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Empirical Relation to Estimate Breakdown Strength of Solid Insulating Materials

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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 ($\tan\delta$) which may be obtained easily by low voltage non-destructive measurements. The values of electric strength calculated using this equation for Polyethylene, Fiber glass, Leatheroid, Polyethylene coated Leatheroid, Empire Cloth, Mica, Kraft paper, Trivoltherm, Clasefleece and Nomex 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

Solid insulating materials form an integral part of all electrical equipment especially when the operating voltages are high. The design of any electrical apparatus is based on the dielectric strength of the electrical insulation used and the design cannot be completely relied upon unless an assessment of the dielectric strength of insulation against applied voltages is made using high voltage testing.

When high voltage testing is done on component parts, elaborate insulation assemblies, and complete full-scale prototype apparatus, it is possible to build up a considerable stock of design information. Such test data, although expensive, can be very useful, but it can never really be complete to cover all future designs and necessitates use of large factors of safety. A different approach to the problem is the estimation of dielectric strength of the insulation arrangement.

The theory behind dielectric breakdown has not been fully understood. The interaction of fields, particles and atoms on a microscopic level is so complex that exact quantum mechanical solution is simply not possible [1,2]. A number of factors affecting dielectric strength, could be listed and evaluated [3-5]. These include intrinsic material properties, external environmental factors and test conditions that may exist. However, the list can be shortened considerably if the environmental factors and test conditions are kept constant. 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 ($\tan\delta$), sample thickness (t), mobility of charge carriers (μ), number of charge carriers (n), ionization energy (E_i), free path among molecules (λ) and free volume of the material (V_f) would result [6,7].

Out of the above parameters relative permittivity (ξ_r), loss tangent ($\tan\delta$) and sample thickness (t) can be measured in a relatively straight forward manner. Mobility of charge carriers is very difficult to define [7]. However, if the number of charge carriers are known, the volume resistivity (ρ_v) measurement can be used to determine μ through the equation $\rho_v=1/ne\mu$.

Since the mean free path of a free electron in a material is dependent upon the free volume and the molecular agitation within the material, which are themselves 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, which in turn 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 E with ρ_v, ξ_r and $\tan\delta$:

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

This is based on the assumption of performing experiments on the test samples of same thickness, which is again an approximation to eliminate thickness 't' from the above equation.

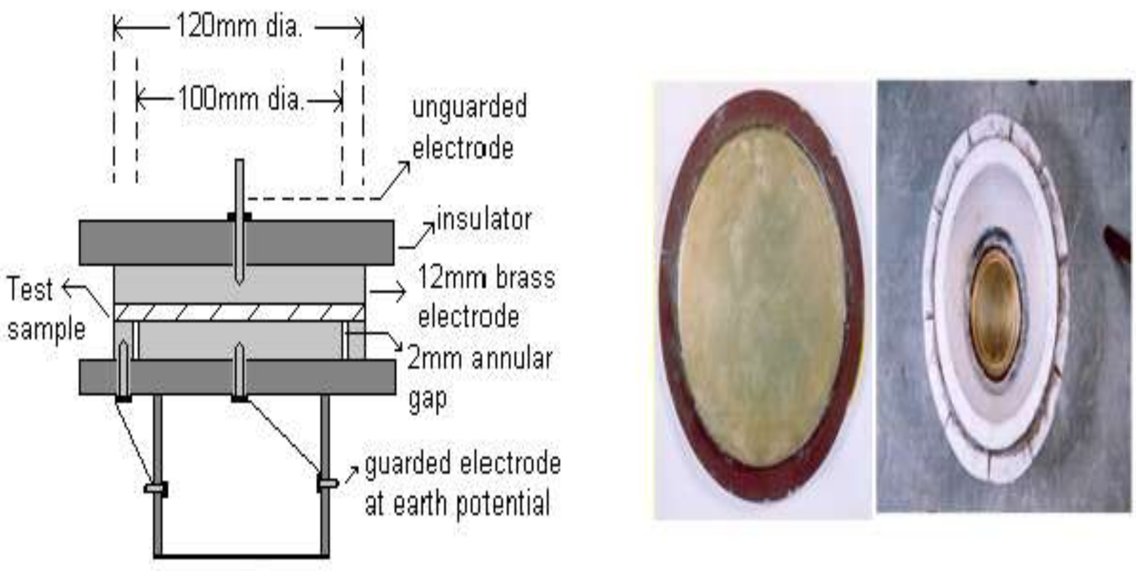
Though Eq. (1) holds good for the evaluation of dielectric strength of a number of solid insulating materials, it suffers from the disadvantage that it is valid for a particular large thickness of 1.397 mm and cannot be used for dielectrics of smaller thickness. However it is well established that the thickness affects the dielectric strength of solid insulating material. To overcome this deficiency of Eq. (1), 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 in the constant 'B' to estimate the BDS of solid insulants.

II. EXPERIMENTAL TECHNIQUES

II.1 Measurement of Relative Permittivity and Loss Tangent of Solid Dielectrics

Fig. 1 shows the three-electrode system as described in [8] 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. Reported values of ξ_r and $\tan\delta$ for Polyethylene, Nomex, Leatheroid, Trivoltherm, Clasefleece and Polythene coated Leatheroid [9] along with ξ_r and $\tan\delta$ measurements carried on Fiber glass, Empire cloth, Mica and Kraft paper using 6451 LCR data bridge shown in Fig.3 [10] have been utilized in developing a single empirical relation to estimate the breakdown strength of all the samples in the present paper.



(a) Schematic of three electrode system **(b) Three electrode system Experimental Setup**

Figure 1. Three-electrode system used to investigate the relative permittivity and loss tangent

(a) PE-ACDF-1Front Panel **(b) Experimental Test Cell with PE-ACDF-1**

Figure 2. Experimental Setup

Figure 3. LCR Data-Bridge

Figure 4. High voltage Testing transformer

II.2 Breakdown Strength of Solid Dielectrics

The electrode assembly for obtaining the electric strength is as per IS: 2584-1963[11]. 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. High Voltage testing (30kVA; 150kV) shown in Fig. 4 was used to determine the experimental values of the breakdown voltages of the samples.

II.3 Sample Preparation

No special efforts were made to clean or modify the test samples 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.

III. RESULTS

Volume resitivities of the materials were not measured practically but noted from the literature available [12-14].

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. 5. For thick samples the slope of straight line is lesser than the slope for thin samples and these decreases in a regular fashion.

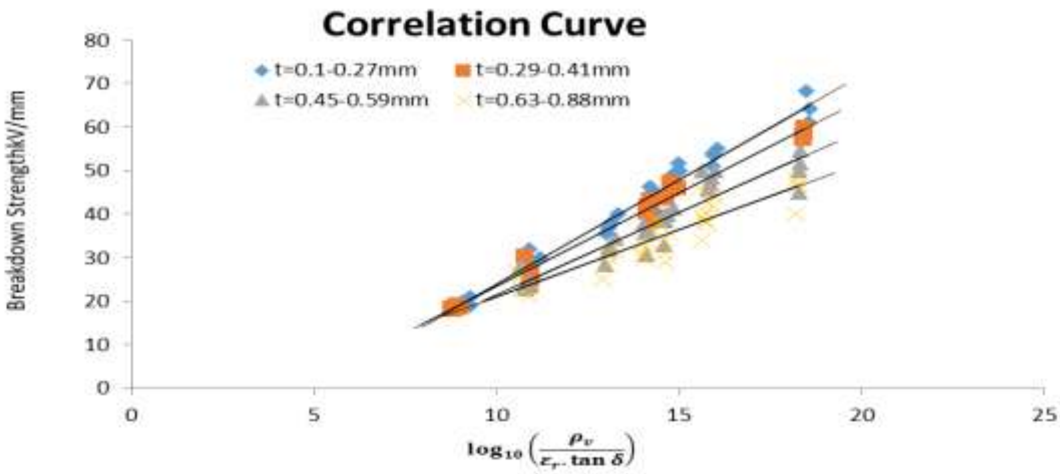


Figure 5. Estimation of Electric Strength

Equations (2) to (5) plotted in Fig. 5 are for four thickness groups of samples [0.1-0.27mm, 0.29-0.41mm, 0.45-0.59mm and 0.63-0.88mm].

$$E1= -23.98+4.79 \log (\rho_v /\xi_r \tan\delta) \text{------}(2)$$

$$E2= -19.17+4.26 \log (\rho_v /\xi_r \tan\delta) \text{------}(3)$$

$$E3= -16.37+3.78 \log (\rho_v /\xi_r \tan\delta)\text{------}(4)$$

$$E4 = -9.82+3.08 \log (\rho_v /\xi_r \tan\delta)\text{-----}(5)$$

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

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

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. 6 shows a plot between 'B' values versus thickness 't' of sample which is again a straight line and mathematically expressed as B= 5.33-2.98t.

Thus final equation (6) may be expressed as

$$E = -17.33+ (5.33-2.98t) \log (\rho_v /\xi_r \tan\delta)\text{----} (7)$$

Here 17.33 is the average of 'A' values of Eqs. (2)- (5).The calculated values using Eq. (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 found to be within ± 10 %.

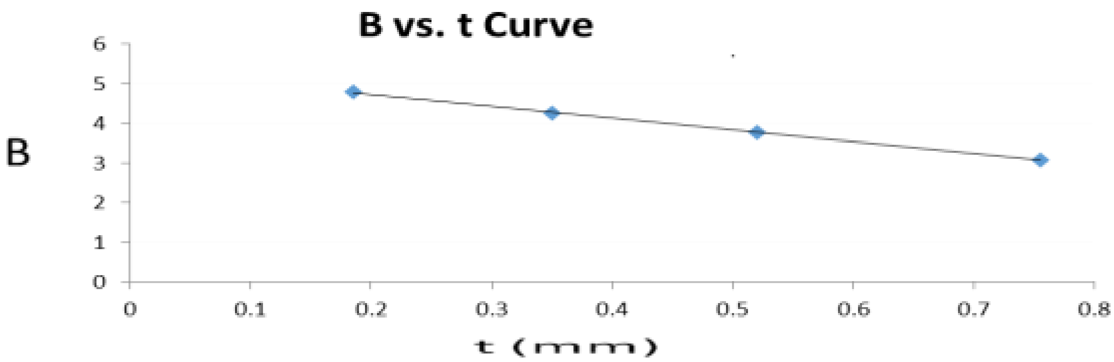


Figure 6. Constant 'B' vs.'t' curve

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

Sample	t (mm)	ε_r	$\tan\delta$	Observed BDS (kV/mm)	$\log_{10}\left(\frac{\rho_v}{\varepsilon_r \cdot \tan\delta}\right)$	Estimated BDS (kV/mm)	%Error
Polyethylene	0.19	2.3075	0.0030	68.42	18.48	70.70	3.33
	0.41	2.3122	0.0035	60.02	18.41	58.30	2.86
	0.59	2.4011	0.0045	50.00	18.28	47.96	4.00
	0.82	2.5636	0.0051	35.97	18.20	35.20	2.13
Fiber Glass	0.16	6.3217	0.0045	46.25	14.20	51.58	11.53
	0.34	6.7320	0.0044	43.38	14.19	43.92	1.25
	0.69	6.9035	0.0056	29.71	14.04	28.63	3.62
	0.52	6.8371	0.0061	37.89	14.04	35.74	5.65
Leatheroid	0.15	4.0071	0.0500	32.00	10.90	35.89	12.17
	0.32	4.3010	0.0610	30.46	10.78	29.84	2.01
	0.47	4.2171	0.0440	24.48	10.93	25.61	4.61
	0.63	4.6245	0.0730	21.58	10.89	20.26	6.07
Polythene Coated Leatheroid	0.27	3.1204	0.0051	40.00	13.32	42.97	7.44
	0.52	3.6350	0.0074	32.69	13.10	32.19	1.51
	0.79	2.8463	0.0130	23.41	12.91	21.08	9.90
Empire Cloth	0.15	2.2126	0.0252	51.66	14.98	55.81	8.04
	0.33	2.4624	0.0251	46.06	14.94	47.60	3.36
	0.52	2.3216	0.0551	38.46	14.62	37.93	1.35
	0.69	2.2274	0.0605	31.15	14.60	30.46	2.19
Mica	0.20	7.1208	0.0050	55.00	16.07	58.74	6.80
	0.20	7.9341	0.0060	54.00	15.94	58.12	7.64
	0.63	8.0016	0.0095	40.31	15.74	37.01	8.20
	0.45	7.9920	0.0070	47.11	15.87	45.97	2.40
Trivoltherm	0.23	2.0830	0.1400	57.82	15.70	55.59	3.85
Kraft Paper	0.41	2.2586	0.4000	18.53	8.74	18.57	0.25
Nomex	0.57	2.4930	0.0920	40.17	14.63	35.79	10.88
Clasefleece	0.45	2.2870	0.0110	40.66	14.60	40.90	0.61

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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