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Carbon Black Effect on Electrical Performance of Semi-Conducting Layers for Power Cables

Loai S. Nasrat[1], Abd Allah A. Ibrahim[1], Amany A. H. El-Shazly[2]
[1]Elec. Power & Machine Department, Faculty of Engineering, Aswan University, Aswan, Egypt
[2]Maintenance Engineer at the Luxor Sports Club, Ministry of Youth and Sports, Luxor, Egypt

Abstract*—The purpose of semiconducting layer is to smooth out the electromagnetic field, eliminate excessive voltage stress attributed to irregularities and voids between conductor and insulation, reduce vented trees at the interface between the insulation and the semi-conducting shield and avoid partial discharge .The semiconducting layer is typically formed from polymers(Poly vinyl chloride or Ethylene propylene rubber or Polyethylene or Cross-linked polyethylene).The polymer is blended on conducting carbon black to enhance the semiconducting layer which can reflect on increasing the performance of the power cable life by which saving both energy and money can be obtained. The aim of this paper is to improve the electrical performance of the Poly vinyl chloride as a semiconducting layer in power cables to increase the life expectancy of the power cable. Blends of PVC with CB were prepared with 0%, 20%, 25%, 30%, 35%, 40%, 45% and 50% by weight percentages concentration. Dielectric strength of the blends was tested with and without silicon rubber (SiR) layer in normal conditions. Also dielectric strength of blends was tested after being exposed to thermal aging for 24, 96 and 168 hrs, in high temperatures (70°C and 90°C). The mechanical characterization showed that the composite polymer enhanced by using carbon black in the tensile strength and the percentage elongation at break.*

Keywords—*Carbon Black (CB); Blends; Silicon Rubber (SiR); Dielectric strength; Tensile strength.*

I. INTRODUCTION

Power cables are built to meet the needs of their end-use applications [1]. In particular, power cables have a semi-conducting layer. The electrically semi-conductive layers usually contain large amounts of an electrically conductive pigment. PVC will be chose as a semi-conductor layer due to its high tensile strength, superior conductivity, better flexibility and ease of jointing [2]. PVC and polyethylene are the two main polymer types used for wire and cable insulation, with PVC comprising about 2/3 of the insulation used for building wiring in the US [3]. Furthermore, PVC is a polymer which is not particularly common in HV applications, so even HV data for failures and ignitions with PVC is rare [4]. When PVC is used for wire/cable insulation, it is not used as a pure polymer. Since intrinsically PVC is a rigid material and wire/cable insulation must be flexible, there has to be a significant loading of a plasticizer. Wickson indicates that typical wire/cable formulations contain 52 – 63% PVC resin, 25 – 29% plasticizer, around 16% filler (but occasionally as low as 5%), 2 – 4% stabilizer, 0.2 – 0.3% wax, and small amounts of lubricants and colorants; occasionally an FR agent is also included. Antioxidants are also often included in small amounts (less than 0.1%). The plasticizer is typically either a phthalate (e.g., diisodecyl phthalate, ditridecyl phthalate) or a trimellitate, e.g., tris(2-ethylhexyl) trimellitate, while CaCO3 and kaolin are common fillers [5]. Thermal degradation of PVC is a two-stage process [6]. Even for pure PVC, understanding and modeling its thermal degradation is complicated by the fact that initiation sites for dehydro-chlorination are dominated by structural abnormalities and cannot be predicted from a representation of an ideal polymer [7]. The dehydro-chlorination is autocatalytic [8], i.e., the presence of HCl gas promotes the reaction. Consequently, PVC formulations for wire/cable insulation use CaCO3 or a similar filler to act as an HCl 'scrubber'[9]. Pure PVC could not be formed into useful products, since its thermal degradation generally starts below the temperature at which molding or extruding would be performed. Consequently, in commercial PVC formulations, stabilizers are added to counteract thermal degradation, to inactivate the HCl that is produced, and thus to reduce the autocatalytic reaction acceleration. Yet, their chemical mechanisms of action are only poorly known [10]. There is only a narrow range of temperatures at which a particular PVC formulation can be successfully extruded; too low a temperature will result in a non-homogeneous mixture, while too high a temperature will lead to micro-pores being formed [11]. Using testing devices [12] with specially-shaped electrodes that minimize electric field non-uniformities and corona-provoked arc initiation, a handbook value of "intrinsic breakdown strength" can be obtained, which for PVC at room temperature [13], is around 350 MV/mm. Such values represent an ideal-case upper limit, not an actual breakdown voltage that might be expected under in-use conditions.

This paper aims to improve electrical performance of semi-conductor layer in power cable. It focuses on trying to find an appropriate weight percentage composition of such blend in order to enhance the electrical and mechanical characteristics of the semi-conductor layer in different conditions. Soft program (Curve fitting) was used to interpreted the equation between different conditions.

II. EXPERIMENTAL AND PROCEDURES

A. Sample Preparation and Dimensions

Eight blend percentages have been prepared from PVC composites of different ratios (0, 20, 25, 30, 35, 40, 45 and 50 wt(%)) of carbon black filler, which were mixed using an electrically heat chamber of Barbender Plasticoder model

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(230 Volt, 40 Amp). Mixing was performed at 160^0 C and 100 RPM for 10 min to allow the torque to reach equilibrium. After the mixing was completed, it was compressed under a pressure of 4 MPa at the same mixing temperature and then molded. The sample was cut and prepared with dimensions that best suited each testing technique according to ASTM.

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 1 mm, and is expressed in volts per unit of thickness. For each test, Samples are in the form of disc with diameter 5 cm and thickness 1 mm according to ASTM. For each test, the average result of five samples has been taken to minimize the error. Figure 1 shows the circuit used for dielectric break down strength test.

By using curve fitting methods, we can create access and modify curve fitting objects. That allowed to like plot and integrate, to perform operations that uniformly process the entirety of information encapsulated in a curve fitting object.

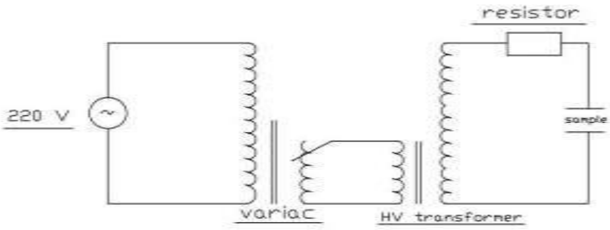

Fig. 1. Schematic diagram for the dielectric strength testing circuit.

C. Tensile Strength and Percentage Elongation at Break Test

Mechanical test such as Tensile strength and percentage elongation at break are performed to illustrate the ability of samples to withstand the mechanical force. The dimensions of the sample are 10cm length and 2 mm thickness for tensile strength and 10 cm length and 2 mm thickness for Elongation at break. All the samples with certain weight percentage addition were tested five times with an average result calculated.

III. Results and Discussion

A. Electrical Results

1. Dielectric breakdown strength of CB/ PVC composites

The dielectric strength for PVC has been studied with different filler wt. % in normal conditions: with and without SiR.

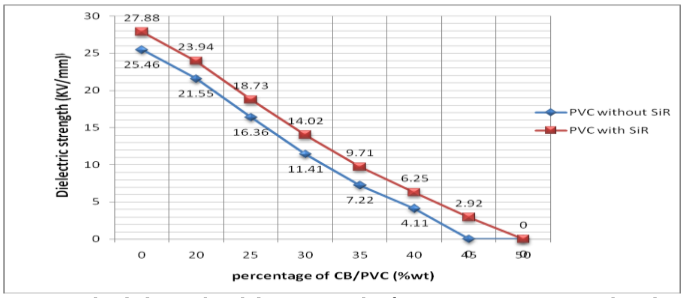

Fig. 2. The dielectric breakdown strength of CB/PVC composites with and without SIR under normal conditions.

Comparison between percentages of CB/PVC leads to 0%wt CB the maximum value in these composites. It reaches to 25.46 kV without SiR and 27.88kV with SiR at normal condition.

It can be observed that, the dielectric strength of samples decreases with increasing of percentage of carbon black with or without SiR under normal condition. This is because of the conductivity of the Carbon Black.

Also it can be concluded that, the dielectric strength of samples with SiR layer are larger than the dielectric strength of PVC samples without SiR layer due to SiR layer act as an insulation layer so this increase the dielectric strength.

2. The dielectric strength of CB/ PVC composites at 70°C for 24, 96 and 168Hrs under thermal aging.

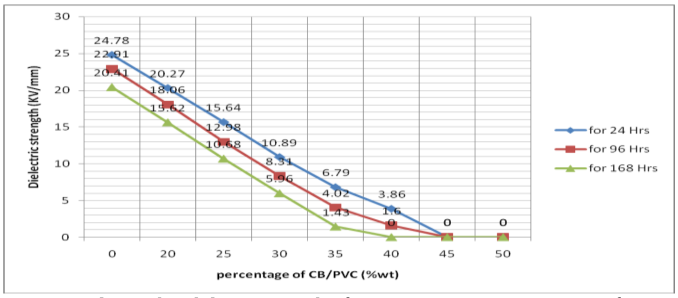

Fig. 3. Dielectric breakdown strength of CB/ PVC composites at 70°C for 24, 96 and 168Hrs under thermal aging.

It can be observed that, the dielectric strength of samples decreases with increasing of percentage of carbon black at 70°C for 24, 96 and 168Hrs under thermal aging. This is because of the conductivity of the Carbon Black.

Also it can be concluded that, the percentage decreasing of dielectric strength of samples at 70°C increase with increasing the duration of thermal aging.

Comparison between percentages of CB/PVC leads to 0%wt CB the maximum value in these composites. It reaches to 24.78 kV for 24 Hrs, 22.91 kV for 96 Hrs and 20.41kV for 168 Hrs at 70°C under thermal aging.

3. The dielectric strength of CB/ PVC composites at 90°C for 24, 96 and 168Hrs under thermal aging.

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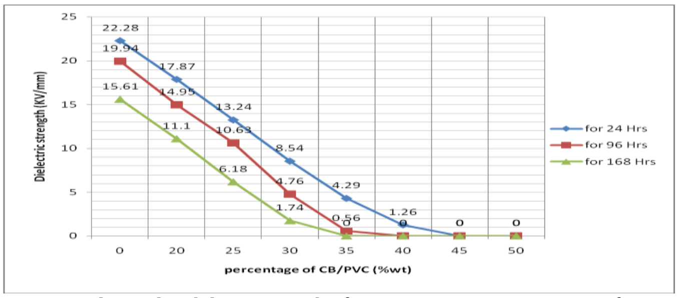

Fig. 4. Dielectric breakdown strength of CB/ PVC composites at 90°C for 24, 96 and 168Hrs under thermal aging.

It can be observed that, the dielectric strength of samples decreases with increasing of percentage of carbon black at 90°C for 24, 96 and 168Hrs under thermal aging. This is because of the conductivity of the Carbon Black.

Also it can be concluded that, the percentage decreasing of dielectric strength of samples at 90°C increase with increasing the duration of thermal aging.

Comparison between percentages of CB/PVC leads to 0%wt CB the maximum value in these composites. It reaches to 22.28 kV for 24 Hrs, 19.94 kV for 96 Hrs and 15.61kV for 168 Hrs at 90°C under thermal aging.

4. Tensile strength for of CB/ PVC composites

The tensile strength for PVC has been studied with different filler wt. % in normal conditions

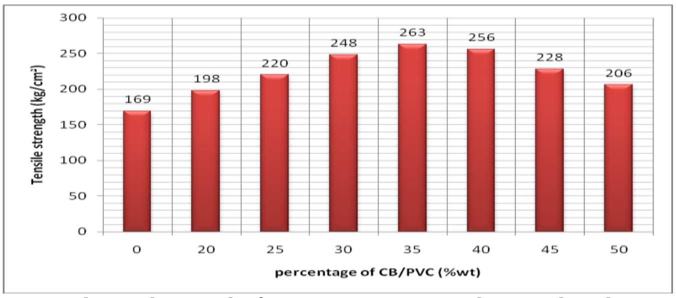

Fig. 5. The tensile strength of CB/PVC composites under normal conditions.

It can be observed that, the tensile strength of the samples increase and then begins to decrease. Starting from sample K1 the tensile strength was measured 169 Kg/cm². Samples staring from sample K2 till sample K5 the trend for the tensile strength recorded was almost increasing. Sample K5 recorded the largest value for the tensile stress of all samples it was recorded an average of 263 Kg/cm². Starting from sample K6 to K8 the samples recorded tensile strength was decreasing.

5. The elongation at break for of CB/ PVC composites

The elongation at break for PVC has been studied with different filler wt. % in normal conditions

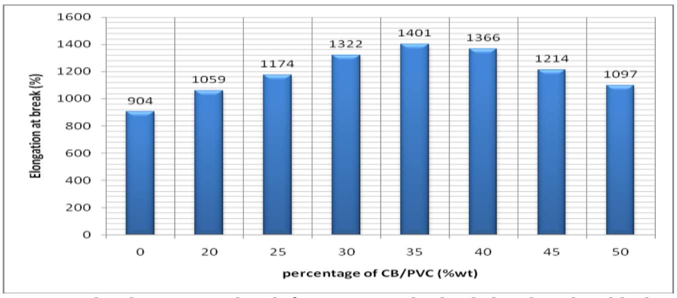

Fig. 6. The elongation at break for PVC samples loaded with carbon black filler with various percentages under normal condition.

It can be observed that the elongation of the samples increase and then begins to decrease. Starting from sample F1 the elongation percentage was measured 904%. Sample staring from sample F2 till sample F5 the trend for the elongation % recorded was almost increasing. Sample F5 recorded the largest value for the elongation % recorded of all samples it was recorded an average of 1401%. Starting from sample F6 to F8 the samples' recorded elongation % was decreasing.

B. Soft Program (MATLAB) Results

Curve fitting (regression analysis) is used to find the "best fit" line or curve for a series of data points. Most of the time, the curve fit will produce an equation that can be used to find points anywhere along.

1. Curve fitting for the dielectric strength results for the PVC samples with different carbon black filler percentages under normal condition.

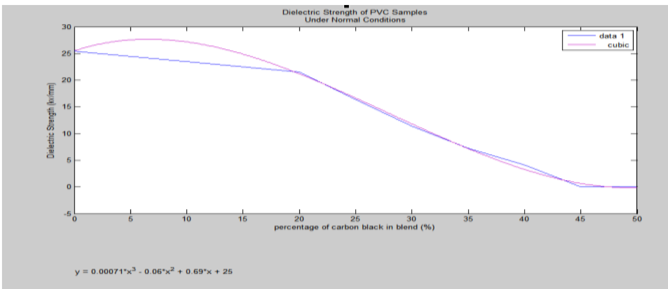

Fig. 7. Curve fitting of dielectric strength for PVC samples loaded with carbon black filler with various percentages under normal condition.

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00071\ x^3- 0.06x^2+0.69x+25$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00071

B is a constant = -0.06

C is a constant = 0.69

D is a constant = 25

2. Curve fitting for the dielectric strength results for the PVC samples with different carbon black filler percentages with SiR layer under normal condition.

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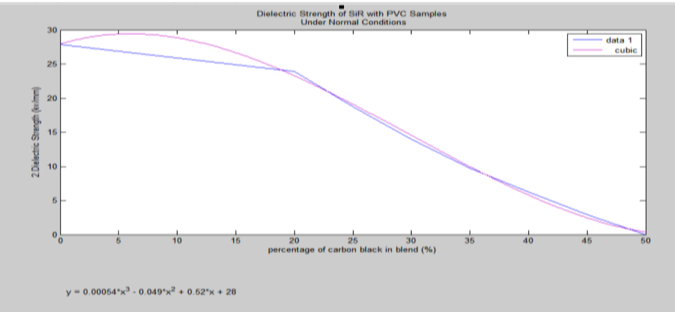

Fig. 8. Curve fitting for the dielectric strength of PVC Samples with different carbon black filler percentages with SiR layer under normal condition.

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00054x^3- 0.049x^2+0.52x+28$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00054

B is a constant = - 0.049

C is a constant = 0.52

D is a constant = 28

3. Curve fitting for the dielectric strength results for the PVC samples loaded with different carbon black filler percentages under thermal Aging for 24 hrs at (70°C).

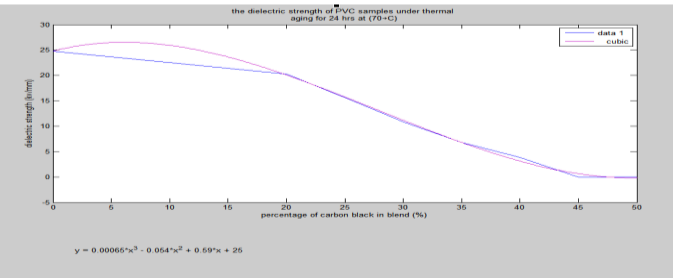

Fig. 9. Curve fitting for the dielectric strength of PVC samples loaded with different carbon black filler percentages under thermal Aging for 24 hrs at (70°C).

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00065x^3- 0.054x^2+0.59x+25$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00065

B is a constant = -0.054

C is a constant = 0.59

D is a constant = 25

4. Curve fitting for the dielectric strength results for the PVC samples loaded with different carbon black filler percentages under thermal Aging for 96 hrs at (70°C).

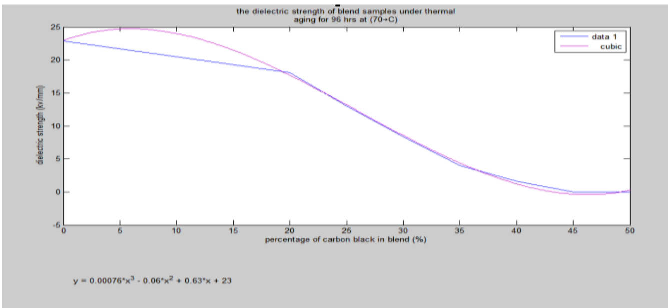

Fig. 10. Curve fitting for the dielectric strength of PVC samples loaded with different carbon black filler percentages under thermal Aging for 96 hrs at (70°C).

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00076x^3- 0.06x^2+0.63x+23$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00076

B is a constant = -0.06

C is a constant = 0.63

D is a constant = 23

5. Curve fitting for the dielectric strength results for the PVC samples loaded with different carbon black filler percentages under thermal Aging for 168 hrs at (70°C).

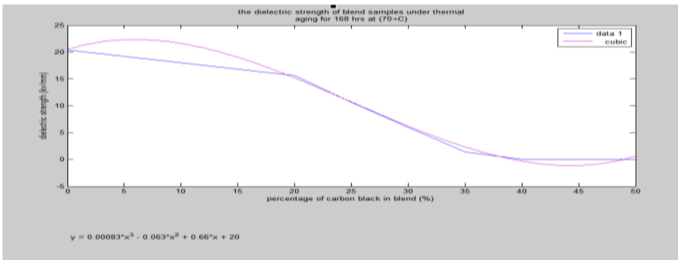

Fig. 11. Curve fitting for the dielectric strength of PVC samples loaded with different carbon black filler percentages under thermal Aging for 168 hrs at (70°C).

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00083x^3- 0.063x^2+0.66x+20$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00083

B is a constant = -0.063

C is a constant = 0.66

D is a constant = 20

6. Curve fitting for the dielectric strength results for the PVC samples loaded with different carbon black filler percentages under thermal Aging for 24 hrs at (90°C).

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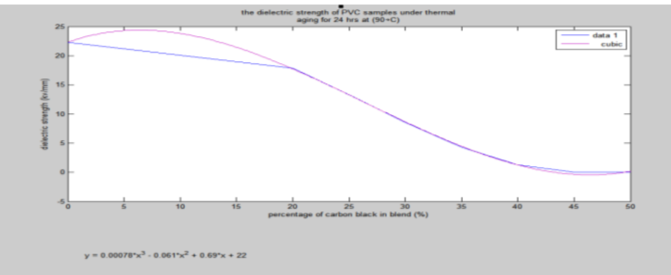

Fig. 12. Curve fitting for the dielectric strength of PVC samples loaded with different carbon black filler percentages under thermal Aging for 24 hrs at (90°C).

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00078x^3- 0.061x^2+0.69x+22$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00078
B is a constant = -0.061
C is a constant = 0.69
D is a constant = 22

7. Curve fitting for the dielectric strength results for the PVC samples loaded with different carbon black filler percentages under thermal Aging for 96 hrs at (90°C).

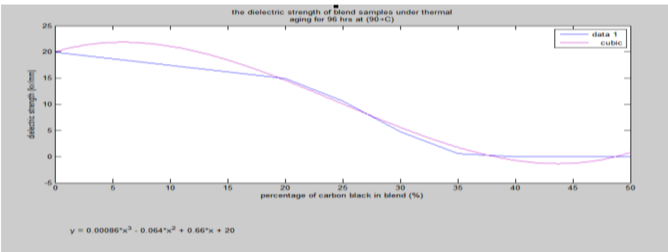

Fig. 13. Curve fitting for the dielectric strength of PVC samples loaded with different carbon black filler percentages under thermal Aging for 96 hrs at (90°C).

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00086x^3- 0.064x^2+0.66x+20$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00086
B is a constant = -0.064
C is a constant = 0.66
D is a constant = 20

8. Curve fitting for the dielectric strength results for the PVC samples loaded with different carbon black filler percentages under thermal Aging for 168 hrs at (90°C).

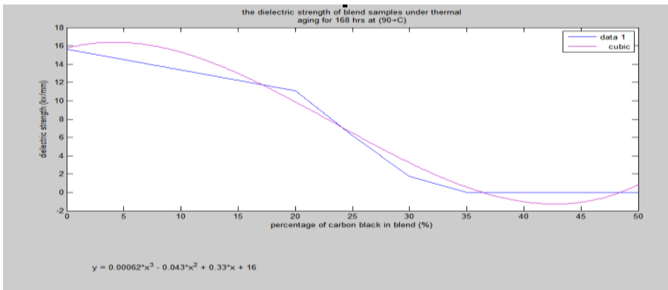

Fig. 14. Curve fitting for the dielectric strength of PVC samples loaded with different carbon black filler percentages under thermal Aging for 168 hrs at (90°C).

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00062x^3- 0.043x^2+0.33x+16$

Where Parameter Y can be represented value of dielectric strength (kV/mm), Parameter X varies to CB(%wt).

A is a constant = 0.00062
B is a constant = -0.043
C is a constant = 0.33
D is a constant = 16

9. Curve fitting for the tensile strength results for the PVC samples with different carbon black filler percentages under normal condition.

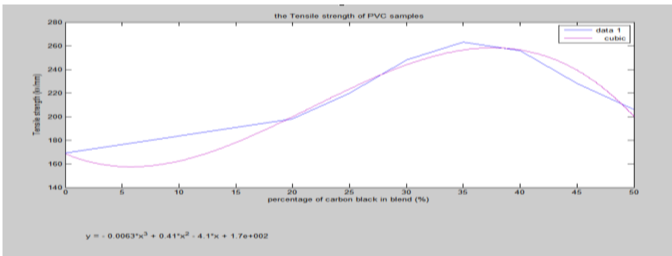

Fig. 15. Curve fitting of tensile strength for PVC samples loaded with carbon black filler with various percentages under normal condition.

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y=0.00063x^3+0.41x^2- 4.1x+1.7e+002$

Where Parameter Y can be represented value of tensile strength (kg/m²), Parameter X varies to CB(%wt).

A is a constant = -0.0063
B is a constant = 0.41
C is a constant = -4.1
D is a constant = 1.7e+002

10. Curve fitting for the elongation at break results for the PVC samples with different carbon black filler percentages under normal condition.

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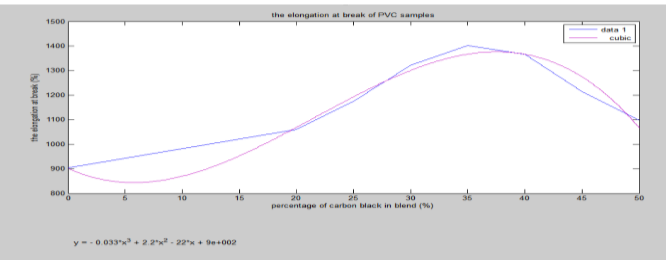

Fig. 16. Curve fitting of elongation at break for PVC samples loaded with carbon black filler with various percentages under normal condition.

From the calculation of the program the best curve fitting for the data obtained can be represented by 3th degree polynomial equation as follow:

$Y=Ax^3+Bx^2+Cx+D$

$Y= - 0.033x^3+2.2x^2- 22x+9\ e+002$

Where Parameter Y can be represented value of the percentage elongation at break (%), Parameter X varies to CB(%wt).

A is a constant = -0.033

B is a constant = 2.2

C is a constant = -22

D is a constant = 9e+002

By substituting in this equation by x= 30, y = 1300 which is the same value premeasured.

IV. CONCLUSION

It can be concluded from this work that:

- The addition of carbon black to PVC blends decreased the dielectric breakdown strength.
- The dielectric strength decreased at 90°C as compared with those at 70°C under thermal condition.
- The dielectric strength decreased with increasing the duration of thermal aging.
- The tensile strength of the samples increase and then begins to decrease
- The elongation of the samples increase and then begins to decrease.
- The addition of carbon black enhances the electrical and mechanical of the PVC blends
- As a result of previous points, the suitable percentage of carbon black adding to PVC sample ranging from 30-34% of the weight of PVC.

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BIOGRAPHIES OF AUTHORS

	**First Author:** Dr. Loai Nasrat is a professor at Elec. Power & Machine Department, Faculty of Engineering, Aswan University, Aswan, Egypt. He has been actively involved in both basic and applied research in the area of HV engineering. His research interests include HV insulators, polymeric materials, HV cables insulations and environmental studies. Author and co-author of more than 60 papers on HV polymeric insulating materials, published in technical journals and proceedings of national and international conferences.
	**Second Author:** Dr. Abd Allah Ahmed Ibrahim, is a professor at Elec. Power & Machine Department, Faculty of Engineering, Aswan University, Aswan, Egypt.
	**Third Author:** Eng. Amany Abo El- Hassen EL-Shazly Ahmed received the B.Sc of Electrical Engineering degree in 2013 from Faculty of Engineering, South valley University, Qina, Egypt. She works as a maintenance engineer in the Luxor Sports Club, Ministry of Youth and Sports, Luxor, Egypt from 2014 for now.