The Whale Optimization Algorithm (WOA) was used to calculate the optimal Al_2O_3 filler percentage for the best dielectric strength value.

Keywords: Low Density Polyethylene, Micro and Nano Fillers, Dielectric Strength, Thermal Effect, tensile strength, Whale Optimization Algorithm (WOA).

INTRODUCTION

Electrical equipment with power ratings ranging from small to hundreds of megawatts is made up of various insulating and dielectric materials. The proper choice of insulating material is determined by a variety of factors, including dielectric strength, permittivity, arc resistance, thermal conductivity, thermal coefficient of expansion, chemical resistance to corrosion, and so on. Recently, the development and application of nano fillers in electrical insulation have gained popularity. Polymer nanocomposites with small amounts of well dispersed nanoparticles have an advantage over conventional composites [1-3].

Nowadays, the most common inorganic fillers in LDPE are SiO_2, ZnO, MgO, $BiFeO_3$, and TiO_2 nanoparticles. Currently, several studies seek to dope inorganic materials with structure or property in order to increase the dielectric characteristics of LDPE [4-6]. One promising strategy for creating new polymer composites with improved mechanical, electrical, and thermal properties is to incorporate a small number of nanoparticles into the polymer system [7-9].

The cable conductor temperature rises because the heat produced by conductors takes time to dissipate. In practical operation, the operating temperature of cables is always below a safe value to minimize thermally related insulation degradation [10-12]. Heat is thought to be one of the most damaging environmental factors that cause cable insulation to deteriorate, according to the findings of multiple investigations [13-15].

This research aims to investigate, analyze, and document the impact of micro- and nano- Al_2O_3 fillers on the electrical and mechanical properties of LDPE insulators. Curve-fitting solutions were used to provide interpolated values for different percentages of the inorganic filler. The Whale Optimization Algorithm (WOA) was used to determine the optimal Al_2O_3 filler percentage for maximum dielectric strength.

EXPERIMENTAL

Materials

Micro and nano Al_2O_3 are the fillers used in this paper, which are supplied by Nanotech, Egypt. For better amalgamation, natural resin, ultra-pure LDPE, was purchased from SABIC, KSA, in the form of granules. The powdered material had an average particle diameter of less than 0.2 mm, a density of 0.924 g/cm^3, and a melt flow rate of 2.00 g/10 min at 190 °C.

Preparation of Composites

As a proportion of the overall weight of the LDPE polymer, the material concentrations of the fillers were determined. The samples were created by combining micro- and nano- Al_2O_3 fillers with the base polymer (LDPE). Reference materials included a pure LDPE sample devoid of Al_2O_3 filler. The mixing formula is displayed in Table 1. A twin extruder was used to combine LDPE and Al_2O_3 in a direct fashion, with a spin speed of 15 rpm, a spinning torque of 28 Nm, and a heating temperature of roughly 175 °C. The extruder's molten composite is cooled in a water bath and then granulated with a speed-regulated pelletizer machine.

Table 1: The mixing formulation of samples

Type of filler	Sample code	Filler loading (%)
LDPE	B	0
Micro Al_2O_3	A10	10
	A20	20
	A30	30
	A40	40
Nano Al_2O_3	A1	1
	A3	3
	A5	5
	A7	7

Characterization Dielectric Strength Test

Under specific working conditions, all insulating materials break down at a specific voltage threshold. When an insulating material is exposed to a voltage higher than its dielectric breakdown strength, the dielectric strength is stated in voltage gradient elements, such as voltage per thickness (kV/mm). An essential electrical property of insulators is their dielectric strength. The dielectric strength is usually observed as an electrical arc across the electrodes, which causes a catastrophic decrease in resistance. The test sample should be in disc form with a diameter of 5cm and a thickness of 1mm. the dielectric strength test in accordance with ASTM D-149 [16].

Up until the breakdown, the voltage progressively increased at a nearly constant rate of 2 kV/sec. Measurements were made on nine LDPE composite specimens. In this paper, the dielectric strength of the micro- and nano- composites is measured using the circuit shown in Fig-1. The average results for nine specimens of each test have been taken to minimize the error. Breakdown strength properties were studied at four different temperatures (25℃, 60℃, 100℃, 120℃).

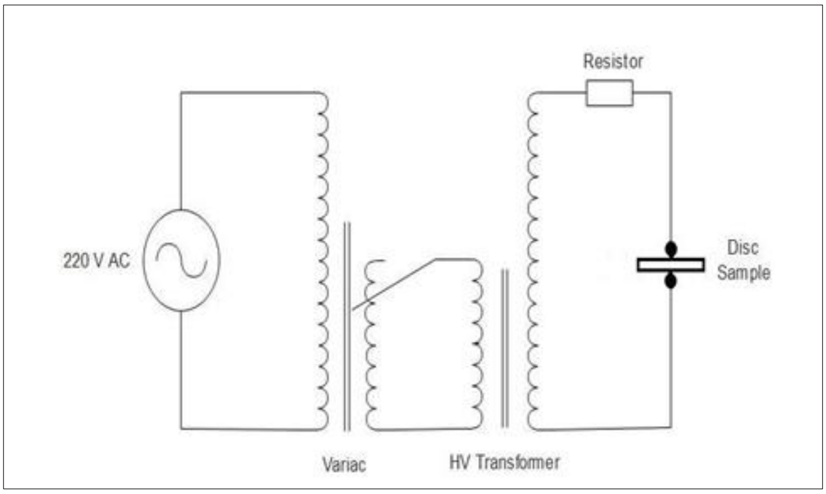

Fig. 1: Dielectric strength schematic diagram

Mechanical Test

Tensile strength is a critical test for describing the mechanical performance of a material [17]. The tensile strength and elongation at break of the composite samples were determined using a Zwick Roell LTM electrodynamic testing machine. Figure 2 shows a schematic diagram. ASTM D-412 [18], was used to evaluate the test.

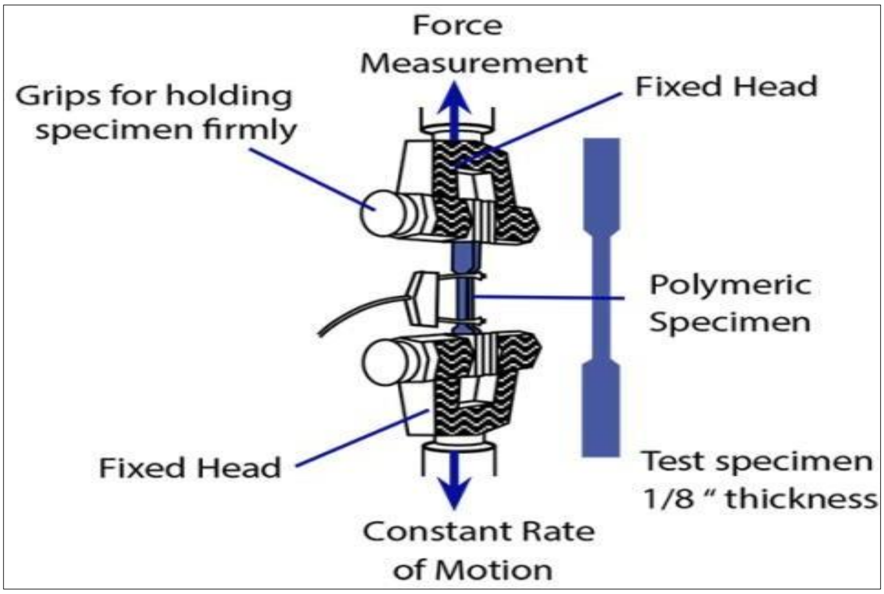

Fig. 2: Tensile strength specimen and the applied test

RESULTS AND DISCUSSION

Dielectric Strength Test Results

The dielectric strength of LDPE with different percentages of Al_2O_3 filler has been obtained at four different temperatures (°C). To reduce the error percentage, the reading was repeated 10 times to take the average.

Experimental values of dielectric strength (kV/mm) for LDPE with different filler percentages at various temperatures (°C) are shown in Tables (2), (3), (4), and (5).

Table 2: Average values of dielectric strength (kV/mm) for micro and nano Al_2O_3 composite samples at 25°C

Acronym	Type of filler	Dielectric strength (kV/mm)
B	Blank	23.59
A10	Micro Al_2O_3	26.14
A20		29.08
A30		33.28
A40		30.05
A1	Nano Al_2O_3	27.31
A3		30.00
A5		35.78
A7		40.45

Table 3: Average values of dielectric strength (kV/mm) for micro and nano Al_2O_3 composite samples at 60°C

Acronym	Type of filler	Dielectric strength (kV/mm)
B	Blank	21.21
A10	Micro Al_2O_3	23.34
A20		26.07
A30		30.94
A40		27.11
A1	Nano Al_2O_3	25.94
A3		27.12
A5		34.91
A7		37.65

Table 4: Average values of dielectric strength (kV/mm) for micro and nano Al_2O_3 composite samples at 100°C

Acronym	Type of filler	Dielectric strength (kV/mm)
B	Blank	17.34
A10	Micro Al_2O_3	20.91
A20		22.87
A30		27.68
A40		24.52
A1	Nano Al_2O_3	23.23
A3		24.92
A5		32.69
A7		35.17

Table 5: Average values of dielectric strength (kV/mm) for micro and nano Al_2O_3 composite samples at 120°C

Acronym	Type of filler	Dielectric strength (kV/mm)
B	Blank	15.80
A10	Micro Al_2O_3	17.05
A20		18.46
A30		24.29
A40		21.60
A1	Nano Al_2O_3	20.48
A3		22.82
A5		30.41
A7		32.65

Comparing the LDPE composite with 7% nano Al_2O_3 filler (sample A7) to the other filler concentrations, the results in Tables (2) demonstrate that sample A7 has the highest dielectric strength (40.45 kV/mm). Sample B, which is made entirely of LDPE, has the lowest dielectric strength (23.59 kV/mm). Compared to the LDPE composite with micro Al_2O_3 filler, the LDPE composite with nano Al_2O_3 filler has a higher dielectric strength. The dielectric strength of an LDPE composite containing 30% micro Al_2O_3 filler (sample A30) is 33.28 kV/mm. When micro Al_2O_3 concentrations are above 30%, the dielectric strength falls by 9.7%.

Table (4) and Fig (3) show that samples A1, A3, A5, and A7 gradually increase their nano- Al_2O_3 content from 0 to 1, 3, and 7%, respectively, increasing their dielectric strength by 25.36%, 30.42%, 46.96%, and 50.7%.

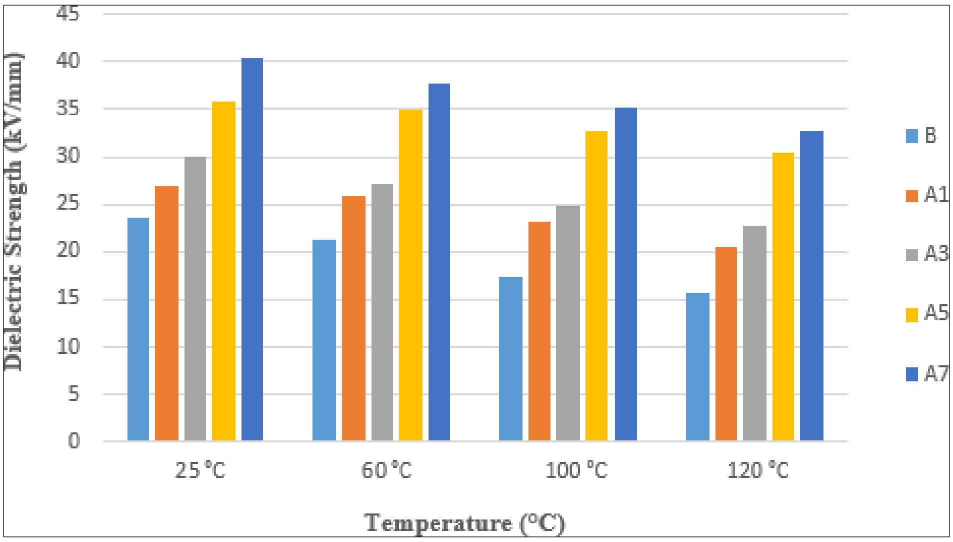

Fig. 3: Dielectric strength (kV/mm) of LDPE/Al_2O_3 nano composites at different temperature (°C)

It can be seen from the tables that, compared with both neat and LDPE/ Al_2O_3 micro and nano filler composites, it was revealed that the greater the temperature, the lower the dielectric strength value. According to practical experience, adding fillers to the polymer increases the dielectric strength value. When all mixing ratios at the same temperature were evaluated, it was determined that 30% for micro filler and 7% for nano filler had the best dielectric strength values compared to the rest of the mixing, as shown in figs (3), and (4).

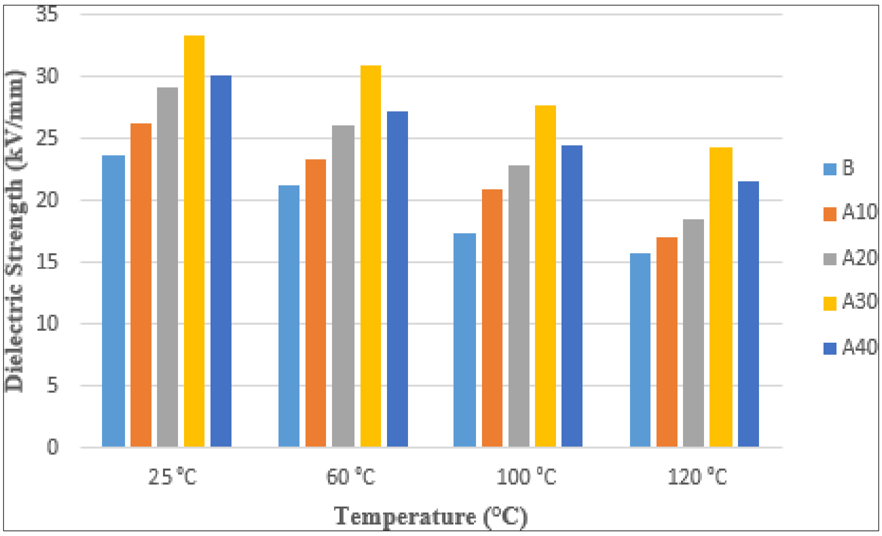

Fig. 4: Dielectric strength (kV/mm) of LDPE /Al_2O_3 micro composites at different temperature (°C)

Whale Optimization Algorithm

The Whale Optimization Algorithm is a brand-new meta-heuristic optimization method for solving optimization issues. This algorithm uses three operators to simulate how humpback whales search for prey, encircle prey, and engage in bubble-net foraging [19]. The WOA was used to predict the optimum concentration of Al_2O_3 filler by inserting the polynomial equation that has been acquired from the MATLAB fitter program, which leads to predicting the highest dielectric strength values.

Firstly, using MATLAB curve fitting software, insert the experimental data to acquire a polynomial equation with a minimum error square. Secondly, the acquired polynomial equation was inserted in various places in WOA m files to acquire the optimum concentration of Al_2O_3 filler. For all test functions, the simulation parameters of the algorithm were lower bounds equal to 10, upper bounds equal to 60, and the number of iterations equal to 100. Then it can be predicted that the optimum concentration of Al_2O_3 filler will improve the electrical properties.

In this work, the obtained data from the experimental dielectric strength test were employed to characterise the relationship between the ratio of the filling material and the dielectric strength by developing the curve-fitting solutions, as shown in Figs. 5 (micro filler case) and 6 (nano filler case).

For Micro Filler Case

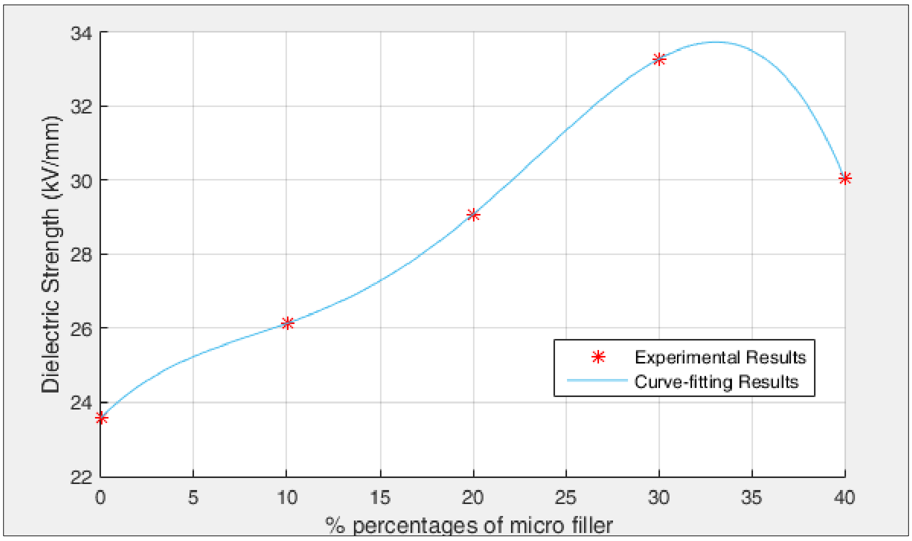

Fig. 5: Curve fitting criterion results for Dielectric Strength (kV/mm) of LDPE/ Al_2O_3 micro composites at 25°C

The data obtained can be expressed as the following 4th order equation:

$$Y = -4e^{-5}\,X^4 + 0.0025\,X^3 - 0.046\,X^2 + 0.5\,X + 24 \quad (1)$$

Where y is the value of dielectric strength (kV/mm), and x is the Al_2O_3 filler concentration in the LDPE composite. From the applied WOA, based on Eq. (1), it can be concluded that the optimal percentage of the Al_2O_3 micro filler concentration was 31.942, and the optimal dielectric strength for the optimal filler percentage at room temperature was 32.8812 kV/mm.

For Nano Filler Case

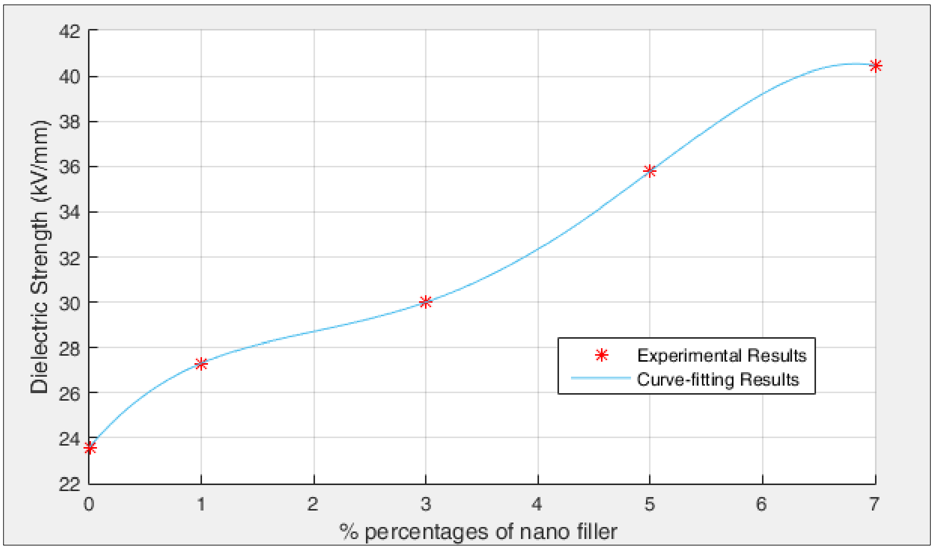

Fig. 6: Curve fitting criterion results for Dielectric Strength (kV/mm) of LDPE/ Al_2O_3 nano composites at 25°C

The data obtained can be expressed as the following 4th order equation:

$$Y = -0.037\, X^4 + 0.52\, X^3 - 2.2\, X^2 + 5\, X + 24 \quad (2)$$

From the applied WOA, based on Eq. (2), it can be concluded that the optimal percentage of the Al_2O_3 nano filler concentration was 6.9821, and the optimal dielectric strength for the optimal filler percentage at room temperature was 40.7448 kV/mm.

Mechanical Test Results

The highest stress a material can sustain while being stretched or pulled without necking is known as its tensile strength. Divide the load at break by the initial minimum cross-sectional area to find the tensile strength. Mega Pascals (MPa) are used to express the outcome. To assess the impact of rising temperatures on the mechanical characteristics of the polymer, Figures 7 and 8 show the tensile strength of micro- and nano- Al_2O_3-filled LDPE composites as a function of filler loading at 25°C and 100°C.

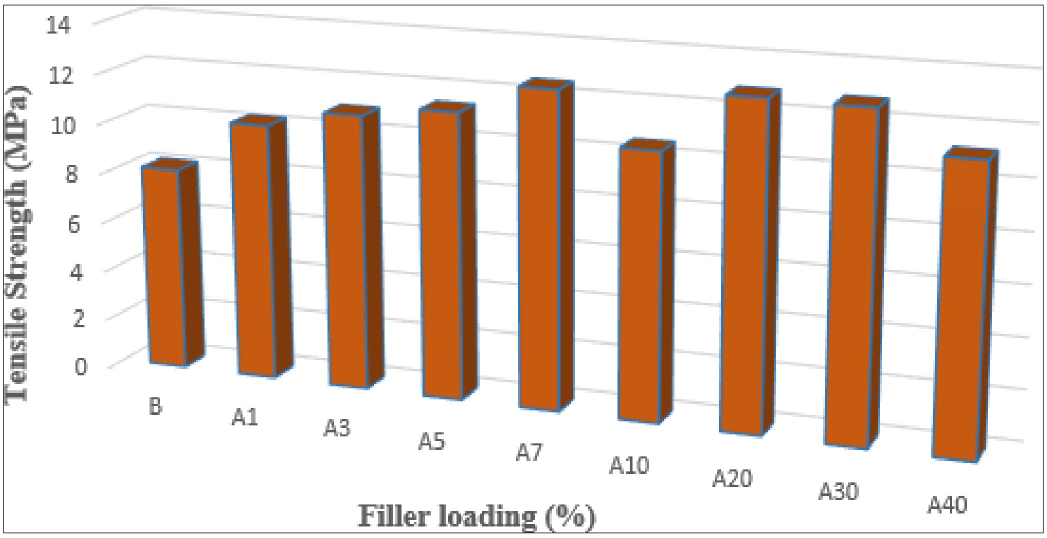

Fig. 7: LDPE tensile strength with Al_2O_3 nano and micro filler concentration at 25°C

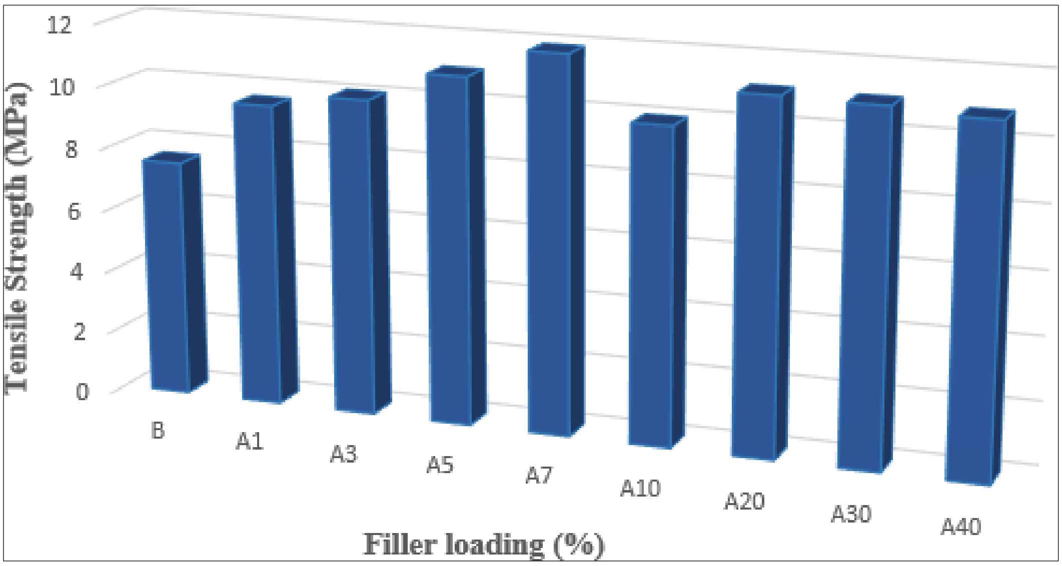

Fig. 8: LDPE tensile strength with Al_2O_3 nano and micro filler concentration at 100°C

Al_2O_3 loaded LDPE composites improve tensile strength at the 7 wt.% loading level, as shown in Fig. 7. It can be seen that there is a marked increase in the tensile strength with increased micro Al_2O_3 concentrations. When compared to the other concentrations for the same filler grain size, LDPE loaded with 7 wt% nano Al_2O_3 and 20 wt% micro Al_2O_3 records the maximum tensile strength.

Nano Al_2O_3 filled composites outperform micro Al_2O_3 filled composites in terms of tensile strength. A small amount of nano Al_2O_3 added to LDPE increases crosslinking density while increasing tensile strength and elongation at break.

Exposing samples to high temperatures influences their physical properties, such as elasticity and size, which also influence the value of the tensile strength, as shown in fig. 8.

CONCLUSION

The studies presented in this paper focus on the electrical and mechanical behaviour of LDPE micro and nano composites with Al_2O_3 particles as a function of filler concentration and polymer host structure. The experimental results lead to the following conclusion:

- The dielectric strength has been improved significantly with nano filler loading.
- Using nano composites with reduced filler content can improve electrical performance while also improving flexibility and ease of processing during product manufacturing.
- Continuously raising the temperature influences the physical properties of the samples, such as shrinkage and deformation.
- The addition of nano filler improved the tensile strength of LDPE.
- High temperatures negatively affect the dielectric strength and tensile strength values.
- The addition of nano fillers to LDPE improves the dielectric strength of polymer compounds by up to 7% percent. But when the ratio of nano filler increases, it positively affects the economic cost of cable.

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