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Electrical Characteristics of XLPE Cables Containing Different Levels of Calcium Carbonate Filler

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Abstract – **Cross-linked polyethylene (XLPE) is widely used in high and medium voltage cables insulation due to its low dielectric losses and its ability to improve cables properties in high temperatures. This paper aims to improve XLPE electrical properties (dielectric strength) for high voltage cables in respect of mechanical characteristics by adding inorganic filler. Blends of XLPE with inorganic filler: Calcium Carbonate ($CaCO_3$) were prepared with 20%, 30 % and 50 % by weight percentages concentration. The dielectric strength of the blends was tested in several thermal conditions such as (0 , 25 and 100^{0}C). Also dielectric strength of blends was tested after being exposed to thermal aging for 24 hours(hrs) in high temperatures (130 , 170 and 190^{0}C). Elongation at break test was applied to check various properties of the blends.**

Keywords – **XLPE Cables, Calcium Carbonate Filler, Dielectric Strength, Electrical and Mechanical Properties.**

I. Introduction

High voltage cables are used when underground transmission is required. These cables are laid in ducts or may be buried in the ground. Unlike in overhead lines, air does not form part of the insulation, and the conductor must be completely insulated. Thus cables are much more costly than overhead lines. Also, unlike for overhead lines where tapping can easily give, cables must be connected through cable boxes which provide the necessary insulation for the joint [1].

The use of power cable is assumed to be started back in 1880, with the start of incandescent lighting. The growth rate of urban electrification was too high to accommodate the number and size of the feeders required for distribution using overhead lines. The overhead line system was not only considered technically and aesthetically inadequate, but also it was assumed to pose safety hazards. For these reasons, underground electrification technology was introduced by the early 1890’s [2].

The development of polyethylene in 1941 triggered a dramatic change in the insulation of cables for the transmission and distribution of electrical energy.

There are two major types of extruded dielectric insulation in wide use today for medium voltage cables:
(a) Cross-linked polyethylene(XLPE) or tree-retardant Cross-linked polyethylene(TR-XLPE).
(b) Ethylene propylene rubber.

Thermoplastic polyethylene (PE), which was widely used through the 1970, was introduced during World War II for high-frequency cable insulation. PE was furnished as 15 kV cable insulation by 1947. Large usage began with the advent of Underground Residential Distribution (URD) systems early in the1960s.

The development of modem URD systems may be viewed as the result of drastically lowering first costs through technology [3].

Inorganic fillers have been recently introduced to improve XLPE insulation for cables .Several studies aimed to improve electrical performance of XLPE high voltage cables using inorganic fillers [4]-[13].

This paper aims to improve XLPE properties (electrical and mechanical) by adding inorganic filler as $CaCO_3$. It focuses on trying to find an appropriate weight percentage composition of such blend in order to enhance the dielectric strength of the insulation in different temperature conditions. Also, some mechanical properties of the blend were investigated such as elongation at break and tensile strength. Soft program(Robustdemo) was used to interpreted the equation between different temperatures and the filler percentage.

II. Experimental Procedure

A. Blend preparation

XLPE was made from High-density polyethylene (HDPE). HDPE was mixed with dicumyl peroxide 4-methoxy phenol 3% weight percentage (3 wt%) as cross linked agent in absence of filler to prepare XLPE according to (ASTM F876 - 10e1). $CaCO_3$ with different ratios (20,30 and 50 wt%) was mixed with XLPE using an electrical heat chamber of Barbender Plasticoder model (C.W. pra , instrument,INC.50 Hackensack,230 Volt, 40Amp).Table 1 shows different XLPE blends concentrations.

Table 1 : Blends formulations

Blend symbol	Filler added to XLPE	Filler weight %
A	without filler	0
B	$CaCO_3$	20
C	$CaCO_3$	30
D	$CaCO_3$	50

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B. Dielectric Breakdown Strength Test

Dielectric strength of an insulating material is the maximum electric field strength that it can withstand intrinsically without breaking down, without experiencing failure of its insulating properties. It is expressed in voltage gradient items, such as voltage per thickness (kV/mm). It is one of the major electrical properties for insulation.

The failure is characterized by an excessive flow of current (arc) and by partial destruction of the material. Dielectric strength is measured through the thickness of the specimen (which is equal to 1mm) ,and is expressed in volts per unit of thickness. Sets of blends have been prepared and tested using A.C voltage according to IEC 60243 in different temperatures range. Samples are in the form of disc with diameter 5 cm and thickness 1 mm. For each test, the average result of 5 samples has been taken to minimize the error .Fig.1 shows the circuit used for dielectric break down strength test.

The relation (equation) between different temperatures and the inorganic filler percentage was interpreted by the MATLAB.

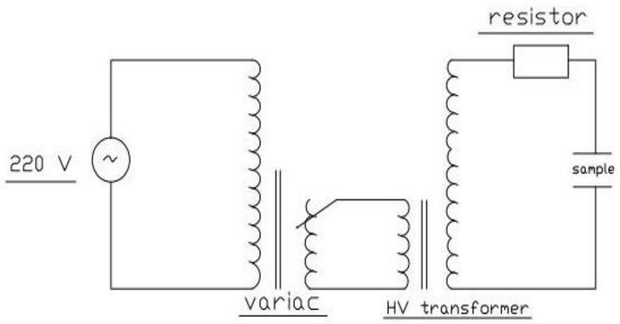

Fig.1. Dielectric breakdown strength test.

C. Elongation at Break Test

Mechanical tests such as elongation at break test were performed to illustrate the ability of blend samples to withstand the mechanical forces. The elongation at break (El %) of a material is the percentage increase in length that occurs before it breaks under tension. Elongation behavior of a polymer sample is a type of deformation. It means simply a change in shape that a sample undergoes under stress. El% is the length of a sample (L) after being stretched divided by the original length of the sample (L_0), and then multiplied by 100.

L / L_0 x 100 = % elongation

Elongation is recorded at the moment of rupture of the specimen, often expressed as a percentage of the original length. It corresponds to the breaking or maximum load. The test was carried out according to (ASTM D-638) .

III. Results and Discussion

A. Dielectric Breakdown Strength Measurements

The dielectric strength for XLPE has been studied with different filler wt% in different temperatures : 0°C (to simulate the climate of snowy regions), 25 °C(to simulate room temperature) and 100 °C (to simulate maximum temperature loading of the cables).Fig.2 shows the comparison of breakdown strength for new blends with different filler wt% and the virgin sample without any additives. It can be interpreted that the dielectric strength of XLPE was improved by adding $CaCO_3$ filler.

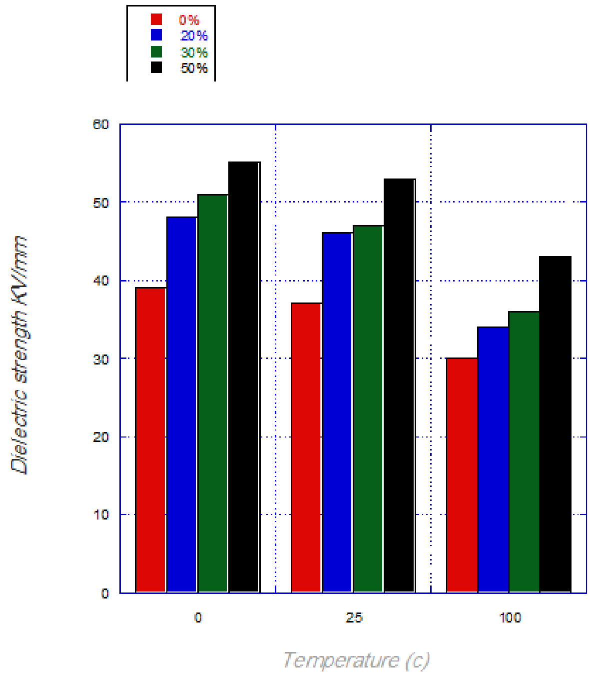

Fig.2. Dielectric breakdown strength of XLPE blends in different temperatures.

- For 0°C the dielectric strength of XLPE with $CaCO_3$ (20, 30 and 50 wt %) was improved by (23, 30 and 41 %) to reach (48, 51 and 55 kV/mm) respectively compared to virgin XLPE (39 kV/mm).
- Also for 25°C the dielectric strength of XLPE with $CaCO_3$ (20, 30 and 50 wt %) was improved by (24, 27 and 43 %) to reach (46, 47 and 53 kV/mm) respectively compared to virgin XLPE (37 kV/mm).
- Finally for 100°C the dielectric strength of XLPE with $CaCO_3$ (20, 30 and 50 wt %) was enhanced by (13, 20 and 43 %) to reach (34, 36 and 43 kV/mm) respectively compared to virgin XLPE (30 kV/mm).

Furthermore, the dielectric strength test was carried out after the blends were exposed to thermal aging for 24 hrs in several high temperatures (130,170 and 190 °C). Fig.3 shows that, the XLPE breakdown strength was improved by adding inorganic filler with different wt% despite the decrease of dielectric strength of XLPE due to high thermal stress.

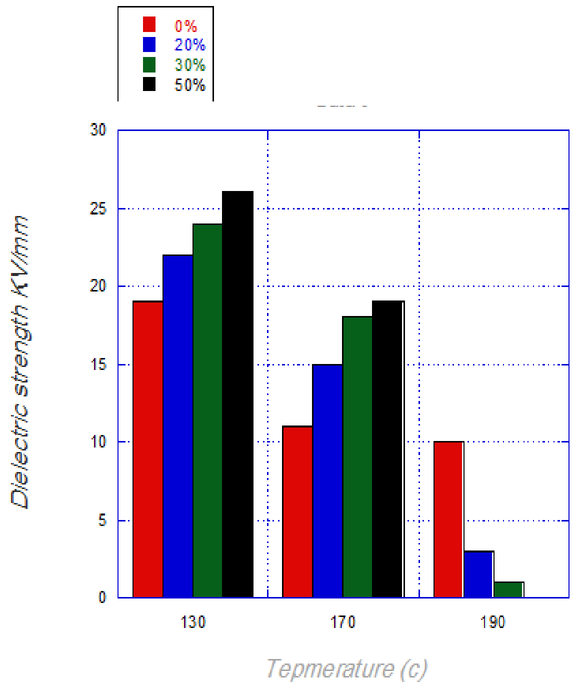

Fig.3. Dielectric breakdown strength of XLPE blends after thermal aging for 24 hrs in several temperatures.

- As for 130 °C, the dielectric strength of XLPE with $CaCO_3$ (20, 30 and 50 wt %) was improved to reach (22, 24 and 26 kV/mm) respectively compared to virgin XLPE (19 kV/mm).
- Also for 170 °C, the dielectric strength of XLPE with $CaCO_3$ (20, 30 and 50 wt %) was improved to reach (15, 18 and 19 kV/mm) respectively compared to virgin XLPE (11 kV/mm).
- Finally for 190 °C, the dielectric strength of XLPE with $CaCO_3$ (20, 30, 50 wt %) was enhanced to reach (3, 1, 0 kV/mm) respectively compared to virgin XLPE (10kV/mm).

It can be interpreted from fig.2 and fig.3 that the breakdown strength of XLPE insulation is inversely proportional to temperatures. Also high temperatures have high impact on insulation weakness. It can also be observed that the inorganic filler dramatically improved the dielectric strength of XLPE even in a severe thermal stress.

B. Soft Program (MATLAB) Results

Robustdemo shows the difference between ordinary least squares and robust regression for data with a single predictor. With no input arguments, robustdemo displays a scatter plot of a sample of roughly linear data with one outlier. The bottom of the figure displays equations of lines fitted to the data using ordinary least squares and robust methods, together with estimates of the root mean squared errors.

1. Robustdemo for the dielectric strength results with different percentages of CaCO3 filler tested at 0 ^{0}C.

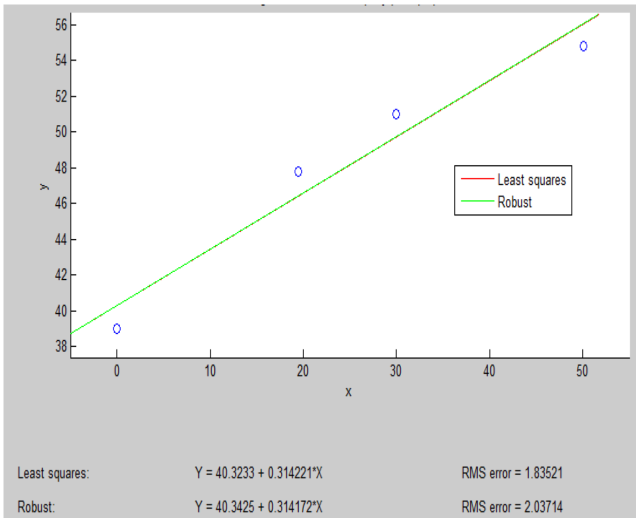

Fig.4. Robustdemo results for the Dielectric strength (kV/mm) of XLPE with different $CaCO_3$ filler percentages at 0°C.

From the calculation of the program, the equation for the data obtained can be represented by two linear equations as follow:

Y= 40.3233 + 0.314221X RMS error = 1.83521% (1)

Y= 40.3425 + 0.314172X RMS error = 2.03714% (2)

Where Y is the dielectric strength value, X percentage of concentration of $CaCO_3$ in the sample.

The equation (1) is chosen to minimize the RMS error:

Y= 40.3233 + 0.314221X

2. Robustdemo for the dielectric strength results with different percentages of $CaCO_3$ filler tested at 25 ^{0}C.

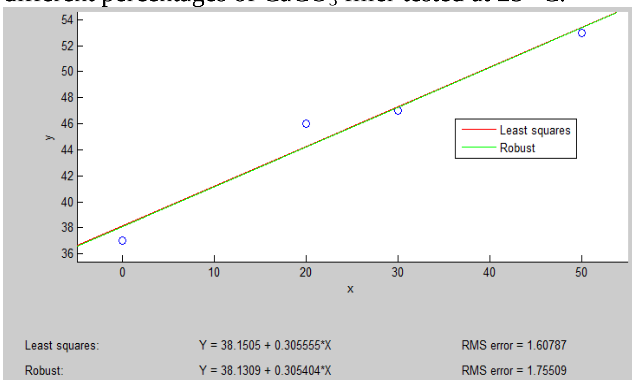

Fig.5. Robustdemo results for the Dielectric strength (kV/mm) of XLPE with different $CaCO_3$ filler percentages at 25°C.

From the calculation of the program the equation for the data obtained can be represented by two linear equations as follow:

Y= 38.1505 + 0.305555X RMS error = 1.60787% (3)

Y= 38.1309 + 0.305404X RMS error = 1.75509% (4)

Where Y is the dielectric strength value, X percentage of concentration of $CaCO_3$ in the sample.

The equation (3) is chosen to minimize the RMS error:

Y= 38.1505 + 0.305555X

3. Robustdemo for the dielectric strength results with different percentages of CaCO3 filler tested at 100 ^{0}C.

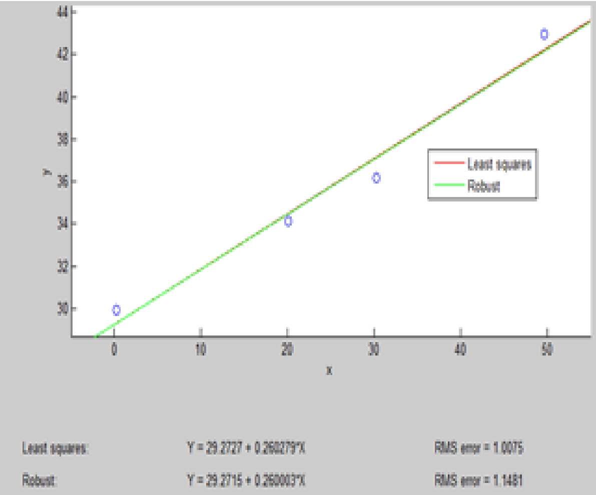

Fig.6. Robustdemo results for the Dielectric strength (kV/mm) of XLPE with different $CaCO_3$ filler percentages at 100°C.

From the calculation of the program the equation for the data obtained can be represented by two linear equations as follow:

Y= 29.2727 + 0.260279X RMS error = 1.0075% (5)

Y= 29.2715 + 0.260003X RMS error = 1.1481% (6)

Where Y is the dielectric strength value, X percentage of concentration of $CaCO_3$ in the sample.

The equation (5) is chosen to minimize the RMS error:

Y= 29.2727 + 0.260279X

4. Robustdemo for the dielectric strength results with different percentages of CaCO3 filler thermally stressed for 24 hrs aging at 130 ^{0}C.

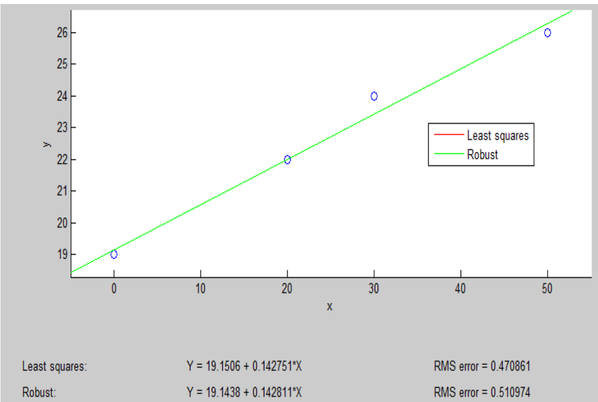

Fig.7. Robustdemo results for the Dielectric strength (kV/mm) of XLPE with different $CaCO_3$ filler percentages thermally stressed for 24 hrs aging at 130°C.

From the calculation of the program the equation for the data obtained can be represented by linear two equations as follows:

Y= 19.1506 + 0.142751X RMS error = 0.470861% (7)

Y= 19.1438 + 0.142811X RMS error = 0.510974% (8)

Where Y is the dielectric strength value, X percentage of concentration of $CaCO_3$ in the sample.

The equation (7) is chosen to minimize the RMS error:

Y= 19.1506 + 0.142751X

5. Robustdemo for the dielectric strength results with different percentages of CaCO3 filler thermally stressed for 24 hrs aging at 170 ^{0}C.

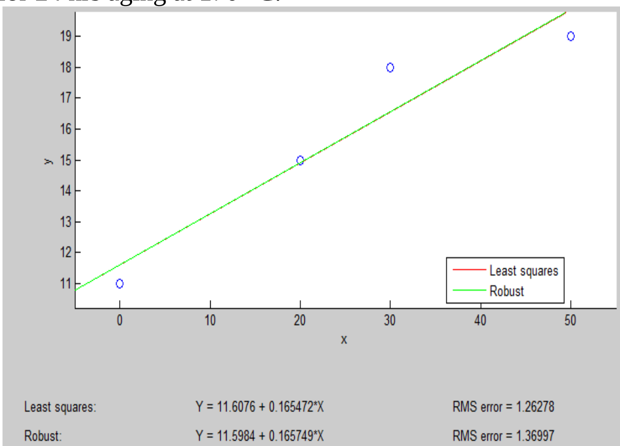

Fig.8. Robustdemo results for the Dielectric strength (kV/mm) of XLPE with different $CaCO_3$ filler percentages thermally stressed for 24 hrs aging at 170°C.

From the calculation of the program the equation for the data obtained can be represented by two linear equations as follow:

Y= 11.6076 + 0.165472X RMS error = 1.26278% (9)

Y= 11.5984 + 0.165749X RMS error = 1.36997%(10)

Where Y is the dielectric strength value, X percentage of concentration of $CaCO_3$ in the sample.

The equation (9) is chosen to minimize the RMS error:

Y= 11.6076 + 0.165472X

6. Robustdemo for the dielectric strength results with different percentages of $CaCO_3$ filler thermally stressed for 24 hrs aging at 190 ^{0}C.

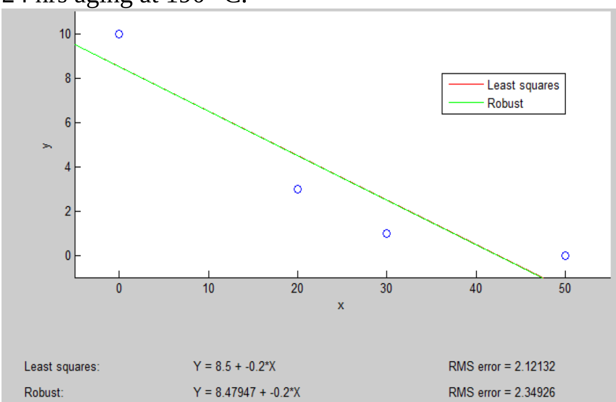

Fig.9. Robustdemo results for the Dielectric strength (kV/mm) of XLPE with different $CaCO_3$ filler percentages thermally stressed for 24 hrs aging at 190°C.

From the calculation of the program the equation for the data obtained can be represented by two linear equations as follow:

Y= 8.5 - 0.2X RMS error = 2.12132% (11)

Y= 8.47947 - 0.2X RMS error = 2.34926% (12)

Where Y is the dielectric strength value, X percentage of concentration of $CaCO_3$ in the sample.

The equation (11) is chosen to minimize the RMS error:

Y= 8.5 - 0.2X

The dielectric strength can be obtained from the equation with filler percentages varying from 0% to 50%. The error percentage will be varying from 0.47086% to 2.12132%.

C. Elongation at Break Test

The El% test was carried out to investigate the mechanical properties of XLPE after adding $CaCO_3$ in different wt%.Table 2 shows the values of El% of XLPE blends.

Table 2: Elongation at break % of different XLPE blends

BLEND SYMBOL	EL %
A	19.04
B	11.71
C	9.64
D	8.21

Table 2 shows that virgin XLPE had the greater value of El% compared to other blends with various fillers concentrations. The inorganic filler did not improve El%, contrariwise it decreased it. The XLPE/$CaCO_3$ (20 wt %) had the better El% than others concentrations. The worst concentration was XLPE/$CaCO_3$ (50 wt %). El% is inversely proportional to the increase of filler concentration.

IV. CONCLUSION

The following conclusions can be drawn from this work:

1. For low temperatures, the XLPE dielectric strength was improved by the increase of $CaCO_3$ concentrations by almost 41% for 50wt%.
2. The XLPE dielectric strength was decreased by the effect of high temperatures.
3. At high temperatures, the inorganic filler in different concentrations enhanced the dielectric breakdown strength of XLPE. It was improved by the increase of filler concentrations by almost 43% for 50 wt%,.
4. The dielectric strength can be obtained from the robustdemo program with filler percentages varying from 0% to 50%.
5. The molecules became more interlinked because of the increase of $CaCO_3$ concentrations, and this leads to the improvement of electrical characteristics of XLPE.
6. The inorganic filler lowered the mechanical properties of XLPE. The mechanical properties were decreased by the rise of filler concentrations.
7. It may be recommended to add 20 wt % of $CaCO_3$ to XLPE for enhancing both: dielectric strength (kV/mm) by almost 18-25 %. Also this concentration had a low impact on mechanical properties.

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