Polymer Process Engineering
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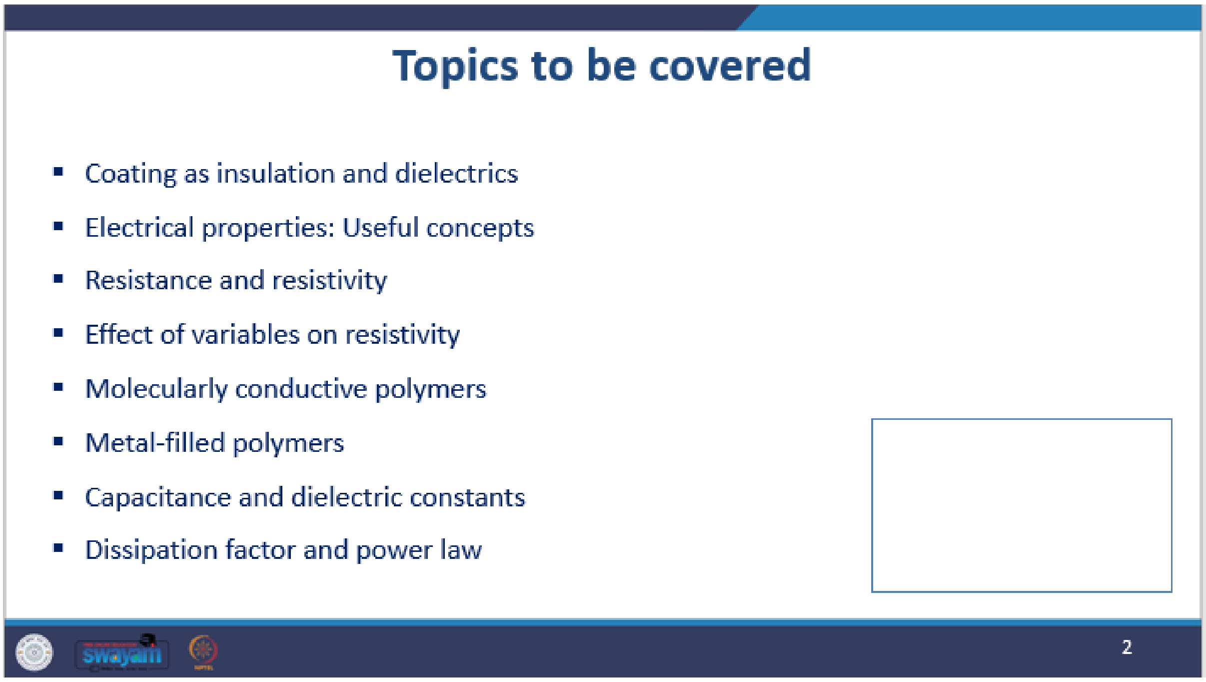
Lecture- 52
Functions of Coatings-I

Hello friends, welcome to the functions of the coating under the edges of the polymer process engine. Now, let us talk about what topics we are going to cover in this particular segment. We will discuss the coating as an insulation and dielectrics, then we will discuss the electrical properties with the useful concepts. We will have a talk about resistance and resistivity, and then we will discuss the effect of variables on resistivity. We will talk about the molecularity of conductive polymers and then metal-filled polymers. We will discuss the capacitance and dielectric constants dissipation factor, and power loss.



Now, let us talk about the coating as insulation and dielectrics. So, organic coatings they serve the important function of providing electrical insulation and dielectric isolation for electronic components. The effectiveness of coating in providing insulation is evaluated through parameters like insulation resistance, volume resistivity, surface resistivity, and dielectric strength. The coating also plays a very vital role in strong electrical current and conducting current, which is characterized by parameters like dielectric constant, capacitance, dissipation factor, and conductivity.

Coatings as Insulation & dielectrics

- Organic coatings serve the important function of providing electrical insulation and dielectric isolation for electronic components.
- The effectiveness of coatings in providing insulation is evaluated through parameters such as insulation resistance, volume resistivity, surface resistivity, and dielectric strength.
- Coatings also play a role in storing electric current and conducting current, which are characterized by parameters like dielectric constant, capacitance, dissipation factor, and conductivity.
- Understanding the precise electrical values and how they vary with factors such as composition, purity, structure, and environment is crucial for selecting reliable coatings for electronic equipment.

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So, the understanding the precise electrical values and how they vary with the factors such as composition, purity, structure and environment which is very crucial for selecting reliable coating for electronic equipment.

Electrical Properties

- Electrical properties refer to the characteristics and behavior of materials in relation to the flow of electric current or the presence of an electric field.
- When it comes to natural fiber reinforced composites, their electrical properties can vary depending on several factors, including the type of fibers, matrix material, fiber content, fiber orientation, and processing techniques.

Here are some key aspects related to the electrical properties of these composites:

- **Conductivity:** Natural fibers, such as cotton, hemp, and flax, are generally poor conductors of electricity. When these fibers are used as reinforcements in composites, they typically do not significantly enhance the electrical conductivity of the resulting material. However, if the composite incorporates conductive fillers or additives, such as carbon nanotubes or metal nanoparticles, it may exhibit improved electrical conductivity.

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Let us talk about the electrical properties. They refer to the characteristics and behaviour of material in relation to the flow of electric current or presence of an electric field. When it comes to the natural fibre reinforced composites their electrical properties can vary depending on several factors like the type of fibre, whatever matrix material being used, the fibre content, fibre concentration, fibre orientation and processing different type of processing techniques. Some of the aspects which are related to the electrical properties of these composites like conductivity, the natural fibres such as cotton, hemp, flux all generally poor conductors of electricity.

Electrical Properties

- **Dielectric Constant:** The dielectric constant, also known as the relative permittivity, is a measure of a material's ability to store electrical energy in an electric field. Natural fiber reinforced composites typically have dielectric constants lower than those of metals or inorganic materials. This property can be advantageous in applications where low electrical losses and good insulation properties are required.

- **Dielectric Strength:** Dielectric strength refers to the ability of a material to withstand electrical breakdown under an applied voltage. While natural fiber reinforced composites generally have lower dielectric strength compared to metals or ceramics, their dielectric strength can still be sufficient for many applications. It is important to consider the specific requirements and voltage levels of the intended application when selecting the appropriate composite material.

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So, when these fibers are used as a reinforcement of composites, they typically do not significantly enhance the electrical conductivity of the resulting material. However, if the composite incorporates conductive fillers or additives such as carbon nanotubes or metal nanoparticles, it may exhibit improved electrical conductivity. The dielectric constants, the dielectric constants, are also known as the relative permittivity. It measures the material's ability to store the electrical energy in an electric field. So, natural fiber-reinforced composites typically have dielectric constants lower than those of metals or inorganic materials.

Electrical Properties

- **Surface Resistivity:** Surface resistivity measures the resistance of a material to the flow of electrical current across its surface. Natural fiber reinforced composites typically exhibit higher surface resistivity compared to conductive materials. However, the addition of conductive fillers or coatings can be employed to improve the surface conductivity of the composites, if needed.

It is crucial to note that the electrical properties of natural fiber reinforced composites can be influenced by various factors, including fiber orientation, moisture content, temperature, and environmental conditions. Therefore, careful consideration and testing are essential to determine the suitability of these composites for specific electrical applications.

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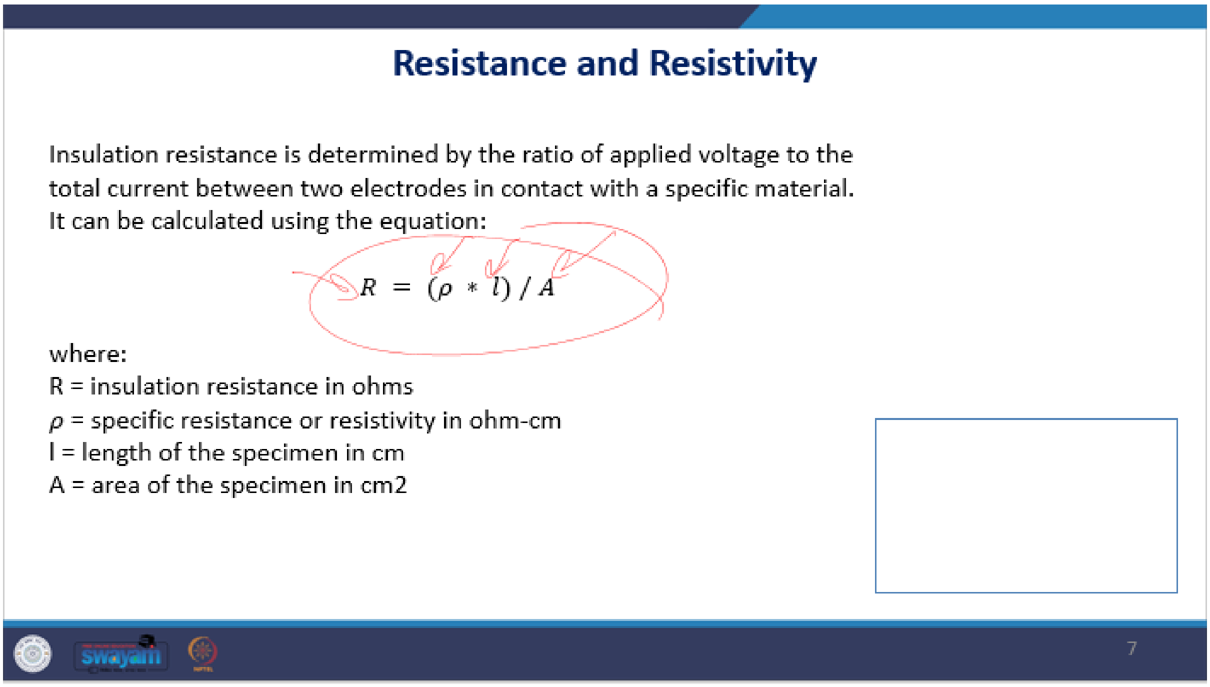
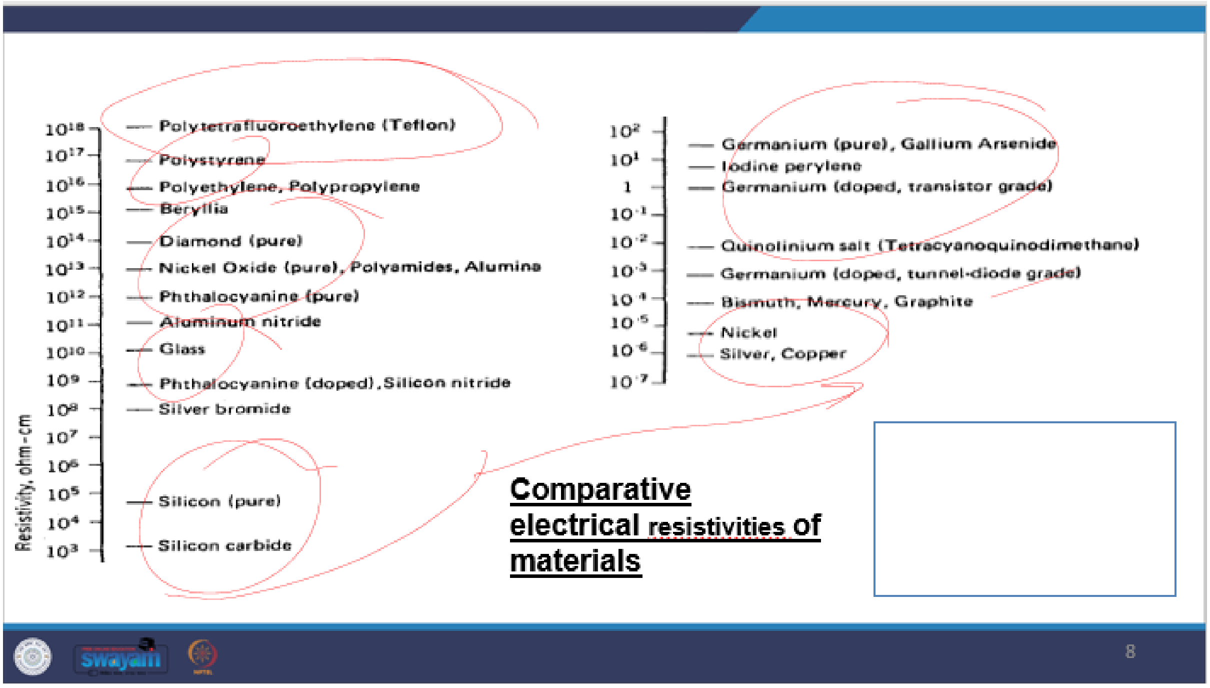
Now, this property can be advantageous in applications where the low electrical losses and a good insulation properties are required. Then the dielectric strength, the dielectric strength this refers to the ability of a material to withstand the electrical breakdown under an applied voltage. While natural fibre reinforced composite generally have lower dielectric strength compared to metals or ceramics and their dielectric strength can still be sufficient for many applications. It is important to consider the specific requirement and the voltage level of intended application when selecting the appropriate composite material. Surface resistivity, surface resistivity this measures the resistance of material to flow of electrical current across its surface.

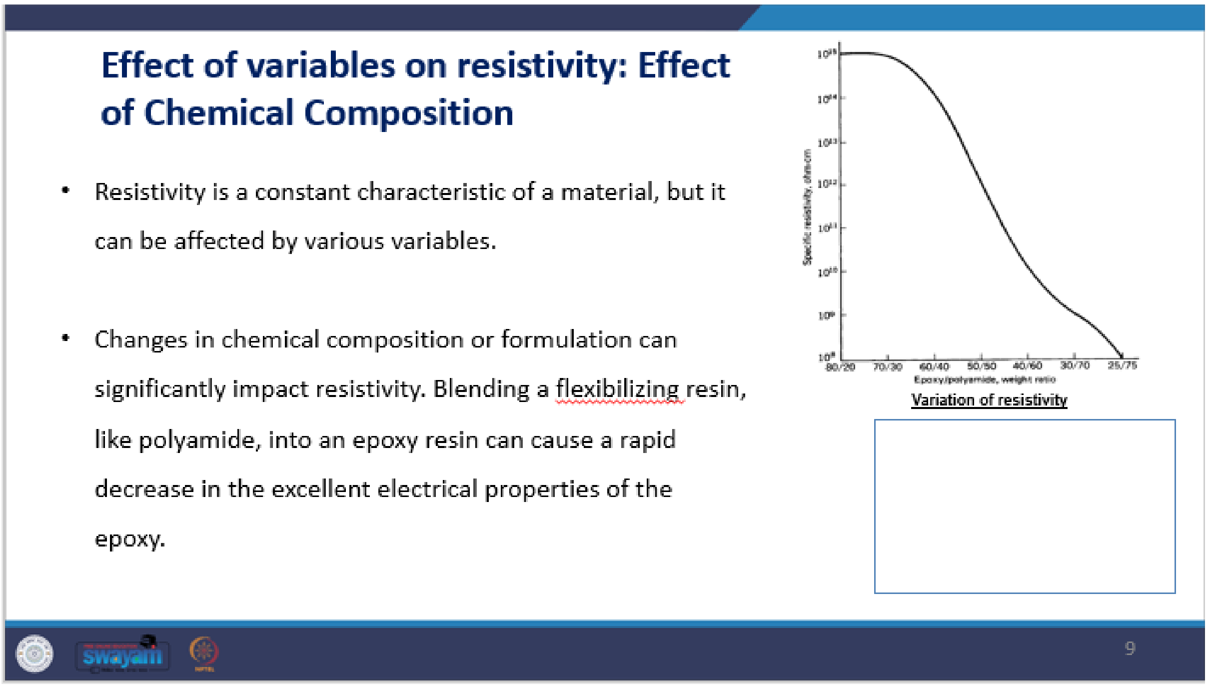
Now, natural fibre reinforced composite typically exhibits higher surface resistivity compared to the conductive materials. However, the addition of conductive fillers or coatings can be employed to improve the surface conductivity of the composite if needed. Now, it is crucial to note that the electrical properties of natural fibre reinforced composite can be influenced by various factors like orientation, moisture content, temperature, environmental conditions and the careful consideration and testing of the it is essential to determine the suitability of these composites for a specific electrical application.



Now, the insulation resistance is usually determined by the ratio of applied voltage to the total current between two electrodes in contact with specific materials and it can be calculated using this particular equation, which is R is equal to rho into L over A, where R is the insulation resistance in ohms, rho is the specific resistance or resistivity in ohms centimetre, L is the length of the specimen in centimetre and area of specimen in square centimetre is represented as A. Now, here you see that the this is the comparative chart of electrical resistivities of different materials like PTFE, this is possesses the high electrical resistivity, then polystyrene, then diamond, you can see the glass, the silicon, then germanium, iodine, all these things are in listed.



Then let us talk about the effect of variables on resistivity effect of chemical composition. This is a constant characteristic of a material but it can be affected by various variables, the change in the chemical composition or formulation, this can significantly impact the resistivity, blending a flexibilization resin like polyimides into the epoxy resin, this can cause a rapid decrease in the excellent electrical properties of the epoxy. Now, let us talk about the effect of impurities under the effect of variables on resistivity, the minor amount of impurities can also be influenced the resistivity. Now, trace amount of impurities has been utilised in the design of semiconductor devices, where addition as low as 1 ppb can increase the conductivity by 2 orders of magnitude. Now, ionic impurities in plastic along with the moisture can significantly lower the resistivity values by 6 to 11 orders of magnitude which can affect the performance of organic insulating coating.



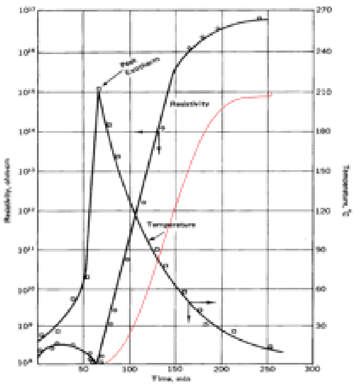
Effect of variables on resistivity: Effect of impurities

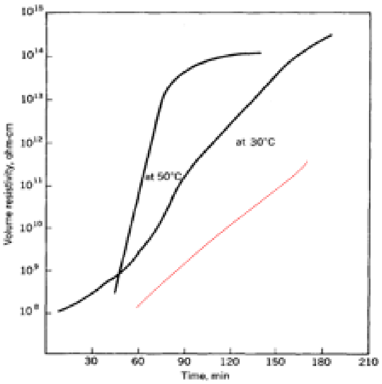
- Minor amounts of impurities can also influence resistivity. Trace amounts of impurities have been utilized in the design of semiconductor devices, where additions as low as 1 ppb can increase conductivity by two orders of magnitude.
- Ionic impurities in plastics, along with moisture, can significantly lower resistivity values by 6 to 11 orders of magnitude, which can affect the performance of organic insulating coatings.
- Resistivity values are also dependent on the degree of cure or polymerization advancement of the coating resin. As the cure advances, electrical resistivity generally increases, although there may be a small decrease at the peak exothermic temperature.

The resistivity values are dependent on the degree of the curing or the polymerization advancement of the coating raising. Now, as a cure advances the electrical resistivity generally increases although there may be a small decrease in the peak exothermic temperature. Now, if we talk about the degree effect of the degree of cure, the 2 competent phenomena are occurring a decrease in the resistance as the temperature rises to the reaction exotherm and an increase in the resistance as the resin polymerizes and becomes fully cured. Now, this is exemplified for an amine-cured epoxy system as per this figure this apparent that these curves may also be useful in determining when resin polymerization is essentially completed. Now, if we talk about the temperature effect, the temperature resistivity relationship can be used to determine the completion of resin polymerization.

Effect of variables on resistivity: Effect of the degree of cure

Two competing phenomena are occurring: a decrease in resistance as the temperature rises to reaction exotherm and an increase in resistance as the resin polymerizes and becomes fully cured. This is exemplified for an amine-cured epoxy system in Figures. It is apparent that these curves may also be useful in determining when resin polymerization is essentially Completed.





Now, here you see the temperature versus volume resistivity because of different polymer coating, this is the best example of electrical resistivity versus the temperature curves. Now, when we talk about the effect of contaminants, which play a very vital role in surface resistivity, it gives a good idea of how these polymers can be used for a variety of products like moisture contaminants, they have a more pronounced effect on surface resistivity compared to the volume resistivity. The contamination like fingerprints, then can cause a significant reduction in the surface resistivity, while volume resistivity may take longer to change in humid or contaminating environments. Here you see polyethylene, polystyrene, polymethyl methacrylate, and silica glass all these things and this gives the surface resistivity at 50 percent humidity and 96 percent humidity; you can see the effect of the contaminants over the surface resistivity. Then we talk about the effect of humidity on surface resistivity, the effect of humidity on surface resistivity, which can vary depending on the type of hardener used in the epoxies.

Effect of contaminants on Surface Resistivity

- Moisture and contaminants have a more pronounced effect on surface resistivity compared to volume resistivity. Contamination, such as fingerprints, can cause significant reductions in surface resistivity, while volume resistivity may take longer to change in humid or contaminating environments.

Material	Surface Resistivity, ohms/square	
	At 50% Humidity	At 96% Humidity
Polyethylene		
As received..	$>10^{18}$	2.4×10^{9}
Contaminated with fingerprints	. . . .	4.6×10^{7}
Freshly shaved surface.	. . . .	2.2×10^{11}
Polystyrene		
As received., ...	10^{18}	1.8×10^{11}
Contaminated with fingerprints	. . . .	5.5×10^{9}
Poly methylmethacry late		
As received..	10^{18}	2.0×10^{14}
Contaminated with fingerprints	. . . .	1.2×10^{12}
Silica glass, clean.	10^{18}	5.0×10^{8}

Effects of Contaminants on Surface Resistivity

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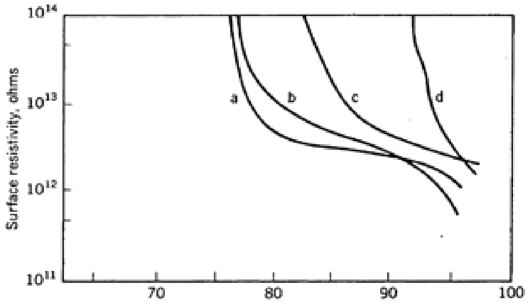
Like aromatic amine cured epoxies, they display higher stability at higher relative humidity levels compared to the anhydride or aliphatic amine cure type. Now, let us talk about the electrical properties, it has been observed that the anhydride cured sample resistivity limit of to about say 5 into 10 to the power 12 ohms per square, a value that is still considered adequate to for most electrical applications. Now, this resistivities can recover after removal from a humid environment with aromatic amine cured epoxies, this demonstrates the fastest recovery rate. Let us talk about the conductance and conductive polymers, the conductance and conductivity, the the reciprocal of resistance is called the conductance, this is expressed in units of ohms inverse and the reciprocal resistivity is the specific conductance expressed in units of ohms inverse centimeter inverse or milli ohms per centimeter and molecularly conductive polymers. known as intrinsically conductive polymers or ICP or conjugated polymers, they are the class of polymers that exhibits electrical conductivity due to their unique molecular structure.

Effect of humidity on Surface Resistivity

- The effects of humidity on surface resistivity can vary depending on the type of hardener used in epoxies. Aromatic amine-cured epoxies display higher stability at higher relative humidity levels compared to anhydride- or aliphatic amine-cured types.



Effect of humidity on surface resistivity of cured epoxy resins at 35°C: (a) epoxy resin cured with methyl nadic anhydride, (b) epoxy resin cured with diethylenetriamine, (c) epoxy resin cured with aromatic amine, (d) Novolacepoxy resin cured with aromatic amine.

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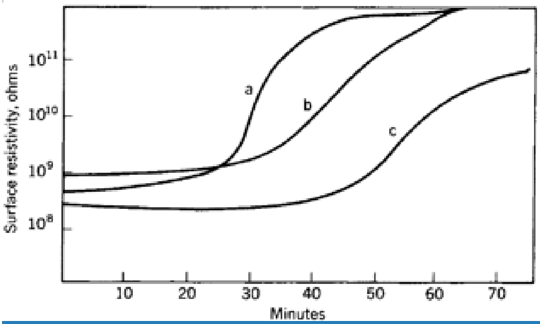
So, unlike traditional polymers, which are typically insulators, molecularly conductive polymers possess delocalized pi-electron system along their polymer chain, allowing for the efficient movement of charge carriers, electrons or holes.

Electrical Properties

- However, it has been observed that the anhydride-cured sample resistivity leveled off to about 5 $x\ 10^{12}$ ohms/square, a value that is still considered adequate for most electrical applications.
- Resistivities can recover after removal from a humid environment, with aromatic amine-cured epoxies demonstrating the fastest recovery rate.



Recovery of surface resistivity for cured epoxy resins at 25°C after 80% humidity: (a) epoxy cured with aromatic amine, (b) epoxy cured with methyl nadic anhydride, (c) epoxy cured with diethylenetriamine

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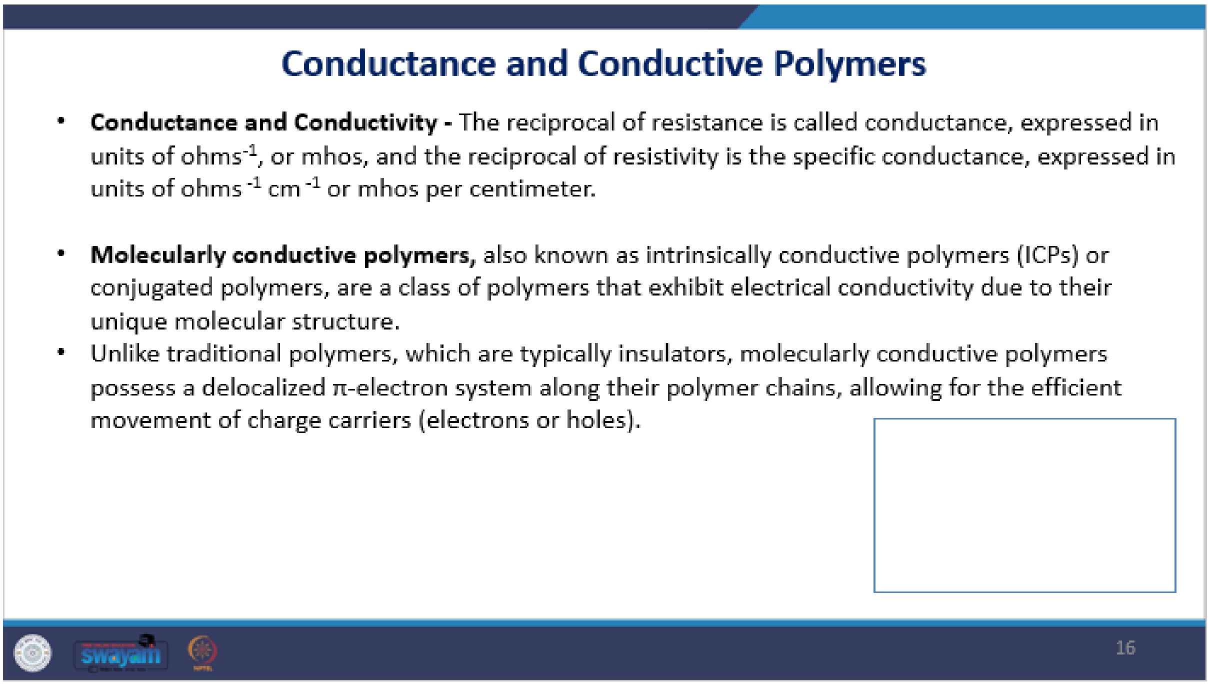
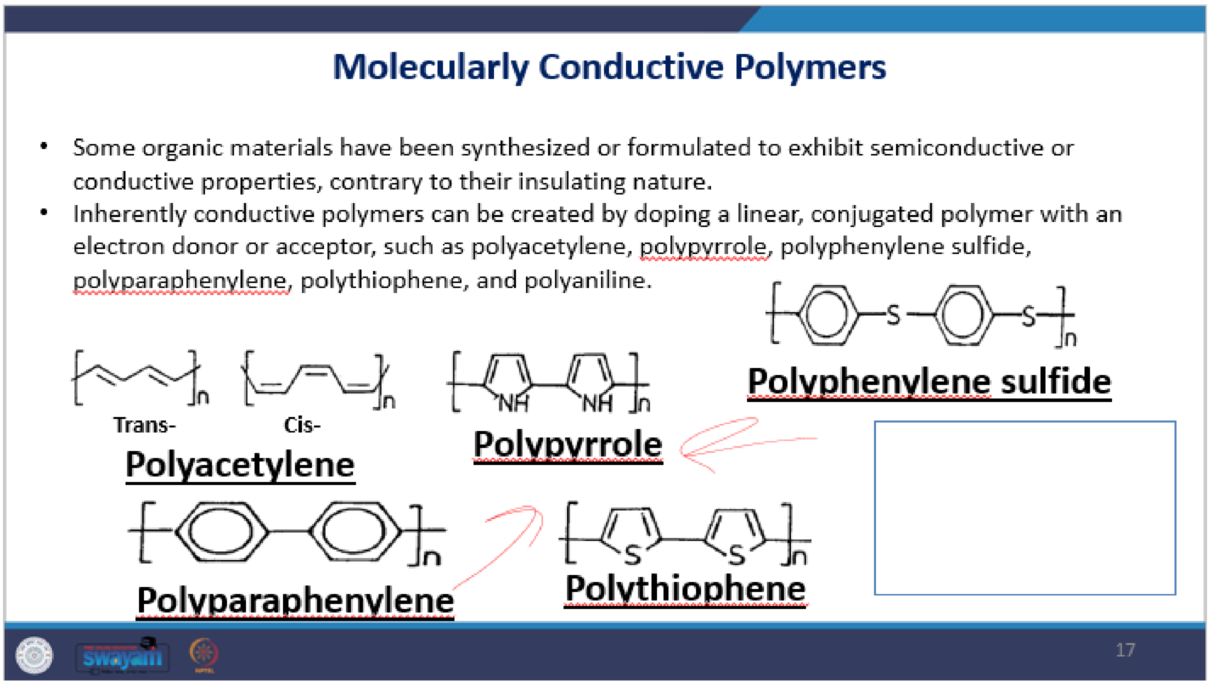
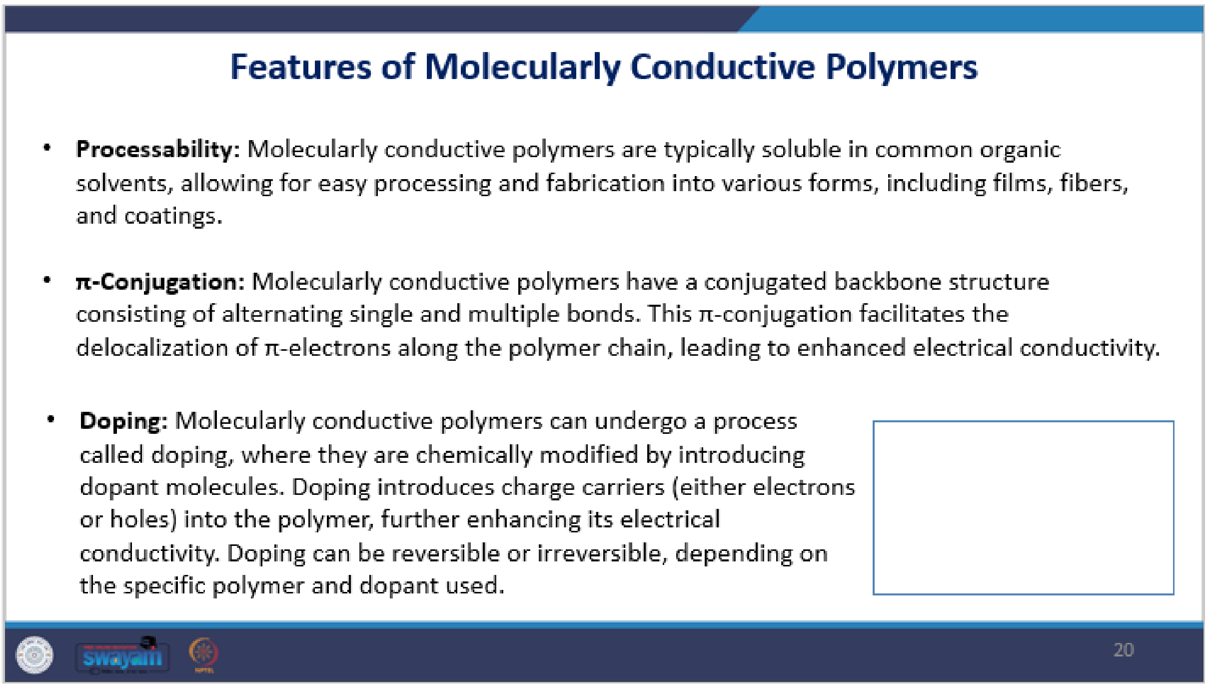
Now, if we talk continue to talk about molecularly conductive polymers, some organic materials they have been synthesized or formulated to exhibit semi-conductive or conductive properties contrary to the insulating nature. The inherently conductive polymer can be created by doping a linear conjugated polymer with an electron donor or acceptor such as polyacetylene, polypyrrole, polyphenylene sulfide, polyparaffenylene, polythiophene, and polyaniline. So, all these are represented over here in their structural form. Now, these polymers have low conductivity in their undoped state, ranging from semiconductor to insulators, and doping is achieved by exposing the thin film or powder of polymers to electron donating or electron extracting dopant.

So, the conductivity of polymer is primarily depends by the type and amount of dopant resulting in a range from semiconductor behaviour to true metallic conductivity. Let us take example of polyparafenylene doped with iodine as a semiconductor while doping with an arsenic pentafluoride converts it into the metallic range. Similarly, the conductive polymers are still in research phase and yet not yet commercially available. Now, handling and shaping of these materials can be challenging and they are insoluble in most organic and aqueous solution. So, the long-term stability is a concern as many of these polymers are susceptible to oxidation.





Now, there are various features attributed to the molecularly conducting polymers. One is the processability, the molecularly conductive polymers are typically soluble in common organic solvents allowing for easy processing and fabrication into various forms including film, fibre, coating. Then pie conjugation, the molecularly conductive polymers have been having conjugated backbone structure consisting of alternating single and multiple bonds and these pie conjugation facilities are re-localised, delocalisation of pie electrons along the polymer chain and leading to the enhanced electrical conductivity. The doping, the molecularly conductive polymers can undergo a process called doping where they are chemically modified with introducing dopant molecule. The doping introduces the charge carriers either electron or holes into the polymer further enhancing its electrical conductivity.



This doping can be reversible or irreversible depending on the specific polymer and dopant used. The variable conductivity, the electrical conductivity of a molecularly conductive polymer can vary over a wide range from insulating to semiconducting to metallic depending on the factors such as polymer structure, doping level, processing conditions. Optical and electronic properties, the molecularly conductive polymer often exhibits interesting optical and electronic properties such as fluorescence, electroluminance and photoconductivity. These properties make them useful in applications such as organic light emitting diode, OLEDs and photovoltaic devices. Environmental stability, the stability of molecularly conductive polymers this can vary depending on the chemical structure and its specific dopant use.

Features of Molecularly Conductive Polymers

- **Variable Conductivity:** The electrical conductivity of molecularly conductive polymers can vary over a wide range, from insulating to semiconducting to metallic, depending on factors such as polymer structure, doping level, and processing conditions.
- **Optical and Electronic Properties:** Molecularly conductive polymers often exhibit interesting optical and electronic properties, such as fluorescence, electroluminescence, and photoconductivity. These properties make them useful in applications such as organic light-emitting diodes (OLEDs) and photovoltaic devices.
- **Environmental Stability:** The stability of molecularly conductive polymers can vary depending on their chemical structure and the specific dopants used. Some polymers may exhibit sensitivity to moisture, oxygen, or UV radiation, which can affect their long-term performance and durability.

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Some polymers may exhibit sensitivity to moisture, oxygen or ultraviolet radiation which can affect the long-term performance and durability. The applications, the molecularly conductive polymer have found application in a wide range of fields including organic electronic sensors, energy storage devices, electrocomic displays, actuators. Examples of molecularly conductive polymers include polyaniline, polythiophene, polypyrols. Ongoing research and development offer continue to explore new and new molecularly conductive polymers and enhance their properties for various technological applications. Let us talk about the metal-filled polymers.

Molecularly Conductive Polymers: Applications and Examples

- **Applications:** Molecularly conductive polymers have found applications in a wide range of fields, including organic electronics, sensors, energy storage devices, electrochromic displays, and actuators.
- **Examples** of molecularly conductive polymers include polyaniline (PANI), polythiophene (PT), and polypyrrole (PPy). Ongoing research and development efforts continue to explore new molecularly conductive polymers and enhance their properties for various technological applications.

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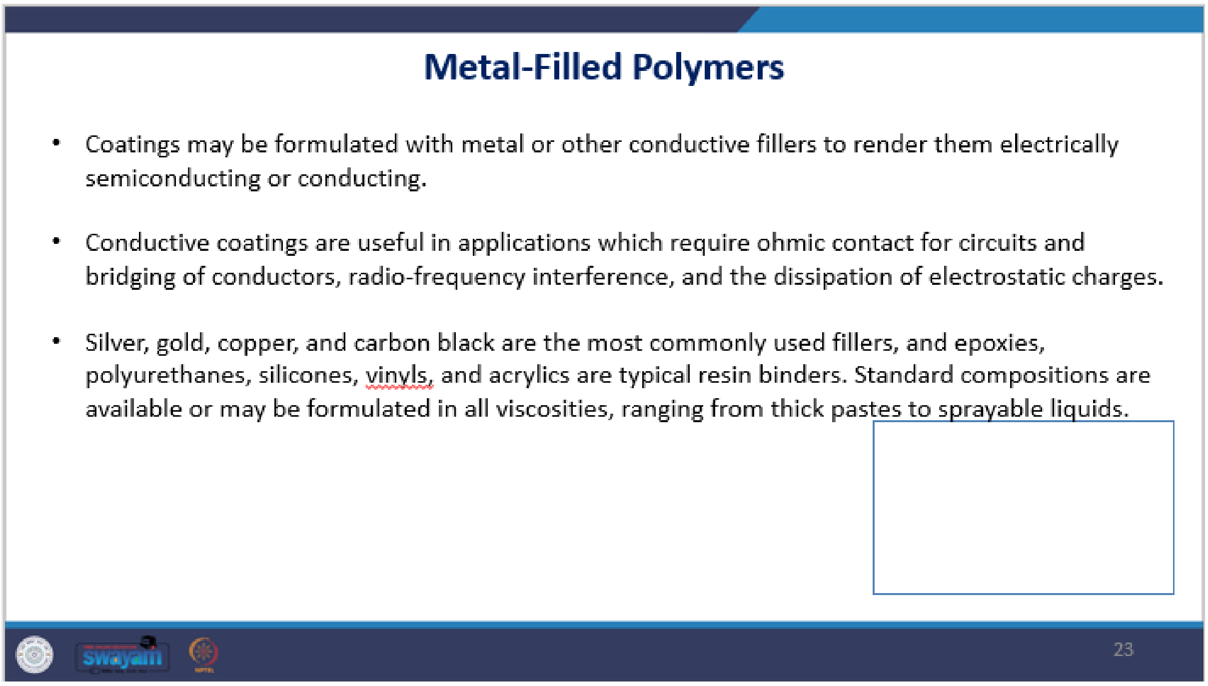
The coating may be formulated with metals or other conductive fillers to render them electrically semiconducting or conducting. Now, conductive coating is useful in applications with the required ohmic contact for circuits and bridging of conductors, radio frequency, interference, and dissipation of electrostatic charges. Silver, gold, copper, and carbon blacks are the most commonly used fillers and epoxies, as polyurethanes, silicones, vinyl, and acrylics and they are typical resin binders. Standard compositions are available or may be formulated in all viscosities ranging from thick pastures to sprayable liquids. These coatings can be formulated with conductive fillers such as silver, gold, copper, and carbon black or impart electrical conductivity or semiconducting properties.



And these are very beneficial for applications requiring ohmic contact, circuit bridging, radio frequency, interferences, shielding, and electrostatic charge dissipation. There are certain noble metals like gold, platinum require thorough cleaning to remove the high resistance surface oxide layer while metal oxides may gradually form over time and leading to decreased conductivity. The degree of cure of the resin binder also influences the conductivity baking type formulation and generally provides better conductivity than air drying varieties. For high conductance silver or gold fillers are typically used and with optimal formulation and cure conductivity values of approximately 103 milli ohms centimeter per centimeter can be achieved. Now, in this particular table we have enlisted the conductivity data of various filled epoxies like silver filled epoxy is cured, the initial value is 3000 and after say 40 days humidity cycling 1250 and after 50 hours 20 percent salt is played becomes 1400.

Metal-Filled Polymers

Composition	. . .Conductivity (mhos/cm). . .		
	Initial Value	After 40 days Humidity Cycling	After 50 hr 20% Salt Spray
Silver-filled epoxy cured 6 hr at 180°C	3,000	1,250	1,400
Silver-filled epoxy air dried 36 hr	100	700	---
Gold-filled epoxy cured 6 hr at 50°C	200-700	---	---

Conductivity Data for Filled Epoxies

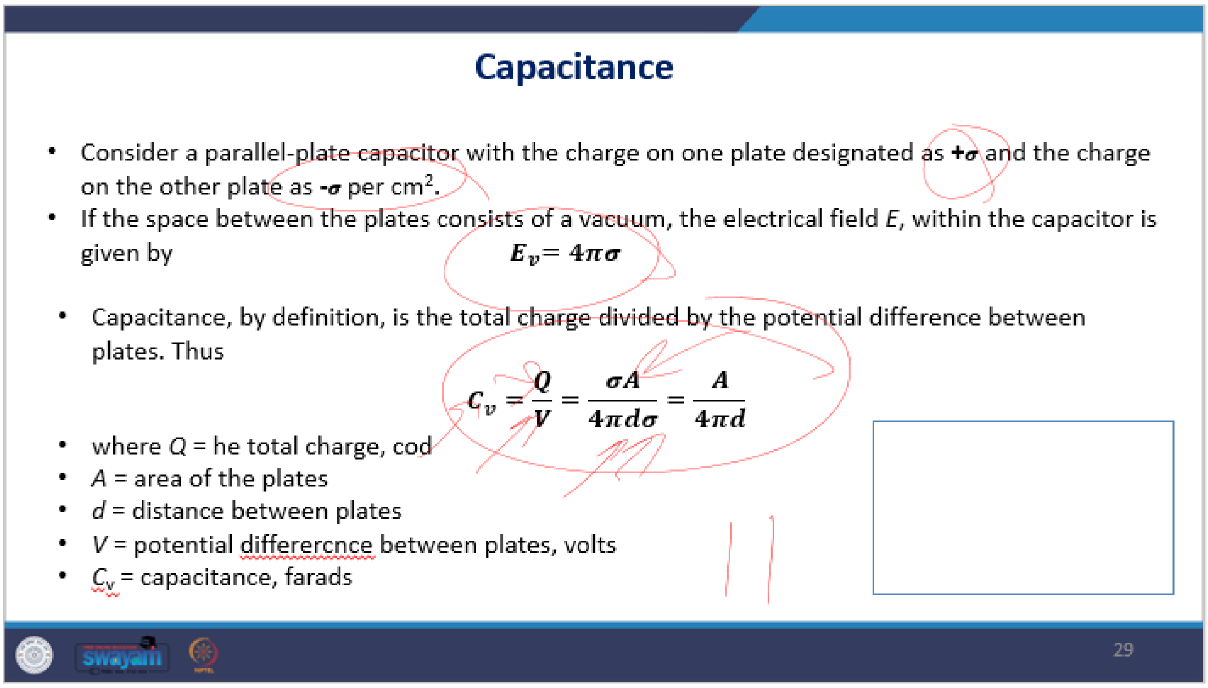
The conductivity silver-filled epoxy air dried for 36 hours and the gold-filled epoxy cured for 6 hours at 50 degrees Celsius. The various values have been given. Now, let us talk about the comparison of the conductive filler's advantages and disadvantages. Now, if we use the silver filler that is an electrical conductor, the advantage is very high conductivity, but a disadvantage is that the high-cost silver migration can occur under certain conditions and tarnishes and corrodes. Gold or electrical conductors have very high conductivity and very inert and stable which is which possesses a high cost than silver subject to the government control and audit the copper and electrical which is the electrical conductors. This is the high conductivity low cost. This requires the extra steps for cleaning and removing of oxides conductivity decreases with age.

Metal-Filled Polymers

Filler (Use)	Advantages	Disadvantages
Silver (Electrical conductor)	Very high conductivity	High cost; silver migration can occur under certain conditions; tarnishes and corrodes
Gold (Electrical conductor)	Very high conductivity; very inert and stable	Higher cost than silver; subject to government controls and audit
Copper (Electrical conductor)	High conductivity; low cost	Requires extra steps for cleaning to remove oxides; conductivity decreases with age
Aluminum (EMI shielding)	High conductivity; low cost;gocd EM1 shield	Can oxidize; shielding decreases with rising frequency

Comparison of Conductive Fillers

Aluminium this is the high conductivity low cost this can oxide and shielding decreases with rising frequency. Then steel this is a low cost but disadvantage is that the low conductivity the graphite and carbon black low cost and a very good EMI shield but though low conductivity shielding decreases with the rising frequency this must be a large volume percentage. Let us talk about the capacitance. Now, consider a parallel plate capacitor with the charge on one plate designated as plus theta to charge on the other plate with minus theta per centimetre square. If the space between the plates consists of a vacuum the electrical field E within the capacitance given by E v is equal to 4 pi theta and capacitance by the definition is the total charge divided by the potential difference between the plates.



So, C v is equal to Q over v, and that is small theta a over 4 pi d small theta and which is equal to an over 4 pi d where Q is the total charge, the a is the area of the plates d is the distance between the plates v is the potential difference between the plates and C v is the capacitance in farad. Now, this capacitance effect from the plastic substrate adhesives or coating they are crucial for the reliable functioning of high-frequency linear high-speed digital circuits. The high capacitance can cause delays in switching times and changes in the component values. The coupling capacitance between the circuit paths and integrated circuits on multi-layer boards limits the present computer operations. This reduces the computing speed between the integrated circuits and increases the power consumption.

Capacitance

- Reductions in parasitic capacitance can be achieved through proper material selection and circuit geometry design.
- Capacitance (C) is directly proportional to the dielectric constant (k) of the insulator, the area (A) of the conductors, and inversely proportional to the distance (d) between conductors.

$$C = \frac{kA}{d}$$

- Low capacitance can be achieved by minimizing the area (A), using insulators with low **dielectric constants (k)**, and increasing the distance (d) between conductors.
- The trend toward microminiaturization and the use of thin conductor lines and insulation layers of 5 mils or less requires insulating materials with very low **dielectric constants** while maintaining other necessary engineering and manufacturing properties.

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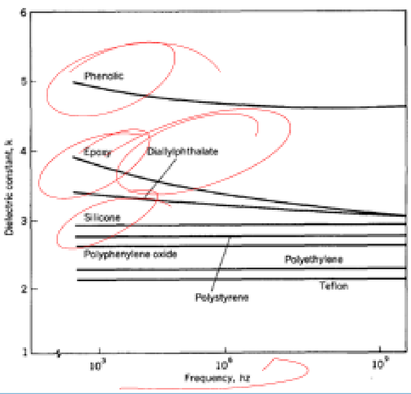
The reduction in the parasitic capacitance can be achieved through the proper material selection and circuit geometry design. Now, this capacitance C is directly proportional to the dielectric constant k of insulator and area of conductor and inversely proportional to the distance between the conductors. So, C is equal to k a over d. The low capacitance can be achieved by minimising the area using insulators with a low dielectric constants k and increasing the distance between the conductors. The trend towards the towards micro miniaturisation and use of thin conductor lines and insulation layers of 5 mils or less this requires insulating material with a very low dielectric constant while maintaining the necessary engineering and manufacturing properties.

Dielectric constant

For high-frequency linear circuits, such as those used in radar assemblies, the dielectric constant of insulators again becomes important, especially since it may vary with changes in frequency. Graphs showing the variation of the dielectric constant as a function of frequency for some commonly used polymers are given in Figure.

Variation of dielectric constant with frequency



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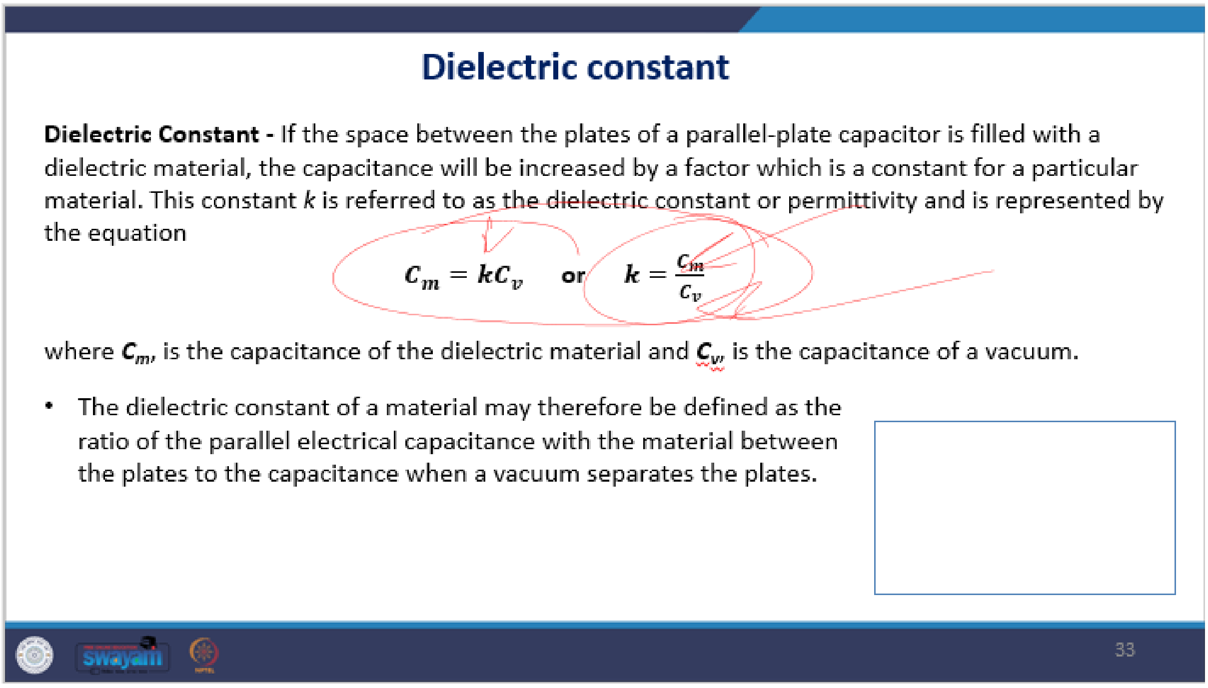
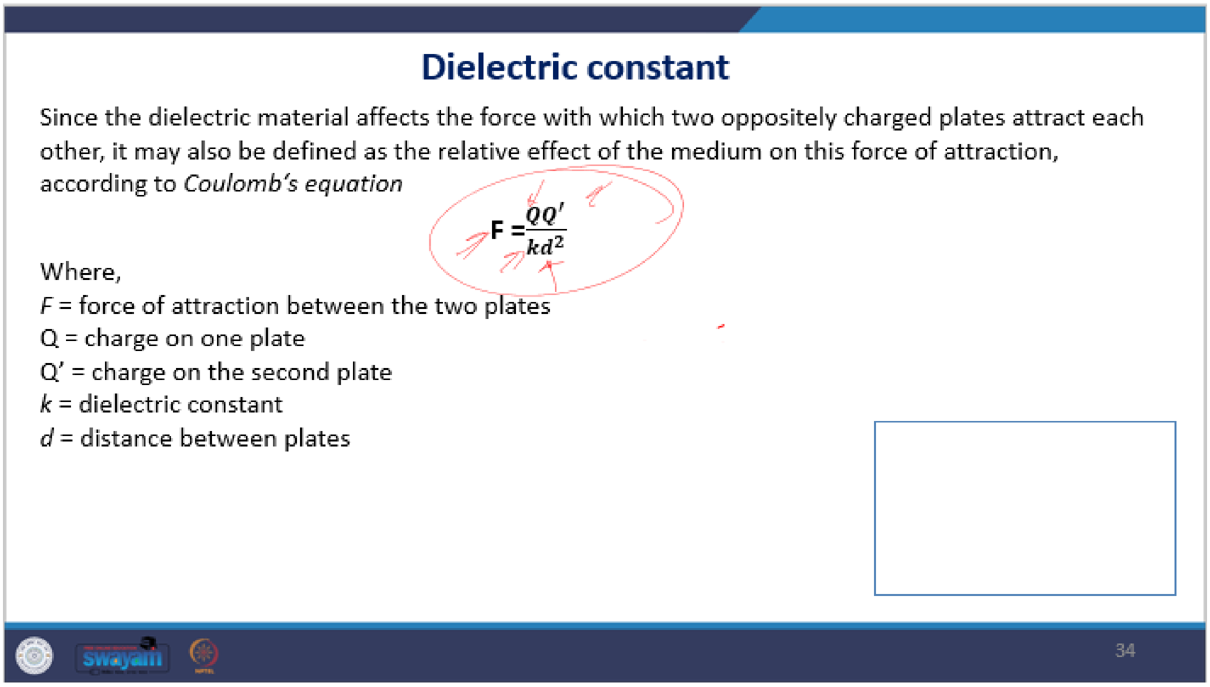
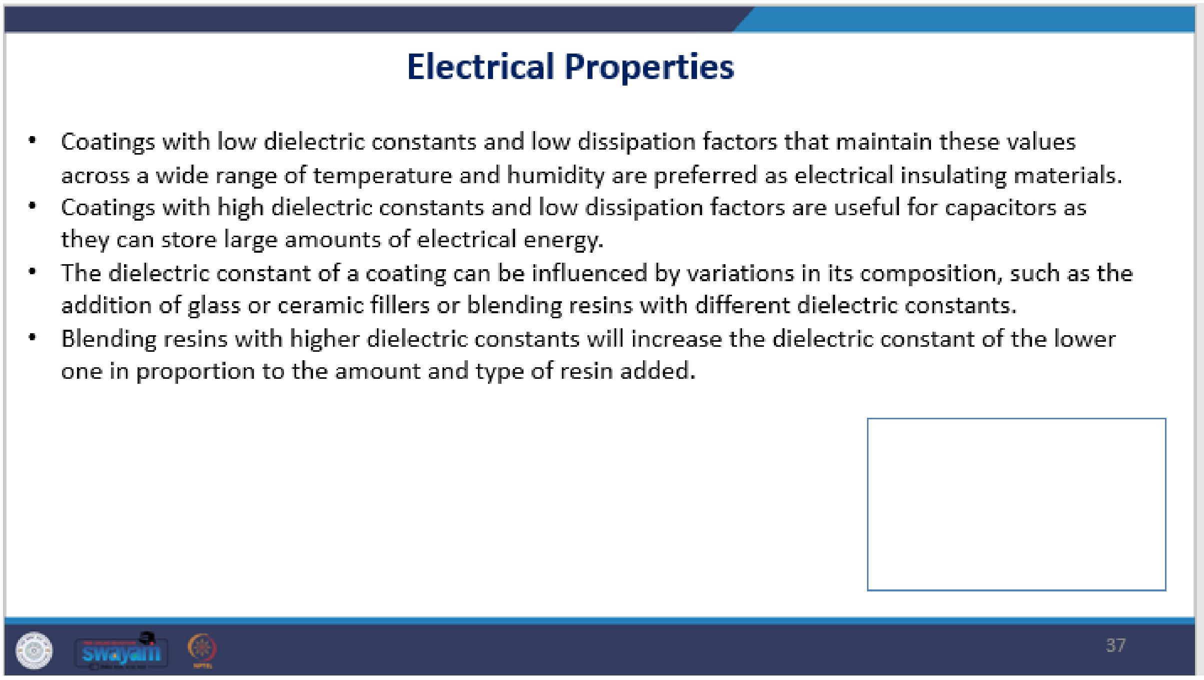
The dielectric constants for high-frequency linear circuit such as those used in the radar assemblies the dielectric constant of insulator again becomes important. Especially it may vary with the with the change in frequency. Now, this particular graph shows the variation of the dielectric constant as a function of frequency of some commonly used polymers like phenolic epoxies, silicones all these things. Now, if the spaces between the plate of the parallel plate capacitors filled with dielectric material the capacitance will be increased by a factor which is constant for a particular material and the constant k is referred as a dielectric constants or permittivity and represented by this particular equation that is Cm is equal to k Cv or k is equal to Cm over Cv where Cm is the capacitance of dielectric material and Cv is the capacitance of the vacuum. The dielectric constant of a material may therefore be defined as the ratio of the parallel electrical capacitance with the material between the plates to the capacitance with the vacuum separate the plates.



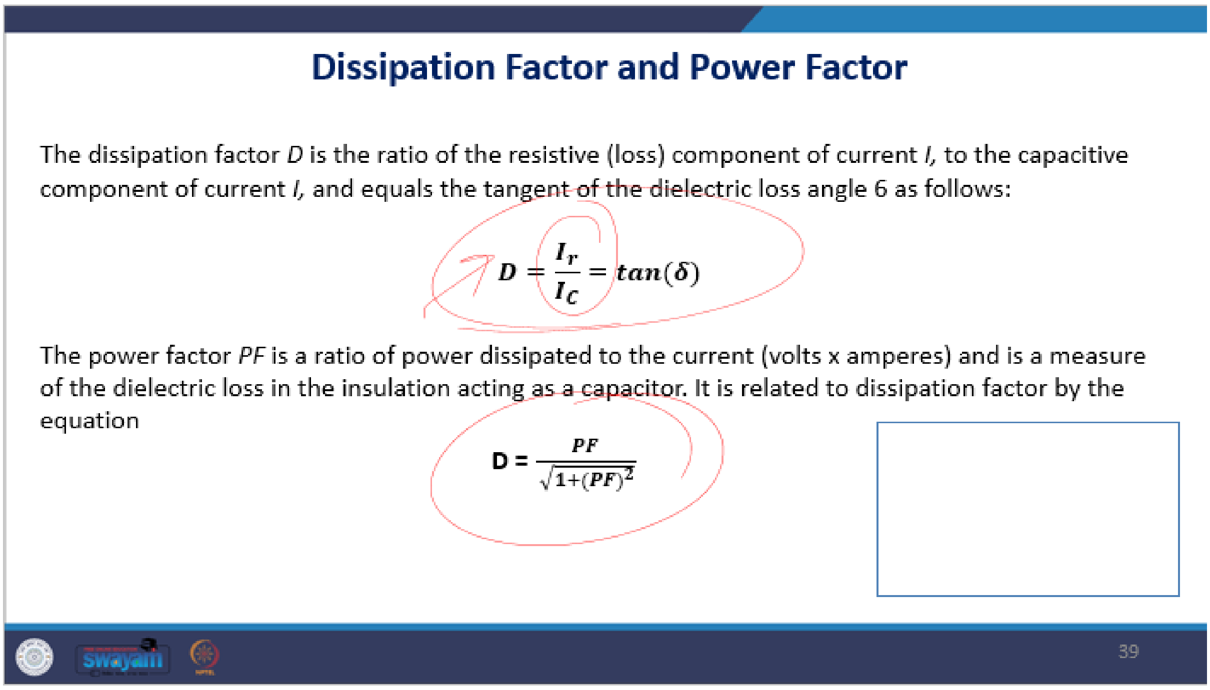
Now, since the dielectric material affects the force with which the two oppositely charged plates attract each other it may also be defined as a relative effect of the medium on the force of attraction and as per the Coulomb's equation f is equal to q q dash over k d square where f is the force of attraction between the two plates, q is the charge, q dash is the charge of the second plate, k is the dielectric constant and d is the distance between the plates. The force of attraction between the plates is attenuated by the high dielectric constant of the material between them. The dielectric constant of a vacuum is 1 and the practical purpose is the dielectric constant of Al is also considered as 1. So, various standards they provide the details of the sample preparation, measuring methods, the equipment for the amazing dielectric constant and the gases generally have dielectric constant slightly greater than 1 while organic compounds especially highly polar type this can have the value up to 100. Now, these dielectric constants they are influenced by the electronic polarizability of the material and the presence of polar group with the permanent dipole moment.



Now, polar polymers tend to absorb more water from the atmosphere, which negatively affect their electrical properties and a non-polar type such as polyethylene, polystyrene, and fluorocarbon generally have better electrical properties. So, more polar structures like polymethyl methacrylate, polyamides, and polyvinyl chloride tend to have inferior electrical properties compared to the non-polar system.



Now, sometimes if you talk about the coating with the low dielectric constant and the low dissipation factor you in maintain these values across a wide range of temperature and humidity which are preferred as electrical insulating materials. coating with a high dielectric constant and a low dissipation factor are also useful for the capacitors as they can store large amount of electrical energy and the dielectric constant of coating this can be influenced by the variation in its composition such as the addition of glass or ceramic fillers or blending resins with a different dielectric constant. Now, this is an example of a typical curve for blending of polysulfide with epoxy.



Let us talk about the dissipation factor and the power factor. Now, dissipation factor D is the ratio of the resistivity losses that is sometimes referred as a loss, resistive component of current I to the capacitive component, capacitive component of current I, and they equal to the tangent of the dielectric loss, and this can be represented as D is equal to IR over IC or tan theta. Now, the power factor is the ratio of power dissipated to the current and is a measure of dielectric loss in the insulation acting as a capacitor. It is related to the dissipation factor by this particular equation D is equal to PF over the square root of 1 plus PF square. Now, the dielectric material has low values of a dissipation factor which are essentially equivalent to the power factor, and military specifications such as MIL 116923 requires dissipation values not greater than 0.02 at 1000 hertz and 25 degree Celsius. So, the loss factor determined by the product of the power factor and dielectric constant measures the signal absorption, and it is denoted by k tan theta or kd that is loss factor is equal to the almost equal to the loss almost equal to the k tan theta or kd.

Electrical Properties

- Dielectric materials have low values for dissipation factors, which are essentially equivalent to power factors.
- Military specifications, such as MIL-1-1 6923, require dissipation values no greater than 0.020 at 1,000 Hz and 25°C.
- The loss factor, determined by the product of the power factor and dielectric constant, measures signal absorption and is denoted by k tan δ or Kd.

  Loss factor $\simeq$ watts loss $\simeq$ k tan δ $\simeq$ Kd

- In high-frequency circuitry operating between 10^7 Hz and 10^{10} Hz, a low loss factor indicates minimal conversion of electrical energy to heat energy and reduced power loss.
- The dissipation factor, along with other electrical parameters, is influenced by frequency, temperature, humidity, and sample purity.

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Now, the variation of the dielectric constant and dissipation factor with the temperature at a constant frequency, both the dielectric constant and dissipation factor for insulating coating will in general, increase with increasing temperature. Now, because coating formulations are not homogeneous and because they contain constituents that become volatile or change on heating, the electrical values may be quite erratic, and no simple linear relationship with the temperature exists.

Variation of Dielectric Constant and Dissipation Factor with Temperature

- At constant frequency, both the dielectric constant and dissipation factor for insulating coatings will, in general, increase with increasing temperature.
- Because coating formulations are not homogeneous, and because they contain constituents which become volatile or change on heating, electrical values may be quite erratic, and no simple linear relationship with temperature exists.

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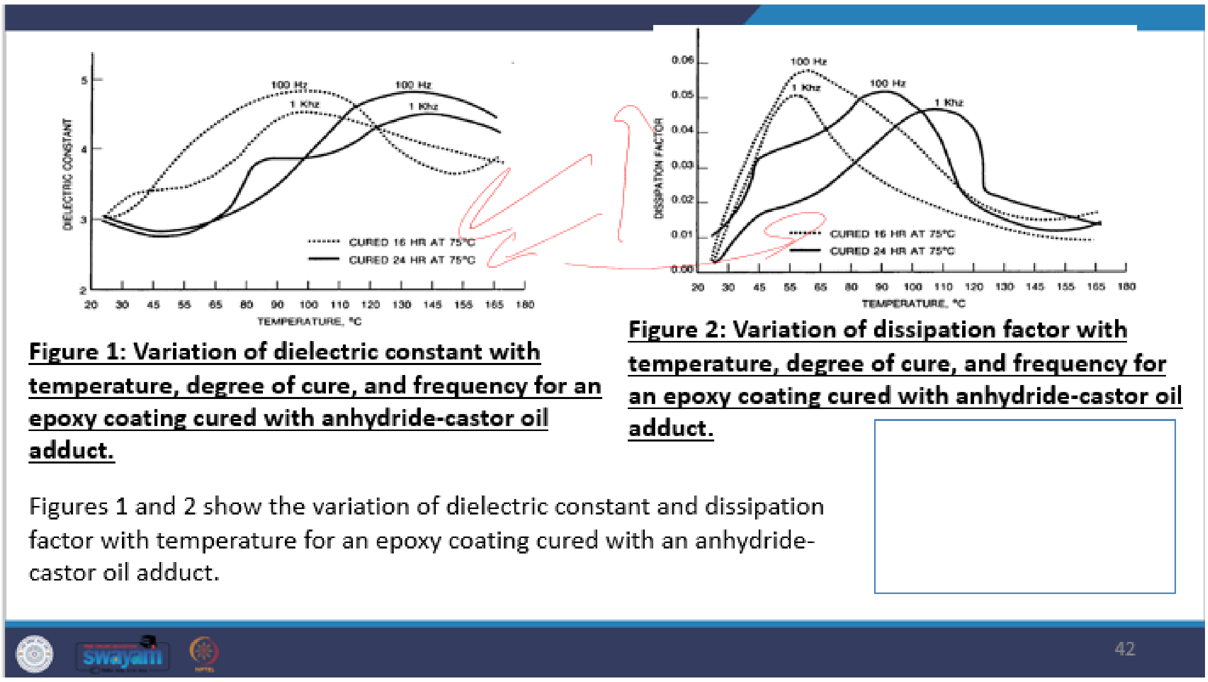
Now, here you see that the variation of dielectric constant with the temperature, degree of cure, and the frequency for an epoxy coating cured with anhydride castor oil adduct. Similarly, here you can observe, you can have a look at the variation of dissipation factor with the temperature, degree of cure, and the frequency of an epoxy coating cured with anhydride castor oil adduct.

The sample temperature this was allowed to stabilize for about 25 minutes prior to the measurement of the electrical properties at each temperature. Therefore, the part of the change attributed to the temperature may be masked by further curing of the polymer at each temperature.

Now, variation of dielectric constant and dissipation factor with the cure, the rate of the change in the dielectric constant and the dissipation factor with increasing temperature may be used as an indication of the degree of cure of the polymer. So, the electrical properties of a fully cured polymer change only slowly with the increasing temperature in comparison with the rapid change in partially cured polymers and this is apparently given in the figure 1 and 2. Now, at room temperature with the electrical properties in question, so, if we talk about the electrical properties of 2 samples which are almost identical and therefore, at this temperature one cannot differentiate between the 2 cure conditions.



Further data on the change of dielectric constant and dissipation factor with the degree of cure, they are given in this particular table. Here you see that different samples and after cure of 16 hour and 74 degree Celsius, similarly after post cure and after additional cost cure, it is been given for the various dielectric constants. Now, here you see the different dissipation factors, say after cure of 16 hours at 74 degree, all the conditions are similar and you can see the change with respect to the frequency how it goes down.

Variation of Dielectric Constant and Dissipation Factor with Cure

- The rate of change in the dielectric constant and the dissipation factor with increasing temperature may be used as an indication of the degree of cure of a polymer.
- Electrical properties of a fully cured polymer change only slowly with increasing temperature, in comparison with the rapid changes in a partially cured polymer.
- This is apparent from previous Figures 1 and 2, where an additional 8 hr of cure at 75°C resulted in a lower rate of change for both the dielectric constant and the dissipation factor.

Now, the optimum curing time and temperature obtained from a plot of the dielectric constant to our dissipation factor versus time at constant temperature or even more apparent for the epoxy system, which is shown that is the establishment of the epoxy cure schedule from dissipation factor data and this is from the dielectric constant data, you can see the difference. Now, initial values immediately after mixing of the 2 component system upon activating the 1 component coating, they are high, but they decrease as the polymerization and hardening progresses.

Effect of Cure on Electrical Properties of Epoxy Cured with Anhydride-Castor Oil Adduct

Sample	After Cure of 16 hr at 74º ± 2ºC	After Postcure of 5 hr at 74º ± 2ºC	After Additional Costcure of 16 hr at 120º ± 2ºC
Dielectric Constant			
At 100 hz			
1	4.31	3.77	3.08
2	4.30	3.73	3.04
3	4.32	--	3.07
At 1 khz			
1	3.91	3.52	3.07
2	3.87	3.49	3.02
3	3.93	--	3.07
At 10 khz			
1	3.63	3.39	3.05
2	3.57	3.35	3.00
3	3.65	--	3.04

Contd.

Ultimately, at some optimum time, these values will level off and stabilize. It can be seen that the cure of these epoxy resin is essentially completed in 3.5 hours at 120 degree Celsius, but it requires 12 hours at 66 degree Celsius to achieve the same degree of cure. Other investigators they have also shown the same type of a thing and the degree of hardening and cross linking of an epoxy system may be followed by the dielectric measurement over a frequency range of 30 to 1010 hertz. Let us talk about the dielectric strength and breakdown voltage.

Variation of Dielectric Constant and Dissipation Factor with Cure

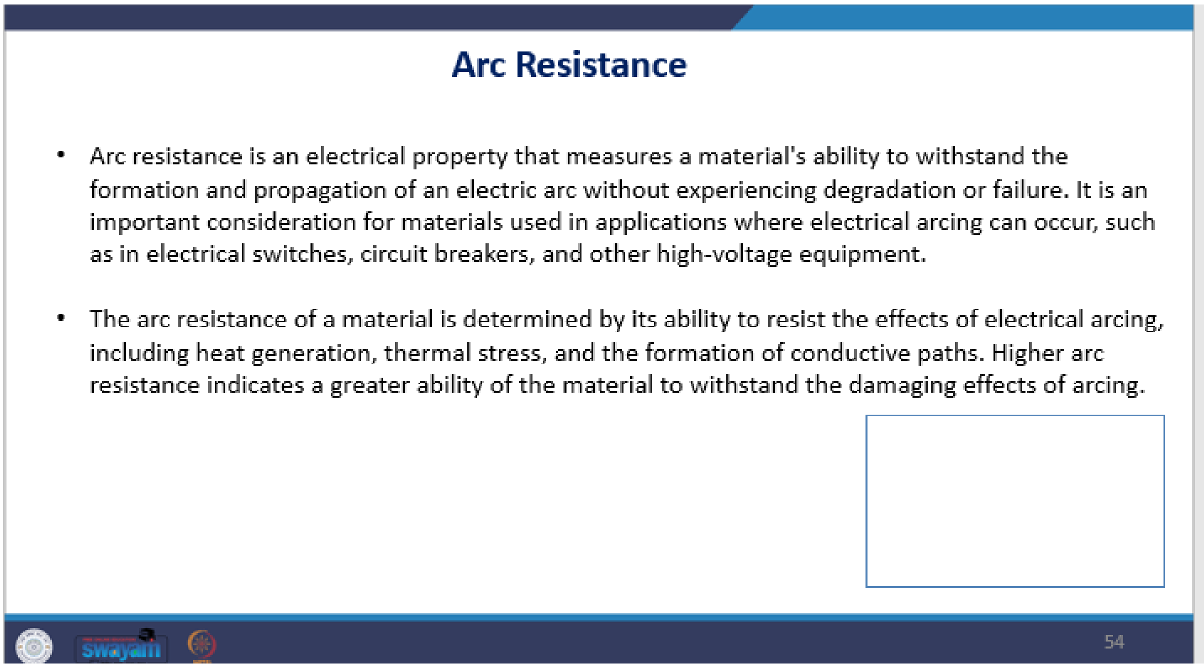
- Initial values immediately after mixing a two-component system or upon activating a onecomponent coating are high, but they decrease as polymerization and hardening progress. Ultimately, at some optimum time, these values will level off and stabilize.
- It can be seen that the cure of this epoxy resin is essentially complete in 3.5 hr at 120°C but requires 12 hr at 66"C20 to achieve the same degree of cure.
- Other investigators have also shown that the degree of hardening and crosslinking of an epoxy system may be followed by dielectric measurements over a frequency range of 30 to 1010 hz.
- A correlation of mechanical properties with electrical changes may also be performed, and once the exact correlation has been established and standard curves have been obtained, they may be used for rapid quality-control testing and inspection

These dielectric strength and breakdown voltage are important electrical properties that relate to the ability of a material to withstand electrical stress without experiencing electrical breakdown. The dielectric strength is the maximum electric field strength that a material can withstand before electrical breakdown occurs. It is a measure of insulation capabilities of material and typically expressed in a unit of volts per unit thickness. And dielectric strength indicates the maximum voltage that can be applied across the material without causing electrical breakdown and it is a very critical properties in application where electrical insulation is required.

Dielectric Strength and Breakdown Voltage

- Dielectric strength and breakdown voltage are important electrical properties that relate to the ability of a material to withstand electrical stress without experiencing electrical breakdown.
- **Dielectric Strength:** Dielectric strength is the maximum electric field strength that a material can withstand before electrical breakdown occurs. It is a measure of the insulation capability of a material and is typically expressed in units of volts per unit thickness (V/m or kV/mm). Dielectric strength indicates the maximum voltage that can be applied across the material without causing electrical breakdown and is a critical property in applications where electrical insulation is required.

Let us talk about the breakdown voltage. This referred as a breakdown field and breakdown distance is the voltage at which the electrical breakdown occur in a material. It represents the point at which the insulating properties of the material fail and electrical current starts to flow. The breakdown voltage is typically measured by gradually increasing the applied voltage until breakdown occurs. It is expressed in volts or kilovolts. The arc resistance, the arc resistance in the an electrical property that measures the material's ability to withstand the formation and propagation of an electric arc without experiencing the degradation or failure.



It is an important consideration for materials used in application where electrical arcing can occur such as the electrical switches, circuit breakers, other high voltage equipments and the arc resistance of material is determined by its ability to resist the effects of electrical arcing including the heat generation, thermal stress and the formation of conductive path. Higher arc resistance indicates the greater ability of the material to withstand the damping effect. Now these arc resistances are typically measured using the standardized test method given in ASTM or IEC. In these tests, the high voltage electrical arc is generated between the two electrodes and material being tested is placed in the path of the arc and the resistance of the material to the arc is evaluated that is based on various factors such as appearance of surface damage, tracking, carbonization and ability to maintain the electrical insulation properties. Then the material composition, the chemical composition of the structure of the material can affect the arc resistance and polymer with the high carbon content.

For example, it may exhibit the lower arc resistance due to their susceptibility to carbonization during the arcing. Then the filler additives, the inclusion of filler and additive in the material this can improve the arc resistance, filler like glass fibre, flame retardant additives, this can enhance the material's ability to dissipate heat and resist arcing. The material thickness, the thicker the material generally have higher arc resistance as they provide more insulation and distance for arc propagation. Surface condition, the surface condition of the material including smoothness and cleanliness, this can impact the arc resistance. The temperature and humidity, the environmental conditions such as temperature and humidity can influence the arc resistance of a material.

Elevated temperature and high humidity levels can decrease the arc resistance by promoting the breakdown of the insulating properties of the material.

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So, dear friends in this particular segment we discussed the various aspects related to these polymers, and for your convenience, we have enlisted several references which you can utilise as per your needs. Thank you very much.