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BREAKDOWN STRENGTH OF SOLID INSULATING MATERIALS IN AMBIENT MEDIUM

A. Masood[1], M.U. Zuberi[2], A.Alam[3]

[1,2,3]*Department of Electrical Engineering, Z.H.College of Engineering and Technology*
Aligarh Muslim University, Aligarh (India)

ABSTRACT

The objective of this research was to determine if a relationship could be found between dielectric strength and other properties of electrical insulating materials in ambient medium on an empirical basis by using variables predicted by basic theory. A simple equation to predict the dielectric strength of a solid insulating material in the ambient medium has been proposed using ASTM electrode system. The equation requires the values of volume resistivity (ρ_v), relative permittivity (ξ_r), thickness (t) and loss tangent (tanδ), which may be obtained easily by low voltage non-destructive measurements. The values of electric strength calculated using this equation for Polyethylene, Nomex, Leatheroid, Trivoltherm, Clasefleece and Polyethylene coated Leatheroid are quite in agreement with the experimentally measured values. It is expected that the equations obtained will help the designers as a handy tool for quick estimation of breakdown strength of solid dielectrics.

***Keywords:* Breakdown Strength, Loss Tangent, Volume Resistivity, Relative Permittivity, Solid Dielectrics**

I. INTRODUCTION

The theory behind dielectric breakdown has always been to a great extent equal part of speculation, art and science. The interaction of fields, particles and atoms on a microscopic level is so complex that exact quantum mechanical solution to all but the simplest atomic structure has been impossible [1,2]. A myriad of factors, which might influence dielectric strength, could be listed and evaluated [3-5]. These include intrinsic material properties, a host of external environmental factors and assorted test conditions that may exist. However, if the environmental factors and test conditions are kept constant the list can be shortened considerably. If this were the case, then a list of intrinsic material properties which might affect the dielectric strength such as relative permittivity (ξ_r), loss tangent (tanδ), ionization energy (E_i), sample thickness (t), mobility of charge carriers (μ), number of charge carriers (n), free path among molecules (λ) and free volume of the material (V_f) would result [6,7].

Out of the above parameters ξ_r, tanδ, and t can be measured in a relatively straight forward manner. However, the others cannot be measured readily.

Mobility of charge carriers is very difficult to define [8]. However, the volume resistivity (ρ_v) measurement can be used to determine μ through the equation $\rho_v=1/ne\mu$, if the number of charge carriers are known.

The mean free path of a free electron in a material is dependent upon the free volume of a material and the molecular agitation within the material. Both of these are temperature dependent. The increase in free volume with temperature leads to an increase in the mean free path. However, the increased molecular agitation at high temperatures tends to decrease this path. Thus, the measurement and calculation of this parameter is most difficult.

Furthermore, from the energy considerations, the kinetic energy which an electron acquires when subjected to an electric field is dependent upon the mean free path between collisions. Also, the mean free path λ should be equal to the cube root of the free volume V_f.

With these constraints in measuring the above listed intrinsic properties, Swanson et al [6] suggested a relationship given by equation (1) to correlate the dielectric strength E with volume resistivity, relative permittivity and loss tangent.

$$\textbf{Dielectric Strength, } E=A+B\log(\rho_v/\xi_r \tan\delta) \text{ -----} \qquad (1)$$

This is based on the assumption of performing experiments on the test samples of same thickness in a group, which is again an approximation to eliminate t from the above equation.

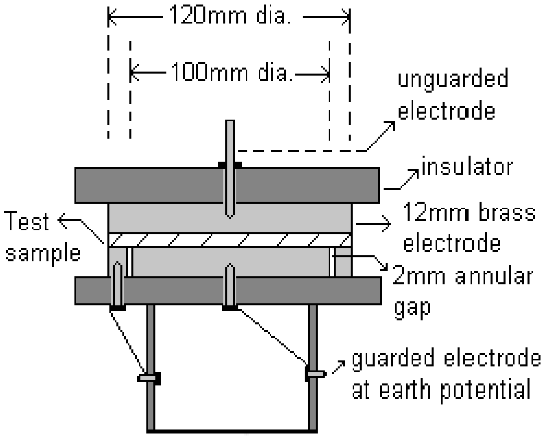
Though Eq. (1) holds good for the evaluation of dielectric strength of a number of solid insulating materials, it suffers from the disadvantage that it is valid for a particular large thickness of 1.397 mm and cannot be used for dielectrics of smaller thickness. However it is well established that the thickness affects the dielectric strength of solid insulating material.

Using the above approach the breakdown strength (BDS), relative permittivity (ξ_r), loss tangent ($\tan\delta$) and thickness (t) of different solid insulating materials in the ambient medium have been measured and correlated incorporating the thickness of the samples to estimate the BDS of solid insulants.

II. EXPERIMENTAL TECHNIQUES

2.1 Measurement of Relative Permittivity and Loss Tangent of Solid Dielectrics

Fig. 1 shows the three-electrode system as described in [9] to measure the relative permittivity and loss tangent of various dielectrics. Measurements were made using Automatic Capacitance & Dissipation Factor test system PE-ACDF-1 as shown in Fig. 2. Its user-friendly GUI, along with its settings allows display of results on the same back-lighted colored LCD display and printed by an integrated panel printer. Measurement of ξ_r and $\tan\delta$ were carried on Polyethylene, Nomex, Leatheroid, Trivoltherm, Clasefleece and Polyethylene coated Leatheroid.



(a) Schematic of three electrode system

(a) PE-ACDF-1Front Panel

(b) Three electrode system Experimental Setup

Figure1. Three-electrode system used to investigate the relative permittivity and loss tangent

(b) Experimental Test Cell with PE-ACDF-1

Figure 2. Experimental Setup

2.2 Breakdown Strength of Solid Dielectrics

The electrode assembly for obtaining the electric strength is as per IS: 2584-1963[10]. Five samples of equal thickness were tested with this arrangement. Taking the ratio of average breakdown voltage to average thickness of the sample, electric strength was determined.

2.3 Sample Preparation

No special efforts were made to clean or modify the test samples i.e. Polyethylene, Nomex, Leatheroid, Trivoltherm, Clasefleece and Polyethylene coated Leatheroid in any way since it was assumed that any contaminants such as ionic impurities which would influence the dielectric strength would also influence other properties being measured. Thus the materials were tested as received in the laboratory.

The sample thickness was measured at some randomly distributed 20 points, spread all over the sheet area with a micrometer having a least count of 0.01mm. The average of the 20 measurements was taken as the average thickness of the sample.

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III. RESULTS

Volume resitivities of the materials were not measured practically but noted from the literature available [11-13].

Collecting all relevant data for different insulating material samples, log ($\rho_v/\ \xi_r \tan\delta$) was calculated for each of them. Samples were grouped together according to thickness and for each group measured electric strength was plotted against the quantity log ($\rho_v/\ \xi_r \tan\delta$).

The plot is as shown in Fig. 3. For thick samples the slope of straight line is lesser than the slope for thin samples and these decreases in a regular fashion.

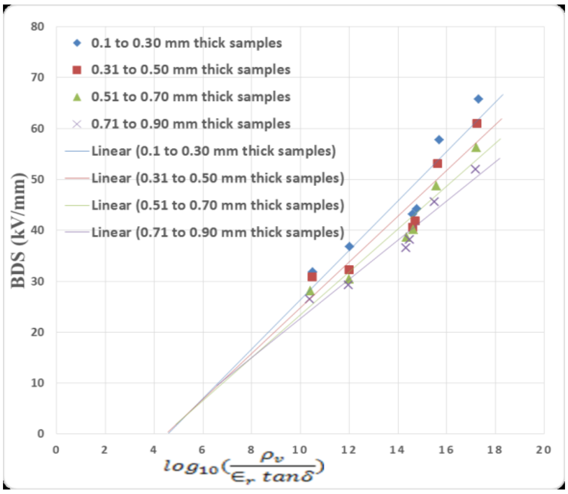
Equations (2) to (5) plotted in Fig. 3 are for four thickness groups of samples [0.1-0.3mm, 0.31-0.5mm, 0.51-0.7mm and 0.71-0.9mm].

$$E_1 = -22.09+4.853 \log (\rho_v/\ \xi_r \tan\delta) \quad \text{------(2)}$$

$$E_2 = -20.18+4.500 \log (\rho_v/\ \xi_r \tan\delta) \quad \text{------(3)}$$

$$E_3 = -18.73+4.213 \log (\rho_v/\ \xi_r \tan\delta) \quad \text{------(4)}$$

$$E_4 = -15.65+3.840 \log (\rho_v/\ \xi_r \tan\delta) \quad \text{-----(5)}$$



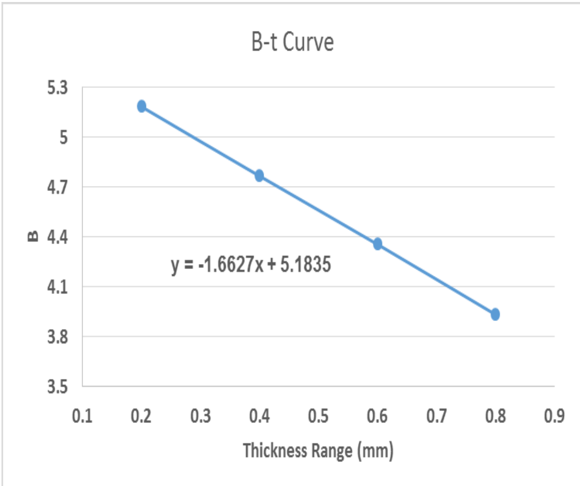


Figure 3. Estimation of Electric Strength **Figure 4. Constant 'B' vs. 't' curve**

Thus all the measured data can be put in the form of an equation

$$E = -A+B \log (\rho_v/\ \xi_r \tan\delta) \quad \text{------ (6)}$$

Considering the mean value of a particular range of thickness of samples, it was observed that that constant 'B' is inversely related to thickness't' of the sample. Fig. 4 shows a plot between 'B' values versus thickness't' of sample which is again a straight line and mathematically expressed as B= 5.1835-1.6627t.

Thus final equation (6) may be expressed as

$$E = -19.165+ (5.1835-1.6627t) \log (\rho_v/\ \xi_r \tan\delta) \quad \text{---- (7)}$$

Here 19.165 is the average of 'A' values of Eqs. (2)- (5).

The calculated values using eqs (7) and measured values of electric strength of various solid insulating materials mentioned earlier are listed in Table 1. Errors in most of the cases are within ± 10 %.

TABLE1. Estimation of Electric Strength of solid insulating materials with percentage error.

Material	Dielectric Constant (ξ_r)	Dissipation Factor ($\tan\delta$)	$\text{Log}[(\rho_v)/\ \xi_r\tan\delta]$	Thickness 't' mm	Measured E (kV/mm)	Calculated E (kV/mm)	% Error
Polyethylene density=1.0634g/cm^3 ρ_v=2.1x10$^{16}\Omega$cm	2.5202	0.0413	17.3048	0.19	65.789	65.068	1.00
	2.5257	0.0473	17.2449	0.39	61.025	59.041	3.25
	2.5763	0.0509	17.2045	0.58	56.206	53.423	4.90
	2.6029	0.0532	17.1809	0.79	52.025	47.324	9.00
Leatheroid Density=0.9989 g/cm^3 ρ_v=1.6×10$^{10}\Omega$cm	2.526	0.2019	10.4965	0.17	31.760	32.276	1.60
	2.636	0.2051	10.4712	0.35	30.857	29.019	5.95
	2.990	0.2131	10.3998	0.52	28.077	25.75	8.28
Nomex Density=1.1226 g/cm^3	2.493	0.092	14.6395	0.57	40.175	42.844	6.60
	2.687	0.125	14.4738	0.76	38.158	37.570	1.50
Trivoltherm Density=1.1287 g/cm^3 ρ_v= 1.5×10$^{15}\Omega$ cm	2.083	0.1410	15.7081	0.23	57.826	56.251	2.70
	2.194	0.1608	15.6286	0.45	53.111	50.153	5.50
	2.309	0.1786	15.5608	0.69	48.695	43.63	10.3
Polyethylene Coated Leatheroid Density=1.0594 g/cm^3 ρ_v= 3.4×10$^{11}\Omega$cm	2.497	0.1311	12.0165	0.19	36.842	39.326	6.80
	2.555	0.1330	12.0002	0.39	32.307	35.25	9.13
	2.592	0.1346	11.9887	0.56	30.357	31.81	4.8
	2.648	0.1396	11.9636	0.77	29.221	27.532	5.70
Clasefleece Density=1.1481 g/cm^3	2.348	0.0191	14.3483	0.66	38.636	39.464	2.10
	2.419	0.0198	14.3196	0.87	36.552	34.347	6.00

IV. CONCLUSION

Empirical formula suggested as given by Eq (7) for estimation of electric strength of solid insulating material is simple and gives results with errors within 10% and thus may be useful provided thickness is small. It is expected that the equation obtained will help the designers as a handy tool for quick estimation of breakdown strength of solid dielectrics.

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