Study the Effect Of Increasing the Mechanical Strength of Epoxy Composites Reinforced with Iron Powder on the Dielectric Strength of the Insulator and Their Thermal Conductivity

MAHMOUD M S AL-SOUD
Department of Electrical Engineering,
Al-Ahliyya Amman University,
Amman,
JORDAN

Abstract: - Iron powder (Fe) was added to epoxy polymer with a weight percentage of 1% and for particle size <60µm, It was added after being roasted at a temperature of 300 C°, Iron-reinforced samples, and pure samples were formed by manual molding method at a temperature of 80 C° to be compatible with the test devices. The thermal conductivity and breakdown voltage of these insulators were measured after increasing the mechanical strength and comparison between them.

Key-Words: - Composite Materials, Epoxy, iron powder, Dielectric Strength, thermal conductivity, tensile test.

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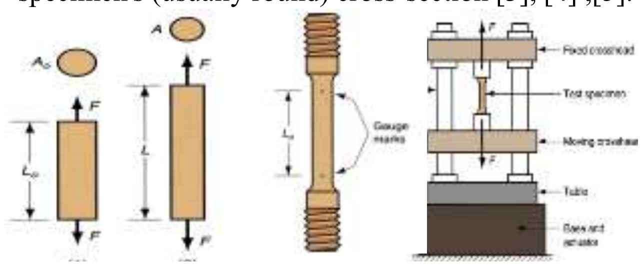
1 Introduction

Epoxy composites are vital electrical insulating materials known for their electrical insulation capabilities and high chemical stability at low voltages (under 15 kilovolts). However, they are mechanically weaker than other insulators like porcelain, rubber, and glass when exposed to medium and high voltages, [1], [2]. In composite applications, it is crucial to ensure that both components are chemically stable and do not react under combined thermal, mechanical, and electrical stresses throughout the equipment's expected lifespan. Additionally, they should have similar dielectric constants.

Materials can undergo three types of static stresses: tensile, compressive, and shear. Tensile stresses cause the material to elongate, whereas compressive stresses cause the adjacent parts to slide relative to each other. The stress-strain curve represents the key relationship that defines the mechanical properties of materials when subjected to these three types of stress, [3], [4].

2 Tensile Properties

The tensile test is the most widely used method for examining the stress-strain relationship, especially for metals. In this test, a force is applied to pull the material, which causes it to elongate while reducing its diameter, as shown in Figure 1(a). ASTM (American Society for Testing and Materials) standards define the preparation of the test specimen and the procedures for conducting the test. The typical specimen and general setup for the tensile test are shown in Figure 1(a), 1(b) and 1(c), respectively. The test specimen begins with an original length, L0, and area, A0. The length is measured between the gauge marks, and the area is calculated based on the specimen's (usually round) cross-section [3], [4] ,[5].



(a) (b) (c)

Fig. 1: Tensile test (a) Tensile force applied in (1) and (2), resulting in the elongation of the material, (b) Typical test specimen and (c) Setup of the tensile test

Three tests were conducted to compare pure epoxy composite insulators and insulators reinforced with iron powder by 1%.

2.1 Tensile Test

The tensile test is one of the most common measures of (stress-strain), and when a material is stretched and pulled, the tensile stress will be applied to the unit area and can be expressed in the following equation:

$$\sigma = \frac{F}{A_0} \quad (1)$$

where:
σ : Tensile stress (N/m^2)
F : tensile force (N)
A_0: area (m^2)

If the tension causes an elongation, then the tension strain can be found from the following equation:

$$\epsilon = \frac{l_1 - l_0}{l_0} \quad (2)$$

where :
ϵ : Tensile strain
l_0 : Sample length before elongation (mm)
l_1 : Sample length after elongation (mm), [6]

Figure 2 represents a tensile test device connected to a computer to draw the relationship between elongation and force. A tensile test was performed on the prepared samples using the tensile test device shown in Figure 2.

(a) (b) (c)

Fig 2: (a) tensile test device, (b) reinforced sample fracture and (c) pure resin sample fracture.

Two test were performed:

A. In the first test we applied tensile forces for several samples of pure polyester resin insulating material under specific conditions and the results are shown in Figure 3.

B. In the second test, tensile forces were applied to several samples of the polyester resin insulating reinforced with iron powder under specific conditions, and the results are shown in Figure 3.

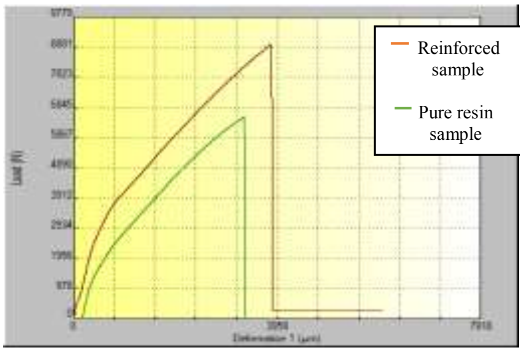


Fig. 3: this curve shows the relation between applied forces (Y-axes) and Elongation (X-axes)

2.2 Thermal Conductivity Test

Cylindrical samples with a thickness (L) of 3 mm and a diameter of 25 mm were prepared from samples of polymeric materials reinforced with iron and pure materials. Figure 4 shows the test device used to measure the thermal conductivity.

(a) (b)

Fig . 4: (a) reinforced sample; (b) pure resin sample

Thermal Conductivity Measurement:

When there is a thermal difference between two surfaces, the heat will transfer from the surface with the higher temperature to the surface with the lower temperature, and this phenomenon is known as thermal conductivity. On this basis, thermal conductivity can be defined as the rate of heat flow across a unit area over a unit of time when there is a thermal gradient between two surfaces of one degree Celsius, [7].

Fourier Law can be used in calculating the thermal conductivity coefficient (k), and this law states:

$$q = -k\frac{dT}{dx} = -k\frac{d}{dx}\left(T_1 - \frac{T_1 - T_2}{L}x\right) = k\frac{\Delta T}{L} \quad (3)$$

where (including the SI units)
q : is the local heat flux density, $W \cdot m^{-2}$
K : is the material's conductivity, $W \cdot m^{-1} \cdot K^{-1}$,
ΔT : is the temperature gradient, $K \cdot m^{-1}$.
L : is the thickness, m

This formula, which represents the simplest solution for heat conduction, resembles Ohm's law when we consider the temperature difference as a potential difference driving a current. Therefore, we can observe that Q = qA.

$$Q = \frac{\Delta T}{L/kA} \equiv \frac{\Delta T}{R_{t_{slab}}} \quad \text{is like} \quad I = \frac{\Delta V}{R} \qquad (4)$$

Here, L/kA takes on the role of thermal resistance for the slab, which we denote as R_{slab},$R_{t\_}$. The thermal resistance, Rt,R_t, has units of (K/W). Figure 5 illustrates how heat flow through the slab can be represented in a diagram that is directly analogous to an electric circuit, [7].

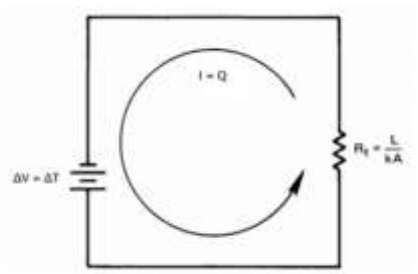


Fig. 5: Ohms law analogy to conduction through a slab

The thermal conductivity test was performed on pure epoxy resin samples and iron powder-reinforced samples at different temperatures. The Table 1 (Appendix) shows the test results.

2.3 Breakdown Test

Dielectric strength refers to an insulating material's ability to withstand the maximum voltage applied to it over an extended period without experiencing breakdown or failure, [8]. It can be quantified by the electric field (E), which is the field intensity at which the insulating material fails or collapses, and is represented by the following equation, [8], [9]:

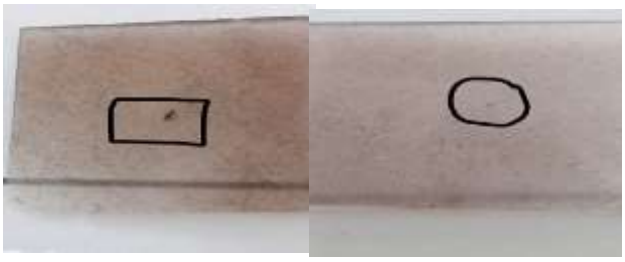
$$E = \frac{v}{h} \qquad (5)$$

where:
E: electric field (Kv/mm).
V: The maximum voltage applied to the insulator (v).
h: Thickness of the insulating material (mm), [10].

The inference of a breakdown in the insulating material is through the occurrence of one of the following cases:
1. A hole occurs in the insulating material.
2. Melting or burning of the insulating material, [11].

When an alternating voltage is applied to an insulating material, various phenomena occur within the dielectric, including polarization and electrical conductivity. As the voltage increases, the leakage current within the insulating material also increases. When the voltage reaches its maximum value, the insulating material undergoes breakdown. At this point, the conduction current within the material continues to leak, and the voltage starts to decrease due to the reduction in the material's resistance, [12].

The dielectric measuring system consists of the following parts which are shown in Figure 6:
1. High voltage transformer (0-90) Kv, (50) Hz.
2. Transformer insulation oil to prevent flashover.
3. Spherical electrodes of well-conducting copper alloy immersed with samples in transformer oil to prevent flashover.
4. Samples of pure resin and iron powder reinforced which are 1.5 mm thick.



(a) (b)

(c) (d)

Fig. 6: (a) samples under test; (b) breakdown moment; (c) iron reinforced sample shape after breakdown; (d) pure resin sample shape after breakdown

3 Procedure

The transformer voltages were gradually raised between the conducting electrodes until the samples collapsed, the value of the breakdown voltage of the samples is recorded, and when you apply this value and the value of the sample thickness in which the electrical failure occurred in equation (5), the Dielectric strength is obtained.

The breakdown voltages of the iron-reinforced sample were recorded at 32 kV and the epoxy-resin sample at 37 kV, the Table 2 shows dielectric strength.

Table 2. The dielectric strength

	Breakdown voltage (Kv)	**Thickness (mm)**	**dielectric strength (Kv/mm)**
Iron–reinforced	32	1.5	21.33
Pure resin	37	1.5	24.66

4 Conclusion

The dielectric strength depends on the thickness of the sample and the rate of rise of the voltage in addition to its decrease with an increase in the amount of iron powder added to the epoxy compositions. A transformation of the epoxy-based compositions occurred as a result of adding iron powder and thus the tensile strength increased. In the iron-reinforced samples, irregular cracks and deformations appeared in the boundaries of the electrical breakdown region, while a state of fusion, perforation, and regularity of the electrical breakdown point appeared for the pure resin samples. As the surrounding environment temperature increases, the thermal conductivity decreases, and the results are shown in Table 1 (Appendix). The thermal conductivity of iron-reinforced samples increased by 17% more than the pure resin at a surrounding temperature of 12 ° C, and by 9% more than the pure resin at 22 ° C, so the thermal conductivity of iron-reinforced sample is higher than the pure resin sample, and this percentage is considered as a disadvantage.

References:

[1] S.F.Khor, Z.A.Talib, H.A.A.Sidek, W.M.Dand and B.H.Ng *"J.Am.Applied Sci."*, 6, 1010-1014 , (2009) .

[2] M.Koleva, A.Zheglova, *"Electro physical characteristics of polymer composites"*, 3rd Ed., (2009) .

[3] Avollone E.A., And Baumeister III, t. (eds.) marks standara handbook for Mechanical engineers 10th ed. McGraw-Hill book company , new york, 1996.

[4] Beer ,F.P and Russell,j.E. Vetor machanice for Engineers, 6th ed.McGraw –Hill book company new york 1996.

[5] Budynas, R.G. Advanced strength and Applied strees Analysis 2nd ed . McGraw – Hill book company new york 1998.

[6] Dov Sherman and David Brandon, (1999) *"Advanced Engineering Materials",* 1, 3-4, John Wiley Inter Science, December.

[7] Lienhard, J. H., & Lienhard, J. H. (2011). A heat transfer textbook. Mineola, NY: Dover Publications.

[8] Blyth, A. R., (1979) "Electrical Properties of Polymers", Cambridge University Press, London.

[9] Pampuch, R., (1976) "Ceramic Materials an Introduction to Their Properties", Elsevir scientific pub.com , Amsterdam.

[10] Mehta, V. K., (2004) "Principles of Electrical Engineering and Electronics" , S. Chand & Comp. LTD. Ramnagar , New Delhi India.

[11] Stanek, J., (1977) "Electric Melting of Glass", Elsevier Scientific Comp , LTD ,Amsterdam.

[12] Tareev, B. (1979) "Physics of Dielectric Materials", Mir Publishers , Moscow.

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Conflict of Interest

The authors have no conflicts of interest to declare.

APPENDIX

Table 1. The test results

	Current (I) ampere	Voltage source (V)	A=π(.025)^2 /4 m^2	T1 C^o	T2 C^o	K= I*L/AΔT (W/m.k)	
Pure resin insulator	1.1	12	0.0005	12	32	3.3	**Test 1: At surrounding medium of 12 C^o**
Iron – reinforced insulator	1.1	12	0.0005	17.5	34	4	
Pure resin insulator	1.1	12	0.0005	26.6	47.8	3.113	**Test 2: At surrounding medium of 22 C^o**
Iron–reinforced insulator	1.1	12	0.0005	26.2	45.4	3.437	