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Estimation of Dielectric strength and Tensile strength for XLPE Nanocomposites Insulators using Machine Learning Algorithm

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Abstract: *For electrical and electronics applications, polymeric materials have become a better choice. These applications demand multifunctionality in a single material, which is uncommon in polymers. Mixing polymer with other materials is a cost-effective technique to create multi-functional products. Property enhancement in nanocomposite systems, where the fillers typically have nanometer-scale dimensions, is usually accompanied by tradeoffs. The impact of nanofillers on the dielectric and mechanical properties of the cross-linked polyethylene (XLPE) matrix is discussed in this research. Preparation of XLPE loaded with 0-7 wt% Titanium dioxide (TiO2) and Zeolite nanofillers. The dielectric strength and tensile strength of nanocomposites were measured using ASTM standard procedures. The dielectric strength and tensile strength results were evaluated and forecasted using a Machine Learning Algorithm. The use of nanofillers enhanced dielectric strength and tensile strength, according to the findings. In general, TiO2 has better qualities than Zeolite nanofiller based on the attributes measured. When 5 wt% TiO2 is added to the XLPE matrix, the dielectric strength and tensile strength of the material improves when compared to pure XLPE.*

Keywords: *XLPE, Nanocomposites, Dielectric strength, Tensile strength, Machine learning algorithm*.

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I. INTRODUCTION

Because of its superior dielectric qualities, high flexibility and mechanical strength, superior chemical resistance, low cost, and ease of processing, cross-linked polyethylene (XLPE) has been widely used as an insulator in high-voltage cables [1-3]. Furthermore, the usage of XLPE as an insulating material in underground and distribution cables is susceptible to unfavorable weather and contamination, resulting in insulation failure.

When compared to pure polymers, polymer composites incorporating nano-sized fillers have a considerable deal of potential to improve mechanical, electrical, and thermal properties without modifying polymer compositions or processing [4-7]. Metal oxides, clay, carbon nanotubes, graphene, cellulose, glass, and carbon fibers could be used as fillers [8].

Electrical strength is frequently used to evaluate the main properties of a successful insulating system. Mechanical and thermal qualities, on the other hand, are key aspects that can have a significant impact on the performance of electrical insulation or even cause failures.

The effectiveness of the interaction between the matrix and the filler is strongly related to the qualities of nanocomposites in general. Hydrogen bonding, van der Waals forces, polar contacts, and mechanical interlocking are all examples of interactions [9].

In cable insulation, dielectric strength is a key component in determining whether an insulating material would fail catastrophically when subjected to an external applied field. It is primarily impacted by the polymer's cohesive energy density and free volume or mobility [10].

The goal of this study is to investigate the dielectric and mechanical properties of XLPE with TiO2 and Zeolite nano fillers. The dielectric strength and tensile strength of XLPE were also estimated and predicted using a machine learning method.

II. EXPERIMENTAL PROCEDURE

2.1 Materials and samples preparation

Pure cross-linked low density polyethylene pellets having a density of 0.924 g/cm3 were supplied by SABIC KSA. NanoTech Company in Egypt also provided TiO2 and Zeolite nanofillers.

Preparing Materials and Samples Melt mixing and compression molding were used to create XLPE nanocomposites in a single screw extruder. The fillers were dried in an oven at 80°C to remove moisture before mixing. Table 1 lists nanocomposites formulations.

Table 1 Formulations of XLPE nanocomposites.

Formulations	Type of nano filler	Acronym	XLPE (wt %)	Nano filler (wt %)
1	Pure XLPE	B	100	0
2	TiO2	T1	99	1
3		T3	97	3
4		T5	95	5
5		T7	93	7
6	Zeolite	Z1	99	1
7		Z3	97	3
8		Z5	95	5
9		Z7	93	7

2.2 Dielectric strength test

TERCO instrument kits from Sweden were used to measure dielectric strength according to ASTM D-149. The disc-shaped test specimens had a diameter of 5 cm and a thickness of 2 mm. After clipping and testing 10 samples for each filler concentration, extreme value statistics were applied to each population's results. The tests were carried out in the Aswan University Faculty of Engineering's high-voltage laboratory. The purpose of this test is to see how high temperatures and the presence of dissolved salt at various levels affect the insulating property. Separate groups of specimens were evaluated in the following media conditions in this context:

- Group A was tested by AC voltage; samples were at room temperature (30°C).
- Group B was tested by AC voltage; samples were exposed to high temperature (250°C).
- Group C was tested by AC voltage; samples were thermally stressed at 120°C for 24hrs.
- Group D was tested by AC voltage; samples were thermally stressed at 160°C for 24hrs.
- Group E was tested by AC voltage; samples were immersed in solution of 20000 µS/cm salinity.
- Group F was tested by AC voltage; samples were immersed in solution of 50000 µS/cm salinity.

2.3 Tensile strength test

Tensile strength was used to illustrate the ability of composite specimens to resist mechanical strength. As shown in Fig. 2, the sample should be in the shape of a dumbbell with a length of 5 cm and a thickness of 2 mm. The test was performed using the Zwick Roell LTM electrodynamic testing machine in accordance with ASTM D-412.

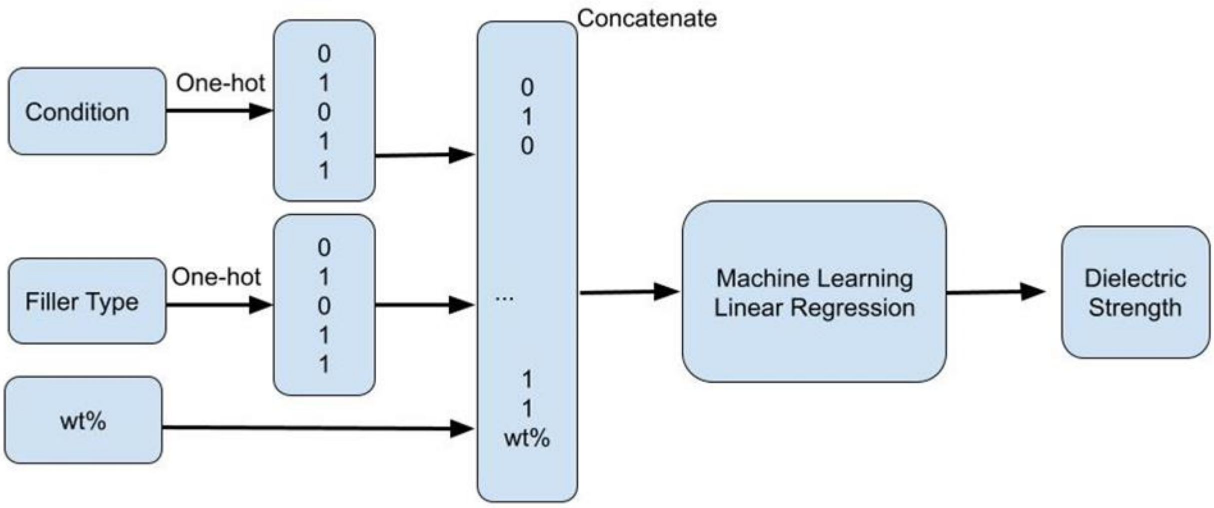
2.4 Machine learning algorithm

Machine Learning (ML) is the process of creating computer algorithms that can learn from data. Early Artificial Intelligence (AI) approaches that dealt largely with deductive inference [11], i.e. the derivation of theorems from axioms, can be contrasted to machine learning's inductive inference, i.e. generalizations from a set of observed cases. ML is a subfield of AI that connects with a variety of other scientific fields, including statistics, cognitive psychology, and information theory. Linear Regression is well study Machine Learning algorithm used to model the relationship between a scalar response variable with one or more explanatory variables. It can be seen that a regression model can only accept inputs in numerical format. However, the data we have might come in different types, including both scalar and categorical. For examples, a set of six conditions 30°C, 250°C, thermal aging at 120°C, thermal aging at 160°C, low salty wet water and high salty wet water) has been used as an input data. If an experiment is conducted at 250°C, it will be encoded as [0, 1, 0, 0, 0, 0]. This is because the condition 250°C is at the second position in the list of the 6 conditions.

2.4.1 Machine learning's linear regression model for dielectric strength

The dielectric strength is estimated based on 3 inputs: the conditions of the experiments, the values of wt% and the type of filler. The conditions must be one of these values: 30°C, 250°C, thermal aging at 120°C, thermal aging at 160°C, low salty wet water and high salty wet water. The filler must be one of these types: TiO2 and Zeolite or None, where None means no filler was used. The values of wt% must be any scalar from 0 to 7. As mentioned earlier, the condition and the filler type are categorical so they need to be one-hot encoded. After that, the encoded filler type, encoded condition and the value of wt% are concatenated in that order into a vector, which can then be used to train the regression model. This process can be illustrated in Figure 1.

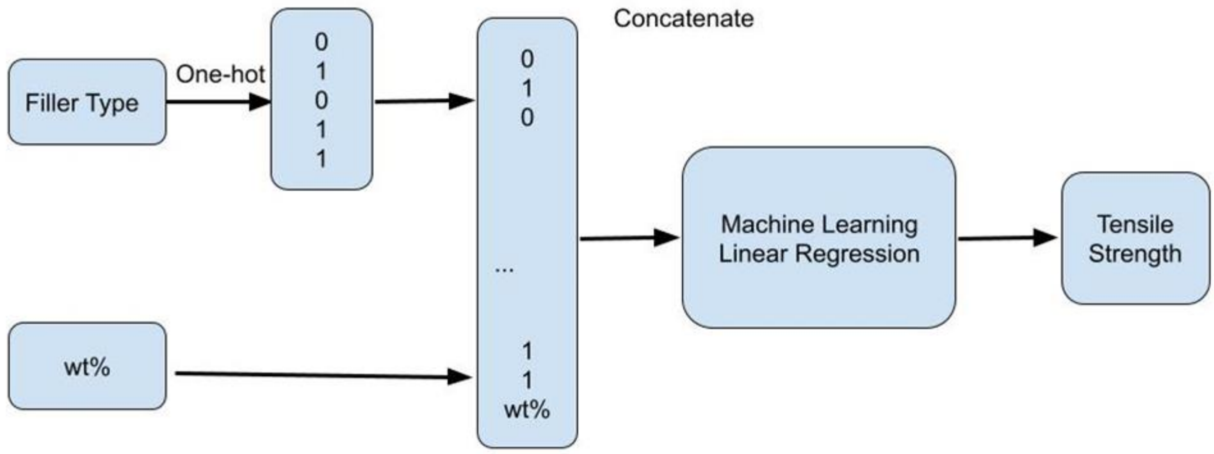
Figure 1. The model prediction for dielectric strength.



2.4.2 Machine learning's linear regression model for tensile strength

The Machine Learning's regression model for tensile strength was built by the same way a regression model for dielectric strength was built. The only different here is that the inputs to the model only include the filler type and the value of wt%. The model can be illustrated in Figure 2.

Figure 2. The model prediction for tensile strength.



III. RESULTS AND DISCUSSIONS

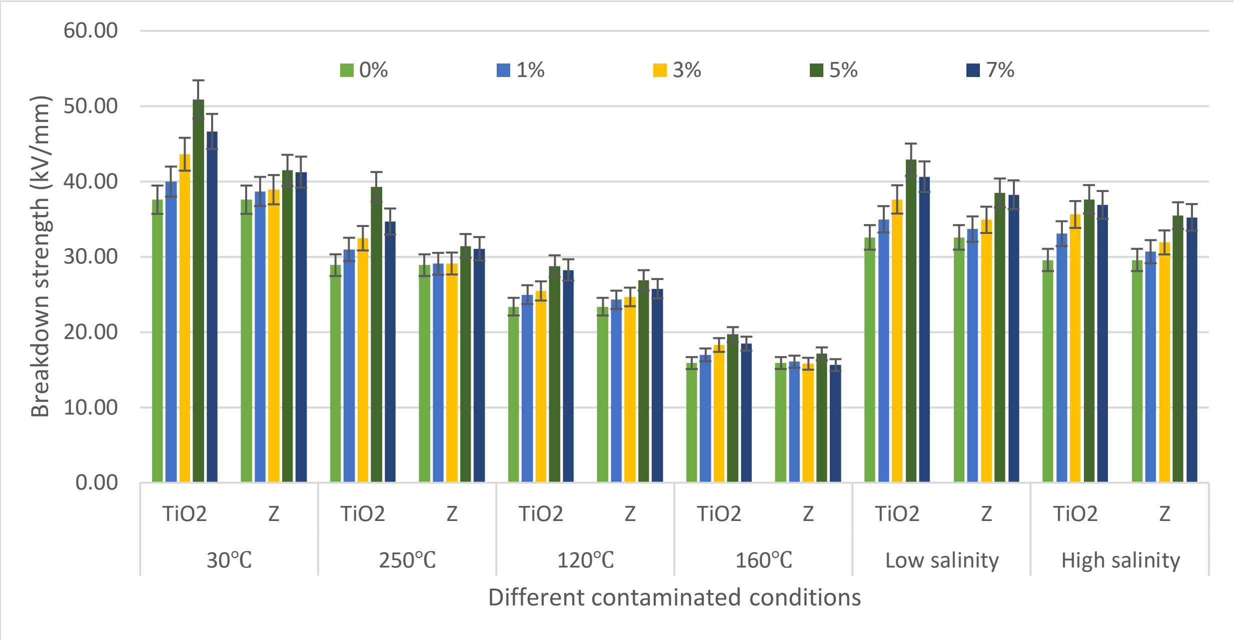
3.1. Dielectric strength test results

Figure 1 shows the reaction scheme of the syntheses of the derivatives of ibuprofen through the esterification reaction, which resulted in the production of 5 derivatives.

The dielectric breakdown strength of XLPE nanocomposites as a function of filler loadings is shown in Figure 3. When 5 wt% filler loading was added to TiO2/XLPE and Z/XLPE nanocomposites, the dielectric strength rose. After that, the trend decreased. TiO2/XLPE nanocomposites had a maximum dielectric strength of 50.89 kV/mm, while Z/XLPE nanocomposites had a maximum dielectric strength of 41.47 kV/mm, which was 35 percent and 10% greater than pure XLPE (37.58 kV/mm), respectively. TiO2 has a better effect than Z nanofiller. High temperatures and salty dampness have a clear impact on dielectric strength since they lower its value.

The influence of interaction zones could explain the increase in dielectric strength [12, 13]. When filler is added to the matrix, particle surface area and interfacial area both increase, resulting in a large number of contact zones. As a result, extra charges (electrons) may become trapped within the interaction zones. As a result, the system requires an extra voltage supply to allow the charges to traverse the samples. The overlapping impact of the interaction zones causes the dielectric strength to decrease with the addition of 7 wt% filler loading. When filler loading reaches a particular threshold, the number of particles grows while the space between them decreases, causing the interfaces to overlap. As a result, conductivity routes arise and the tunneling current between nanoparticles increases. Agglomeration of nanofillers, on the other hand, occurred with excessive filler loading, resulting in defects such as macro or nanovoids at the interface.

Figure 3. Dielectric strength (kV/mm) of nanoTiO2 and nano Zeolite composite samples at different conditions.

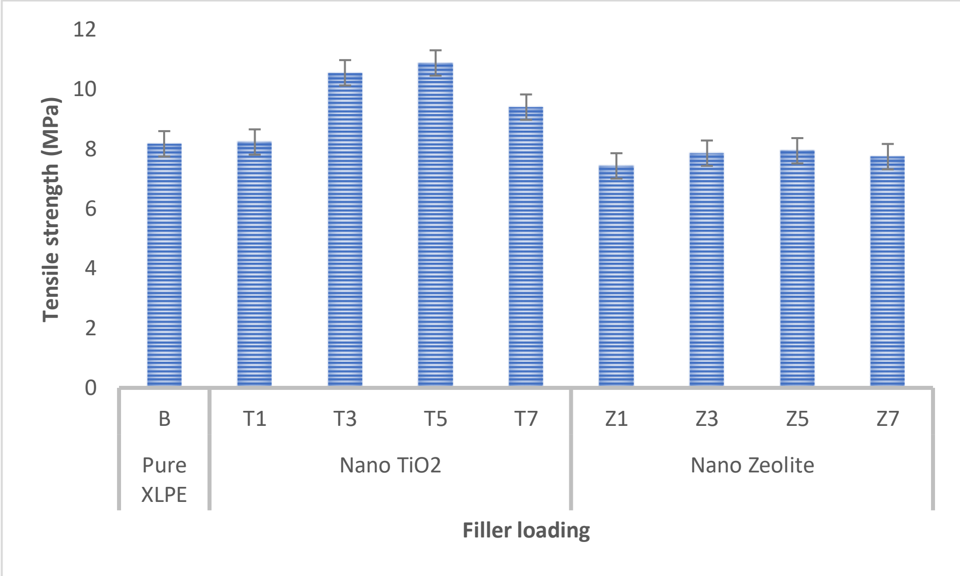


3.2 Tensile strength test results

The tensile strength of XLPE nanocomposites as a function of filler loading is shown in Figure 4. With the addition of 5 wt percent filler loading, the tensile strength of TiO2/XLPE nanocomposites and Z/XLPE nanocomposites increased, but after that decreased. TiO2/XLPE nanocomposites had a maximum tensile strength of 10.89 MPa, whereas Z/XLPE nanocomposites had a maximum tensile strength of 7.95 MPa, both higher than pure XLPE (8.18 MPa). In XLPE, the effect of TiO2 is greater than that of Z nanofiller.

The filler-matrix interaction created within the filler and the matrix by Van der Waals forces [14] possibly explain this pattern. When a force is applied, interaction action is preferred for stress transfer from the matrix to the filler. In terms of reinforcing efficiencies, low filler loading might easily be spread in a matrix, resulting in a large contact surface area and hence higher stress transmission. The current finding is in line with a recent study that found that adding a tiny number of nanofillers (5 wt percent) to a polymer improves its mechanical properties [14].

Figure 4. Tensile strength (kV/mm) of nanoTiO2 and nano Zeolite composite samples.



3.3 Machine learning results

3.3.1 Dielectric strength regression model

The prediction of dielectric strength for XLPE/TiO2 composite samples made by the regression model are shown in Table 2. The calculation of the MSE was also done on Table 2.

The dielectric strength has been investigated in five nanocomposite samples for every condition. Then, the machine learning technique has been used to train the experimental results. After training the machine learning model, the machine learning results have been compared with the experimental values to check the validity of the machine learning technique and evaluate the percentage of error as shown in Table 2.

Table 2. Prediction of dielectric strength for XLPE/TiO2 composite samples.

Acronym	Test condition	Experimental results of dielectric strength	Machine learning prediction	Percentage of error (%)
B		37.58	38.85	0.03379
T1		39.98	42.00	0.05053
T3	30°C	43.62	43.40	0.00504
T5		50.89	44.81	0.11947
T7		46.64	46.21	0.00922
B		28.89	28.40	0.01696
T1		30.98	31.55	0.01840
T3	250°C	32.47	32.95	0.01478
T5		39.29	34.35	0.12573
T7		34.68	35.76	0.03114
B		23.38	22.49	0.03807
T1		24.98	25.64	0.02642
T3	Thermal aging at 120°C	25.47	27.04	0.06164
T5		28.76	28.44	0.01113
T7		28.26	29.85	0.05626
B	Thermal aging at 160°C	15.89	13.98	0.12020

T1		16.98	17.13	0.00883
T3		18.29	18.54	0.01367
T5		19.68	19.94	0.01321
T7		18.47	21.34	0.15539
B		32.58	33.59	0.03100
T1		34.98	36.74	0.05031
T3	20000 µS/cm	37.62	38.14	0.01382
T5		42.89	39.55	0.07787
T7		40.64	40.95	0.00763
B		29.58	30.59	0.03414
T1		31.98	33.74	0.05503
T3	50000 µS/cm	35.62	35.14	0.01348
T5		37.64	36.55	0.02896
T7		36.89	37.95	0.02873

Machine learning technique is used to calculate the dielectric strength of XLPE/TiO2 composite samples. It can be noted from Table 2 that, the rate of errors for the machine learning model ranged from 0.00504% to 0.15539%. Also it can be seen from Table 2 that, the machine learning technique has a minimum value of error.

The prediction of dielectric strength for XLPE/Z composite samples made by the regression model are shown in Table 3. The calculation of the MSE was also done on Table 3.

Table 3 Prediction of dielectric strength for XLPE/Z composite samples.

Acronym	Test condition	Experimental results of dielectric strength	Machine learning prediction	Percentage of error (%)
B	30°C	37.58	38.85	0.033794572
Z1		38.68	39.25	0.014736298
Z3		38.91	40.65	0.044718581
Z5		41.47	42.06	0.014227152
Z7		41.24	43.46	0.053831232
B	250°C	28.89	28.4	0.016960886
Z1		29.07	28.8	0.009287926
Z3		29.11	30.2	0.037444177
Z5		31.45	31.6	0.004769475
Z7		31.07	33.01	0.062439652
B	Thermal aging at 120°C	23.38	22.49	0.038066724
Z1		24.29	22.89	0.057636888
Z3		24.67	24.29	0.015403324
Z5		26.88	25.69	0.044270833
Z7		25.76	27.1	0.052018634

B	Thermal aging at 160°C	15.89	13.98	0.120201385
Z1		16.07	14.38	0.105164904
Z3		15.89	15.78	0.006922593
Z5		20.07	17.19	0.143497758
Z7		18.45	18.59	0.007588076
B	20000 μS/cm	32.58	33.59	0.031000614
Z1		33.68	33.99	0.009204276
Z3		34.91	35.39	0.013749642
Z5		38.47	36.8	0.04341045
Z7		38.24	38.2	0.001046025
B	50000 μS/cm	29.58	30.59	0.034144692
Z1		30.68	30.99	0.010104302
Z3		31.91	32.39	0.015042306
Z5		35.47	33.8	0.047082041
Z7		35.24	35.2	0.001135074

Machine learning technique is used to calculate the dielectric strength of XLPE/Z composite samples. It can be noted from Table 3 that, the rate of errors for the machine learning model ranged from 0.00105% to 0.14350%. Also it can be seen from Table 3 that, the machine learning technique has a minimum value of error.

3.3.2 Machine learning results for predicting dielectric strength of different concentrations of xlpe/tio2 composite samples in different conditions

Machine learning helps to predict all values of dielectric strength for different XLPE/TiO2 composites especially for the samples which are situated between the experimental results.

The trained machine learning model acts as a robust predictor for any other percentages of fillers for example 0.5, 2%, 3.5%, 4% and 6% for nano TiO2 as shown in Table 4.

Table 4 Machine learning results for predicting dielectric strength of XLPE/TiO2 composite samples in different conditions.

Percentages of filler (%)	Test condition	Predicted values of dielectric strength (kV/mm)
0.5	30°C	41.6484
2		42.7009
4		44.1004
6		45.5078
0.5	250°C	31.1957
2		32.2483
4		33.6517
6		35.0552

0.5	Thermal aging at 120°C	25.2857
2		26.3383
4		27.7417
6		29.1452
0.5	Thermal aging at 160°C	16.781
2		17.8336
4		19.2371
6		20.6405
0.5	20000 µS/cm	36.389
2		37.4416
4		38.8451
6		40.2485
0.5	50000 µS/cm	33.389
2		34.4416
4		35.8451
6		37.2485

It can be investigated from Table 4 that the predicted values of dielectric strength of XLPE/TiO2 composites were reasonable according to the experimental values of dielectric strength.

3.3.3 Machine learning results for predicting dielectric strength of different concentrations of xlpe/z composite samples in different conditions

Machine learning helps to predict all values of dielectric strength for different XLPE/Z composites especially for the samples which are situated between the experimental results.

The trained machine learning model acts as a robust predictor for any other percentages of fillers for example 0.5, 2%, 3.5%, 4% and 6% for nano Z as shown in Table 5.

Table 5. Machine learning results for predicting dielectric strength of XLPE/Z composite samples in different conditions.

Percentages of filler (%)	Test condition	Predicted values of dielectric strength (kV/mm)
0.5	30°C	38.8975
2		39.9501
4		41.356
6		42.757
0.5	250°C	28.4449

2		29.4974
4		30.9009
6		32.3043
0.5	Thermal aging at 120°C	22.5349
2		23.5874
4		24.9909
6		26.3943
0.5	Thermal aging at 160°C	14.0302
2		15.0828
4		16.4862
6		17.8897
0.5	20000 µS/cm	33.6382
2		34.6908
4		36.0942
6		37.4977
0.5	50000 µS/cm	30.6382
2		31.6908
4		33.0942
6		34.4977

It can be investigated from Table 5 that the predicted values of dielectric strength of XLPE/Z composites were reasonable according to the experimental values of dielectric strength.

3.3.4 Tensile strength regression model

The prediction of the tensile strength for XLPE/TiO2 made by the Machine Learning's linear regression model are shown in Table 6. The calculation of the MSE was also done on Table 6.

Table 6 Machine learning results and experimental results for tensile strength of XLPE/TiO2 composite samples.

Acronym	Tensile strength results	Machine learning prediction	Percentage of error (%)
B	8.18	8.18	0
T1	8.24	9.3035	0.12906553
T3	10.56	9.6195	0.0890625
T5	10.9	9.9355	0.08848624
T7	9.41	10.2515	0.08942614

Machine learning technique is used to calculate the tensile strength of XLPE/TiO2 composite samples. It can be noted from Table 6 that, the rate of errors for the machine learning model ranged from 0% to 0.12906553%. Also it can be seen from Table 6 that, the machine learning technique has a minimum value of error.

The prediction of the tensile strength for XLPE/Z made by the Machine Learning's linear regression model are shown in Table 7. The calculation of the MSE was also done on Table 7.

Table 7 Machine learning results and experimental results for tensile strength of XLPE/Z composite samples.

Acronym	Tensile strength results	Machine learning prediction	Percentage error (%)
B	8.18	8.18	0
Z1	7.44	7.361	0.01061828
Z3	7.87	7.677	0.02452351
Z5	8.28	7.993	0.03466184
Z7	7.75	8.309	0.07212903

Machine learning technique is used to calculate the dielectric strength of XLPE/Z composite samples. It can be noted from Table 7 that, the rate of errors for the machine learning model ranged from 0% to 0.07212903%. Also it can be seen from Table 7 that, the machine learning technique has a minimum value of error.

3.3.5 Machine learning results for predicting tensile strength of different composite samples

Machine learning helps to predict all values of tensile strength for different composites (TiO2 and Z) especially for the samples which are situated between the experimental results.

The trained machine learning model acts as a robust predictor for any other percentages of fillers for example, 2%, 3.5%, 4% and 6% for nano TiO2 and Z as shown in Tables 8 and 9.

Table 8 Machine learning results for predicting tensile strength of XLPE/TiO2 composite samples.

Percentages of filler (%)	Predicted values of tensile strength (MPa)
0.5	9.2245
2	9.4615
4	9.7775
6	10.0935

Table 9 Machine learning results for predicting tensile strength of XLPE/Z composite samples.

Percentages of filler (%)	Predicted values of tensile strength (MPa)
0.5	7.282
2	7.519
4	7.835
6	8.151

It can be investigated from Tables 8 and 9 that the predicted values of tensile strength of XLPE nanocomposite samples at 0.5, 2, 4 and 6 wt% were reasonable according to the experimental values of dielectric strength.

IV. CONCLUSION

The dielectric strength properties of different weight ratios of nano TiO2 and Zeolite compounded to XLPE were tested at room temperature (30°C), 250°C, thermal aging at 120°C and 160°C for 24 hours, and wet with different salinity levels impact (20000S/cm and 50000S/cm); the results were used to train the machine learning algorithm to anticipate any required dielectric value not physically achievable. The following are the main findings:

a) Pure XLPE has the lowest dielectric strength under all situations.
b) Dielectric strength approach is consistent across all scenarios studied. Dielectric strength increases below filler concentrations of around 5% wt%, but after this value, it decays exponentially until it saturates.
c) The dielectric strength of the XLPE nanocomposite is inversely proportional to the salinity value and thermal aging at high temperatures.
d) The machine learning system takes advantage of the experimental data for proper training, and it was able to accurately estimate and predict dielectric and tensile strength values.

Conflict of interest

There is no conflict to disclose.

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