International Journal of Advanced Technology and Engineering Exploration, Vol 9(96)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2022.10100060

Research Article

Electromechanical characterisation of nano silica filled EPDM-SiR composite for high voltage insulation

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Received: 25-August-2022; Revised: 18-November-2022; Accepted: 20-November-2022

Abstract
Silicone rubber (SiR) and Ethylene propylene diene monomer (EPDM) are broadly employed polymeric materials used in high voltage (HV) insulators. Both have their advantages and disadvantages regarding to mechanical and electrical properties. One of the major advancements of a novel polymer insulator having excellent properties is blending them. The main advantage of such a process is that the intermediate properties are sometimes superior to those of either of the single components. The combination with inorganic nanofiller has been used to improve the existing properties of the blending. In this study, for SiR/EPDM composite with different blending ratios, nanofiller Silica (SiO_2) with (1,3,5, and 7) Phr have been added using a two-roll mill. SiO_2 was selected as the filler material since it has excellent reinforcement, outstanding dielectric characteristics, and better thermal stability. The impacts of the nanofillers on the dielectric strength and volume resistivity were investigated for assessing the electrical properties. Also, the mechanical properties like tensile strength and elongation at break were determined. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are performed. The experimental findings showed that the doping of nanofillers consistently enhanced the electrical and mechanical properties. The greatest improvement at 5 Phr of nano SiO_2 for all SiR/EPDM composite samples. Additional nano-sized particle inclusion led to deteriorating electrical and mechanical properties.

Keywords
Silicone rubber, EPDM, Dielectric strength, Tensile strength, Elongation at break, Nano silica.

1.Introduction
The most important requirement for a power distribution system is effective insulation since a reliable power supply depends heavily on the quality of the insulation [1]. In recent decades, polymer insulators have been increasingly popular and acceptable for use in high voltage (HV) insulation. The significant benefits that a polymeric insulator provides are lightweight, enhanced efficiency in a polluted environment, ease of handling, and hydrophobicity [2, 3].

Among polymers, silicone rubber (SiR) is commonly used as a result of its superior dielectric properties combined with excellent thermal stability, excellent ultraviolet (UV) resistance, and ability to function well under polluted conditions [4, 5].

However, it struggles with poor tracking resistance and more expensive than other insulating materials [6, 7]. Instead, ethylene propylene diene monomer (EPDM) possesses tracking resistance, behaves well under humidity and high temperatures, very good dielectric strength, and cheaper than SiR. Nevertheless, it is less thermally stable and more to UV light and pollution than SiR [8−10]. Hence, the combination of EPDM and SiR would thereby eliminate the deficiencies of each polymer while retaining their advantages.

The usage of SiR/EPDM blend has been expanding steadily for several decades in a variety of industrial fields. According to references [11−15], EPDM blended with SiR would have superior electrical, thermal and mechanical characteristics. In addition, the combination of SiR/ EPDM resulted in a 26% decrease in total cost compared to pure SiR.

When polymeric insulators were first being developed, micron-sized fillers were included into

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pure polymers to improve their performance. However, the enhancement in mechanical properties is significant, the improvement of the electrical characteristics is minimal, and the dielectric strength may occasionally be decreased [16].

Prabu et al. [17] studied the impacts of adding micro SiO_2 and alumina tri-hydrate (ATH) to the equal weight ratio of SiR/EPDM on different electrical and mechanical characteristics. Regarding the electrical properties, there is a negligible improvement compared to mechanical ones.

Recent years have experienced a surge in enthusiasm for incorporating nanoscale fillers into polymeric materials, therefor nanocomposite technology has been evaluated for utilization as (HV) insulators. Nanocomposites are a type of material with tailored properties that have a composite structure [18]. Lewis was the first one who originally introduced the idea of a nanometric dielectric and identified its superior insulating capabilities [19].

The nanofillers should be uniformly distributed throughout the polymer matrix and typically range in size from 1 to 100 nm and content from 1 to 10% [20−22]. In comparison to microparticles, nanofiller has a greater surface area, allowing for the attainment of the appropriate dielectric characteristics with enhancing electrical and mechanical characteristics [23, 24]. Since nanocomposites frequently show significant enhancements in mechanical, thermal, and electrical properties over pure and microcomposite polymers, there has been a surge in interest in this application across the world in recent years.

In nanocomposites, the filler and the host polymer have a large interface, known as the interaction zone, and it has different properties than the particles and the host polymer [25]. This intermediate phase accounts for a significant proportion of the material total volume and can significantly impact material characteristics [26].

Yu et al. [27] observed that nanocomposites exhibit enhanced characteristics despite the decreasing of filler loadings where the nanofillers inclusion may alter the chain movements inside polymer matrix and the crosslinking density, this may have a consequence on how the material's dielectric properties perform. Also, Venkatesalu and Thomas [28] have found that adding nano alumina to SiR shows improvement in dielectric and erosion resistance in comparison to microparticles.

The current study is committed to understanding the consequences of filling several contents of nano SiO_2 to different mixing weight ratios of SiR/EPDM for determining the most suitable composition by studying its variations in electromechanical properties.

The research comprises five sections. In the first section discusses a brief summary of the research done by the others for studying the properties of SiR, EPDM, and their blending and how to improve their properties by doping various types of nanofillers. The next section has provided the descriptions of materials used in the experiments and the successful preparation of nanocomposite samples. Physicochemicalical analysis is performed in this section. Also, the testing techniques of electrical and mechanical properties are also discussed. We provide our experimental findings in the third section. Our comprehension of the experimental findings will be presented in the discussion that follows the third section. Conclusion and recommendations for more research presented in the final section

2.Literature review

There has been extensive usage of nanofillers in the power sector to boost the insulating properties of various polymeric materials. For the purpose of achieving good electrical and mechanical properties, nanofillers are commonly doping in SiR, EPDM, and the different combinations of SiR/EPDM.

According to references [29–33], the addition of Titanium Dioxide (TiO_2), modified fumed silica (MFS), Silicon Carbide (SiC), and SiO_2 nanofillers to pure EPDM polymer enhance the electrical properties of the composites. Furthermore, Boron Nitride (BN) nanocomposite exhibited notably increased tracking failure duration in comparison to pure EPDM [34].

Previous researches [35–37] observed an improvement in SiR performance by adding of a small proportion of fillers. Enhancing the mechanical and also electrical characteristics of SiR was achieved by doping various types of nanofillers like SiO_2, Zirconium Oxide (ZrO_2), BN, and Aluminum Oxide ($Al2O_3$). Adding nano ATH as a non-toxic, non-corrosive, and flame-retardant filler enhanced tracking, erosion, and corona resistance due to superior thermal stability characteristics [38-40].

According to our knowledge, just a few studies were conducted to characterize the electrical and dielectric

properties of nanocomposites based on the combination of SiR/EPDM matrices.

Vijayalekshmi and Majeed [41], evaluated mechanical, electrical, and thermal properties of equal weight percentages (1:1) EPDM/SiR blends after adding different content of organically modified montmorillonite (OMMT) Nano clay. According to the mechanical property results, nanocomposites have significantly improved tensile strength and elongation at break. As per a study on electrical properties, the inclusion of OMMT in EPDM/SiR nanocomposites significantly enhances the dielectric strength and volume resistivity. A thermogravimetric (TGA) study verified that nanocomposites with higher OMMT content had better thermal stability.

Fairus et al. [42], reported adding two types of nanofiller called Al_2O_3 and nano TiO_2 with different contents 1, 2, 3, 4, and 5 Vol% to the equal weight percentage of EPDM/SiR composite. The effects of nanofillers various loadings on surface tracking were studied. They found out that doping nanofillers to EPDM/SiR composite enhances the performance of tracking time by slowing the aging process. According to experimental findings, SiR/EPDM doped with 1 vol% Al_2O_3 nanofiller performed better in terms of tracking time than SiR/EPDM filled with 2 vol% TiO_2 nanofiller did.

Ravindran et al. [43], investigated the mechanical properties and Fourier transform infrared spectroscopy (FTIR) analysis on 1:1 EPDM/SiR composite after adding various contents of nano SiO_2 (0, 2.5, 5, 7.5, and 10) Phr. They examined FTIR analysis, which provided information on the chemical interactions that occurred between the rubber mix and nano SiO_2. The samples' FTIR examination revealed a number of peaks corresponding to different chemical groups that emerged as a consequence of the creation of new bonds. These peaks in EPDM/SiR nanocomposite belonging to Si-H, - Si-CH_2-CH_3, and -Si-CH_3 which develop by the chemical reaction between the rubber mixture and nano SiO_2. The hardness data show that micro and nanocomposites have enhanced hardness, although nano SiO_2 gives the polymer matrix a higher hardness than micro SiO_2 samples. This is explained by the high Si-O-Si group's concentration in nano SiO_2 and the stronger molecular interactions between base polymers and nano SiO_2 as opposed to the weaker molecular interactions in micro-sized samples.

Saleem et al. [44], investigated many types of corona-exposed EPDM/SiR blends after the addition of the various contents of nanofillers BN and SiC. The diagnosis depends on the measurement of volume current and the surface partial discharge (PD). They concluded that adding nano BN to SiR/EPDM composite improved resistance to corona current more efficiently in comparison to the SiC filled counterpart. Adding 3% of BN to the composite has demonstrated improved performance in aging resistance against corona discharge based on the measurements and analysis carried out in this study.

Vijayalakshmi et al. [45], examined the characteristics of electrical and mechanical for SiR/EPDM composite filled with carbon black (CB) as a filler. They chose three different contents (2, 5, and 10) wt% of CB added to an equal blend ratio of SiR/EPDM 1:1. They concluded that adding filler was found to have enhanced its electrical and mechanical properties compared to unfilled samples. Increased filler content at 5% and 10% CB resulted in a decrease in the measured electrical parameters.

Fairus et al. [46], examined the effect of adding different loading contents of nanofiller Al_2O_3 (1, 2, 3, 4, and 5) Vol% to 50:50 EPDM/SiR composite on breakdown strength value. The outcome demonstrated that, among different loading concentrations, doping 1 Vol% $Al2O_3$ to SiR/EPDM composition provides the maximum breakdown strength with 35.28 kV/mm. However, the breakdown strength is decreased when the dosage percentage of nanofiller is increased to 5 Vol%.

Khan et al. [47], studied the mechanical and electrical characteristics of SiR and EPDM composites after the inclusion of micro and nano SiO_2 filler. They observed that adding micro and nano SiO_2 increases all sample tensile strength values. But nano provides a greater improvement than micro. The hardness findings show that both micro nanocomposites have enhanced hardness, although nano SiO_2 provides the polymer matrix with increased hardness over micro SiO_2 specimens. Incorporating micro and nano-SiO_2 particles increased the volume and surface resistivities of all the samples under investigation. Volume and surface resistivities of composites based on nano-SiO_2 filler were found to be greater than those of microcomposites. Where they were all in agreement that the change happened to the properties of the composite after adding the nanofillers. Previous research has centered on only compounding of EPDM and SiR with an equal ratio of 50:50. They

also examined doping EPDM/SiR composites with nanofillers different from what was used in this research, such as OMMT, TiO_2, BN, and SiC, CB, and Layered Silicate.

3.Methods

The testing process used in this study is depicted in *Figure 1*. Firstly, blending of EPDM and SiR with different weight ratios. Secondly, adding various contents of nano SiO_2 to EPDM/SiR different weight ratios composites. Then, electrical and mechanical tests are conducted to find the optimal value of nano SiO_2 for enhancing the electrical and mechanical properties

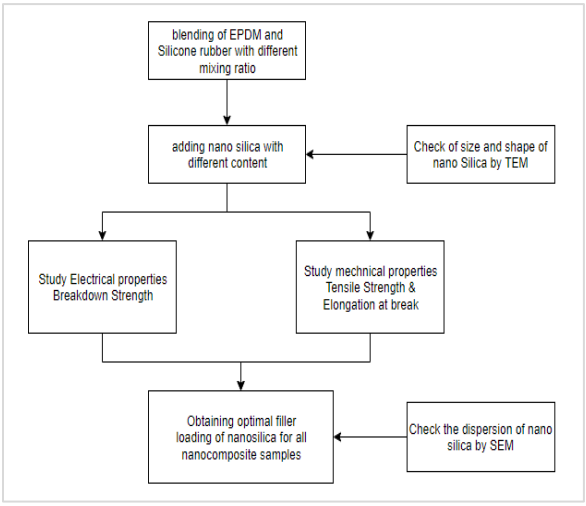


Figure 1 Testing procedures of the study paper

3.1Materials

SiR is bought from A.Faroon Egypt (S.A.E). its appearance is milky white with hardness shore 60 according to (DIN 53505). EPDM was supplied from the national market Wita a Mooney viscosity of 22 MU according to American society for testing and materials (ASTM) D1646 and with a density 0.9 g/cm3. A curing agent is Dicumyl Peroxide 4-methoxy phenol (99% Active) was purchased from Al-Gomhoria Company for chemical supplies in Egypt with specific Gravity/Density: 1.02 @ 45˚C. Nano SiO_2 was bought from Nanotech Egypt.

3.2Nanocomposites preparation

In a two-roll mill operating at ambient temperature, blending of EPDM and SiR was created based on a weight basis. Before beginning the blending process, 15 minutes were spent warming up the two-roll mill. With an operating temperature of 80°C, the two-roll machine front and back rollers were adjusted to 14 rpm and 12 rpm, respectively. EPDM is supplied in block form, so it was first rolled through the roller for 5 minutes. Then, SiR was combined for 15 minutes. Crosslinking Dicumyl Peroxide (99 % active type) with a content of 4 Phr was used to start the blending cycle for 5 minutes. For EPDM/ SiR composites, various nano SiO_2 contents with (1, 3, 5, and 7) Phr were added to the blend. All rubber compounds underwent 15 minutes 150°C vulcanization process in a hydraulic press. The samples were eventually cooled to ambient temperature. The flowchart in *Figure 2* depicts the step-by-step fabrication process of specimen sheets. *Table 1*, shows the mixing formulation for all samples.

3.3Physico-chemical analysis

3.3.1Transmission electron microscopy (TEM)

TEM (Jeol Jem 1400 plus) Japan is being used to determine the nano SiO_2 diameter and shape. The examination was performed at room temperature. The resolution of TEM was 500 nm, and the acceleration voltage was 80 kV.

3.3.2Scanning electron microscopy (SEM)

An instrument of the Zeiss makes and EVO 15 model made in Germany was utilized to acquire the images in order to assess the degree of nano SiO_2 dispersion in EPDM/SiR composite. It was used to observe the dispersion of (1, 3, 5, and 7) Phr nano SiO_2 filled 50:50 EPDM/SiR composites.

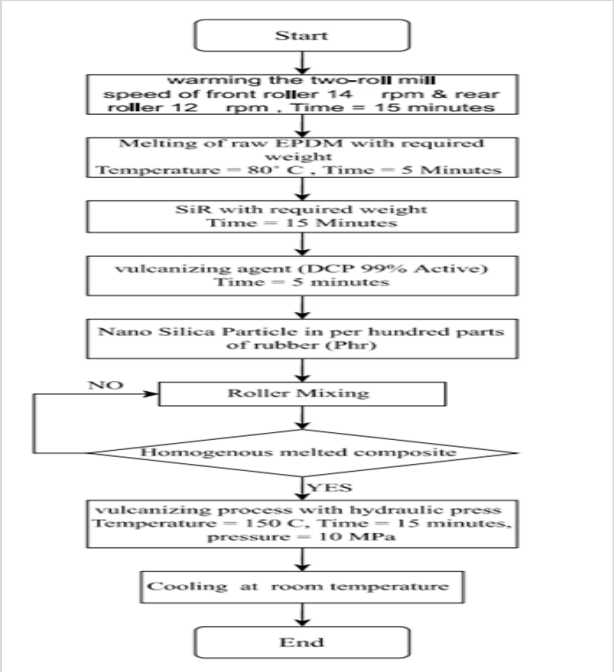


Figure 2 Flow chart of nanocomposite preparation method

Table 1 Composition of nano SiO_2 filled EPDM / SiR composites

Sample	Code	SiR %	EPDM %	Nano Silica (Phr)
SiR/EPDM	B	75	25	0
SiR/EPDM+1Phr SiO_2	B_1	75	25	1
SiR/EPDM+3Phr SiO_2	B_3	75	25	3
SiR/EPDM+5Phr SiO_2	B_5	75	25	5
SiR/EPDM+7Phr SiO_2	B_7	75	25	7
SiR/EPDM	C	50	50	0
SiR/EPDM+1Phr SiO_2	C_1	50	50	1
SiR/EPDM+3Phr SiO_2	C_3	50	50	3
SiR/EPDM+5Phr SiO_2	C_5	50	50	5
SiR/EPDM+7Phr SiO_2	C_7	50	50	7
SiR/EPDM	D	25	75	0
SiR/EPDM+1Phr SiO_2	D_1	25	75	1
SiR/EPDM+3Phr SiO_2	D_3	25	75	3
SiR/EPDM+5Phr SiO_2	D_5	25	75	5
SiR/EPDM+7Phr SiO_2	D_7	25	75	7

3.4Electromechanical properties

According to international electro technical commission (IEC) and ASTM requirements, the assessment of electromechanical parameters was performed. The electrical criteria were examined such as breakdown Strength and volume resistivity. Mechanical parameters like tensile strength and elongation at break of all samples were evaluated.

3.4.1Electrical properties

3.4.1.1Breakdown strength test

For any application in which an electrical field will be present, the breakdown strength of the electrical insulating material will be crucial. In the HV lab at Aswan University, alternative current (AC) breakdown tests were done following IEC 60243-1 (ASTM D 149) Standard. In *Figure 3*, the schematic diagram is displayed. The test included two 36 mm diameter mushroom-shaped electrodes. The test sample should be shaped as a disc with a 5 cm diameter and a 1mm thickness. To prevent surface flashover, the sample under evaluation was positioned between two electrodes and submerged in an oil container.

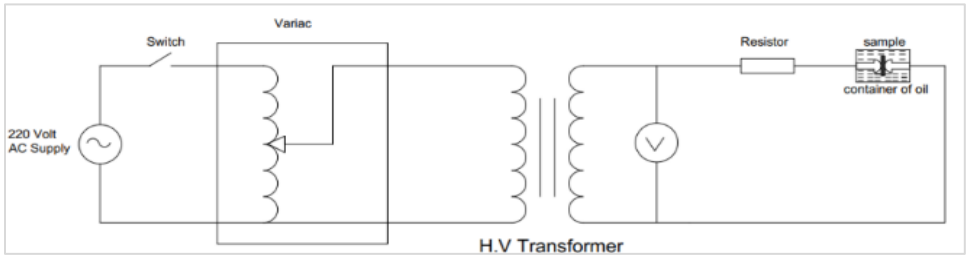


Figure 3 Schematic diagram of HV testing circuit

Insulating materials are often subjected to wet conditions and pollution during outdoor service on their surfaces, resulting in electrical insulation degradation. So, the dielectric strength has been investigated at room temperature under three different testing scenarios:

1. The first scenario is based on testing the samples under dry conditions.
2. The second scenario is based on testing the samples under wet conditions. It is necessary to put the samples in a container filled with boiling distilled water completely submerged. After 120 minutes, the sample must be taken out of the container and cooled at room temperature. This scenario will declare the consequences of moisture on the dielectric strength of samples.
3. The third scenario is based on testing the samples under salty wet conditions. A salient solution of NaCl was used to create artificial contaminants.

The samples were placed in a container of salient solution at room temperature. After 24 hours, the specimens were removed, and all surfaces were wiped clean with a dry cloth. This scenario will declare the effect of the saline attack on HV insulators close to the coast. The Equation 1 was used to get the AC breakdown strength:

$$E = V/t \quad (1)$$

Where:
E: Breakdown Strength - V: the breakdown voltage - t: sample thickness
The results are analyzed with the use of the 2-parameter Weibull distribution. The cumulative probability of dielectric breakdown is expressed mathematically in Equation 2:

$$P(X) = 1 - \exp\left[-(E/\alpha)^{\beta}\right] \quad (2)$$

Where α and β are scale and shape parameters of the Weibull distribution, E is the dielectric breakdown strength and P(x) represents the probability of cumulative failure.

α indicates the cumulative probability of failure of 63.2%, called the Weibull breakdown strength. β, a dimensionless number, determines the shape of the probability density function. The IEC 62539 standard recommends a superior approximation when a test is complete and the sample size is minimal. For the computation of cumulative probability (Pi) corresponding to the i-failure event is provided in Equation 3:

$$Pi = \frac{i-0.44}{n+0.25} \quad (3)$$

Where i represents the i_{th} data from lowest to highest, and n represents the breakdown number. The two Weibull parameters are derived from the Weibull distribution graphic using the aforementioned equations.

3.4.1.2Volume resistivity test

Volume resistance is defined as the resistance to leakage current across the whole structure of an insulator. It was evaluated in accordance with ASTM D-275-99 using BIDDLE / AVO / MEGGER BM25, UK. At room temperature, a 500 V (DC) voltage was applied for 90 seconds.

3.4.2Mechanical properties

For a polymeric insulator to function reliably, mechanical properties are as crucial as electrical ones. Referring to ASTM D-412, the nanocomposites tensile strength and percentage elongation at break are tested at room temperature. The mechanical tests are examined using a dumb-bell shape with 5cm length and 1mm thickness in a Universal test machine (HD-B604-S) at room temperature. Three dumb-bell-shaped samples for each composition were used and the average of them was calculated.

4.Results

4.1TEM analysis

The TEM photo shown in *Figure 4* illustrates that the SiO_2 nanoparticles have spherical and semi-spherical shapes. The average particle size is 30-65 nm.

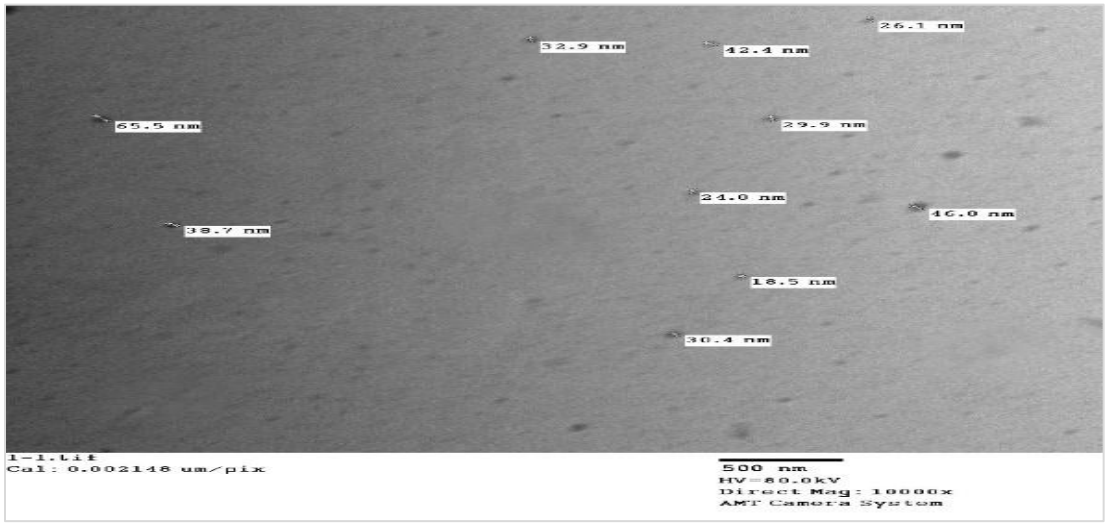
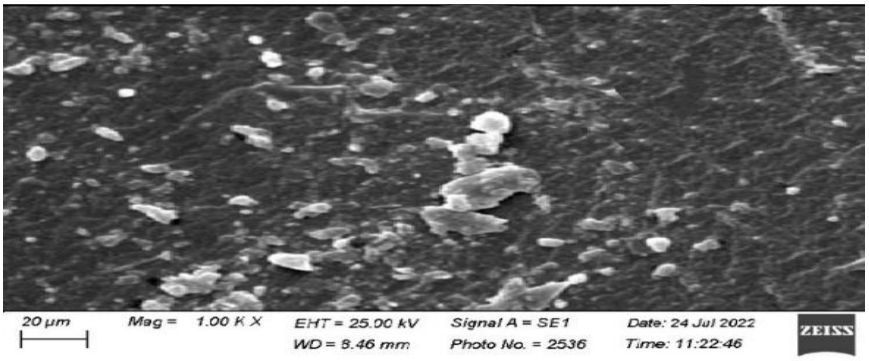


Figure 4 TEM of nano silica

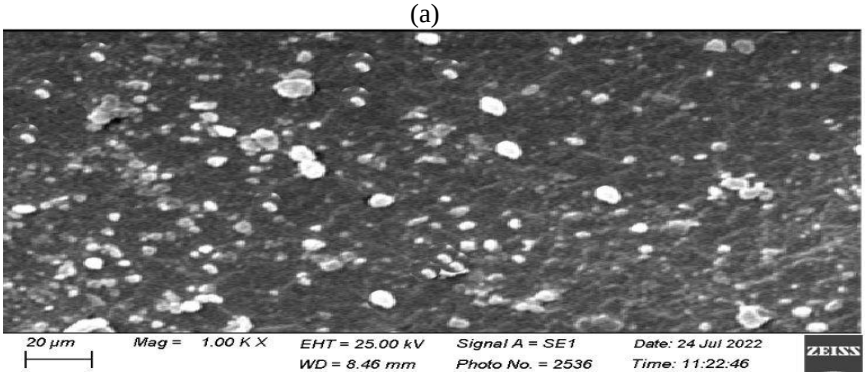
4.2SEM analysis

The surface morphology of EPDM/SiR (50:50) composites loaded with nano SiO_2 is depicted in *Figure 5* (a, b, c, d). It is obvious that the surface of the composites is smooth, homogeneous, and coherent till the filling ratio of 5 Phr. As shown in the figures, the SiO_2 nanoparticles (white spots) are homogenously dispersed with a spherical shape. This result revealed that the surface of the SiO_2 nanoparticles and the matrix of the polymer adhere. EPDM/SiR nanocomposite was become more homogeneous with evenly distributed inclusions by

adding 5 phr of nano SiO_2. As the content of SiO_2 nanoparticles increases (7) Phr, the surface becomes rough with large particle (white spots) aggregates. Indicating that insufficient dispersion of the nanofiller within the composite. From SEM picture 5(e), agglomerates are clearly visible and the particle dispersion is poor.



(a)



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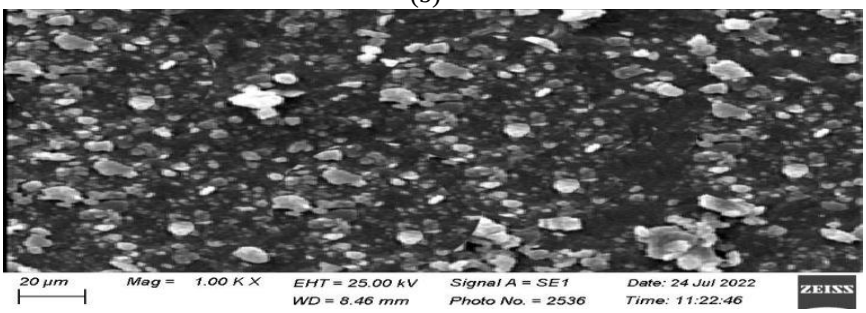
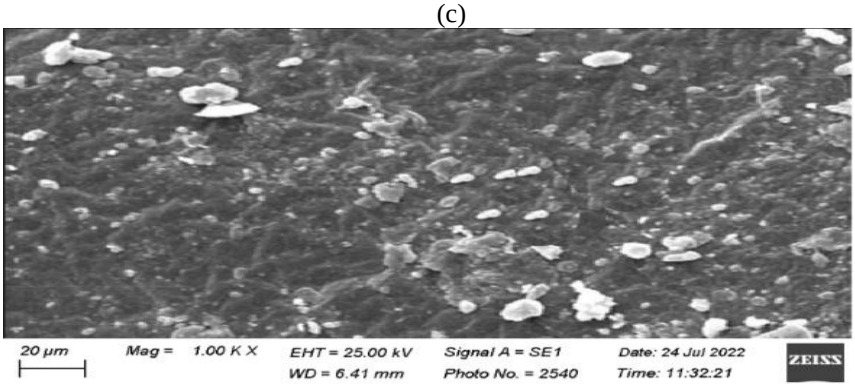


(c)



(d)

Figure 5 (a) SEM of sample C1 (b) SEM of sample C3 (c) SEM of sample C5 (d) SEM of sample C7

4.3Electrical results

4.3.1AC breakdown strength results

Figures from 6 to 14 are given the Weibull plots of the cumulative probability of breakdown against the AC breakdown strength of SiR/EPDM composite samples (B, C, D) loaded with (1, 3, 5, and 7) Phr of nano SiO_2 with 95% confidence intervals under dry, wet, and salty wet conditions. Two Weibull parameters get by Weibull distribution plots are summarized in *Table 2*.

From *Figures 6* to *14* and *Table 2*, we can conclude that:

Increasing EPDM content in EPDM/SiR unfilled composites increases the dielectric strength value. Where sample D (75% EPDM) has the highest dielectric strength with 19.61 kV/mm and sample B (25% EPDM) has the lowest one with 12.89 kV/mm.

The addition of nanofillers results in a consistent increase in breakdown strength for all samples over unfilled samples counterparts.

Increasing breakdown strength compared to unfilled samples under dry conditions, for sample B loaded with (1, 3, and 5) Phr nano SiO_2 is 3.34, 5.45, and 9.02 kV, for sample C is 3.35, 4.53, and 9.32 kV, for sample D is 3.58, 5.33, and 9.2 kV respectively.

The doping of nano SiO_2 to SiR/EPDM composite samples enhances the breakdown strength compared to unfilled composite for sample B loaded with (1, 3, and 5) Phr by 25.91%, 41.99%, and 69.98 %, for sample C is 20.4%, 27.59%, and 56.76%, for sample D is 18.25%, 27.18%, and 46.91% respectively.

The improvement in the dielectric strength till the filling of 5 Phr. Adding 7 Phr nano SiO_2 to all SiR/EPDM composite samples has a negatively impacts on the breakdown strength values as the fillers will agglomerate creating bigger size SiO_2 clusters which are cleared in SEM images.

The wet environment has a negative effect on dielectric strength for all samples. Compared to dry condition, samples B_1, B_3, B_5, and B_7 are decreased by 1.91, 2.69, 4.08, and 3.13 kV, samples C_1, C_3, C_5, and C_7 by 2.22, 2, 5.04, and 3.63 kV, sample D_1, D_3, D_5, and D_7 by 1.56, 2.68, 3.08, and 3.39 kV respectively.

For salt wet conditions, samples B_1, B_3, B_5, and B_7 are decreased by 2.49, 3.52, 4.44, and 4 kV, samples C_1, C_3, C_5, and C_7 by 3.02, 3.69, 6.69, and 4.1 kV, sample D_1, D_3, D_5, and D_7 by 2.44,3.01,3.94, and 4.47 kV compared to dry conditions. Particularly, it is anticipated that dissociated Na and CL will be contained inside polar water cages. The existence of such polar media inside the polymer matrix, particularly close to the surface, may provide an electronic transport percolation channel, lowering the composite's breakdown voltage [48, 49].

Table 2 Weibull parameters of breakdown strength for nanocomposite samples

Code	Weibull parameters (Dry)		Weibull parameters (Wet)		Weibull parameters (Salty Wet)	
	Scale (α) KV/mm	Shape (β)	Scale (α) KV/mm	Shape (β)	Scale (α) KV/ mm	Shape (β)
B	12.89	87.69	11.55	27.67	9.82	26.89
B_1	16.23	35.07	14.32	35.90	13.83	63.34
B_3	18.34	39.50	15.65	50.42	14.82	52.88
B_5	21.91	206.8	17.83	63.27	17.47	50.57
B_7	19.85	76.07	16.72	53.55	15.86	70.78
C	16.42	45.57	15.19	30.29	14.48	29.81
C_1	19.77	103.1	17.55	59.73	16.75	43.43
C_3	20.95	66.02	18.95	32.58	17.26	51.49
C_5	25.74	94.17	20.7	56.44	19.05	203.5
C_7	22.77	101.4	19.14	105.5	18.60	113
D	19.61	52.65	18.88	36.08	17.67	17.67
D_1	23.19	47.88	21.63	72.88	20.75	20.75
D_3	24.94	75.66	22.26	79.64	21.93	21.93
D_5	28.81	106.3	25.73	57.40	24.87	24.87
D_7	26.84	136.3	23.45	68.01	22.37	22.37

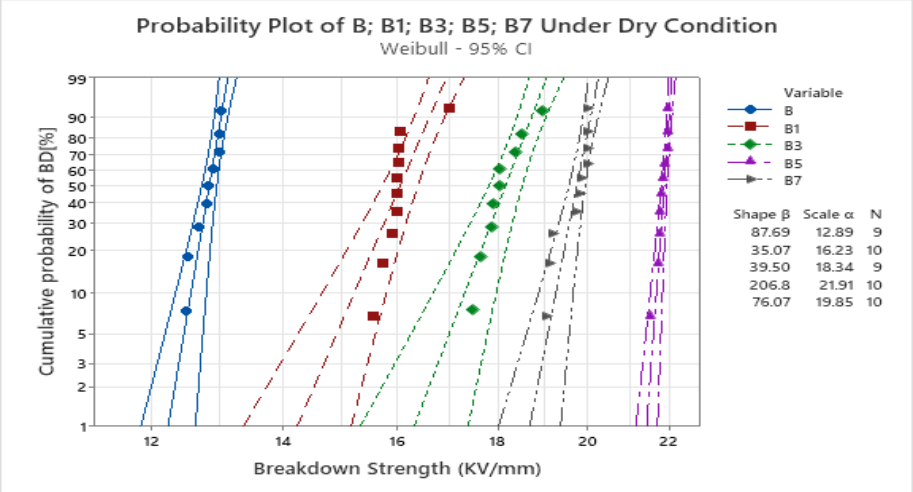


Figure 6 Weibull plot dielectric strength of sample B loaded with Nano SiO_2 under Dry conditions

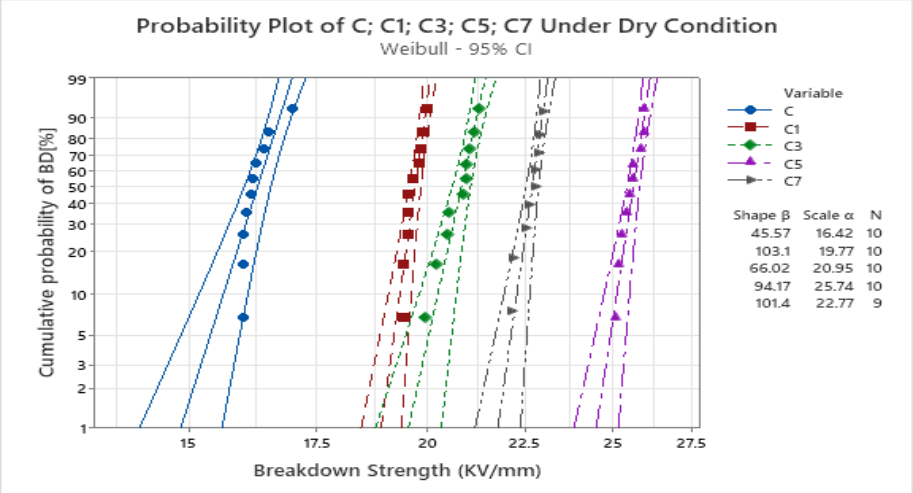


Figure 7 Weibull plot dielectric strength of sample C loaded with Nano SiO_2 under Dry conditions

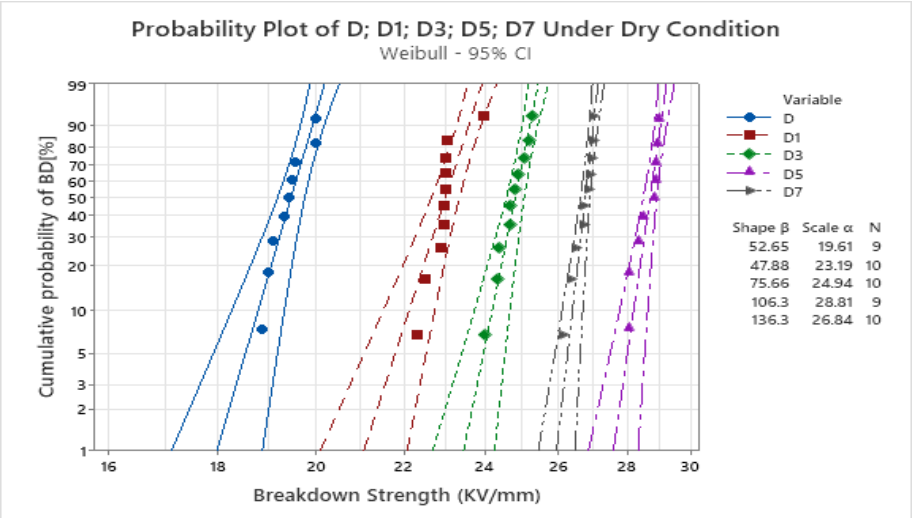


Figure 8 Weibull plot dielectric strength of sample D loaded with Nano SiO_2 under Dry conditions

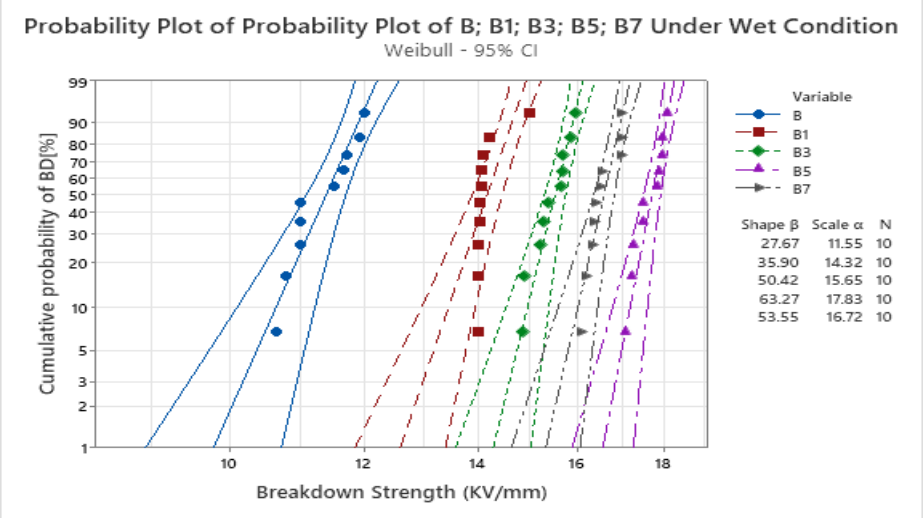


Figure 9 Weibull plot dielectric strength of sample B loaded with Nano SiO_2 under Wet conditions

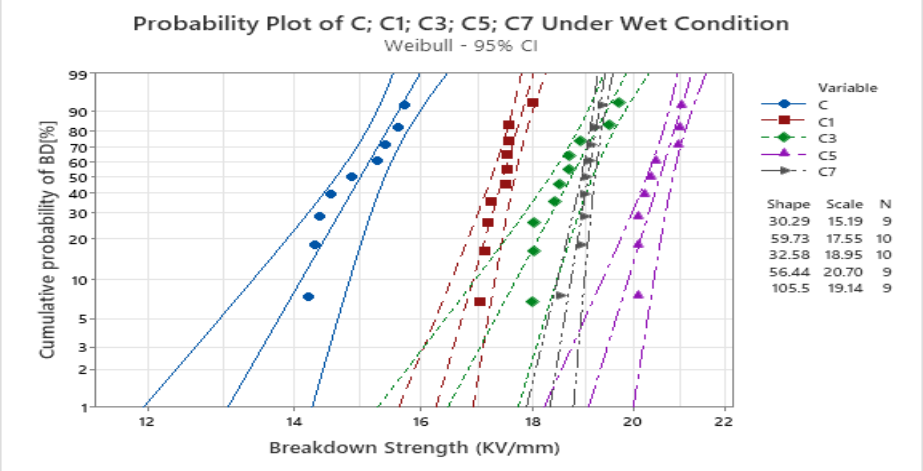


Figure 10 Weibull plot dielectric strength of sample C loaded with Nano SiO_2 under Wet conditions

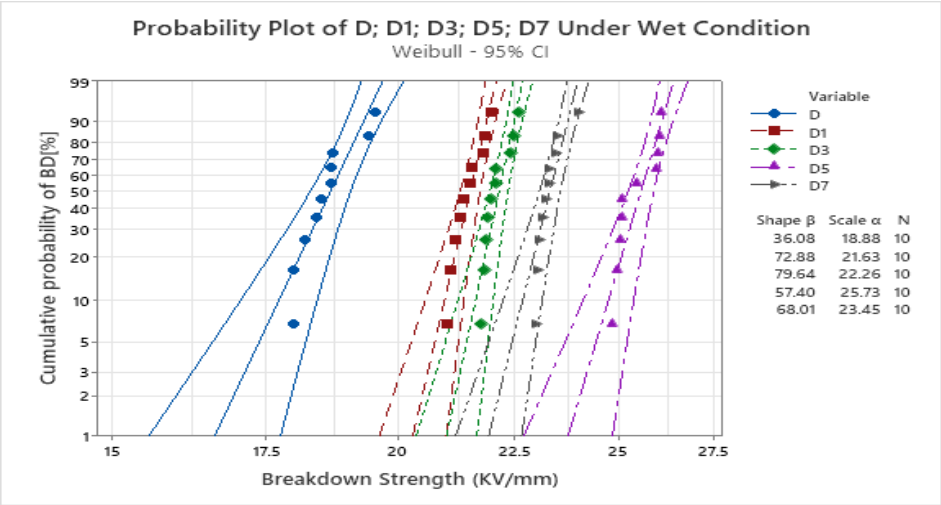


Figure 11 Weibull plot dielectric strength of sample D loaded with Nano SiO_2 under Wet conditions

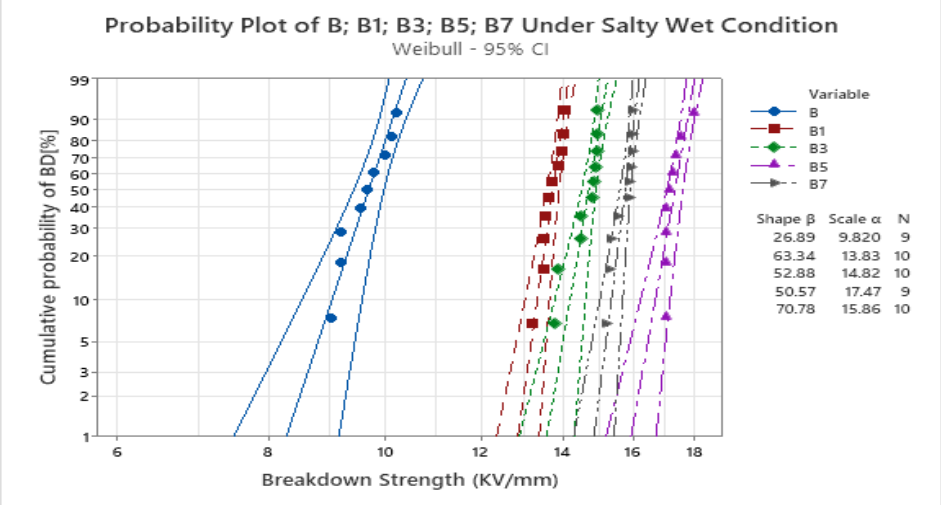


Figure 12 Weibull plot dielectric strength of sample B loaded with Nano SiO_2 under Salty Wet conditions

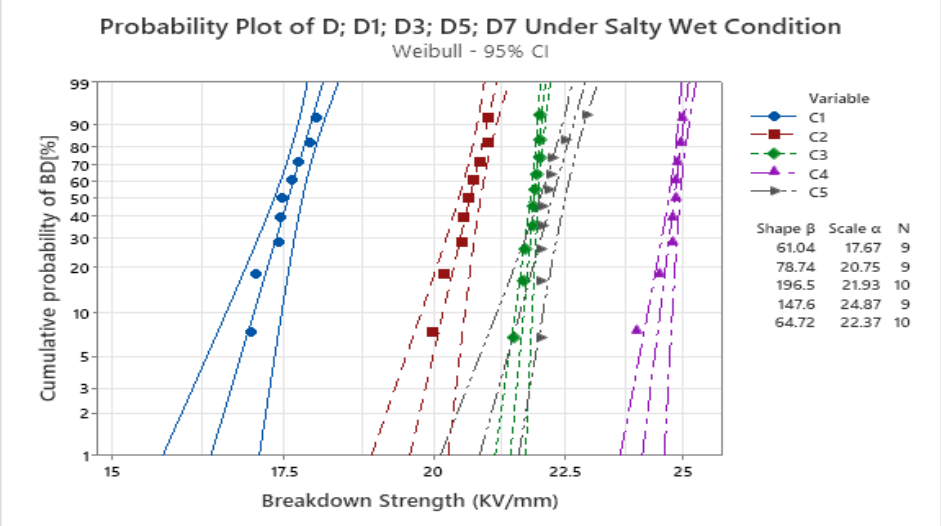


Figure 13 Weibull plot dielectric strength of sample C loaded with Nano SiO_2 under Salty Wet conditions

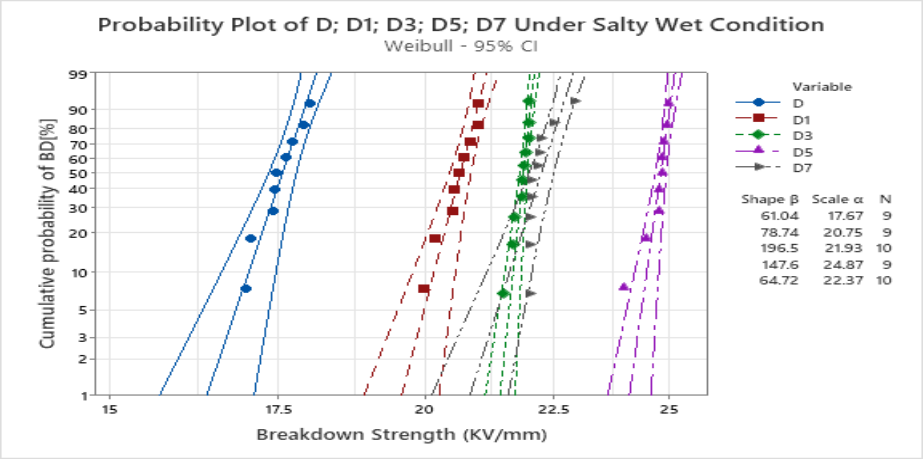


Figure 14 Weibull plot dielectric strength of sample D loaded with Nano SiO_2 under Salty Wet conditions

Table 3 compares the dielectric strength values of the investigated nanocomposites and findings from our previous study on microcomposites with a typical composition (SiR/EPDM/SiO_2) prepared using the same method; however, the used filler was in micro size [50]. It can be observed that nanocomposite samples enhance breakdown strength more effectively than microcomposite samples.

Table 3 Comparison between SiR/EPDM filled with micro and nano SiO_2

Code	Nano silica (Phr)	Scale (α)KV/mm	Code	Micro silica (Phr)	Scale (α)KV/mm
B	0	12.89	B	0	12.89
B1	1	16.23	B_{10}	10	13.66
B3	3	18.34	B_{20}	20	15.43
B5	5	21.91	B_{30}	30	17.39
B7	7	19.85	B_{40}	40	16.91
C	0	16.42	C	0	16.42
C1	1	19.77	C_{10}	10	18.01
C3	3	20.95	C_{20}	20	19.55
C5	5	25.74	C_{30}	30	22.40
C7	7	22.77	C_{40}	40	21.16
D	0	19.61	D	0	19.61
D1	1	23.19	D_{10}	10	21.66
D3	3	24.94	D_{20}	20	23.15
D5	5	28.81	D_{30}	30	24.51
D7	7	26.84	D_{40}	40	23.44

In comparison to micro and pure samples, nano SiO_2 had the largest surface to volume ratio because of its smaller size. This results in enhanced crosslinking, chain immobilisation, and the structure of molecular network. As a result, this improves their resistivities, which raises the opposing electric field and decreases the passage of electrons from the electrode to the material, hence enhancing the dielectric strength [51, 52].

4.3.2Volume resistivity results

Volume resistivity of different combinations of SiR/EPDM composites loaded with several contents of nano SiO_2 (0,1,3,5, and 7) Phr is depicted in *Figure 15*. Exploring the graph, this is simple to deduce that increasing the weight ratio of the EPDM to the composites enhances volume resistivity. Additionally, adding nano SiO_2 to the composites improves the volume resistivity up to 5 Phr; after that, the ohmic value dropped down.

The findings could be properly justified by trapping and detrapping recursive action. When adding a small amount of filler, a part of the injected charges is trapped at the region of electrode contact, resulting in a space charge. Because of its electrostatic barrier properties, this cloud, with the help of other scattered traps, will reduce the mobility of the carriers and increase the volume resistivity. Contrarily, at large filler concentrations, the possibility of clustering rose while the amount of energy trapped decreased. As a result, the conductance increases and the resistivity reduces [53, 54].

4.4Mechanical tests

One of the most key representatives of mechanical qualities is "tensile strength," which refers to a material's resistance to a pulling force. The sample was stretched until it broke in the test machine during the tensile test. The specimen is stretched to the breaking point and the amount of force necessary to break the material under tension is measured. The second test is elongation which is the ratio of the test specimen's broken length to its original length. *Figures 16* and *17* show the values of tensile strength and elongation at break for SiR/EPDM composite samples (B, C, D) loaded with (1, 3, 5, and 7) Phr of nano SiO_2 respectively.

It is clear from *Figures 16* and *17* that adding more content of SiR to the composites enhances the Tensile strength and Elongation at break values. Sample B (75 % SiR) has the largest unfilled tensile strength and elongation at break with 3.54 MPa, and 718.33% respectively. There is a continuous increase in Tensile strength and Elongation at break with doping the nanofiller to the composite till the ratio of 5 Phr. Where, adding nano SiO_2 filler with 5 Phr has a maximum value of tensile strength for all SiR/EPDM nanocomposite samples (4.63 MPa for sample B5, 3.39 MPa for sample C5, and 2.54 MPa for sample D5). Adding nano SiO_2 filler with 5 Phr has a maximum value of Elongation at break with (2584.91% for sample B5, 2035.93% for sample C5, and 1941.01% for sample D5). The addition of nano SiO_2 with 7 Phr decreases the tensile strength and Elongation at break of all composite samples.

The results could be adequately justified by the homogenous dispersion of nanofillers and high cross-linking of the base matrix with the nanofillers that restrict the movement of the polymer chain thus improving mechanical properties till the filling ratio 5 Phr. Further incorporation of nano SiO_2 (doping with 7 Phr) will deteriorate the mechanical properties. This behavior may be caused by the fillers' tendency to agglomerate due to the small size and large surface area forming larger clusters of nano-particles [55].

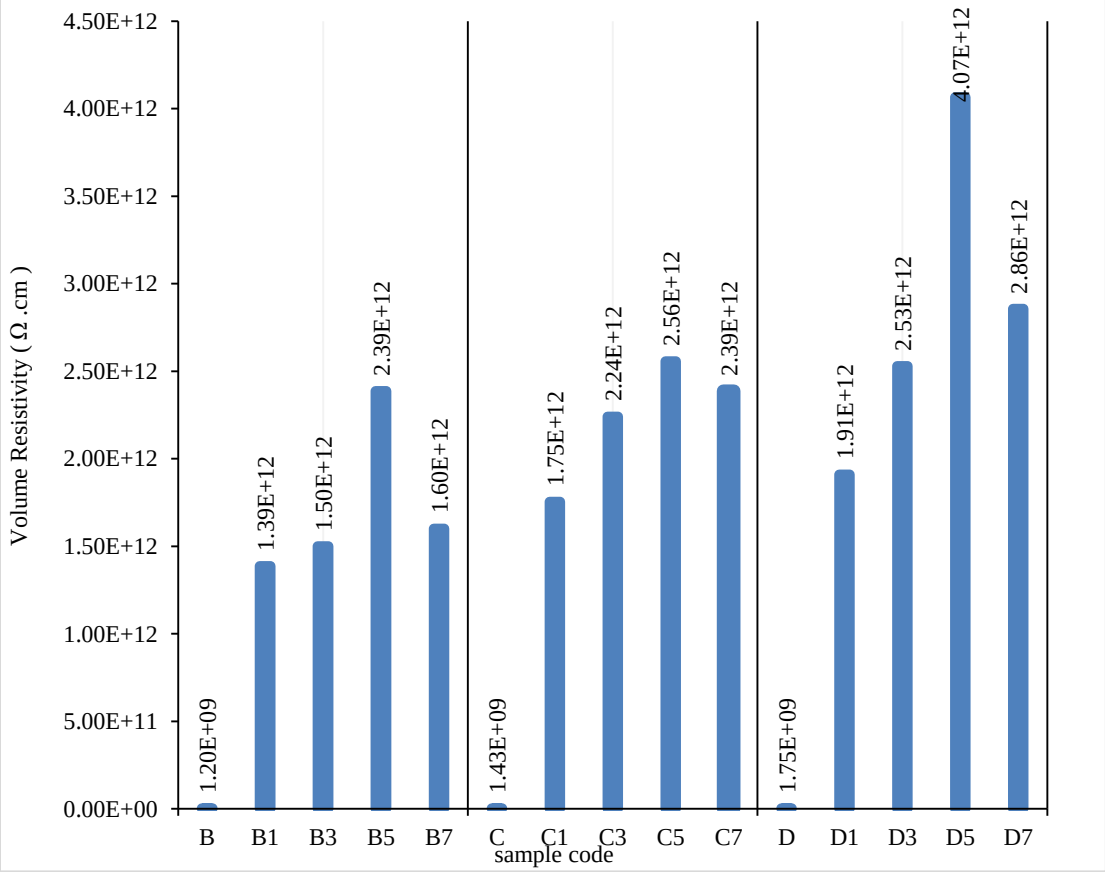


Figure 15 Volume Resistivity (Ω .cm) for SiR/EPDM composite samples loaded with Nano SiO_2

5.Discussion

Interface regions between nanoparticles and polymer matrix upon the inclusion of a small number of nanoparticles into polymers can change the local structures of polymer nanocomposites, leading to an increase in the density and energy of deep traps [56–60].

Traps are often classified by their energy. Low energy traps are called shallow traps. Charges can hop between these traps and travel throughout the material. Deep traps, e.g., traps of high energy, can suppress electrical conduction. They capture free charges and restrict their propagation, thus reducing their harmful impact on the material. Microfillers only give a material with shallow traps, whereas nanofillers provide deep traps. The least improvement as per our previous research [50] is attributed to the shallow traps which are achieved by filling the composites with micro SiO_2.

The increase of the dielectric strength of nanocomposite samples can be explained by deep traps which are considered to be introduced in SiR/EPDM loaded with nano SiO_2.

Deep traps can trap mobile charge carriers and charges are difficult to detrap so reducing the charge carrier mobility of polymer nanocomposites [61] and also limiting charge injection and accumulation of space charges in the nanocomposites which enhances breakdown strength performance [62].

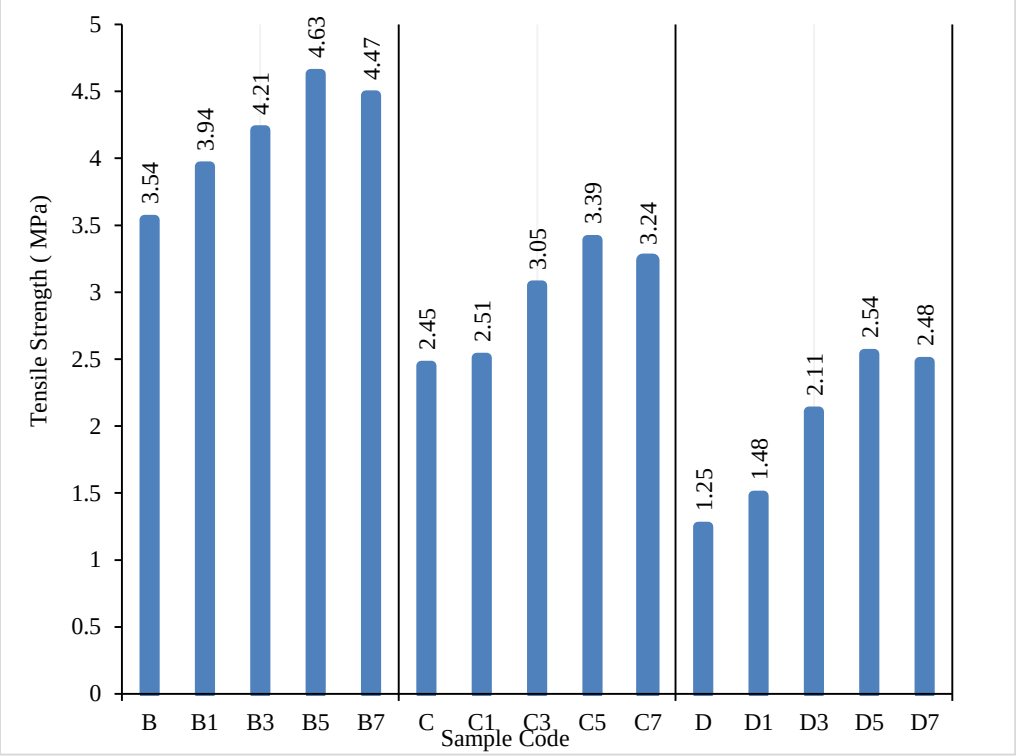


Figure 16 Tensile strength (MPa) for SiR/EPDM composite samples loaded with Nano SiO_2

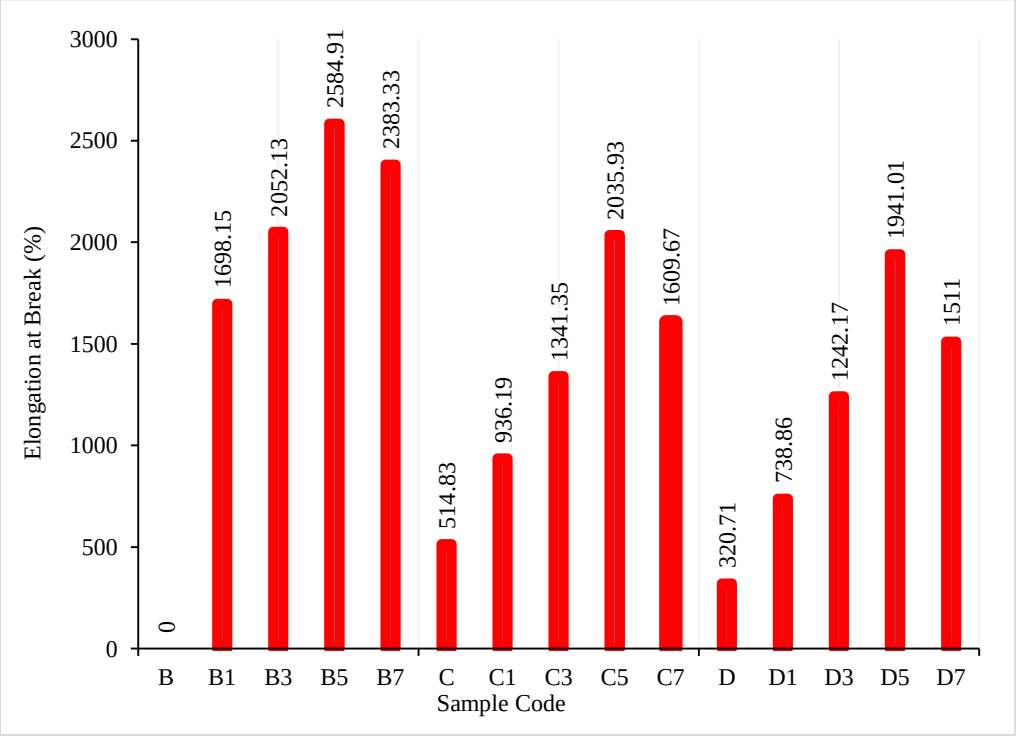


Figure 17 Elongation at break for SiR/EPDM composite samples loaded with Nano SiO_2

In addition, it appears to be a certain limit to the loading levels that can be added to polymers with nanofillers, beyond which the electrical properties are adversely affected. This is called the threshold level of nanofiller [63]. Experimental findings of this research found out that the threshold level of nano SiO_2 filled EPDM/SiR composites is 5Phr. So, with increasing filler doping levels (more than 5Phr), the trap density of deep traps falls causing a decline in the dielectric strength of the composites.

A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

In this study, the electrical and mechanical properties of EPDM/SiR composites loaded with different contents of nano SiO_2 were investigated. This work leads to the following conclusions:

- Increasing the weight percentage of EPDM to the EPDM/SiR composites enhances the breakdown strength performance. contradictory, adding more contents of SiR to the composites improves the mechanical properties.
- The addition of nano SiO_2 to SiR/EPDM composite samples leads to a consistent increase in breakdown strength compared to unfilled samples. The optimum breakdown strength could be accomplished by using 5Phr nano SiO_2 for all SiR/EPDM composite samples. The volume resistivity is improved by increasing the weight ratio of EPDM in the composites.
- Amalgamation of nano SiO_2 to EPDM/SiR composites improves the volume resistivity till the filling ratio 5Phr. The tensile strength and Elongation at break will be improved for all SiR/EPDM nanocomposite samples till 5 Phr.
- This research is recommended mixtures having equal quantities of SiR and EPDM composites with doping 5 phr nano SiO_2 as it presents excellent electrical and mechanical properties. Consequently, this composition presents an excellent promise for insulation systems in H.V applications. However, an increase of more than 50% EPDM has a considerable improvement of the electrical properties, but it is at the expense of mechanical properties.

Further study is advised to improve the efficacy of EPDM/SiR nanocomposites by:

- Investigating the impact of a hybrid combination of micro and nano fillers filling SiR/EPDM composite on the electrical, mechanical, and thermal properties.
- Study the suggestion of combining two or three different nanofiller types to various combinations of SiR/EPDM composite and the influence on the electrical, mechanical, physical, and thermal properties.

Experimental findings in the area of nanocomposites are limited because of the high cost of raw material. So, it is recommended to exploit artificial intelligent techniques such as particle swarm optimization, fuzzy logic, and feed forward neural networks to build a mathematical algorithm based on research results that can be capable of anticipating the values of electrical properties like dielectric strength.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Authors contribution statement

Amir Alber: Investigation, data curation, writing-original draft, writing -review and editing, performing the electrical and mechanical tests, analysis and interpretation of results. **Loai Nasrat:** Conceptualization**,** supervision of all electrical tests in HV lab, guidance, Investigation on challenges. **Hanafy Ismail:** Conceptualization**,** guidance**,** analysis and interpretation of results**. Medhat Hassan:** Supervision in chemical preparation in polymer laboratory, supervision of physical and mechanical tests.

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Appendix I

S. No.	Abbreviation	Description
1	AC	Alternative Current
2	Al_2O_3	Aluminum Oxide
3	ATH	Alumina Tri-hydrate
4	ASTM	American Society for Testing and Materials
5	BN	Boron Nitride
6	CB	Carbon Black
7	DCP	Decumyl Peroxide
8	EPDM	Ethylene Propylene Diene Monomer.
9	FTIR	Fourier-Transform Infrared Spectroscopy
10	HV	High Voltage
11	IEC	International Electro Technical Commission
12	kV	Kilo Volt
13	MFS	Modified Fumed Silica
14	MPa	Mega Pascal
15	NaCL OMMT	Sodium Chloride Organically Modified Montmorillonite
16	PD	Partial Discharge
17	PHR	Parts Per Hundred Rubber
18	SEM	Scanning Electron Microscope.
19	UV	Ultraviolet
20	SiR	Silicone Rubber
21	SiC	Silicon Carbide
22	SiO_2	Silica
23	TEM	Transmission Electron Microscopy
24	TGA	Thermgravimetric Analysis
25	TiO_2	Titanium Dioxide.
26	Wt(%)	Weight Percentage
27	α	Weibull Scale Parameter
28	β	Weibull Shape Parameter