Determination of The Weibull Modulus by Electrical Breakdown and Mechanical Strength for Soda Lime Glass

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Abstract. The interrelationships between mechanical and electrical properties are important to characterize one signifies the other, especially for brittle materials such as glass. The relationship between Weibull modulus from electrical breakdown and Weibull modulus from three-point bending test and other mechanical properties has been studied for soda lime glass slides. The results show that the electrical breakdown and Weibull modulus increased with the rate of rising voltage increases from 20.1-24.7 kV/mm and 10.9-13.78, respectively. The value of Weibull modulus was calculated by using mechanical strength is (12), this result identified the conditions necessary to achieve the same results in electrical breakdown strength test. Therefore, the best rate of rising voltage in the electric breakdown test is 2 kV/s which gives the same results as the mechanical tests. This means that it is possible in the future to evaluate the dielectric products electrically in terms of matching mechanical strength specifications using electrical tests.

Key words: soda lime glass, dielectric, bending, breakdown, Weibull modulus.

1. Introduction

Glass is a poor conductor that conducts electricity at normal temperatures. In this regard, it considers insulator materials. The resistance of glass to electricity varies with its composition. Glass withstand current will lower the temperature, but humidity will increase the conductivity of the current. The rough surface of the glass reduces the resistance to electrical current. [1]

Soda lime glass used in almost all electrical and electronic industries, and insulators are used for light sources (light envelopes) and tubes, cathode ray tubes, capsules and for holding microcircuit components. Glass has high resistance and high electrical breakdown as well as low dielectric constant and low dielectric losses. [2]

When the strength of a series of equivalent glass samples measures, usually find that the results are quite scattered. The reason is the scale-distributing behavior that leads to failure. This behavior is very different from the behavior of metals. Therefore, when we use ceramics, we must adopt different design methods.[3]

Weibull probability of survival analysis has been developed as, among other things, an engineering design method for components made from such materials as ceramics. Failure loads in ceramic components are determined by defect size, and are thus characteristic of the specimens, not the material. The defects have a size distribution and thus the failure loads are variable. An alternative way of describing this situation is that at any given load, a fraction of the specimens tested will survive. Weibull described this fraction, the survival probability (Ps), at any tensile stress as (Eq. (1)):[4]
\[ P_s = \exp\left\{ - \left( \frac{\sigma_{\text{max}}}{\sigma_0} \right)^m \right\} \ldots (1) \]

where \( \sigma_{\text{max}} \) is the maximum strength (either \( \sigma_{\text{max}} = \sigma_{\text{Emax}} \) for electrical strength or \( \sigma_{\text{max}} = \sigma_{\text{Mmax}} \) for mechanical strength), \( \sigma_0 \) = the characteristic strength for which the survival probability is 0.37 (1/e) (so, either \( \sigma_0 = \sigma_{0E} \) for electrical strength or \( \sigma_0 = \sigma_{0M} \) for mechanical strength). To determine Weibull modulus it must take a natural logarithm of both sides of equation (1)

\[ \ln\left( \ln\left( \frac{1}{P_s} \right) \right) = m \ln \sigma_{\text{max}} - m \ln \sigma_0 \ldots (2) \]

Now if we plot \( \ln(\ln(1/P_s)) \) versus \( \ln \sigma \) we will get a straight line of slope (m). The higher the Weibull modulus the lower is the variability of strength. [5]

The Connectivity between mechanical characteristics and electrical characteristics is an urgent necessity for material evaluation.

Electrical breakdown can be classified to two types: 1. Volume breakdown 2. Surface breakdown [6,7]. Dielectric breakdown is the failure of a dielectric to withstand the applied electrical field[8]. Dielectric strength can be measured from the electrical field \( \sigma_{\text{Emax}} \) represents the field in which the dielectric material fails:

\[ \sigma_{\text{Emax}} = \frac{V_{br}}{h} \ldots (3) \]

Where \( V_{br} \) is the maximum voltage applied to the dielectric and \( h \) the thickness of the dielectric materials.

There are many types of electrical breakdown: (a) Intrinsic breakdown, (b) Electromechanical breakdown, (c) Electrothermal breakdown, (d) Erosion breakdown, (e) Streamer breakdown[9].

The three-point bending test was performed by the bending device by this test calculate the strength (\( \sigma_{\text{Mmax}} \)) for each slide according to equation:

\[ \sigma_{\text{Mmax}} = \frac{3PL}{2bh^2} \ldots (4) \]

Where P is the maximum applied load, L is the distance between the supports, b is the width of the slide and \( h \) is the thickness of the slide.[10]

2. Materials and Methods

2.1 Materials

Soda lime glass used as samples, where supplied by SUPERIOR\MARIENFELD company-Germany and its classified as brittle materials. The same glass slides were used in mechanical and electrical strength tests. The typical composition of soda lime glass slides (by %weight) are: 72.3% SiO\(_2\), 13.3% Na\(_2\)O, 8.8% CaO, 4.3% MgO and 1.3% of (Al\(_2\)O\(_3\)+K\(_2\)O+Fe\(_2\)O\(_3\)). The dimension of the samples is fixed (length =76 mm, width =26 and thickness tolerances 0.95 –1.05 mm).

2.2 Dielectric strength measurement

The dielectric strength tested by using high voltage supplier (BAUR - PGO - S -3) Germany with a range (0-60 kV) and frequency (50 HZ). The breakdown has been measured for five rate of rising voltage
(0.5, 1, 2, 3, 5 kV/s). For each rate of rising voltage take 10 point of failure and the calculate the average. The electrical field was found from Equation 3.

2.3 Mechanical strength measurement

The strength has been measured by three-point bending test for 10 samples with the same dimension and take the average values. The samples dimension (76×26×1mm), and the distance between the two supports of devise is 50 mm. The device gives value of maximum force, and the strength measured by equation 4.

3. Results and discussion

The rate of rising voltages (ramping speed) is one of the most parameters in the electrical breakdown strength test of dielectrics. So, that it can determine the value of electric breakdown and types, as well as explain the causes of change in values.

Fig. 1 shows increasing the electrical strength of the dielectric with rate of rising voltages. The low rate of rising voltage means increasing the heat between the electrodes (inside the contact area of the sample) due to increased leakage currents. In addition to the cumulative effects of electrochemical transformations and erosion, which breaks the structure of the material and accelerated the breakdown of the dielectric material as a result of heating processes. The values of the electric breakdown taken at low rate of rising voltage was represented the operational values of the sample, in other words when used as high-voltage insulators. As for the values at which the electric breakdown occurs at high rate of rising voltage, it represents the moment when the circuit is opened or closed.[11]

![Figure 1. Variations of dielectric strength with rate of rising voltage.](image)

The electrical breakdown at a low rate of rising voltage is called “Electrothermal” breakdown, while the electric breakdown at high rate of rising voltages is called “Pure Electrical Breakdown”. [12] In both cases, damage on the contact point of the sample and between electrodes occurs, and it is clearly visible by the eye or using a simple microscope. The damage is accompanied by the appearance of microcracks as
shown in Fig. 2, showing that the extent of damage at the point of breakdown increases in two ways: the first involves electrochemical changes and this is apparent at 0.5, 1 and 2 kV/s, accompanied by limited microcracks and cannot cause fractures in the sample.

![Figure 2. Optical microscopy images for electrical breakdown zone and for different rates of rising voltage.](image)

The second represents an increase in the rate of rising voltage up to 3 and 5 kV/s, where the extent of damage increases significantly, turning into the other type of effects, called “Electromechanical Effect”[13]. This type may cause a sample fraction or the emergence of cracks extending long distances from the edges of the breaking point, and if it reaches the tip of the sample can get a break of the sample. The electrical breakdown strength is exponentially changing with the rate of rising voltage, as in Fig. 1, which means that in high rate of rising voltage the effect on the electrical breakdown is less. The amount of electrothermal breakdown is 20.12 kV/mm at 0.5 kV/s and increased up to 24.66 kV/mm at 5 kV/s which represents pure electrical breakdown.

Since glass is exposed to many factors, leading to the emergence of structural defects such as the residual stresses due to manufacturing processes and annealing, dislocations, nonhomogeneous distribution of glass compounds and the amorphous structure of glass, All of these factors lead to different
results of the electrical breakdown and mechanical strength tests. It is therefore necessary to establish a statistical mechanism by which to assess the degree of discrepancy in the results and the evaluation of the glass products.

The Weibull modulus is one of the best statistical methods to describe this randomization, and it is possible to find variations in measurements. Fig. 3 shows the change in the values of the electrical breakdown strength (x-axis), which represents the logarithm of the greatest electrical stress ($\ln|\sigma_{Emax}|$) where the electrical breakdown occurs. The y-axis represents the logarithm-logarithm inverted probability of survival of the sample without breakdown ($\ln\ln|1/P_s|$), note that the probability of failure can be found from the relationship ($P_f = 1 - P_s$).

Fig. 3(a) shows a change in the probability of survival with electrical breakdown strength at the low rate of rising voltage (0.5 kV/s), that mains at the electrical breakdown associated with the electrothermal changes associated with the breakdown due to the high temperature associated with applied voltage. The Weibull modulus was calculated from the slope of the straight line, and its value ($m=10.875$) and the characteristic strength value of electrical filed is $\sigma_{Eo}= 21$MPa.

When increasing the rate of rising voltage up to 2 kV/s, the Weibull modulus increases to $m=11.934$, as shown in Fig. 3(b). This increase in the Weibull modulus means that the duplicate values of results is large, in other words, the measured values of the maximum electrical field intensity are less variable in the glass samples.

The Weibull modulus is continues in increase with the rate of rising voltages up to $m=13.683$ at the 5 kV/s, as shown in Fig. 4, and $\sigma_{Eo}= 25.5$ MPa, which can be considered as the optimum value for the characterization of electrical strength of soda lime glass samples, as shown in Fig. 3(c,d and e).
Figure 3. Weibull distribution of the electrical breakdown strength with different rate of rising voltage: (a) 0.5 kV/s, (b) 1 kV/s, (c) 2 kV/s, (d) 3 kV/s and (e) 5 kV/s.

Figure 4. The Weibull modulus dependence of rate of rising voltage.

Fig. 5 shows the relation between the characteristic strength value of electrical field and the rate of
rising voltages, representing the high values of the rising which are the most accurate in electromechanical properties.

![Graph](image1.png)

**Figure 5.** Variations the characteristic electrical strength with rate of rising voltage.

Glassware is subject to mechanical failure theories for brittle materials. Microcracks and structural defects are the most important factors determining mechanical strength. Bending strength is one of the mechanical strength types, and characteristics by which resistance is evaluated because it simulates the weakness of these materials, especially tensile strength[14]. Fig. 6 shows the test results of a set of soda lime glass slides, and according to relationship 2. The Weibull modulus can also be found in the same way as in electrical breakdown tests, but replacement the electrical stress with mechanical stress. The slope of the straight line represents the Weibull modulus m=12, and the characterization of electrical strength value is $\sigma_{Mo}=97.52$ MPa. This is the optimum value for bending strength by three point test.

![Graph](image2.png)

**Figure 6.** Weibull distribution of the bending strength.
4. Conclusions

The rate of rising voltages is determining the mechanism of electrical breakdown strength. At low rates, thermal emission increases and electrothermal breakdown occurs, and at high rates, pure electrical breakdown occurs, and often causing it to fracture of sample. In other words, the size of the damage in the area of breakdown increases with increasing the rate of rising voltages as well as extending the microcracks. Increasing the Weibull modulus with the rate of rising voltages increases means obtaining less difference in the results of electrical strength measurements. The Weibull modulus calculated from the mechanical bending test corresponds to the calculated electrical breakdown test at the value of $m=12$. This corresponds to the rate of rising voltage is $2 \, \text{kV/s}$. These conditions determine the adoption of the electrical breakdown tests as an alternative to the mechanical in finding the Weibull modulus to evaluate brittle dielectric products such as glass.

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