



Dielectric Properties of the Laminating Resin

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Degree Thesis
Material Processing Technology
2018

DEGREE THESIS	
Arcada	
Degree Programme:	Material Processing Technology
Identification number:	17891
Author:	Krishna Ojha
Title:	Dielectric Properties of the Laminating Resin
Supervisor (Arcada):	Rene Hermann
Commissioned by:	
<p>Abstract:</p> <p>Resin has been used in industries because of different essence. The main objective of the thesis was to develop a module to study the dielectric constant change during wetting and curing and to study if the wetting of the composite results in an apparent change in capacitance due to a partial or complete displacement of all cavities air by cavity resin. Three different sensors, big finger capacitor with photolithography, sprial and finger sensor were developed in order to perform the research. The designing of the sensor was done with Eagle and Audacity was used to collect the data. Lamination were done with all sensors and results were analysed. For big finger capacitor, lamination was done on the top of it and lamina was first constructed and then the spiral and finger sensors were placed on top. The results analysed illustrates that at lower frequencies the resin molecules oscillates more as compared to the higher frequencies and oscillation stops as the resin gets cured. The demolding time of the lamina can be calculated measuring the relative capacitance at two different frequencies. It also illustrates that if relative permittivity increases as the wetting progress and decreases as the curing progresses.</p>	
Keywords:	Dielectric, Resin, Capacitor & Capacitance, Lamina, Photolithography.
Number of pages:	55
Language:	English
Date of acceptance:	

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FOREWORD

I would like to specially thank my thesis advisor Mr. Rene Hermann for all the guidance, help and time he has invested throughout this research. Furthermore, I would like to thank all the professors and staffs specially to Ms. Marriann Holmberg for her valuable feedbacks while writing the thesis.

Finally, I would like to thank my family and friends who were supportive throughout my studies and encouraged me.

Helsinki, May 2018

Krishna Ojha

1 INTRODUCTION

Resins are widely used in industries for variety of uses as they possess good mechanical and adhesive properties, but they aren't able to fulfill the needed properties of advanced materials. The use of resin as laminating material has been growing widely.

Resin simply is natural or synthetic organic compound that is viscous or non-crystalline in nature. Resin can be basically divided into two groups; thermoset and thermoplastic. Thermoset resins are solids with low melting point that are easy to work with and get cured when heat is applied. Often catalyst is added for the curing of this resin. Thermoset cannot be converted into the original form once cured. [1] Thermoset resins have excellent resistance to solvent and corrosives, fatigue strength, elastic and adhesion properties. The common resins used in manufacturing industries are vinyl ester, polyesters, epoxies, and phenolic. [2]

Thermoplastic resins get soft when heat is applied and can be molded into different shapes when heated to semiliquid state. Thermoplastic resins can be converted into the original form once cured when heated and can be reshaped unlike thermoset resins which allows the recycling of the material. [1] Thermoplastic resins have high impact resistance ability. The common thermoplastic resin used in manufacturing industries are Polypropylene, Polycarbonate, Polyethylene, Nylon, and many more. [2]

Resin not only enhances the mechanical properties but also makes changes in the dielectric of the materials. Dielectric can simply be termed as the permittivity of the material, which refers to the ability of the material to polarize to the applied electric field. [3]

If a force of electrical origin is exerted on a charged body placed at a point, an electric field is said to be existed. The movement in electromagnetic field is perpendicular to the magnetic field. [4] If a force of magnetic origin is exerted on moving charge at a point, a magnetic field is said to be existed. The movement in the electromagnetic field is perpendicular to the electric field. [5]

The capacitance of the air capacitor reflects the dielectricity of air. When the air is replaced by some other liquid i.e. resin this our case, the change in capacitance can be read. This change in capacitance detects the presence of the other material and its dielectricity.

The propose of the thesis is

- To study if the wetting of a composite results in an apparent change in capacitance due to a partial or complete displacement of all cavities air by cavity resin.
- To demonstrate change in dielectric constant of resin due to wetting and curing.

The aim of the study is also to develop a module for monitoring the dielectric properties changes during the curing of the thermosets, which provide curing supervision.

The study is concerned only with the dielectric properties of vinyl ester.

2 METHOD

We study the electromechanical structure of capacitors and their series and parallel connections for measuring the relative di-electricity of the medium in the electric field.

2.1 Capacitors and Capacitance

The electrical device constructed of two conducting plates which are separated by insulating material that are specially designed for storing charges are called capacitors. Though the physical dimension of the capacitors varies but basic configuration is two conductors carrying equal but opposite charges. [6] The Figure 1 shows the basic configuration of a capacitor.

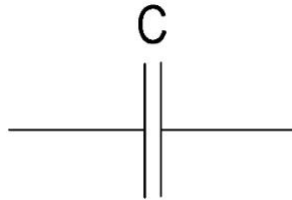


Figure 1. Basic Configuration of capacitor

Varied materials hold different magnitude of charge although they are of same potentials. This charge holding capacity or property of the material is known as capacitance.

When charge is given to a capacitor the potential difference across its plates rises. If a charge Q is given to a capacitor so that its potential difference rises through ΔV , then it's experimentally found that charge Q stored in it is directly proportional to the potential difference ΔV across the plates of the capacitor. So,

$$\begin{aligned} Q &\propto |\Delta V| \\ Q &= C|\Delta V| \\ C &= \frac{Q}{|\Delta V|} \end{aligned} \tag{1}$$

Where C is the proportionality constant, known as capacitance of capacitor.

Therefore, the ratio of the charge on either plate of the capacitor to the potential difference across the plates is called capacitance of capacitor.

Capacitance is measured in coulomb per volt(CV^{-1}), which is known as *farad* (F).

2.2 Dielectric Constant

When an insulating material is placed in between the capacitor plates, the materials causes dielectric. The materials can be paper, plastic, water, glass and so on. Dielectrics are directly proportional to the capacitance, i.e. capacitance increases as the space is filled with the dielectrics. [7]

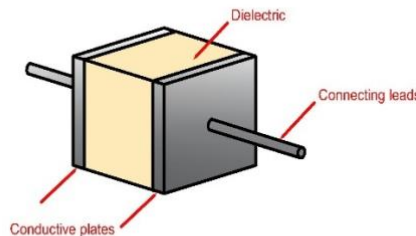


Figure 2. Basic configuration showing the capacitor with dielectric

Let us consider a capacitor has a capacitance of C_o without any dielectrics. If a dielectric material is placed in between the capacitor, the capacitance is

$$\begin{aligned} C &\propto C_o \\ C &= K_e C_o \end{aligned} \quad (2)$$

where, K_e is dielectric constant. It is known experimentally, that the dielectric constant $K_e < 1$. The dielectric constant is unit less. Dielectric constant is also known as relative permittivity. The following table shows some values for dielectric constant and dielectric strength of materials. [7]

Table 1. Dielectric Constant and Dielectric Strength of some materials [7]

Material	Dielectric Constant (K_e)	Dielectric Strength (10^6 V/m)
Air	1,00059	3
Paper	3,7	16
Glass	4-6	9
Water	80	-

2.3 Gauss's Law

Gauss law states that the total electric flux passing through a closed surface enclosing a charge is equal to $\frac{1}{\epsilon_0}$ times the magnitude of net charge enclosed by the closed surface.

If the surface encloses a charge inside it, the electric flux passing through it is

$$\phi = \oiint \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0} \quad (3)$$

where ϵ_0 is the permittivity of vacuum. The closed surface enclosing the charge may be of any shape and such surfaces are called Gaussian Surface. [7]

2.4 Series and Parallel Connection of Capacitor

The capacitors can be connected to the battery, by two separate ways, parallel and series combination ways, which I have discussed below.

2.4.1 Parallel Connection

Let us consider two capacitors C_1 and C_2 with charges Q_1 and Q_2 respectively are connected to each other in parallel as shown in Figure 3.

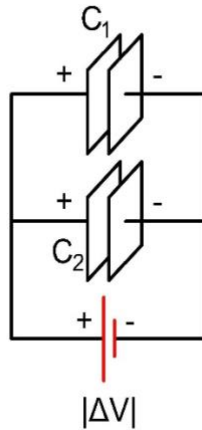


Figure 3. Parallel connection of two capacitors

Left plate of each capacitors is connected to the positive terminal of the battery whereas right plate is connected to the negative terminal making the potential difference same across each capacitor. We have,

$$C_1 = \frac{Q_1}{|\Delta V|} \quad \text{and} \quad C_2 = \frac{Q_2}{|\Delta V|} \quad (4)$$

Let us consider C_T be a single capacitor connected to the battery with a charge of Q with which we are trying to replace two capacitors C_1 and C_2 as shown in Figure 4.

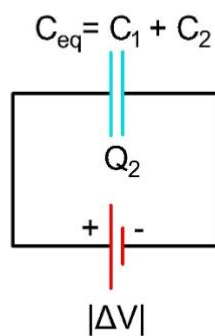


Figure 4. Parallel capacitor with total capacitance

The total charge Q is for both capacitors so,

$$Q = Q_1 + Q_2 = C_1|\Delta V| + C_2|\Delta V| = (C_1+C_2)|\Delta V| \quad (5)$$

Therefore, the total capacitance is given by

$$C_{eq} = C_T = C_1+C_2 = \frac{Q}{|\Delta V|} \quad (6)$$

Lastly, if we have N number of capacitors connected parallel, then the total capacitance is given by

$$C_{eq} = C_T = C_1+C_2 + \dots + C_N = \sum_{i=1}^N C_i \quad (7)$$

This shows that, the equivalent capacitance increases when capacitors are connected in parallel where equivalent capacitance is the sum of all individual capacitance and is always greater than any individual capacitance. [7]

2.4.2 Series Connection

Let us consider two capacitors C_1 and C_2 are connected in series where a potential difference $|\Delta V|$ is applied across the capacitors equally as in Figure 5.

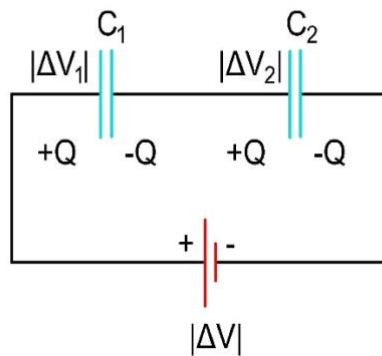


Figure 5. Series Connection of Capacitors

Left plate of the capacitor C_1 is connected to positive terminal whereas right plate of the capacitor C_2 is connected to the negative terminal of the battery. The inner plates of the both capacitors acquire equal and opposite charge to their respective plates.

Therefore, the potential difference across the capacitors are

$$|\Delta V_1| = \frac{Q_1}{C_1} \quad \text{and} \quad |\Delta V_2| = \frac{Q_2}{C_2} \quad (8)$$

where,

$$|\Delta V| = |\Delta V_1| + |\Delta V_2| \quad (9)$$

We know that, the sum of total potential difference across the individual capacitors equals to the sum of total potential difference of numbers of capacitors in series connections. Let C_T be the single capacitor with which we try to replace capacitors C_1 and C_2 .

This means that, $C_T = Q/|\Delta V|$.

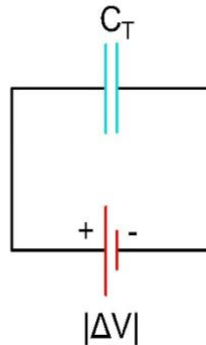


Figure 6. Capacitor with Total Capacitance

Therefore, from equation (9)

$$\frac{Q}{C_T} = \frac{Q}{C_1} + \frac{Q}{C_2}$$

which gives us,

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \quad (10)$$

Lastly, if we have N number of capacitors connected in series, then the total capacitance is given by

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_N} = \sum_{i=1}^N \frac{1}{C_i} \quad (11)$$

If two capacitors are in series combination then,

$$\begin{aligned} \frac{1}{C_T} &= \frac{1}{C_1} + \frac{1}{C_2} \\ \frac{1}{C_T} &= \frac{C_1 + C_2}{C_1 C_2} \\ C_T &= \frac{C_1 C_2}{C_1 + C_2} \end{aligned} \quad (12)$$

This shows that, when capacitors are connected in series the equivalent capacitance decreases. Therefore, in series combination, the reciprocal of the equivalent capacitance is equal to the sum of reciprocals of the individual capacitances. In a series combination the equivalent capacitance is always less than any individual capacitance. [7]

2.5 Parallel Plate Capacitor

Let us consider two metallic plates of equal area A separated by distance d , where top plate carrying the $+Q$ and down plate carrying $-Q$ as shown in the Figure 7.

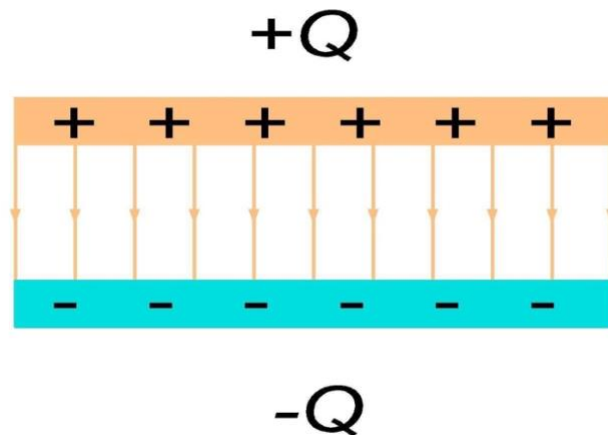


Figure 7. Electric Field between the parallel plate capacitors

The electric field lines at the edge of the plates are not straight lines, and the field is not entirely in between the plates, which is known as edge effect and the non-uniform fields near the edge are known as fringing effects. However, ignoring these effects and idealising that the field lines between the plates are straight lines. [7]

Calculating the electric field between the plates using Gauss's Law,

$$\oiint \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0} \quad (13)$$

Since, the path of integration is straight line from positive to negative plate, electric field lines are always directed from higher potential to lower and capacitance is the magnitude of potential difference. [7] The magnitude of potential difference between the plates is

$$\Delta V = V_- - V_+ = - \int_+^- \vec{E} \cdot d\vec{s} = Ed \quad (14)$$

We know that capacitance,

$$C = \frac{Q}{\Delta V} = \frac{\epsilon_0 A}{d} \quad (15)$$

2.6 Cylindrical Capacitor

Let us consider a solid cylindrical conductor radius a , with charge $+Q$ and is surrounded by a coaxial cylindrical shell with inner radius b , with charge $-Q$ as shown in the Figure 8. Let us consider the L to be the length of both cylinders which is much larger than $b-a$ (*separation of cylinders*) so that the edge effects can be neglected.

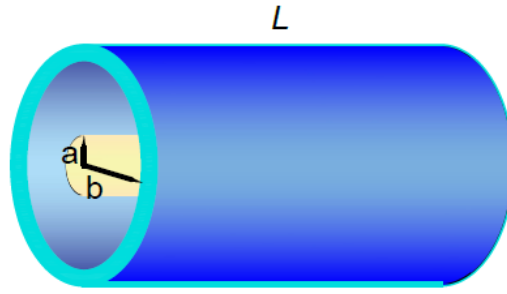


Figure 8. Two Cylindrical Capacitors of Length L and radii a and b

Here, as the symmetry is cylindrical, using Gaussian Surface to be a coaxial cylinder with length $l < L$ and radius r where $a < r < b$.

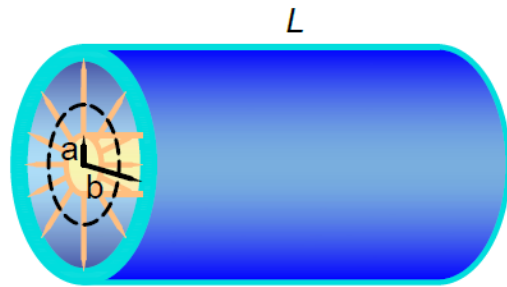


Figure 9. Gaussian Surface for electric field of two cylindrical symmetry capacitors of length L

By Gauss's law, we know

$$\oiint \vec{E} \cdot d\vec{A} = EA = E(2\pi rl) = \frac{\lambda l}{\epsilon_0} \quad (16)$$

$$E = \frac{\lambda}{2\pi \epsilon_0 r} \quad (17)$$

where, $\lambda = Q/L$, which is the charge per unit length.

Since, the path of integration is along the direction of electric field lines from positive i.e. inner conductor to negative i.e. outer conductor plate. The potential difference between the plates is

$$\Delta V = V_b - V_a = - \int_a^b \vec{E}_r \cdot d\vec{r} = - \frac{\lambda}{2\pi \epsilon_0} \int_a^b \frac{dr}{r} = - \frac{\lambda}{2\pi \epsilon_0} \ln\left(\frac{b}{a}\right) \quad (18)$$

We know that capacitance,

$$C = \frac{Q}{|\Delta V|} = \frac{\lambda L}{\frac{\lambda}{2\pi \epsilon_0} \ln\left(\frac{b}{a}\right)} = \frac{2\pi \epsilon_0 L}{\ln\left(\frac{b}{a}\right)} \quad (19)$$

This means that, capacitance C depends only upon the geometrical factors. [7]

2.7 Spherical Capacitor

Let us consider two concentric spherical capacitor shells. The inner shell has a radius of a with a charge of $+Q$ and outer shell has a radius of b with a charge of $-Q$ as shown in Figure 10.

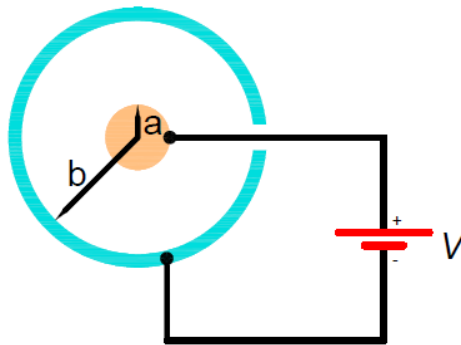


Figure 10. Two concentric spherical capacitors of radii a and b

Using Gauss's law, in the region $a < r < b$ where the electric field is non-vanishing.

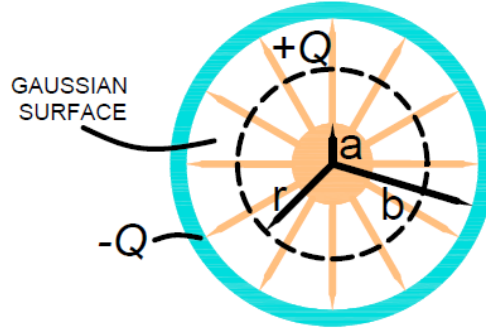


Figure 11. Gaussian Surface for electric field of two concentric spherical capacitors

We have,

$$\oiint \vec{E} \cdot d\vec{A} = E_r A = E_r (4\pi r^2) = \frac{Q}{\epsilon_0} \quad (20)$$

$$E_r = \frac{Q}{(4\pi r^2) \epsilon_0} \quad (21)$$

The potential difference between the two shells is given by

$$\begin{aligned} \Delta V = V_b - V_a &= - \int_a^b E_r \cdot dr = - \frac{Q}{4\pi \epsilon_0} \int_a^b \frac{dr}{r^2} = - \frac{Q}{4\pi \epsilon_0} \left(\frac{1}{a} - \frac{1}{b} \right) \\ &= - \frac{Q}{4\pi \epsilon_0} \left(\frac{b-a}{ab} \right) \end{aligned} \quad (22)$$

Therefore, the capacitance of the capacitor is

$$C = \frac{Q}{|\Delta V|} = 4\pi \epsilon_0 \left(\frac{ab}{b-a} \right) \quad (23)$$

This states that the capacitance C only depends upon the geometric factors.

If the second conductor is placed at infinity meaning that $b \rightarrow \infty$, the capacitance of the isolated conductor becomes,

$$\lim_{b \rightarrow \infty} C = \lim_{b \rightarrow \infty} 4\pi \epsilon_0 \left(\frac{ab}{b-a} \right) = \lim_{b \rightarrow \infty} 4\pi \epsilon_0 \left(\frac{a}{1 - \frac{a}{b}} \right) = 4\pi \epsilon_0 a \quad (24)$$

If the radius of the spherical conductor is R , the capacitance becomes

$$C = 4\pi \epsilon_0 R \quad (25)$$

This clearly states that the capacitance only depends upon geometrical factor. [7]

2.8 In-Plane Capacitor

Let us consider two concentric semi-spherical shells. The inner shell has the radii of a with charge of $+Q$ and the outer has the radii of b with charge $-Q$ as shown in the Figure 12.

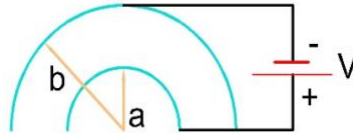


Figure 12. Two concentric semi-spherical shells of radii a and b

Using Gauss's law, in the region $a < r < b$ where the electric field is non-vanishing.

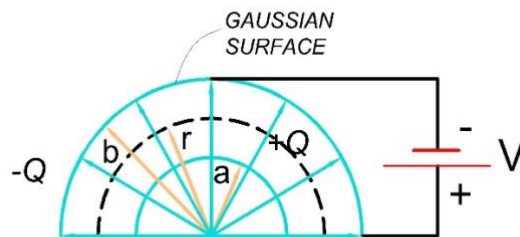


Figure 13. Gaussian Surface for electric field of two semi-circular concentric bodies

We have,

$$\oiint \vec{E} \cdot d\vec{A} = E_r A = E_r (2\pi r^2) = \frac{Q}{\epsilon_0} \quad (26)$$

$$E_r = \frac{Q}{(2\pi r^2) \epsilon_0} \quad (27)$$

The potential difference between the two shells is given by

$$\begin{aligned} \Delta V = V_b - V_a &= - \int_a^b E_r \cdot dr = - \frac{Q}{2\pi \epsilon_0} \int_a^b \frac{dr}{r^2} = - \frac{Q}{2\pi \epsilon_0} \left(\frac{1}{a} - \frac{1}{b} \right) \quad (28) \\ &= - \frac{Q}{2\pi \epsilon_0} \left(\frac{b-a}{ab} \right) \end{aligned}$$

Therefore, the capacitance of the capacitor is

$$C = \frac{Q}{|\Delta V|} = 2\pi \epsilon_0 \left(\frac{ab}{b-a} \right) \quad (29)$$

This states that the capacitance C only depends upon the geometric factors.

If the second conductor is placed at infinity meaning that $b \rightarrow \infty$, the capacitance of the isolated conductor becomes,

$$\lim_{b \rightarrow \infty} C = \lim_{b \rightarrow \infty} 2\pi \epsilon_0 \left(\frac{ab}{b-a} \right) = \lim_{b \rightarrow \infty} 2\pi \epsilon_0 \left(\frac{a}{1 - \frac{a}{b}} \right) = 4\pi \epsilon_0 a \quad (30)$$

If the radius of the spherical conductor is R , the capacitance becomes

$$C = 2\pi \epsilon_0 R \quad (31)$$

This clearly states that the capacitance only depends upon geometrical factors. [7]

2.9 Photolithography

Photolithography is process of transferring a pattern by exposing a radiation to photosensitive material. Photo resistive materials are photo sensitive and are temporarily

coated on wafer surface. This process is used for mainly for the IC patterning process and Printed Circuit Board(PCB). [8]

When a radiation is exposed to the photosensitive material to transfer a pattern, it creates two regions (exposed and unexposed). When developing the board if the exposed material is washed away, then it is called as positive resist and if the unexposed material is washed away, then it is called negative photoresist. [8] The Figure 14 shows the basic demonstration of the development of the positive and negative photoresist.

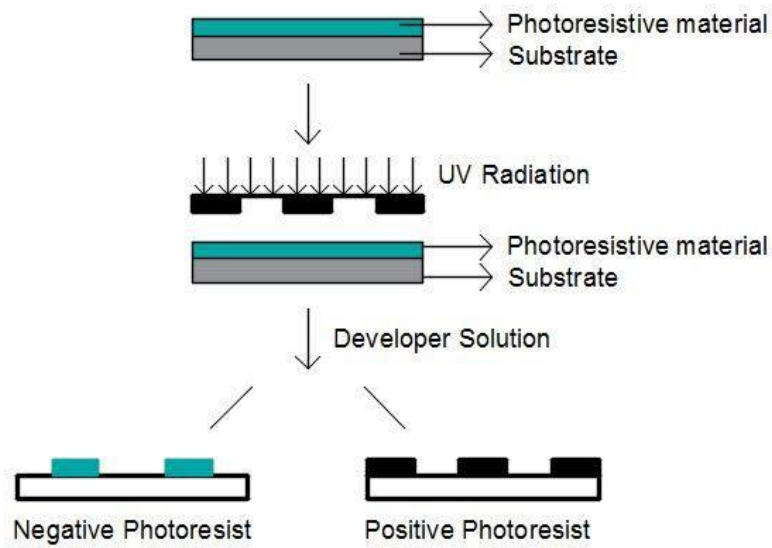


Figure 14. Basic Demonstration of negative and positive photoresist

2.10 Permeability of Textile and Resins Relative Dielectricity

2.10.1 Background

We measure capacitance as function of time as the wetting of the textile starts from 0 to 100% of a constant thickness with a total area. The Figure 15 shows the sketch demonstration of the wetting of the textile.

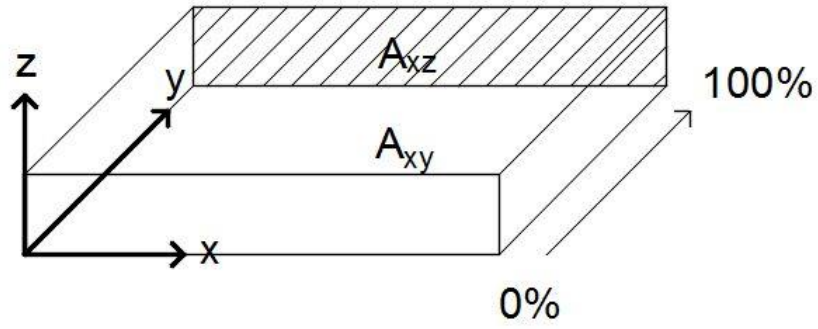


Figure 15. Sketch demonstration of wetting of the textile.

where,

A_{xy} = total area that is wetted (seen from top),

A_{xz} = area corresponding to the cross section that is wetted,

z = thickness of the lamina and

x = width of the lamina.

y = length direction of wetting, 0% is the infusion point 100% is outlet.

The rule of mixtures gives for separate phase compounds:

$$\rho_T = \rho_1 f_1 + \rho_2 f_2 \quad (32)$$

for the density such that void free materials have $f_2 = 1 - f_1$

Same is valid for dielectric mixtures, therefore the equation become,

$$\epsilon_{r(tot)} = f \epsilon_1 + (1 - f) \epsilon_2 \quad (33)$$

In this case, rule of mixture can be used expressed in terms of dielectric mixtures.

2.10.2 Experiment

The data is $C(t) = C_0 + kt$. This means that there is an initial capacitance that increases linearly (approximately for short distances). There are 2 phases during the experiment, the infusion phase and the curing phase.

Infusion Phase

Initially, we have.

$$C_{initial} = C_{textile} + C_{air} \quad (34)$$

We measure the thickness and the density of the lamina at the end to determine the fiber volume fraction f . At the end of the infusion, we fill the volume of the air with resin and the capacitance now becomes,

$$C_{Final} = C_{textile} + C_{resin} \quad (35)$$

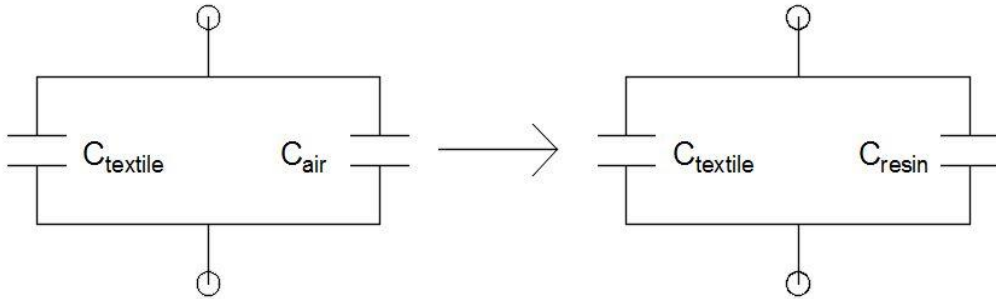


Figure 16. Capacitance change from initial stage to final when air is replaced by resin.

The difference between the initial and final capacitances is

$$\Delta C = C_{resin} - C_{air}. \quad (36)$$

The flow rate is volume per time unit occupied. That is

$$\frac{dV}{dt} = z \frac{dA_{xy}}{dt} \approx z \frac{\Delta A_{xy}}{\Delta t} \quad (37)$$

where,

ΔA is area infused as seen from top.

Δt is time to wet the infused area.

The Equation (34) can be rewritten as follows as well.

$$\frac{dV}{dt} = l \frac{dA_{xz}}{dt} \quad (38)$$

We get that the flow rate in the cross section of the textile (permeability) is

$$\frac{dV}{dt} = z \frac{dA_{xy}}{dt} = l \frac{dA_{xz}}{dt} \quad (39)$$

For a short wetting distance, permeability of the textile can be measured by following equation.

$$\frac{dA_{xz}}{dt} = \frac{z}{l} \frac{dA_{xy}}{dt} \quad (40)$$

where,

z = the thickness of the lamina,

l = the length of the lamina,

dA_{xy} = total area seen from top, and

dt = infusion time.

Its unit is $\frac{m^2}{s}$. The value measured is probably dependent on textile thickness and weave type. If the flow speed in linear direction is needed, divide your result by thickness z or l (dependent which variable you wish to eliminate) and you get unit m/s .

Curing Phase

We wish to find the relative dielectricity and how does it change during curing. Assuming we know that,

fiber volume fraction (f) = 0,5 and

the capacitance at beginning is $C_0 = C_{textile} + C_{air} = 450nF$ (assumed measured).

Because of the fiber volume fraction, we expect both capacitors to be not only of the area but also of the thickness. Whatever the geometry function for just this capacitor, we can say from Equation (33),

$$C_0 \propto f \cdot \epsilon_{fiber} + (1 - f)\epsilon_{air} = [f \cdot \epsilon_{fiber} + (1 - f)\epsilon_{air}]C_{geometry}$$

where, $\epsilon_{air} = 1$, $\epsilon_{glass\ fiber} = 4.3$ and $C_{geometry} =$ capacitance of the capacitor's geometry.

Assuming this numbers, we can say that total capacitance of $450nF$ is made of 2 portions (textile and air). Now, putting values to the equation, we get

$$\epsilon_{total} = f\epsilon_{fiber} + (1 - f)\epsilon_{air}$$

$$\epsilon_{total} = 0.5 * 4.3 + 0.5 * 1$$

$$\epsilon_{total} = 2.65$$

The relative part of air capacitor is than

$$C_{air} = C_0 \frac{(1 - f)\epsilon_{air}}{\epsilon_{total}} = 450 \frac{0.5}{2.65}$$

and for the textile capacitor it is

$$C_{textile} = C_0 \frac{f\epsilon_{fiber}}{\epsilon_{total}} = 450 \frac{2.15}{2.65}$$

We have now two capacitors at the beginning of the infusion. By the time the infusion is done $C_{air} \rightarrow C_{resin}$.

As of above C_{air} is known, and the change in capacitance (ΔC) is also known. We calculated $C_{resin} = C_{air} + \Delta C$. The resin didn't just add but actually replaced the air capacitor. Finally, we get the relative dielectric constant of the resin by

$$\frac{\Delta C + C_{air}}{C_{air}} = \frac{C_{resin}}{C_{air}} = \frac{\epsilon_{resin}}{\epsilon_{air}} \quad (41)$$

$$\epsilon_{resin} = \left[\frac{\Delta C + C_{air}}{C_{air}} \right] \epsilon_{air}$$

$$\epsilon_{resin} = \left[1 + \frac{\Delta C}{C_{air}} \right] \epsilon_{air} \quad (42)$$

where, $\epsilon_{air} = 1$.

This may or may not change as function of time and temperature.

3 EXPERIMENTAL

3.1 Big Finger Capacitor Design

For the development of the Finger Capacitor, we ordered an $20cm \times 15cm$ substrate with photosensitive material in the top. The following procedure were applied for the development of the capacitor.

3.1.1 Alignment and Exposure

Firstly, a capacitor design was made and printed on the plastic paper as a mask, off which the pattern is supposed to be transferred. The Figure 17 shows the pattern designed for the capacitor.

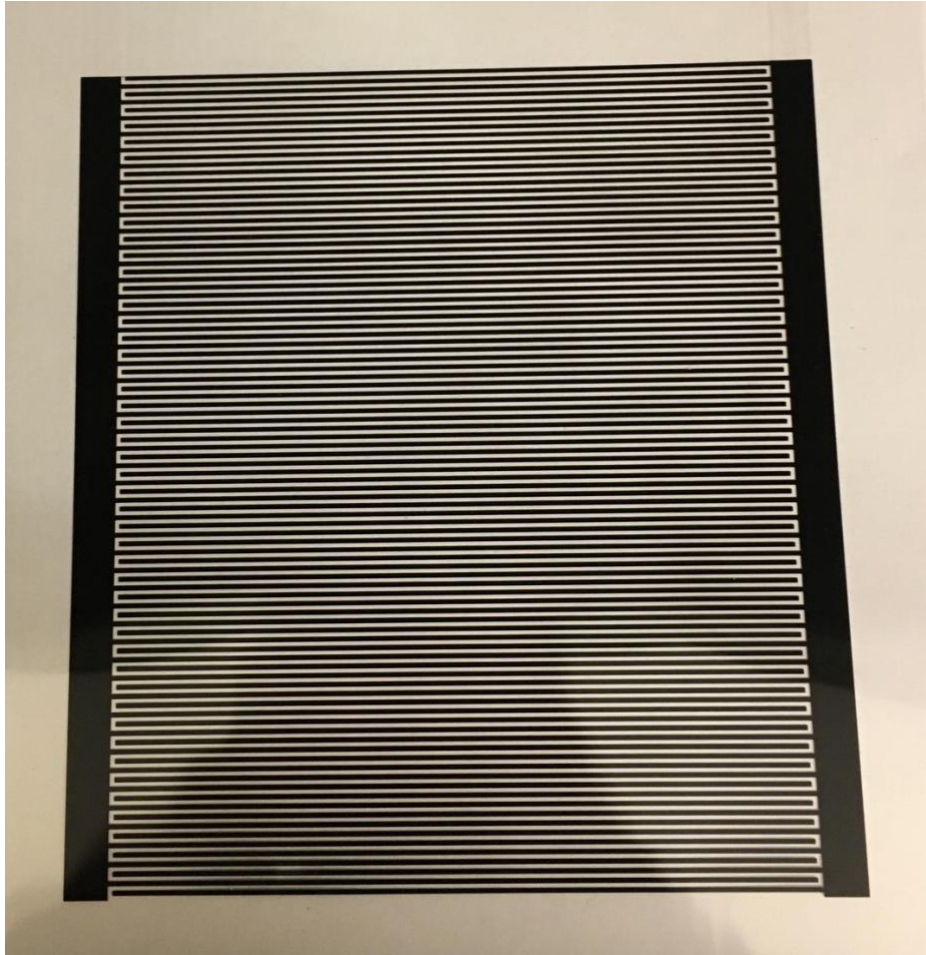


Figure 17. Pattern Designed for the Capacitor

Using the Photolithography instrument, we transferred the pattern shown above in Figure 17, into a substrate with photosensitive material exposing the UV rays on it. The Figure 18 shows the process of the transferring the pattern.



Figure 18. Photolithography Instrument transferring the pattern using UV rays

3.1.2 Development

After the pattern were transferred, the substrate was then treated with the developer solution bath of NaOH (20g/L). The substrate was moved forth and back repeatedly on the developer solution to remove the unexposed material. The Figure 19 shows the substrate being treated with the developer solution.



Figure 19. Substrate in the Developer Solution

When the color gets washed away with the developer solution, the substrate was rinsed and then put into the salt bath for electroplating. It helped to remove the unnecessary copper and the cross links. The Figure 20 shows where the substrate was dip into the heated salt solution to get the final product.



Figure 20. Substrate in a salt solution

After 30 min, the substrate was taken out of the salt solution and the substrate was rinsed with the cold water for a while and left to dry. The capacitor was developed after all these processes.

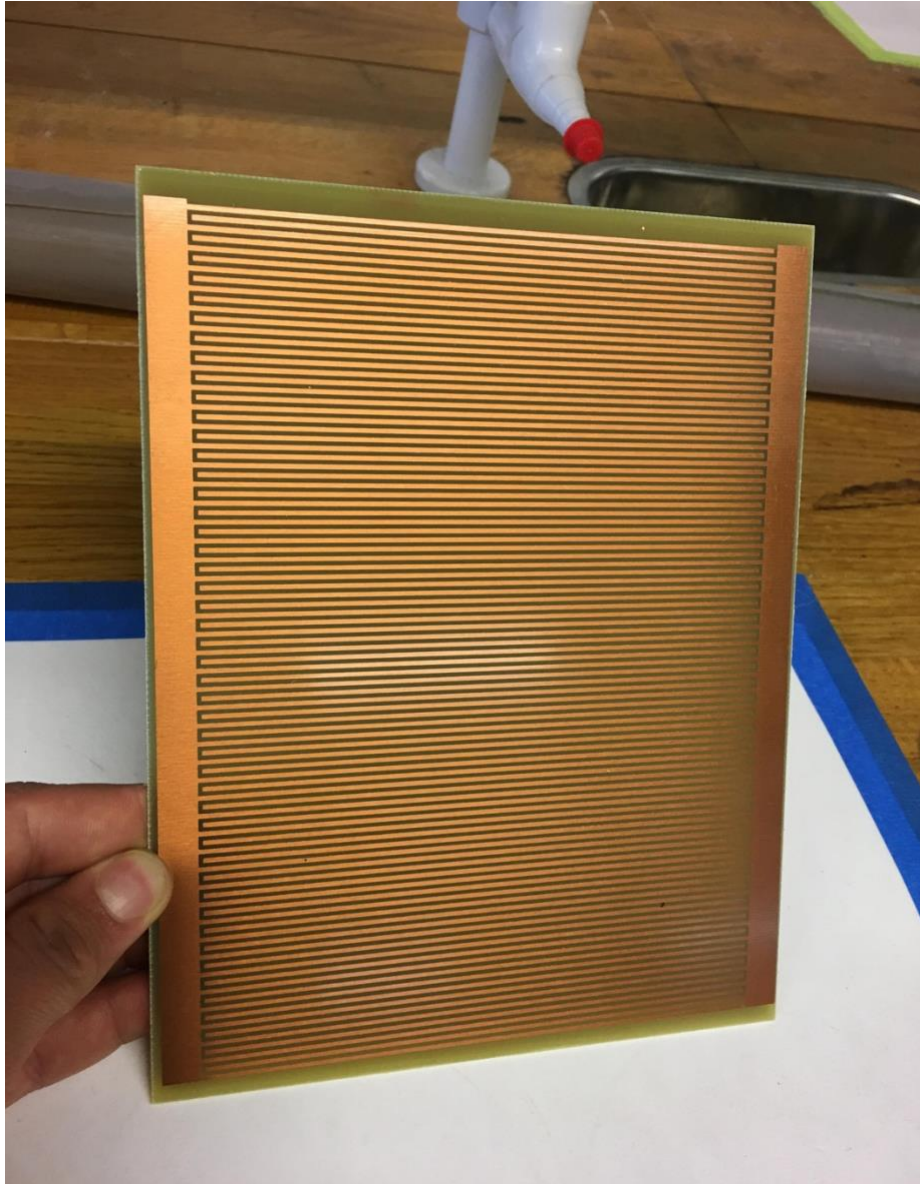


Figure 21. Developed Capacitor with Photolithography

The Figure 21 was the final product (capacitor) developed with the photolithography. This was negative photoresist as the developer solution removed the unexposed material.

3.1.3 Laminating with Big Finger Capacitor

After the development of the Finger capacitor with the photolithography, we made a lamina with glass fiber on the top of the Finger Capacitor to measure the capacitance of the capacitor with a LCR meter at different frequencies.

Firstly, glass fiber of 10cm*15cm were cut and placed on the top of the capacitor. The flow mate was used in order to make the constant resin flow. The lamination was made vacuum tight. The Figure 22 shows the construction of the lamination process.

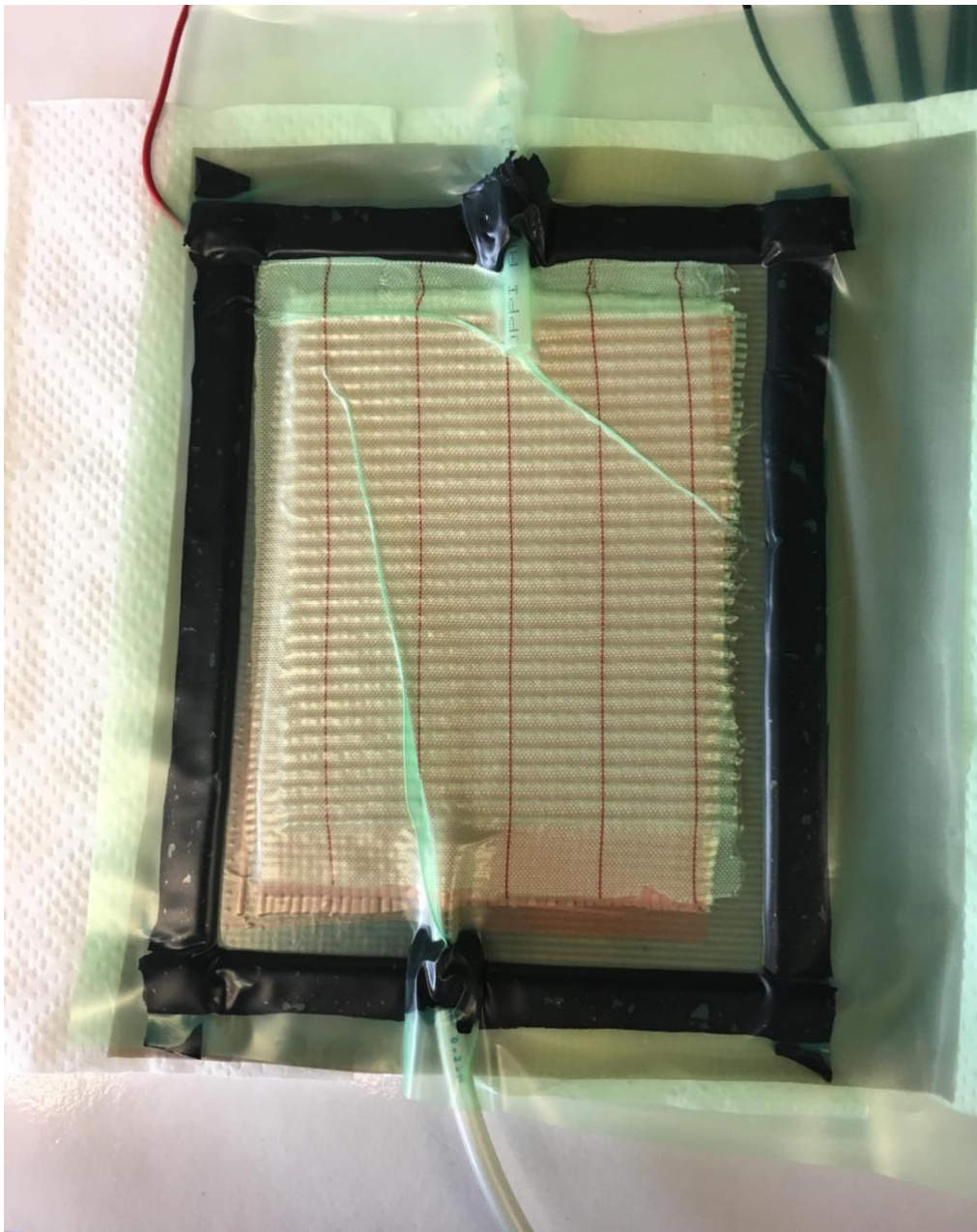


Figure 22. Lamination process construction on Finger Capacitor

After the lamination was all set, resin (vinyl ester) mixed with hardener peroxide was placed in the lamina. The resin flow was after a while when the lamina gets all wet. The Figure 23 shows the lamina after the resin was placed in it and was getting cured.

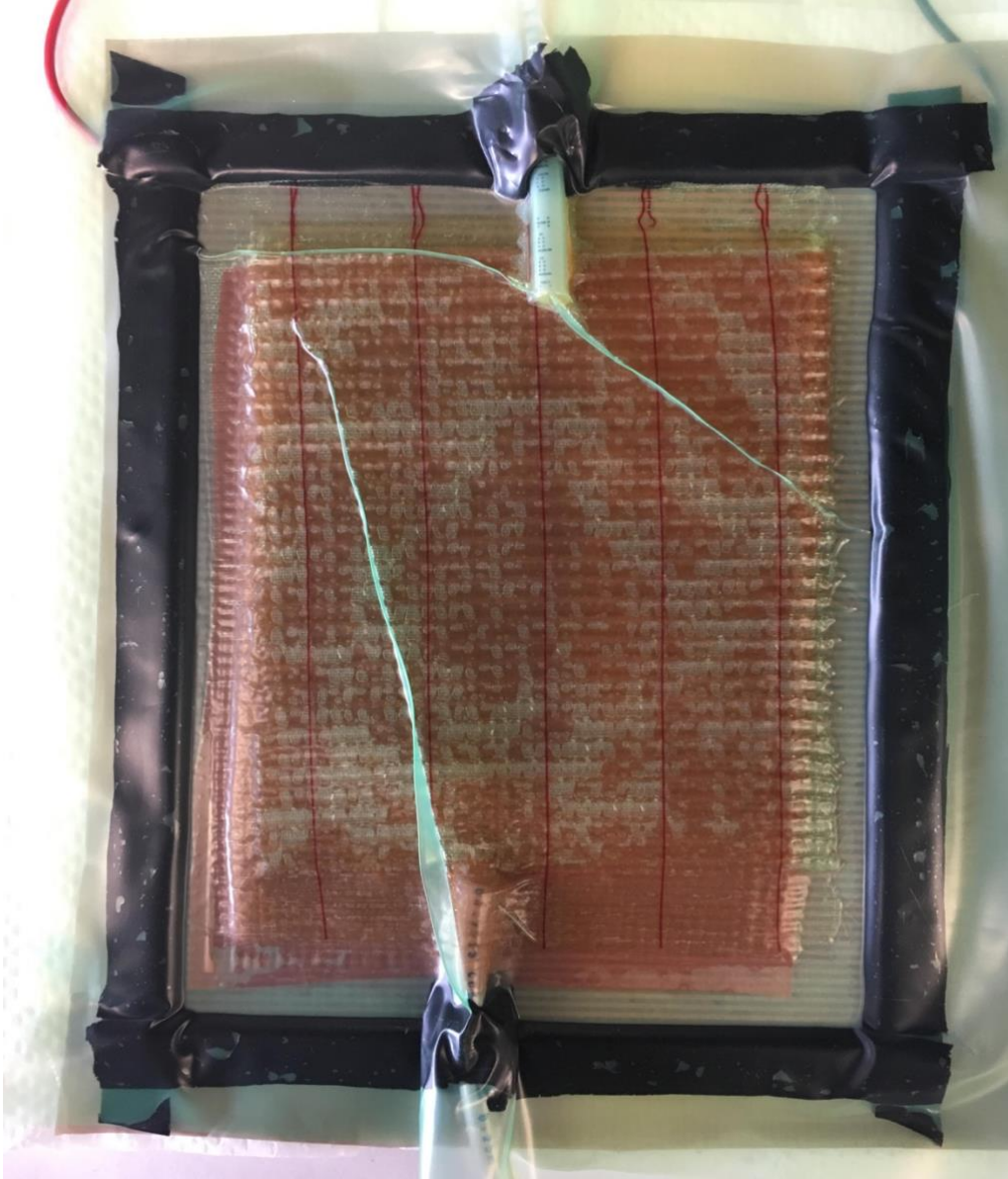


Figure 23. Resin getting cured in lamina

With the LCR meter, measurement was taken from the dry vacuum tight stage to the wet and cured stages at different frequency. The data acquired from the measurement at different time and frequencies are placed in the Table 2.

Table 2. Measurement data acquired by LCR meter

Time (t) in min	Capacitance @ 120Hz [nF]	Capacitance @ 1kHz [nF]	Capacitance @ 10kHz [nF]	Capacitance @ 100kHz [nF]
0	0.495	0.466	0.447	0.434
2	0.620	0.565	0.492	0.473
4	0.625	0.567	0.493	0.475
5	0.681	0.563	0.493	0.478
10	0.677	0.564	0.492	0.478
15	0.633	0.561	0.491	0.477
20	0.625	0.556	0.491	0.476
25	0.619	0.556	0.491	0.474
30	0.623	0.550	0.490	0.474
35	0.619	0.547	0.489	0.472
40	0.605	0.543	0.488	0.474
45	0.604	0.536	0.487	0.472
50	0.596	0.532	0.487	0.474
55	0.580	0.524	0.487	0.472
60	0.575	0.518	0.488	0.478
65	0.580	0.513	0.488	0.476
70	0.577	0.510	0.487	0.474
75	0.568	0.508	0.487	0.475
80	0.557	0.504	0.487	0.474
85	0.545	0.502	0.486	0.473
90	0.533	0.501	0.486	0.473
95	0.524	0.501	0.485	0.472
100	0.522	0.500	0.484	0.471

3.2 Sensor Design

3.2.1 Spiral and Finger Capacitor Design

We designed the following sensor in EAGLE program with the dimension of $96.19\text{mm} \times 25.38\text{mm}$ in which both the capacitors, Spiral and Finger are drawn.

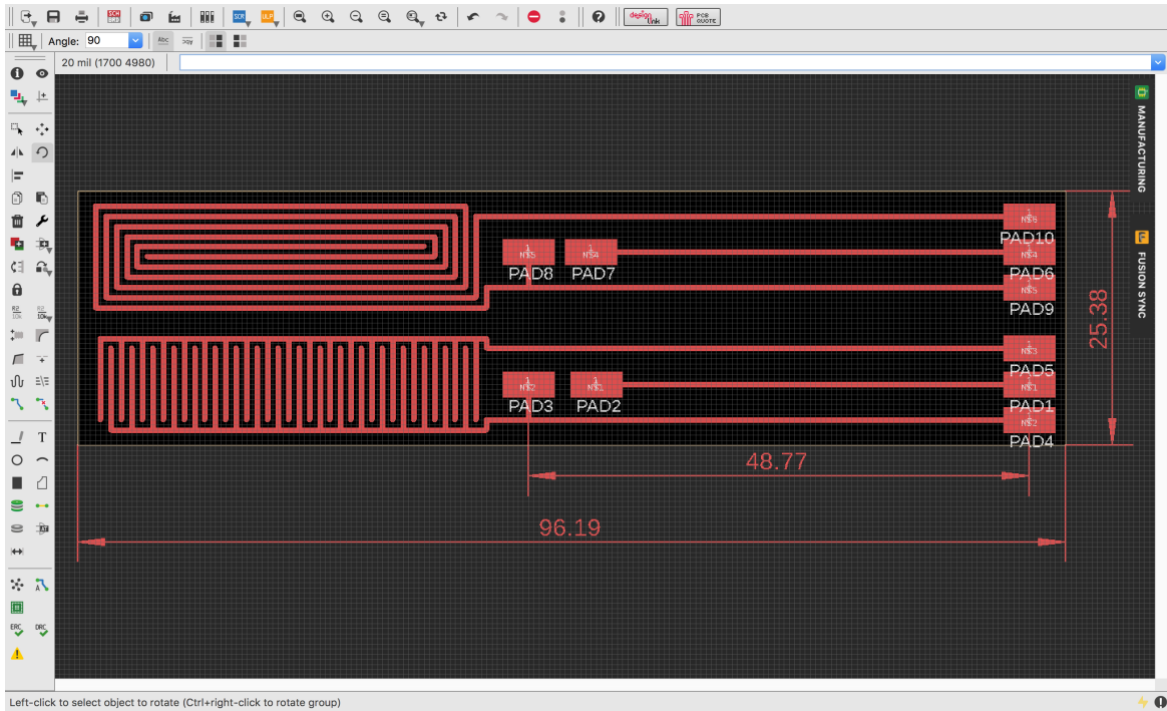


Figure 24. Screenshot of the sensor designed in Eagle program

3.2.2 Manufactured Sensor

After we designed the sensor in the Eagle program, we ordered the flexible sensor from Prinel Piirilevy Oy, which has following properties.

Table 3. Properties of the ordered sensor

Material	Polyimide
Layers	1
Copper Thickness	$18\mu\text{m}$
Board Thickness	$25\mu\text{m}$ to $50\mu\text{m}$
Smallest Track	$150\mu\text{m}$
Smallest Collar	$150\mu\text{m}$

The Figure 25 below is the manufactured flexible sensor obtained from the Prinel Pirilevy Oy.

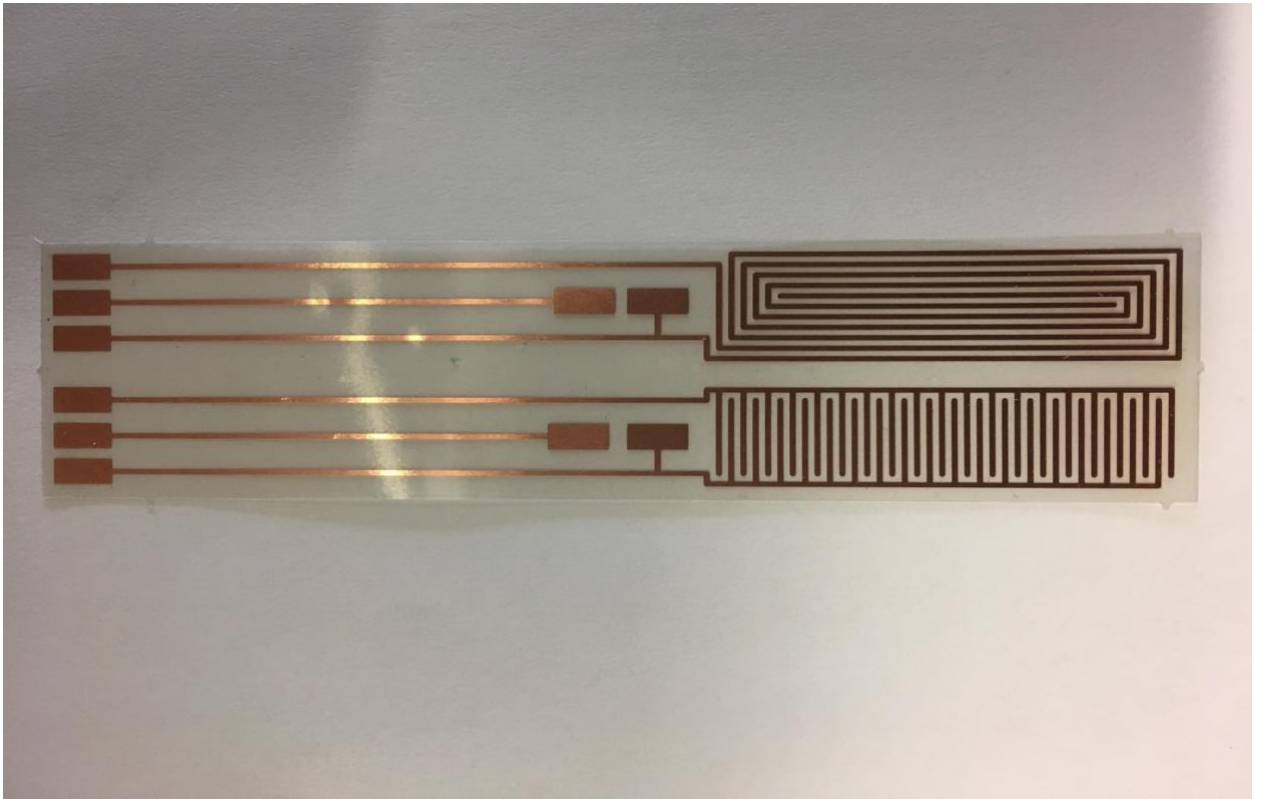


Figure 25. Sensor after manufactured

After we received the sensors, we separated both of them and conducted experiment with both of them individually. We wired the capacitor and also designed the amplifier the signals so that it can be read by the Audacity Software through the microphone of the laptop.

3.2.3 Laminating with Spiral and Finger Capacitor

In order to make the lamina, vacuum lamination method was used. Firstly, the lamination table was cleaned with acetone and the release agent was used on it. Then we cut the glass fiber pieces and placed on the lamination table. The peel ply was placed on the top of the glass fiber and then the release film in order to prevent the foreign materials in the lamination. The flow mate was used in order to make the constant resin flow. The bagging film was placed on the top and sealant were used along all the side. Then the lamination

was made vacuum tight. The Figure 26 shows the sketch demonstration of the lamination procedure.

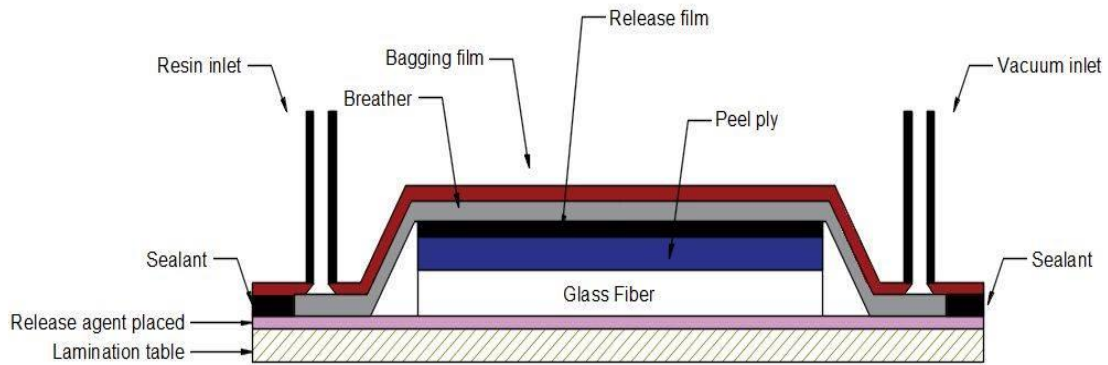


Figure 26. Sketch demonstration of lamination procedure

In case, of both of the sensors we made a small hole through the bagging film and placed the sensor inside it. Sealant were used where the hole was made, and we again checked it to make it vacuum tight. We took couple of measurements for the dry state as well. The Figure 27 shows the sensor placed inside the lamination from the top.

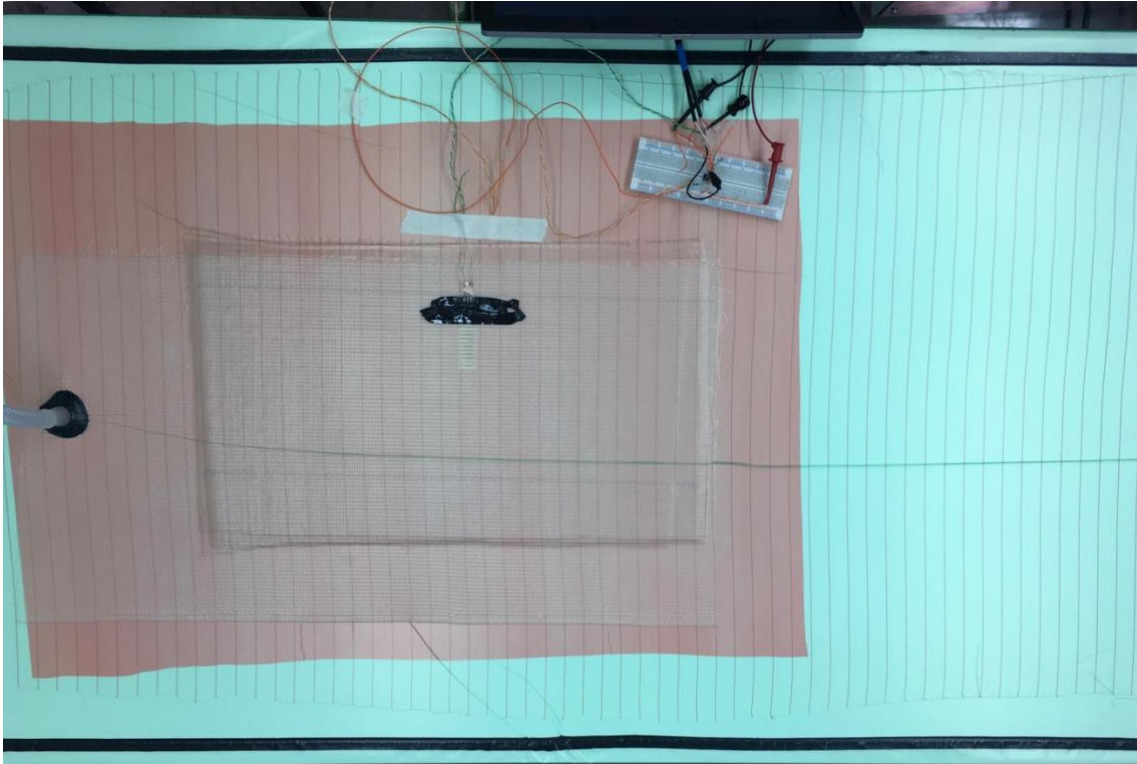


Figure 27. Sensor placed inside the lamination (top view)

For both of the sensors, once the sensor was placed and checked for vacuum tightness, the resin (Vinyl Ester) mixed with the hardener (1.5% Butanox M-50) and then injected for lamination. Once the resin was injected we took couple of measurements as the wetting progresses. When the fibers get completely wet, we took the measurement on the gap of every 10 minutes for 2 and half hours. The Figure 28 shows the when the fiber were completely wet and curing progresses.

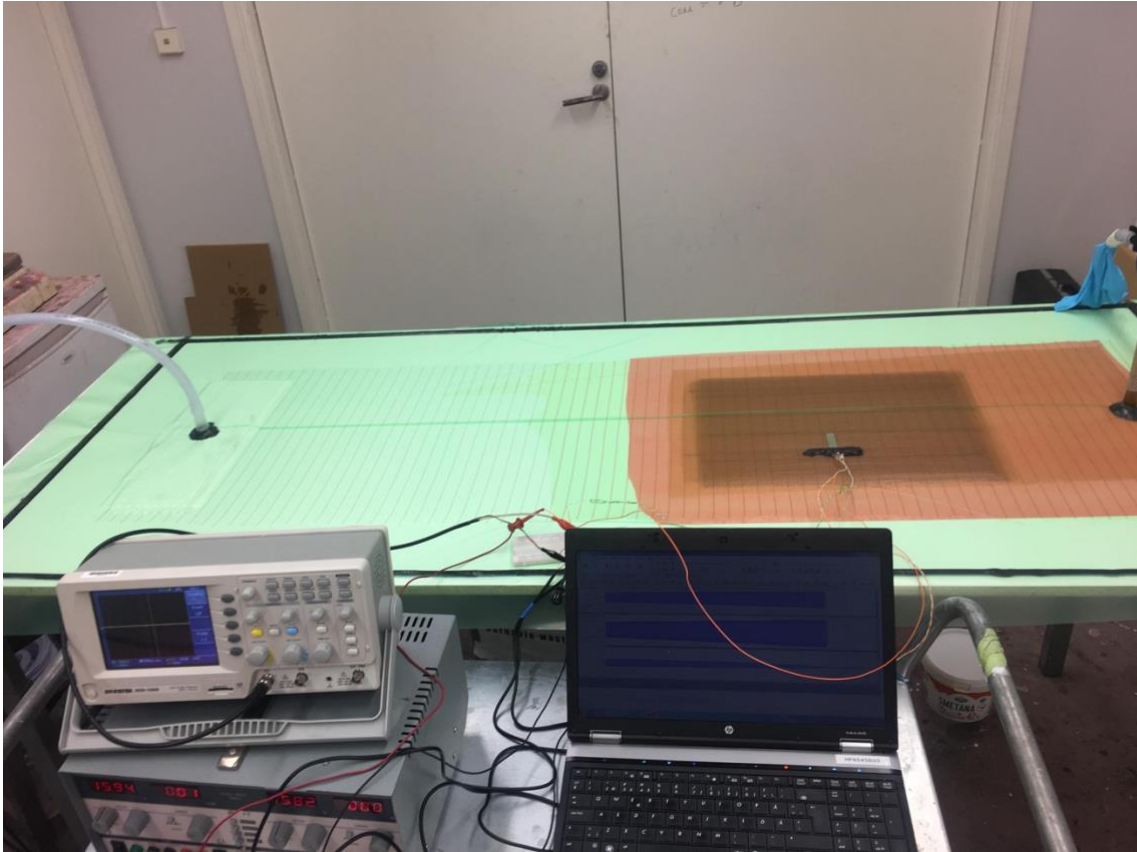


Figure 28. Lamination as the curing progress

The measurements were taken with the audacity software, with an increasing amplitude from 25 to 50 and frequency range of 100Hz to 20,000Hz on a linear scale.

4 RESULTS

The results from the data acquired from the experiments conducted were analyzed and enlisted in this segment.

4.1 Results from Big Finger Capacitor

The data collected from the Big Finger Capacitor are in Table 2. and if we draw a graph of Capacitance (C) in nF at different frequencies along with the time (t) progression, the results were as follows in Figure 29.

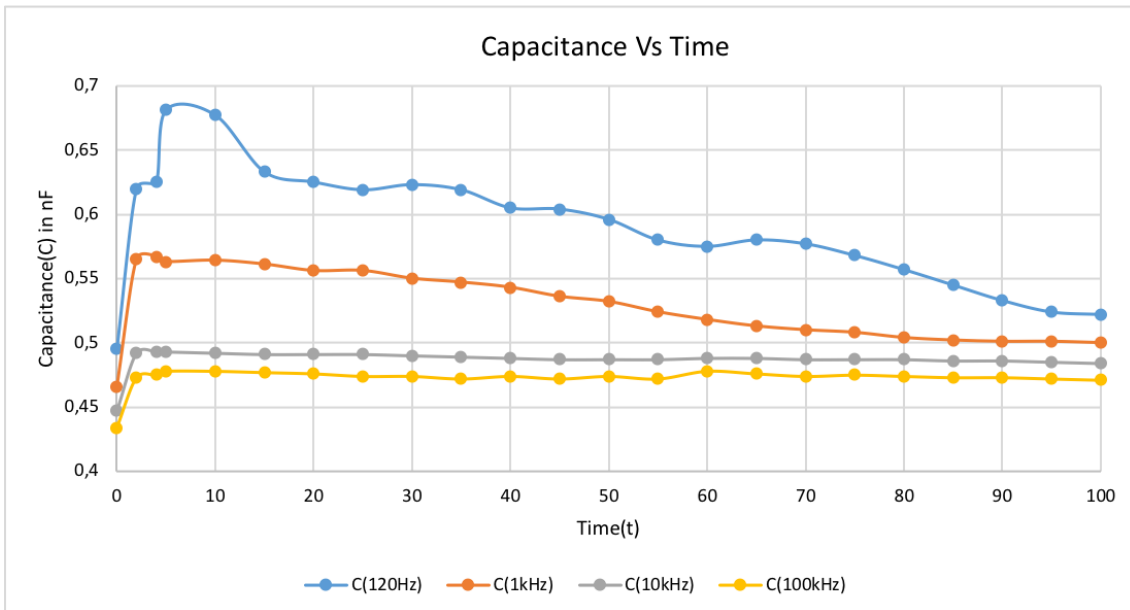


Figure 29. Results from LCR meter at different frequencies and time

From the Figure 29, it clearly shows that the when the resin was placed into the lamina the capacitance increases to a certain level and then decrease again. With Figure 30, we can say that the change in capacitance is 10 percent. The capacitance increment, and decrement were more visible at lower frequency than compared to the higher frequencies. This is because of the easy charge migration at lower frequencies in the form of ionic conduction. We know that the permittivity of the material is frequency dependent. [9] As the frequency reaches to certain level, it gets harder for the dipoles to align themselves faster as they get arrested which decreases the capacitance as the curing progresses.

This is also a proof that lower frequency gives the stronger change in capacitance (ΔC).

From the data Table 2. we calculated the ratio of the capacitance as per the curing progresses with the capacitance at dry state. The ratios of the capacitances are shown below in Table 4.

Table 4. Relative Capacitance at different frequencies

Time (t)	Relative C @ (120Hz)	Relative C @ (1kHz)	Relative C @ (10kHz)	Relative C @ (100kHz)
0	0	0	0	0

2	0.252525253	0.21244635	0.10067114	0.089861751
4	0.262626263	0.2167382	0.10290828	0.094470046
5	0.375757576	0.20815451	0.10290828	0.101382488
10	0.367676768	0.21030043	0.10067114	0.101382488
15	0.278787879	0.20386266	0.098434	0.099078341
20	0.262626263	0.19313305	0.098434	0.096774194
25	0.250505051	0.19313305	0.098434	0.092165899
30	0.258585859	0.18025751	0.09619687	0.092165899
35	0.250505051	0.17381974	0.09395973	0.087557604
40	0.222222222	0.16523605	0.0917226	0.092165899
45	0.22020202	0.15021459	0.08948546	0.087557604
50	0.204040404	0.1416309	0.08948546	0.092165899
55	0.171717172	0.12446352	0.08948546	0.087557604
60	0.161616162	0.11158798	0.0917226	0.101382488
65	0.171717172	0.10085837	0.0917226	0.096774194
70	0.165656566	0.0944206	0.08948546	0.092165899
75	0.147474747	0.09012876	0.08948546	0.094470046
80	0.125252525	0.08154506	0.08948546	0.092165899
85	0.101010101	0.07725322	0.08724832	0.089861751
90	0.076767677	0.0751073	0.08724832	0.089861751
95	0.058585859	0.0751073	0.08501119	0.087557604
100	0.054545455	0.07296137	0.08277405	0.085253456

With the help of the Table 4. we plot a graph in order to draw some conclusion from the data's. The calculated ratios of the capacitance were plot into the graph.

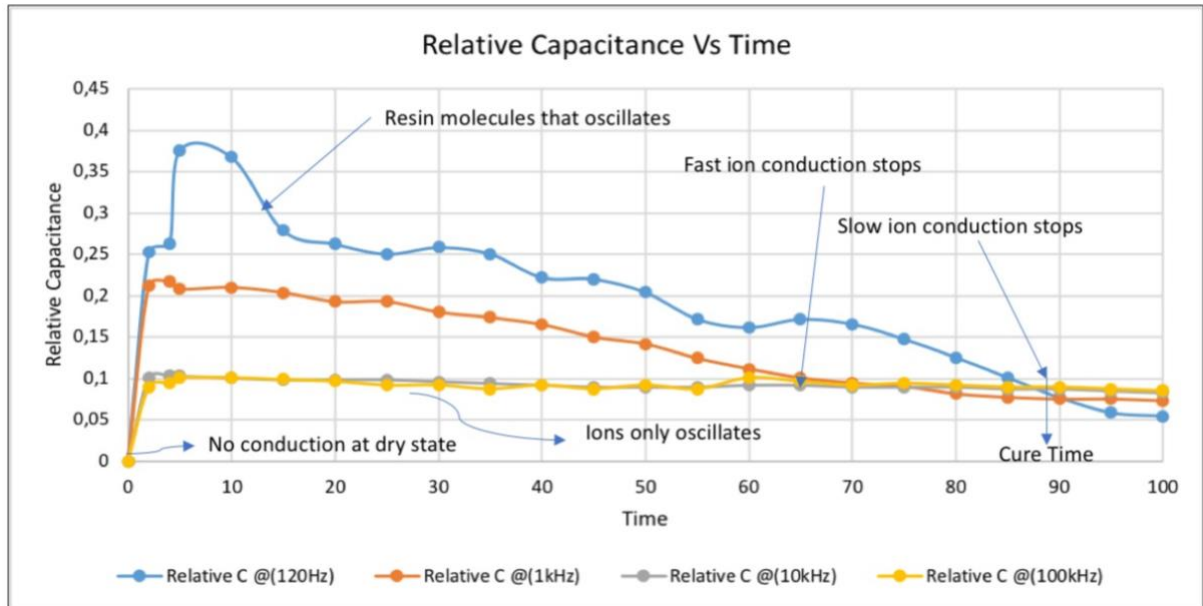


Figure 30. Relative Capacitance at different frequencies

From Figure 30, it can be seen that the capacitance increases as the resin is placed but then decreases. This means that not only the permittivity drops but also the relative permittivity drops as well. The data set from the manufacturer says that the cure time is 70-82 minutes at room temperature. [10] From the Figure 30, the slow ionic conduction stops (i.e. no more charge migration takes place) at around 90 minutes, which means that the resin is already cured.

From this we can also say that if we measure relative capacitance at two different frequencies, one lower than 1kHz and another higher than 1kHz, we can calculate the demolding time of the lamina as well.

4.2 Results from Spiral and Finger Sensor

4.2.1 Spiral Sensor

We collected the data from the spiral sensor while laminating from dry state, partial wet, complete wet state and in every 10 minutes until it gets cured. The data's collected were

analyze them with the help of Scilab software as a Fast Fourier Transform (FFT) graphs. We calculated the relative permittivity at each state and plot them.

The Figure 31, Figure 32, Figure 33, Figure 34, and Figure 35 shows the relative permittivity drawn with frequency for spiral sensor at dry state, partial wet states, complete wet state and every 10 minutes once the lamina was complete wet until 150 minutes.

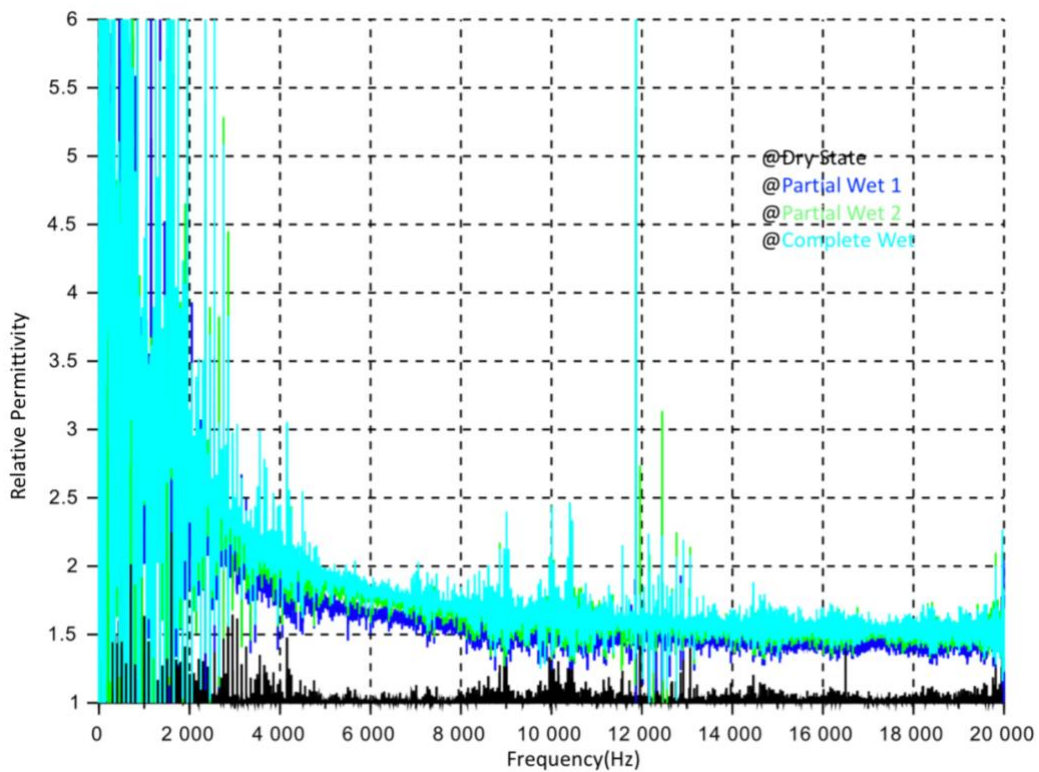


Figure 31. Relative Permittivity against frequency from dry to complete wet state (spiral sensor)

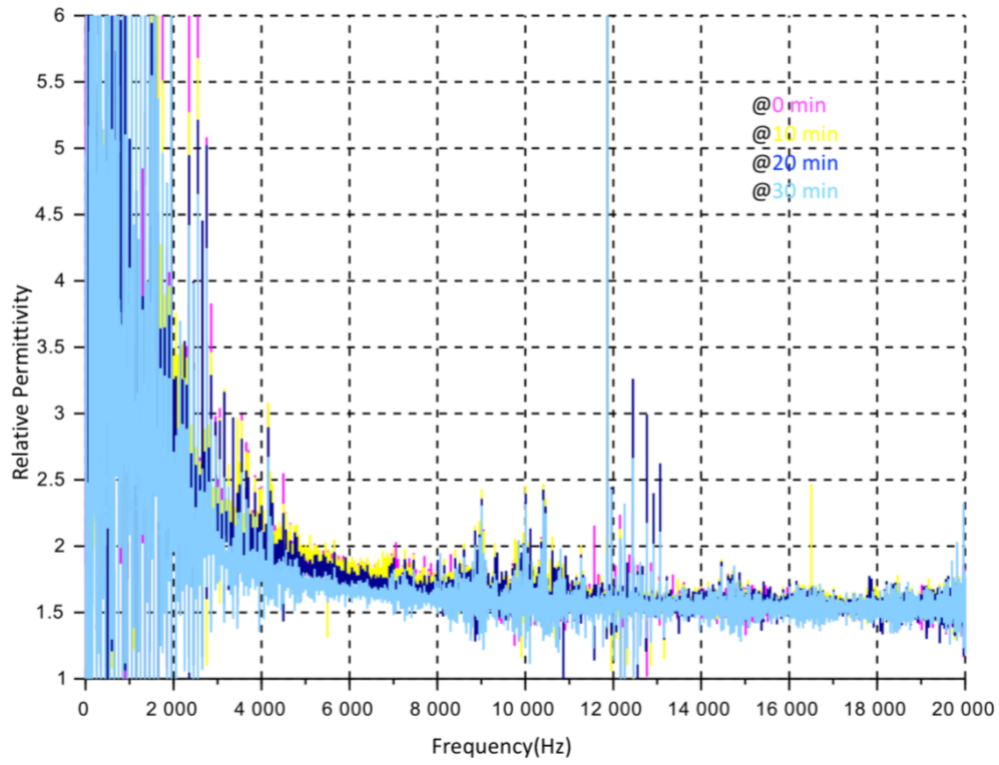


Figure 32. Relative Permittivity against frequency from time 0 to 30 minutes (spiral sensor)

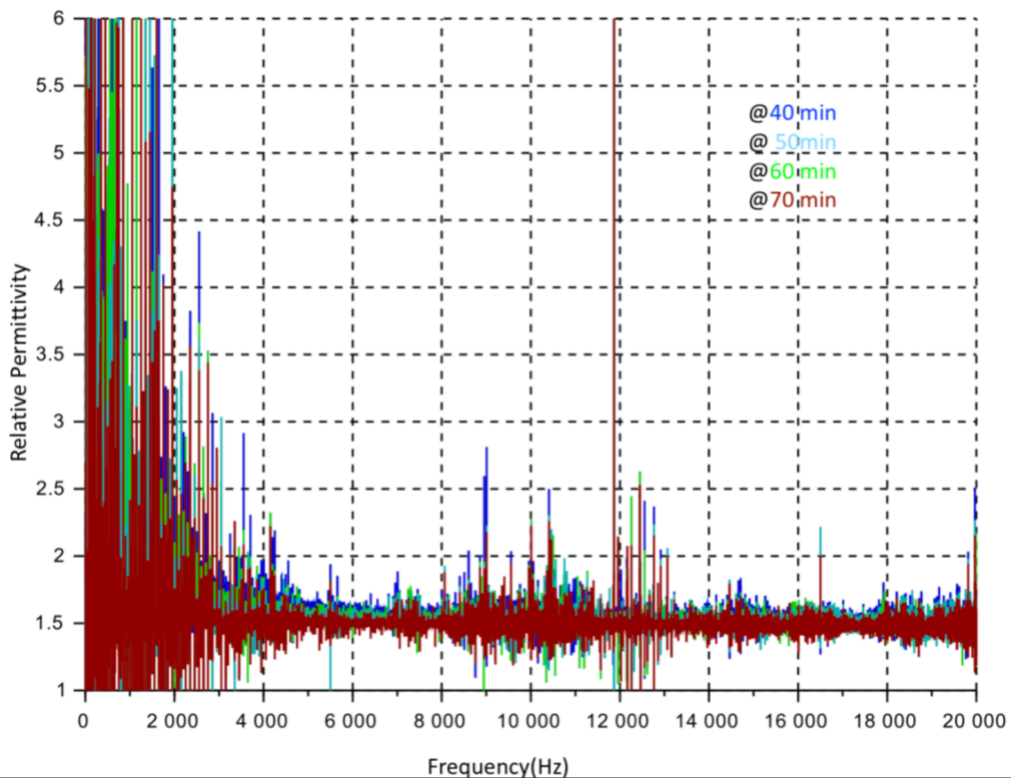


Figure 33. Relative Permittivity against frequency from time 40 to 70 minutes (spiral sensor)

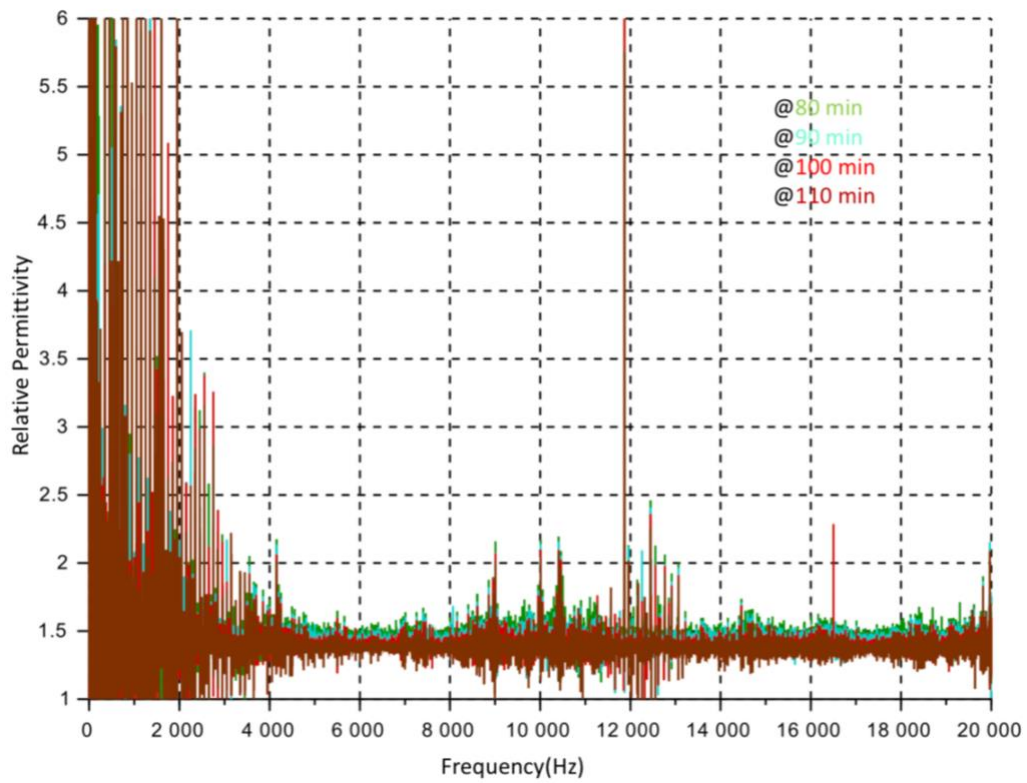


Figure 34. Relative Permittivity against frequency from time 80 to 110 minutes (spiral sensor)

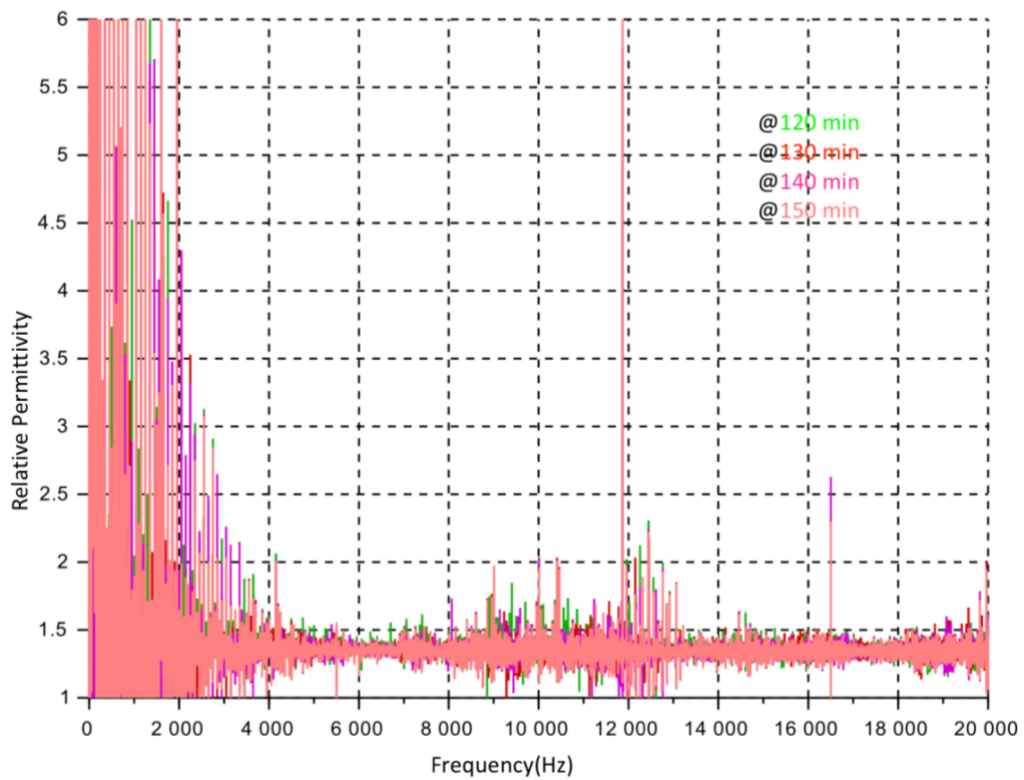


Figure 35. Relative Permittivity against frequency from time 120 to 150 minutes (spiral sensor)

The Figure 36, show the relative permittivity drawn with frequency, at dry state, complete wet, at 30 min, 70 min, 110 min, and 150 min as the curing progresses for spiral sensor.

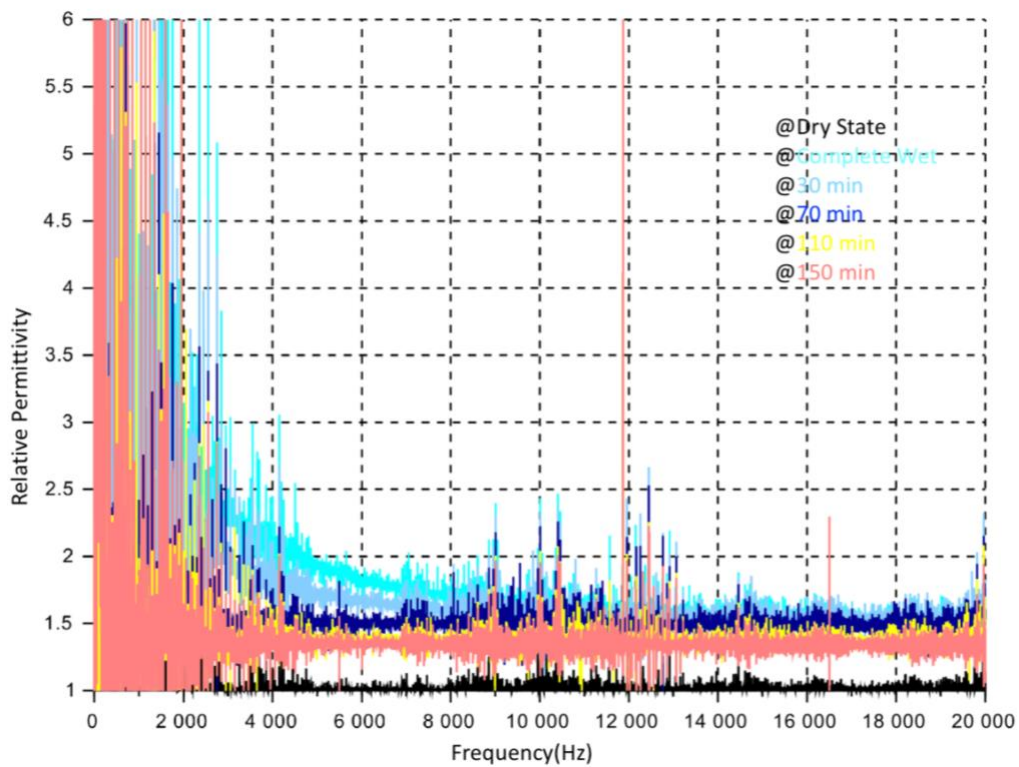


Figure 36. Relative Permittivity against frequency of some specific points (spiral sensor)

4.2.2 Finger Sensor

In case of finger sensor as well, we collected the data from the spiral sensor while laminating from dry state, partial wet, complete wet state and in every 10 minutes until it gets cured. The data's collected were analyze them with the help of Scilab software as a Fast Fourier Transform (FFT) graphs. We calculated the relative permittivity at each state and plot them. As noise was seen beyond 10kHz, we only plot the frequency up to 10 kHz.

The Figure 37, Figure 38, Figure 39, Figure 40, and Figure 41 shows the relative permittivity drawn with frequency for finger sensor at dry state, partial wet states,

complete wet state and every 10 minutes once the lamina was complete wet until 150 minutes.

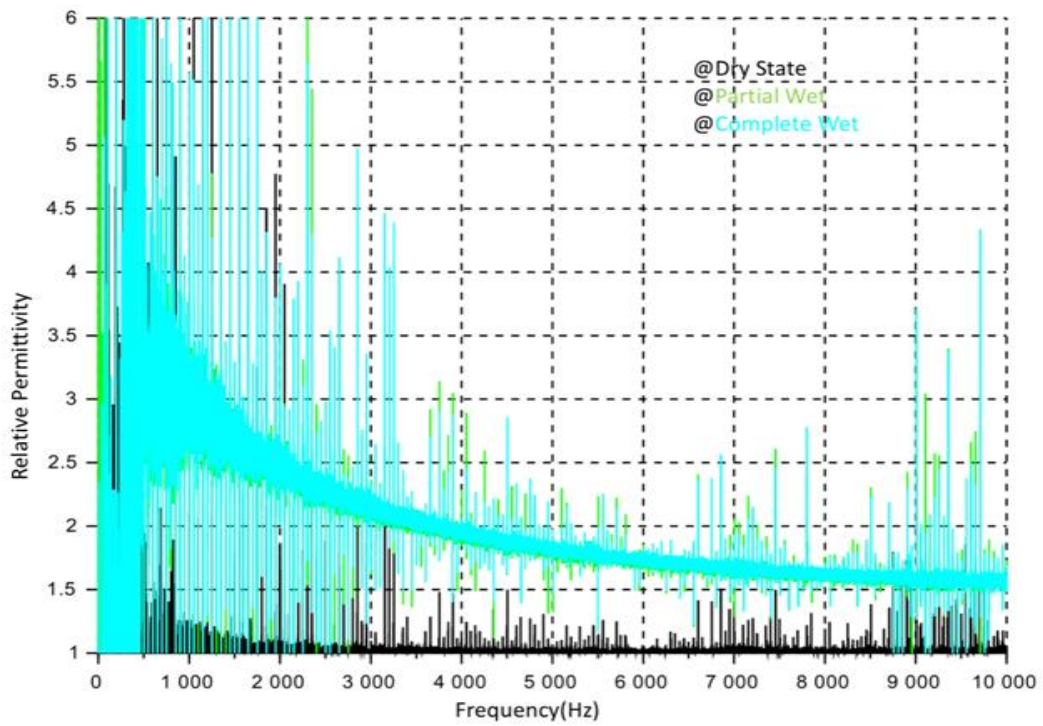


Figure 37. Relative Permittivity against frequency from dry to complete wet state (finger sensor)

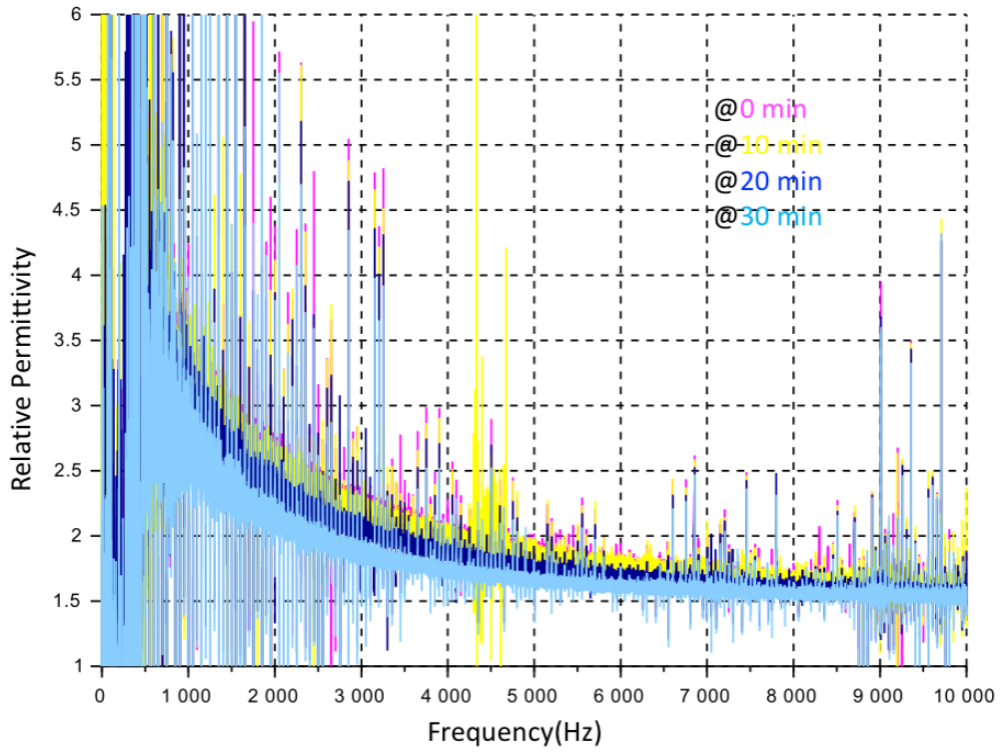


Figure 38. Relative Permittivity against frequency from time 0 to 30 minutes (finger sensor)

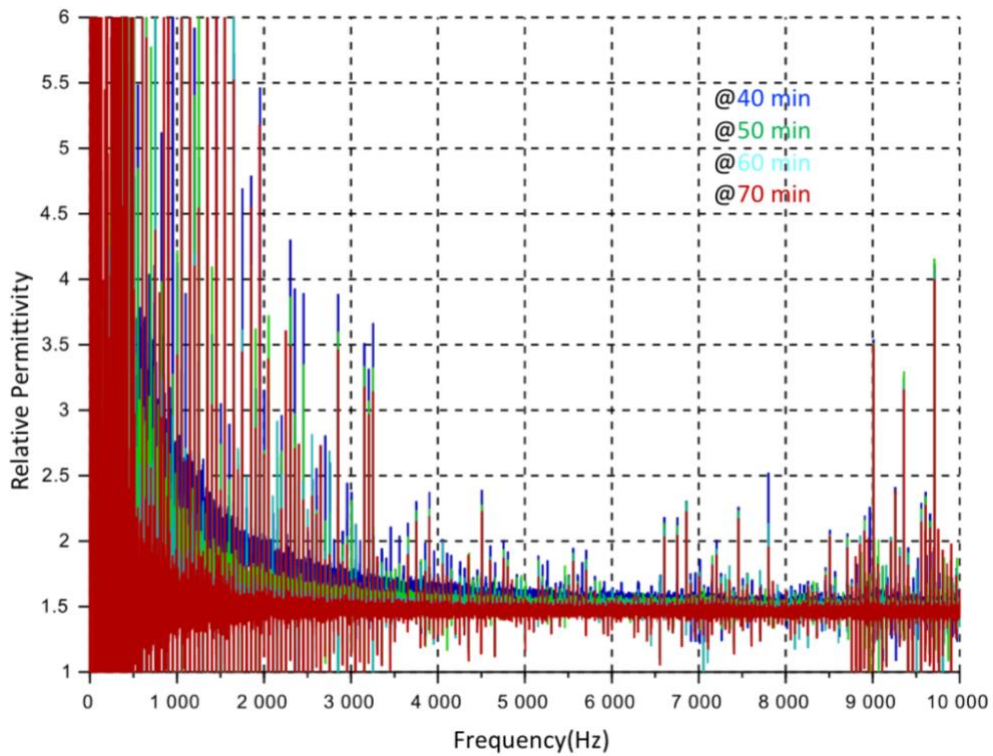


Figure 39. Relative Permittivity against frequency from time 40 to 70 minutes (finger sensor)

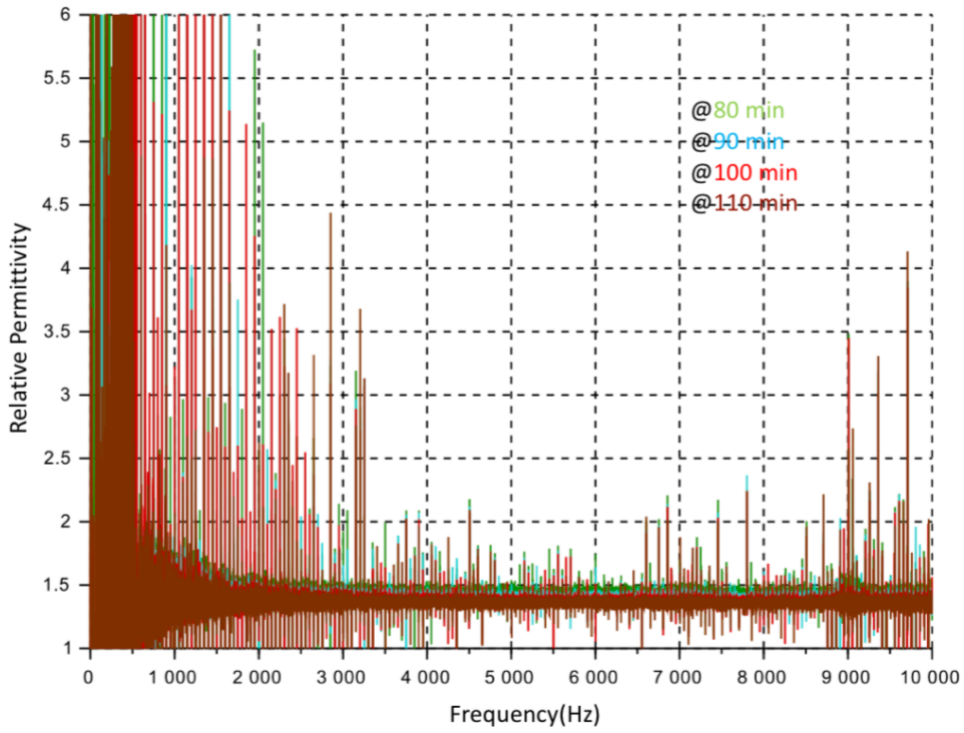


Figure 40. Relative Permittivity against frequency from time 80 to 110 minutes (finger sensor)

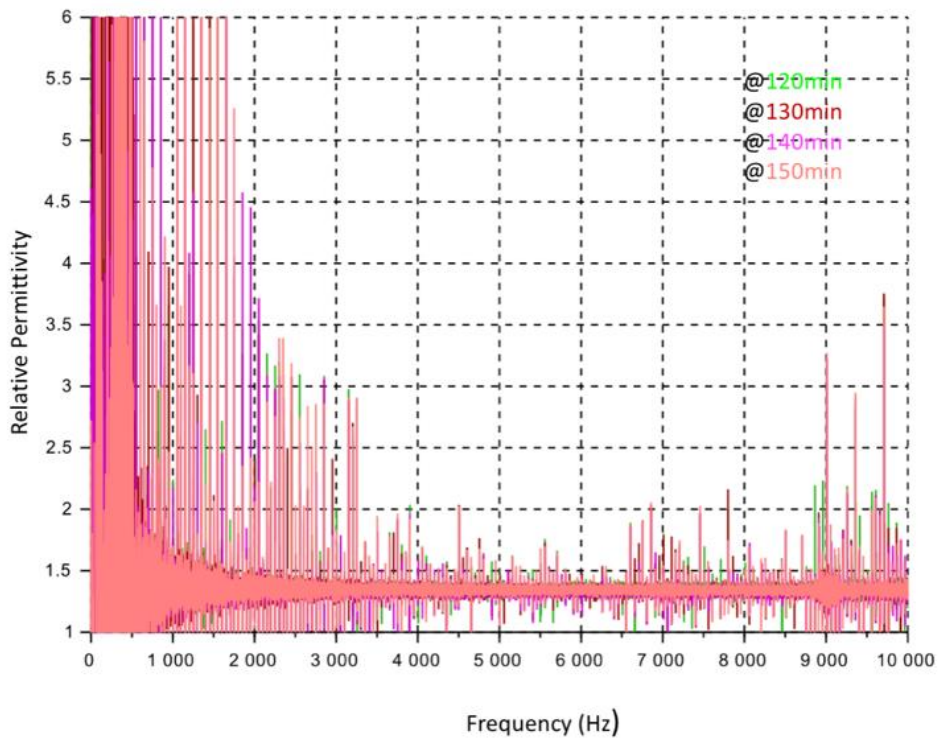


Figure 41. Relative Permittivity against frequency from time 120 to 150 minutes (finger sensor)

The Figure 36, show the relative permittivity drawn with frequency, at dry state, complete wet, at 30 min, 70 min, 110 min, and 150 min as the curing progresses for finger sensor.

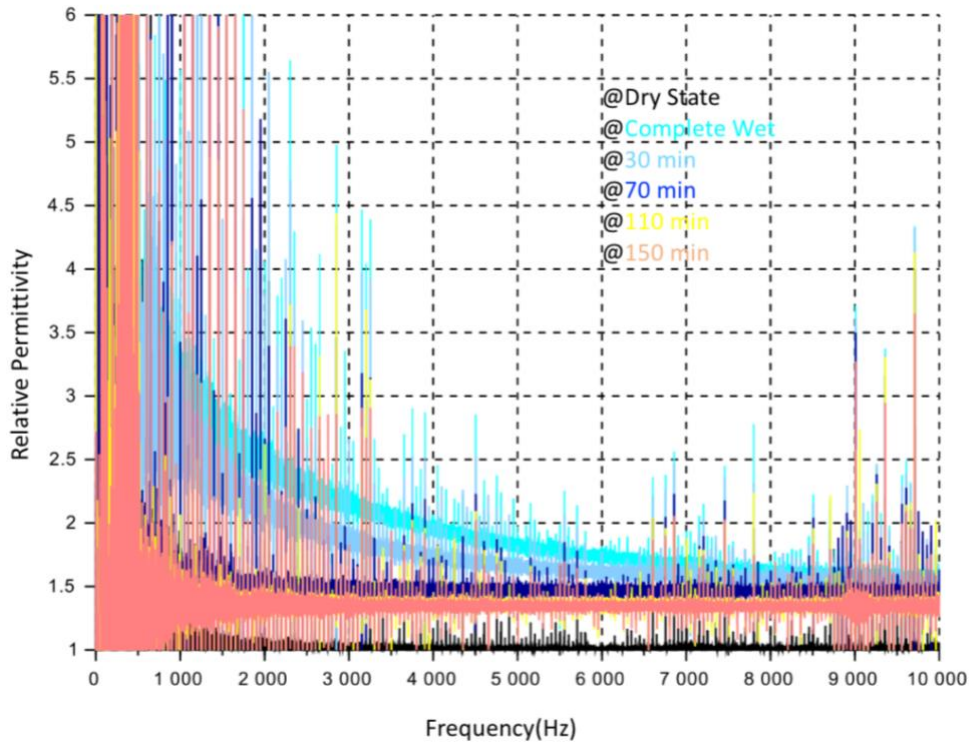


Figure 42. Relative Permittivity against frequency at specific points (finger sensor)

In Figure 31 and Figure 37, we plot the frequency and relative permittivity measured by spiral and finger sensor respectively at dry state and as the wetting progresses. We can see that the relative permittivity ≥ 1 at dry state (resin was not injected), which is the relative permittivity of the air and textile as previously mentioned. When resin was injected, the lamina starts to get wet. The air inside was being replaced by resin as described in theory. The relative permittivity suddenly jumps when the lamina starts to get wet and as wetting progresses the relative permittivity increases. At lower frequency, the relative permittivity shifts are seen more as compared to the higher frequencies but there is some sort of noise at lower frequencies as well.

This certainly proves that the dielectric properties of the resin changes during wetting.

In Figure 36 and Figure 42, we plot the frequency and relative permittivity measured by spiral and finger sensor at dry state, complete wet state, 30 min, 70 min, 110 min and 150 min. This clearly shows us that as the resin was injected into the lamina, relative permittivity increase and is maximum at complete wet state. As the resin starts to get cured, certainly at 30 min the relative permittivity decreases as compared to the complete wet state. Furthermore, the same decrement of the relative permittivity continues at 70 min, 110 min and 150 min.

This signifies that as wetting takes places relative permittivity increases, but as the curing progresses in lamina, the relative permittivity decreases.

There have been studies carried out for the dielectric properties of the epoxy, using a capacitance method with comb capacitor. The study was focused at one measurement frequency where they demonstrate that the permittivity decreases as the curing progresses. When the epoxy was treated with hardener, due to the cross-linking molecular weight rises. The reaction was exothermic reaction. The macro and micro molecular changes occur during curing, decreasing the ionic conduction, and relaxation time dropping the relative permittivity. [11]

The results we obtained with the spiral and finger sensor, signifies the same behaviors of the vinyl ester resin as of the epoxy resin mentioned. Thus, the results not only show the dielectric changes of vinyl ester but also demonstrate the previous studies.

5 CONCLUSION

The results retrieved from the experiments done with the big finger sensor designed with photolithography, spiral and finger sensors designed were able to execute the major objective and presumption of the research. The wetting of the composite results the change in the capacitance due to the complete or partial displacement of the air cavities by resin was should by the big finger sensor. However, it also demonstrates the demolding time of the lamina with the capacitance measurement at two different frequencies. The flexural finger and spiral sensor were than able to exhibit change in the dielectric properties of the resin in the lamina during wetting and curing. On comparing the results indicated by both sensors, it can be seen that the spiral sensor was more sensitive and can exhibit more relevant results if improvised.

For the further studies, there are a lot of possibilities yet to be explored. Even with the spiral and finger sensor, one can examine the dielectric properties along with the temperature as well. The study can only be focused at certain frequencies only, to evaluate the differences. Even with the improvement of the electronics, one can amplify the signals at the lower frequencies to get rid of the noise. As the spiral sensor seems to be more sensitive than the finger, there can be the possibility of study the resonance of the molecule of the resin during wetting and curing. However, the module developed for the monitoring of the dielectric properties and the results of this research can be a starting point for future researches.

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