An experimental study of cellulose as an insulating material in presence of moisture

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Abstract: The paper presents a review of the insulating properties of cellulose in the presence of moisture. Cellulose is the most abundant natural polymer present on the earth's surface and as such can be widely used for various electrical applications for providing insulation.

IndexTerms **– Cellulose, insulation, dielectric constant, dielectric loss**

I. INTRODUCTION

Cellulose is a natural polymer with an empirical formula of $(C_6H_{10}O_5)_n$. In terms of electrical properties natural polymers show properties that fall between conductors and insulators. However for a natural polymer to be conductive, a conjugated bond structure consisting of alternate single and double bond needs to be present. This conjugated structure consists of sigma bond and pi bonds and can be seen in polymers like polyaniline and polypyrrole as shown in Fig.1

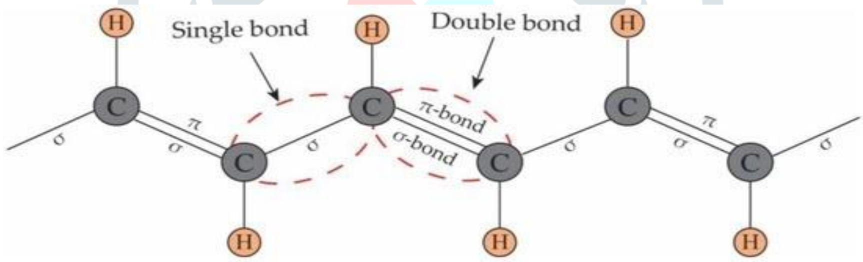

Fig. 1, conjugated bond structure

The unique characteristic of conducting polymers is the conjugated molecular structure of the polymer main chain where the pi electrons delocalize over the whole polymer chain. The electrons in pi bonds of these materials undergo overlapping of p_z orbitals and can move from one part of the polymer matrix to the other, thus resulting in conduction. However the conductivity of these naturally occurring polymers is quite low and needs to be enhanced by the process of doping. Thus conjugated polymers become conducting polymers after doping [1]. Cellulose lacks this conjugated bond structure and as such in its purest form acts as an excellent insulator for use in various electrical applications as is seen in Fig. 2.

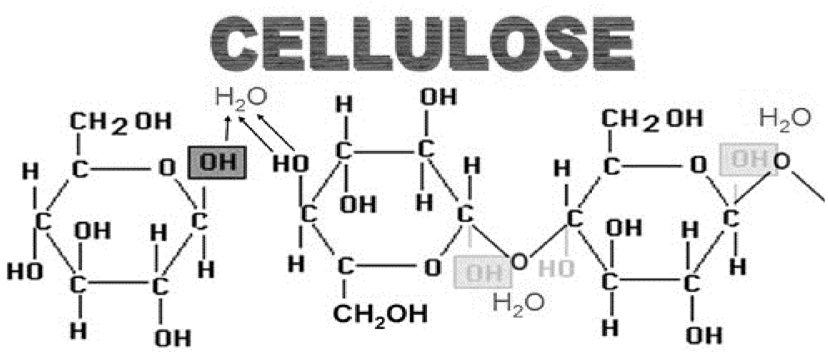

Fig. 2 , cellulose structure

II. INSULATING PROPERTIES OF CELLULOSE

In order to demonstrate the insulating properties of cellulose a simple experiment was performed showing how cellulose can affect the conductivity of a solution using a conductivity meter. A conductivity meter is an apparatus that is used to measure the electrical conductivity of a solution, i.e. it measures the aqueous solution's ability to transmit an electrical current. A solution's ability to conduct is determined by the ions in the solution and the temperature.

Conductivity measurements were taken for a 20 ml, 1:1 solution comprising of ethanol and water. Same procedure was repeated after mixing 0.02 grams of cellulose to it so as to make a solution of strength 0.01%. Following observations were made as is shown in Table 1.

Table 1, conductivity measurements at different temperatures

Solution	25ºC	35ºC	45ºC
Ethanol and water	12.83µ S	17.28 µS	23.3 µS
Cellulose, ethanol and water	1.61µ S	1.83 µS	3.48 µS

It is seen that the conductivity of the solution decreased drastically from its earlier value. The measurements were taken at different increasing temperatures and it was seen that with an increase in temperature the conductivity increased in both cases. This is because of the fact that on increasing the conductivity the kinetic energy of the molecules increases and it becomes more conductive. The behavior is plotted in Fig.3

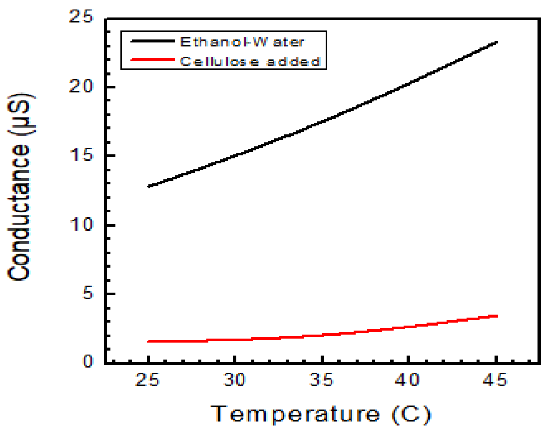

Figure 3, variation of conductivity with temperature

From the above experiment it can be said that cellulose imparts high insulation even in the presence of moisture. The reason behind such a behavior is that the current carrying H+ ions in the solution (ethanol and water) get attached or adsorbed by the cellulose and now a fewer number is present in the solution. In other words we can also say that the viscosity of the solution has increased and as such it becomes less conducting.

This property of cellulose makes it a suitable candidate for use in insulating oils which are used in transformers. Any moisture (source of H+) which can degrade the insulating performance of the oil gets adsorbed by the cellulose and thus can't affect the insulating properties to a greater extent [2].

III. INSULATION IN PRESENCE OF MOISTURE

The insulating properties of cellulose in presence of moisture were studied by many researchers and it has been shown that the insulation degrades with the amount of moisture present. The water molecules get attached to the hydroxyl ions of the cellulose molecules and some of them are retained in the bulk of the matrix. These water molecules are not restricted to only one site but can undergo detachment and attachment to neighboring OH groups, thus resulting in site to site transport. [3]

Resistance and dielectric constant are main parameters to be taken into account for studying the insulation in presence of water. For dc analysis resistance is taken into consideration, while for ac analysis the dielectric variations are considered.

The variation of resistance has been studied by many researchers and it is known to degrade with increased water content. Lieste[4] stated that the insulation degradation due to moisture is more in contaminated cellulose samples as compared to the pure ones and that the surface conductance of clean, untouched pressed amber at 50% relative humidity was one fifth of that touched by hand. The presence of naturally occurring salts like magnesium also act as contaminants and increase the water retention capacity in cellulosic fibers. Field [5], who found that within one minute of exposure to moisture the conductance increased to a value of 10% of initial value in presence of 100% relative humidity. This was followed by a gradual increment till an equilibrium stage was reached where no further water could be retained by cellulose. The variation of surface conductivity with moisture levels was given by [6] and is shown in Eq. 1

$$\frac{\log \sigma}{\sigma o} = ßm, \qquad (1)$$

where ß is the propagation constant, m is moisture content, σ is the conductivity at a given moisture level and σ_0 is the initial conductivity.

The volume resistance also decreases with increased water content and was given separately by [7] and [8] and as in Eq.2 and Eq.3 respectively

$$R = -0.085H + a \qquad (2)$$

$$R = \frac{K}{M^n} \qquad (3)$$

where R is the volume resistance, H is the humidity level, a is a constant, K and M are material constants.

The insulation of cellulose in presence of ac signal is studied in terms of dielectric constant and dielectric loss. Thus dielectric constant of a material is defined as the ratio of the capacitance of a parallel plate capacitor with material in between to the capacitance in vacuum. However this dielectric constant is a complex quantity and is given as Eq.4

$$\varepsilon_r = \varepsilon' - \varepsilon'' \qquad (4)$$

Where ε'' is called the dielectric loss factor and ε' is the usual dielectric value. For insulating mediums like cellulose and silicon dioxide the value of this constant is relatively low and is approximately 6 and 3 respectively. On the other hand conducting medium has a higher value of the constant example silicon with a dielectric constant of approximately 11. This can be contributed to the fact that as the material starts losing its insulation, it suffers from more dielectric loss ε'' , which increases the overall value of ε_r

The dielectric constant increases rapidly with the increase in moisture level. The rapid increase can be attributed to the fact that water molecules being polar in nature undergo dielectric polarization i.e., they tend to align with the applied electric field. With the application of alternating electric field, these water molecules start oscillating thus resulting in the production of heat. As a result the dielectric loss factor ε'' increases. More the moisture content more the number of molecules that undergo polarization and hence more the loss factor [9].

Hearle [10] showed that the resistance of a material is related to its dielectric constant as shown in Eq. 5

$$log\ R = \frac{a}{\varepsilon} + b \qquad (5)$$

where a and b are material constants.

Coulomb's law can also be used as an alternate explanation to the decrease in insulation. The coulomb’s force is given as in Eq. 6

$$F = \frac{q_1 q_2}{4\pi\varepsilon r^2} \qquad (6)$$

An increase in the dielectric constant increases the force of attraction between the nucleus and the negatively charged electrons decreases. As a result chances of ionization increase, which increase the conduction as is shown in figure

IV. Conclusion

From the above study it is quite clear that cellulose is an excellent insulating medium and imparts good insulation even in solution phase. Thus it makes a suitable candidate to be used in various electrical applications

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