CHARACTERIZATION OF LOCALLY AVAILABLE MICA MINERALS FOR CAPACITOR APPLICATIONS

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Degree of Master of Science

Department of Materials Science and Engineering

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Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree

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Declaration

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institution of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Name of the supervisor: Prof. S U Adikary

Signature of the Supervisor: Date:

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Abstract

Mica is a group of minerals of the hydrated alumino silicate of iron, magnesium, potassium, lithium and sodium etc. Commercially, the two most widely used micas in the electrical industry are the muscovite and phlogopite types. Phlogopite is the widely available mica type in Sri Lanka.

Micas from different mining locations (Mathale, Mailapitiya, Badulla and Kebethigollewa) in Sri Lanka were characterized using XRD and SEM methods. Two different methods, namely ceramic method and flake method were used to study the dielectric properties of locally available mica. Dielectric behaviour of mica characterized above has been investigated by measuring capacitance (C) and loss tangent (D) at selected frequencies, with a precision LCR meter in a controlled environment. Then the relative permittivity, ε_r for each specimen was calculated and behaviour of ε_r with frequency was studied. Five flake specimens each obtained from four different locations and five ceramic disc specimens each prepared with powdered mica of two different locations were used for the study. Size, shape and method of preparation of the specimens were kept constant throughout the experiment. Graphs between ε_r and $\log_{10}$[frequency] of silvered mica flakes, and that of silvered mica discs were plotted separately. Accordingly, samples prepared by both methods have also been compared. Finally, average loss tangent D_{avg} values of silvered mica were plotted as a function of average relative permittivity, $(\varepsilon_r)_{avg}$ at defined frequencies and investigated location wise.

Scanning Electron Microscopic (SEM) analysis of Mathale and Mailapitiya samples confirmed that they have typical mica like flaky structures with layers. The XRDs of mica samples from different locations revealed different crystal structures & poly types. Sample from Mathale revealed two crystal structures Phlogopite 1 M and Phlogopite 3T, while Mailapitiya sample revealed two crystal structures Phlogopite 1 M and Biotite. Phlogopite 1 M and Hendricksite (Zinc- rich mica) were found fairly abundantly and Wustite ($Fe_{0.92}O$) was found in small concentrations in Badulla sample, while Phlogopite 3T was found abundantly in Kebethigollewa sample.

Dielectric properties including dielectric constant (ε_r) and dielectric loss tangent (D) have been done in the frequency range from 1 kHz to 1MHz. The results showed that the dielectric constant (ε_r) and loss tangent (D) decrease with the increasing frequency at room temperature. As per the results, Kebethigollewa flake mica and sintered Mathale mica were the best types with higher ε_r and lesser D, at low radio frequency ranges. However, flake mica showed comparatively higher ε_r values than that of mica dielectrics obtained from the same source and manufactured by ceramic method. These results are also found compatible with the results of similar studies carried out by the researches in different countries.

Hence, it can be concluded that locally available mica can be applied as dielectrics for capacitors within low radio frequency range. Even though both methods can be used, flake method is more suitable for applications which require higher ε_r values while ceramic method is better, where low capacitance applications are required. Ceramic method may be further developed by using other techniques such as slip casting method. Kebethigollewa and Mathale mica flakes are the best sources in terms of dielectric properties.

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INTRODUCTION

1.1 General

Mica mining and exporting in Sri Lanka has a long history and it dates back as far as 1896. Major Mica deposits are found in Mathale, Madumana, Pallekelle, Thalathu – Oya, Badulla, Maskeliya, Madugoda, Naula, Haldummulla, Mailapitiya, Kebithigollewa and Madampe areas. [1]

Mica is a group of minerals of the hydrated alumino silicate of iron,magnesium,potasium,lithium and sodium etc. There are about 37 different micas easily identified by their unique flaky structures. The important commercial types of mica are brown mica or phlogopite which contains iron and magnisium; the " white (or clear) mica" or muscovit**e** which contains potassium and aluminum.

Mica is classified as sheet, scrap and flakes. One important quality of mica which makes it very important in electrical industry is its latent and superb dielectric strength. There are various insulating materials but it is mica alone, which possesses high dielectric strength. Mica has unique qualities in that it does not crack, shrink, swell or disintegrate even at much high temperatures. [2]

Capacitor is a widely used electrical component, consisting of an insulator or a dielectric between two conductors. The conductors apply voltage across the insulator. Selecting the correct type of capacitor is very important, since it has a major impact on any circuit. If the correct type of capacitor is not used, the circuit may not work correctly. Eelectrolytic, ceramic, tantalum, plastic, sliver mica, and many more capacitor types are available. Each type has its own benefits and weaknesses and can be used in different applications. [3]

Silver mica capacitors have been widely used as high performance capacitors over the years. Even though the cost of silver mica capacitors is higher than many other types, they are still used today in a variety of applications specially for radio frequency applications. Reason is they are able to provide stability, very high levels of accuracy and low loss. [4]

Although various forms of mica are used for capacitors, they all are mechanically and chemically very stable, making capacitors manufactured with mica have similar properties with dielectric constant ranging from around 5 to 7. [[5]

Due to its layered structure mica can be split into very thin flat sheets along the lines of the weak bond. The sheets having about 0.025 mm to 0.1 mm thicknesses are used in manufacturing capacitors.

In case of silvered mica capacitors, silver paste is used for coating mica films, already fabricated to the required sizes and dried in kiln, for manufacturing of capacitors. In this study, mica flakes of different locations in Sri Lanka were used to make silvered mica capacitors.

Manufacture of ceramic capacitors involves preparation of a mixture of fine ceramic powders and resin binders, cast in to cylinders /discs of the required thickness, silver electroding, baking to remove the organic binders, and then sintering at a temperature between 1200 ^{0}C and 1500 ^{0}C. Same procedure was applied for the manufacturing of sintered mica capacitor, using the mica obtained from different locations in Sri Lanka.

1.2 Background of the study

Since the government is forcing the mineral exporters towards adding value to minerals, there are requests from mica exporters, to conduct studies and researches and find out more appropriate value additions applicable to local mica. One of the major exporters, who is also a proprietor of the mica mines in Mathale, has requested the same and provided the researcher with mica samples mined at different locations in Sri Lanka. Main objective of this research is to evaluate the applicability of local mica in manufacturing capacitors.

1.3 Objectives

1.3.1 General objective

To evaluate the applicability of local mica in manufacturing capacitors

1.3.2 Specific objectives

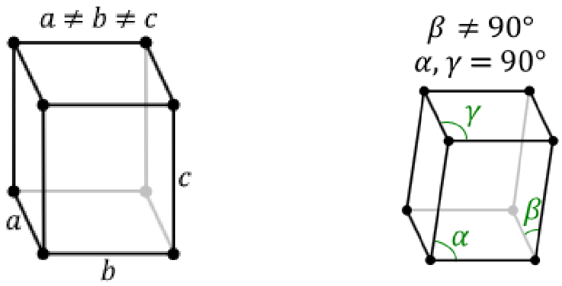
- To obtain the micro structures and chemical compositions of the local mica samples by using XRD and SEM techniques.
- To measure the capacitance and loss tangent of mica obtained from selected locations in Sri Lanka
- To calculate the relative permittivity, (ε_r) at different frequencies.

2. LITERATURE SURVEY

2.1 Mica Group

The natural micas are a group of sheet structure silicate minerals, with different chemical compositions and physical properties.Micas are characterized by excellent basal cleavage, high degree of flexibility, and toughness.

All micas form hexagonal monoclinical crystals with a remarkable cleavage in the direction of the large surfaces (i.e. (001) ,which permits them to split easily into optically flat films ,as thin as one micron in thickness .Structures of micas are based on sheets of linked (SiAl)O_4 tetrahedrons which makes their basal cleavage. (see Figure 2.1)



Orthorhombic ($\alpha=\beta=\gamma=90^0$) Monoclinic ($a \neq b \neq c$)

Figure 2.1: Orthorhombic and Monoclinic Crystal Systems

In common micas are monoclinic .However there are various forms such as hexagonal, orthorhombic, triclinic etc.which are called polytypes By using XRDs, polytypes can be identified.

Table 2.1: Poly types of mica mineral [5]

Designation	Crystal System	Number of layers per unit cell
1M	Monoclinic	1
$2M_1$	Monoclinic	2
$2M_2$	Monoclinic	2
3T	Hexagonal (Trigonal)	3
8 TC	Triclinic	8
12M	Monoclinic	12
18M	Monoclinic	18

2.1.1 Mica Crystal structure

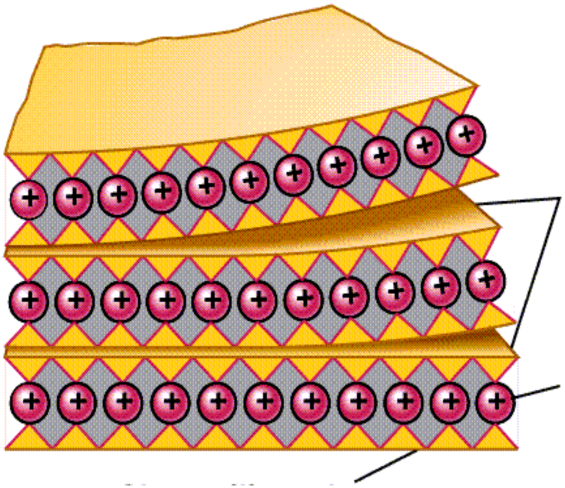


Figure 2.2 : Mica crystal structure [6]

2.1.2 Compositions of mica

The compositions of mica are often very complex and difficult to interpret.Micas are silicates of varying compositions of Al & K ,containing hydroxyl,Mg,Fe,Na,Li and F.The silica contents varies between 33% & 55% .

The mica minerals have the general formula $AR_{2-3}\square_{1-0}T_4O_{10}X_2$, [5]
where ;

A is an interlayer cation (K, Na, Ca, Ba, Cs, NH_4);
R is an octahedral layer cation (Al, Mg, Fe^{2+}, Li, Ti, Mn^{2+}, Zn, Cr, Na)
$\square$ is a vacancy in the octahedral layer;
T is a tetrahedral layer cation (Si, Al, Fe^{3+}, Be , B);
O is oxygen;and X is an anion not bonded to T (OH ,F ,Cl ,O, S)

2.1.3 Main types of mica

There are 37 different mica minerals and followings are the four principle types.

muscovite – $KAl_2(OH,F)_2AlSi_3O_{10}$
phlogopite – $KMg_3(OH,F)_2AlSi_3O_{10}$
biotite – $K(Mg,Fe)_3(OH,F)_2AlSi_3O_{10}$
lepidolite – $K_2Li_3Al_3(OH,F)_4\ (AlSi_3O_{10})_2$

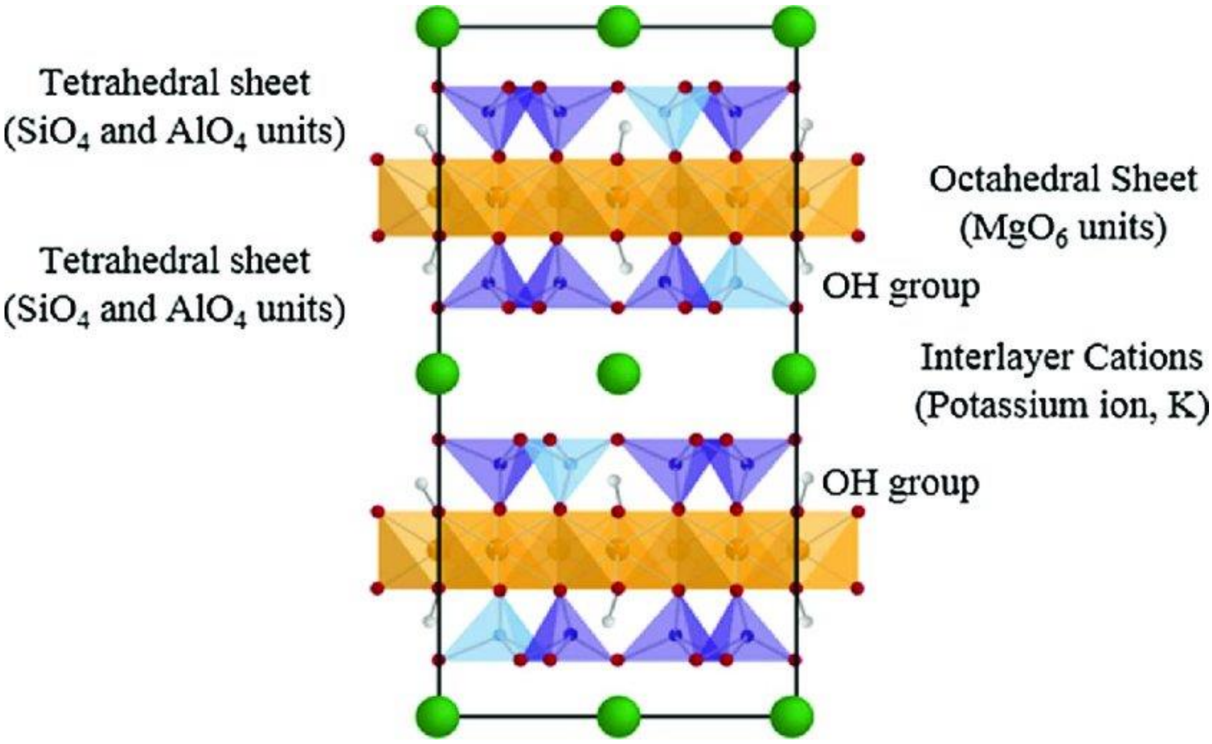


Figure 2.3: Phlogopite mica crystal structure [7]

2.1.4 Different forms of mica

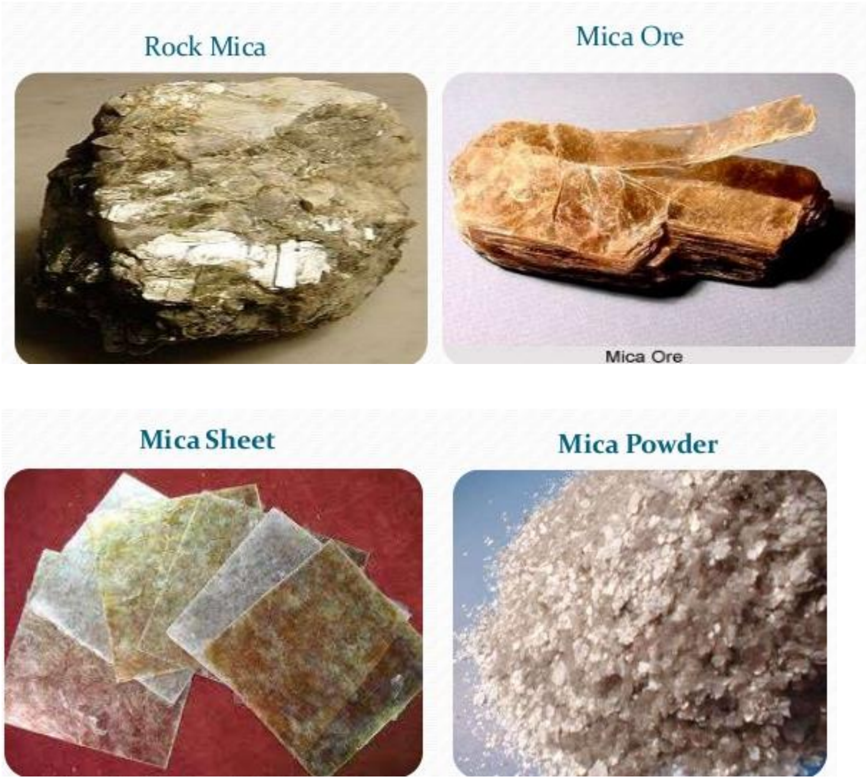


Figure 2.4 : Different forms of mica [8]

Sheet mica- is mainly used in manufacturing of electrical apparatus & machines such as dynamos ,motors,transformers,condensers,switch boards etc.Clear and transparent mica sheets are used for windows in,coal,gas and oil stoves,lamp shades etc.

Scrap mica - These are used in manufacturing wall papers,lubricants,fancy paints,rubber goods,electrical insulators,coverings for steam pipes & roofing papers etc.[[9]

2.1.5 Properties of Mica

Some important characteristics of mica for use in industries are as follows.

2.1.5.1 Thermal properties

The best quality of mica for electrical, electronics and strategic industries like aeroplane, rocket, radar, super computer is muscovite. In reality there is no change in the basic quality of muscovite even up to 700 ^{0}C.It can also face sudden and wide variations of temperature without undergoing any damage to its physical and chemical character. These thermal and other qualities of muscovite give it a significant place in modern industries. [10]

2.1.5.2 Dielectric properties

One important quality of mica which makes it very important in electrical industry is its latent and superb dielectric strength. One of these properties is the dielectricstrength or the ability to withstand a large field strength without electrical. breakdown. There are various insulating materials but it is mica alone, which possesses high dielectric strength. Mica has unique qualities in that it does not crack, shrink, swell or disintegrate even at much high temperatures. [10]

2.2 Sri lankan mica industry.

The mica industry in Sri Lanka dates back to the eighteen nineties when mining was carried out on a small-scale in the Badulla district. During the Second World War, mica mining was encouraged by the government. Department of Mineralogy purchased mica on behalf of the Anglo-American Mica Mission based in India, at favourable prices and advices on mining and preparation of mica for the market were also given. [11]

The major type of mica found in Sri Lanka is phlogopite which is widely distributed in the Central, Sabaragamuwa and Uva provinces. Muscovite or white mica is rare in comparison, the best known locality being Pinnawela, near Balangao; other muscovite-bearing pegmatite has been recorded from Mariarawa and Udumulla in Passara. Biotite or "black mica” has been recorded from a number of localities such as Kaikawela in Mathale district and from Polgolla in Kurunegala district. Lepidolite, the lithium mica, pale lilac in colour, has been recorded from Kaikawela. In the past phlogopite mica has been mined from comparatively shallow workings at Naula, Wariyapola, Mailapitiya, Madumana, Talatu Oya, Pallekelle and Hanguranketa in the Central province; at Godakawela and Madampe in the Sabaragamuwa province; at Badulla, Haldumulla and Ulwita in the Uva province; at Polgolla in the North-Western Province and near Kebetigollewa in the North-Central province. [1]

2.3 Capacitors

2.3.1 Introduction to capacitors

Capacitor is a widely used electrical component, consisting of an insulator (a dielectric) between two conductors. The conductors facilitate easy applying voltage across the insulator. The symbol for capacitance is C and the unit is farad (F), named after Michael Faraday.

Capacitors are manufactured for specific purposes and different values of capacitance. Capacitors are named according to the dielectric. Examples are ceramic, mica, paper, air, film and electrolytic capacitors. Capacitors used in electronic circuits are small and cost-effective.

Table 2.2: Dielectric materials [4]

Material	Dielectric Constant $k\varepsilon$	Dielectric Strength, V/mil (‘kV/inch)
Air or vacuum	1	20
Aluminium oxide	7	-
Ceramics	80-1200	600-1250
Glass	8	335-2000
Mica	3-8	600-1500
Oil	2-5	275
Paper	2-6	1250
Plastic Film	2-3	-
Tantalum Oxide	25	-

2.3.2 Dielectric constant (k_ε) or relative permittivity (ε_r)

This indicates the ability of an insulator to concentrate electric flux. It is the ratio of flux in the insulator compared with the flux in air or vacuum

The capacitance of a capacitor is determined only by its physical construction and not by external circuit parameters such as frequency, voltage, etc. [12]

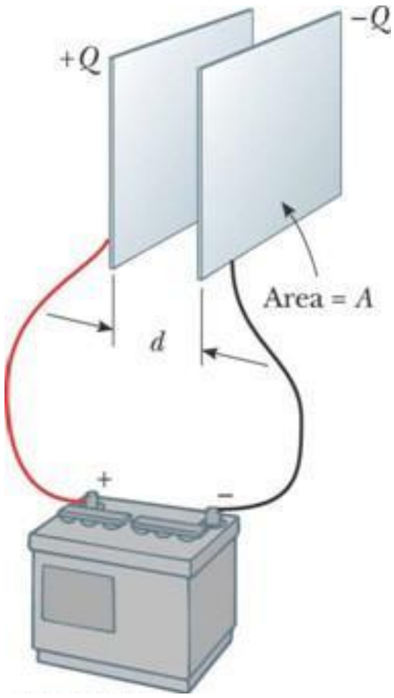


Figure 2.5 : A parallel plate capacitor [13]

The dielectric constant (k_ε) or relative permittivity (ε_r) of an insulator (mica) in a capacitor is

$$\varepsilon_r = C \times d / \varepsilon_0 A$$

Where,

ε_0 - dielectric constant of air or vacuum

C - capacitance of the specimen

D - thickness of the specimen (mica) used

A -area of specimen electrodes [12]

2.3.2.1 Dielectric Properties and Frequency

Dielectric properties of materials depend on frequency, temperature, moisture content, structural composition etc. Figure 2.4 shows how various forms of polarization will effect dielectric properties at various frequencies.

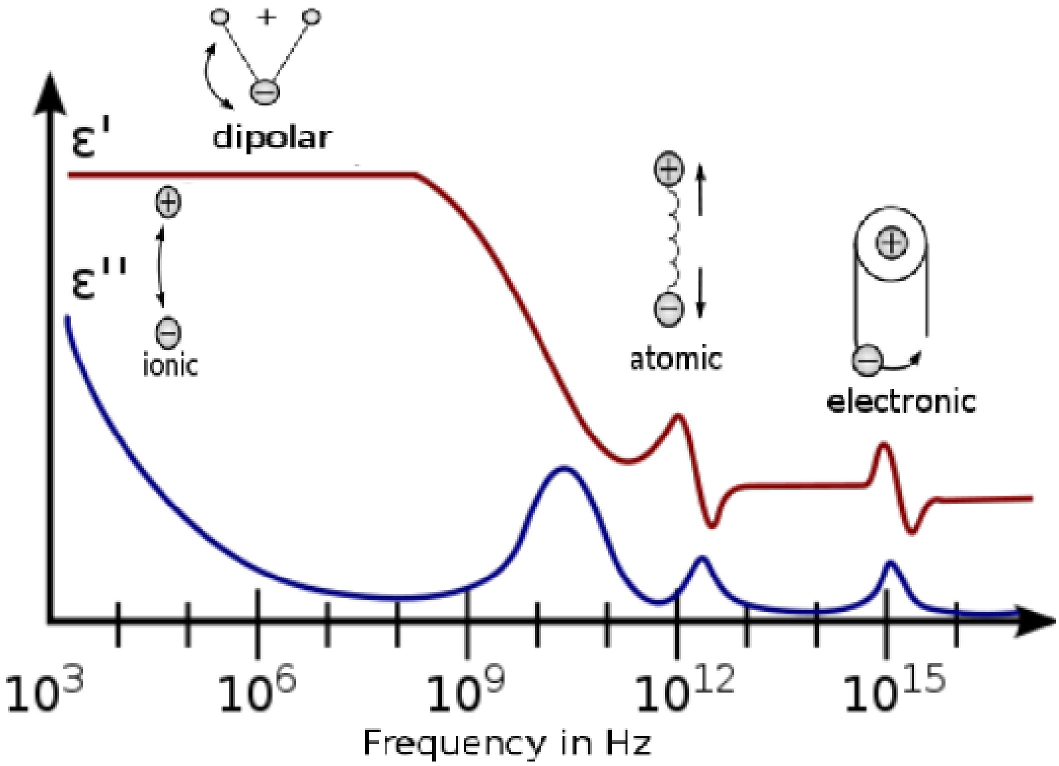


Figure 2.6: Frequency dependence of dielectric properties [14]

Scattering of stored energy as heat within the material will make higher loss factors. Figure 2.6 shows a sharp decline of the effective polarization, caused by decrease in dielectric constant and increase in loss tangent.

2.3.3 Mica capacitors

Silvered mica: Silver paste is used for coating mica films, already fabricated to the required sizes and dried in kiln, for manufacturing of capacitors.

Mica capacitors: consist of stacking mica blades between layers of metal foils. Silver solution consisting of silver oxide powder is coated on the clean mica sheet, by screen printing method. This process includes screen printing, drying in a firing unit, 12-hour baking, cooling and filming. [15]

2.3.3.1 Construction of mica capacitors

2.3.3.1.1 Stacked mica foil sections

Perfect mica sheets are selected and stacked between tin foils. Individual stacked units cut into sections are also the capacitors themselves. Required electrical properties can be measured with these individual as well as stacked units. [15]

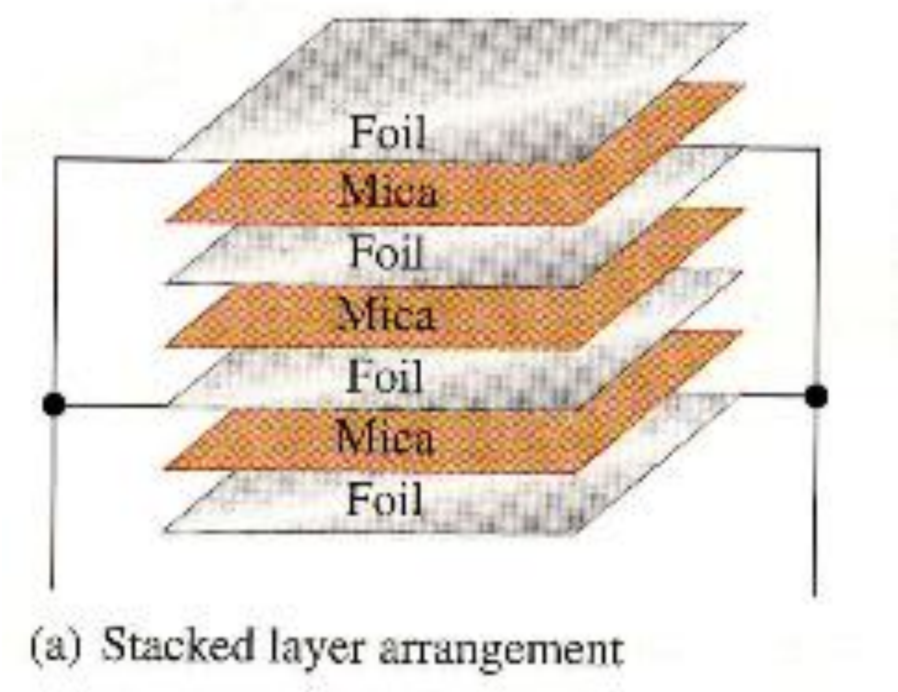


Figure 2.7 : Stacked layer arrangement [16]

2.3.3.1.2 Sintered chips

Top edges of multiple layers of mica are silver coated and stacked together. Terminals are directly soldered with a silver paste. [17]

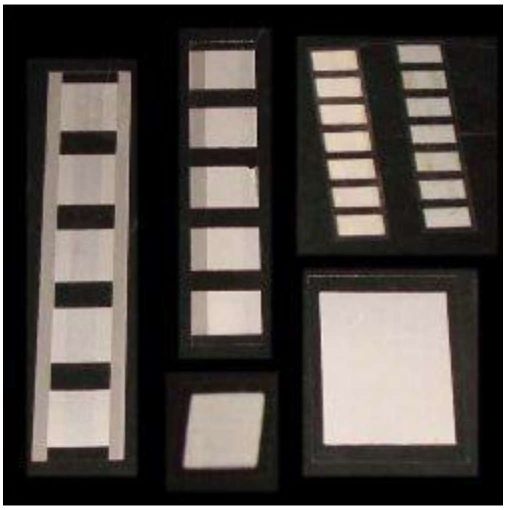


Figure 2.8 : Sintered Mica Chips [18]

2.3.3.1.3 Stacked silver mica capacitors

Cut mica films are cleaned with de-greasing agents. Applying silver on both sides by using screen printing makes a good adhesion between mica and silver. Several layers are used to get the capacitance [18].

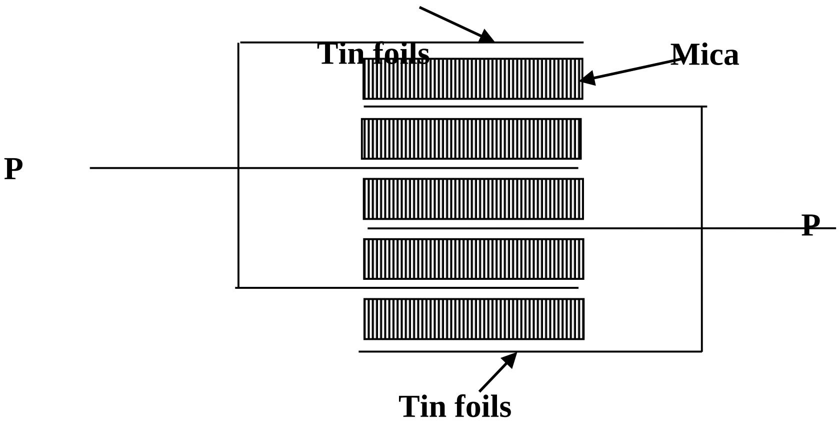


Figure 2.9 : Stacked mica capacitors [17]

For Silver mica capacitors, the Silver paste is coated directly on to the mica layer and using multiple layers, necessary capacitance can be obtained.

2.3.4 Studies on mica capacitors

In 2005, Rajesh Roy and Arun Pandya studied how properties of mica capacitors vary, before and after gamma irradiation. As a part of the study, observed the properties of thin film capacitors made with phlogopite mica. Followings are the findings of the study. [19]

They have assessed the characteristics and capacitance of various sizes and thicknesses of mica films. Phlogopite micas of 20 µm and 40 µm thickness have been used to prepare the capacitors. A 0.20µm thickness pure aluminum were coated over 1 cm^2 and 4 cm^2 areas of mica and copper and silver contacts were used.

Considering the thickness and area four batches namely A, B, C and D have been formed as below.

Table 2.3 Summary of capacitances [19]

Batch	Theoretical values (pF)
A (20 µm,1 cm^2)	233.88
B (20 µm,4 cm^2)	935.51
C (40 µm,1 cm^2)	116.94
D (40 µm,4 cm^2)	467.76

The experimental average relative permittivity (ε_r) of the used phlogopite mica samples at 1 kHz was 5.283. Taking this value and using equation (1) above, capacitance for each batch above have been calculated and shown in Table 2.3. It is clear that values are within 100 pF and 1000 pF. Further those results have been verified by the variation in capacitance - frequency behaviour ranging from 100 Hz to10 MHz

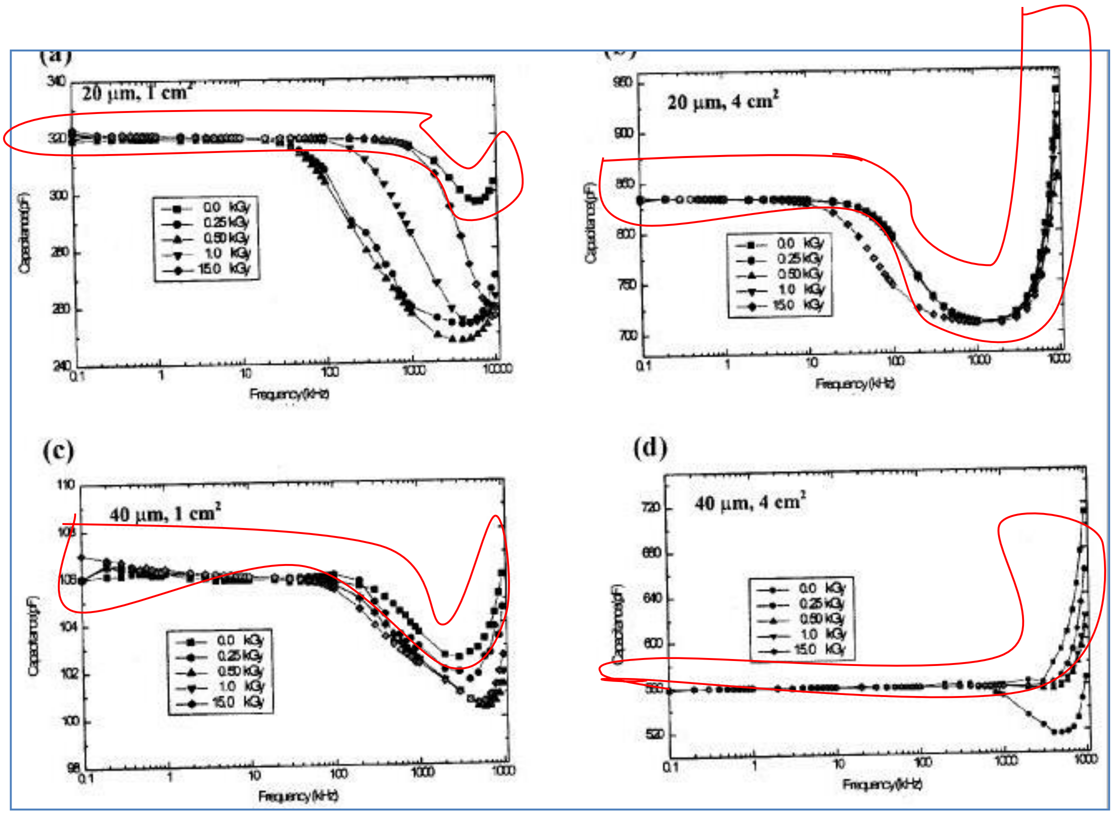


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Figure 2.10: Capacitance–frequency of mica [19]

Figure 2.10 illustrates the Capacitance–frequency characteristics of dissimilar batches of mica measured at frequencies from 100 Hz–10 MHz before and after gamma irradiation.

The capacitance–frequency relationship shows how capacitance vary with frequency It is observed a shift in the curves. The above graphs show at frequencies less than 10 kHz, capacitance remains same during irradiation but at frequencies beyond 10 kHz, it has shown a higher variation in capacitance.

R. P. Deshpande in 2012 mentioned that after an endurance test on mica capacitors which were under shelf storage over 10,000 hours, practically no variation has been shown in capacitance value or loss tangent (D) and frequency stability for both capacitance and D is impeccable, as shown in the Figure 2.11 below.

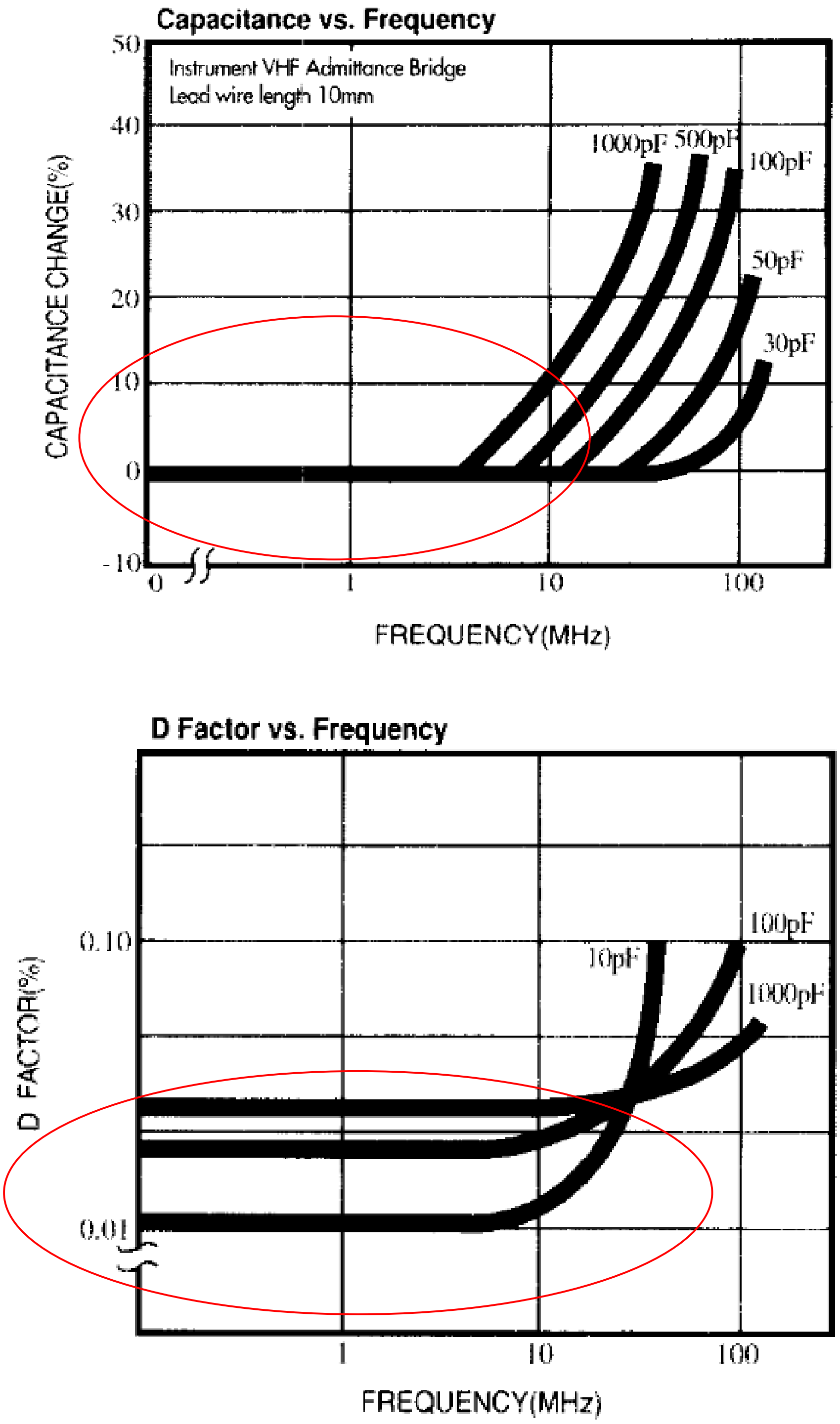


Figure 2.11: Relation of D and capacitance value of mica capacitor with frequency, JoKwang [20]

The dielectric properties of mica have been investigated by measuring various parameters (Dissipation factor (tan δ), capacitance against 10 MHz to 120 MHz frequency .at selected temperatures to 1050 ^{o}C by Lakhwant Singh, Sukhnandan Kaur, Mohan Singh and Navjeet Kaur. [20]

2.4 Radio Frequencies (RF) and Capacitors

RF is any of the electromagnetic wave frequencies that lie in the range of 20 kHz to 3 MHz and the frequencies used in radio communications.One of the main properties of RF is its ability to flow through paths that contain insulating materials ,like the dielectric insulators of capacitors.This is because the capacitive reactance in a circuit decreases with frequency. [21]

As designated by the ITU (International Telecommunication Union),Radio Frequency bands are as follows
3kHz -30 kHz Very Low Frequency (VLF)
30 kHz- 300 kHz Low Frequency (LF)
300 kHz-3 MHz Medium Frequency (MF)
3 MHz -30 MHz High Frequency (HF)

3 METHODOLOGY

3.1 Materials Used

3.1.1 Mica

Samples from four different locations in Sri Lanka i.e. Kebethigollewa (K), Mathale (MT), Mailapitiya (MP) and Badulla (B) were used in this study.

Figure 3.1: Mica samples used for the study

3.1.2 Silver paste

A conductive silver paste was used.

3.1.3 Poly Vinyl Alcohol (PVA)

A solution was prepared, dissolving 1.5 g of PVA (Poly Vinyl Alcohol) crystals in 100 ml of de -ionized water, to be used as a binder in fabricating powder mica discs.

3.2 Apparatus

3.2.1 Ball mill

A ball mill is a type of grinder consists of a hollow cylindrical shell rotating about its axis .It is used to grind and blend materials . Impact caused by the balls when they dropping from top of the shell of the mill will do size reduction.

3.2.2 Standard Sieves

The test sieve used has following specifications: BS 410 Laboratory Test Sieve, Frame material: brass, aperture size: 75 µm, Mesh material: Stainless Steel, Manufacturer: ENDCOTTS LTD. London, England.

3.2.3 Uni Axial Press

The Uni Axial Press with dial gauge used to prepare discs. Conditions used were pressure: 7 bars, duration: 1 minute.

3.2.4 Mould

A cylindrical shaped mould with 2.5 mm thickness and 10 mm diameter was used to prepare discs of mica powder.

3.2.5 Micrometer Screw Gauge

This was used to measure thickness of silvered mica flakes High Accuracy Digimatic Micrometer, make: Mitutoyo- Made in Japan, range: 0.0001 mm.

3.2.6 X -Ray Diffractometer

This provides the "fingerprint" of a crystalline material to identify unknown phases in a mixture. It can be used for mineral identification and determination of lattice parameters.

The XRD analysis was conducted with a Rigaku Ultima IV diffractometer. Specifications: Powder type, employing Copper $K_{\alpha 1}$ X rays with a wavelength of 1.54060^0A, Tube Voltage 40 kV; Tube Current 30 mA; Scan angle (range), 3^0 -160^0, Scan speed used = 20/min, Sampling width = 0.020, Size of the powder used: less than 90µm, Scan angle (range) used =3^0 -140^0 .

3.2.7 Scanning Electron Microscope (SEM)

This is used to identify Crystalline / amorphous structures of materials, Crystal defects and nano particles etc. Specifications: Type: LEO, 15X to 300X, magnification Resolution: 3. 5nm.Since mica is non-conductive material, sample was gold sputtered to make it suitable for SEM.

3.2.8 Programmable Electric Furnace

Temperature range used 900^0C to 1240^0C for 2 h in an electric furnace using a heating rate of 5 ^{0}C/min. and furnace cooling.

3.2.9 Vernier Caliper

This was used to measure diameter and thickness of the sintered mica discs. make: Mitutoyo- Made in Japan, Serial no. 51498026

3.2.10 LCR Hi tester

This was used to measure Capacitance, (C), Loss Tangent, (D) and Frequency of silvered mica flakes and sintered mica discs

Figure 3.2: LCR Hi tester

3.3 Experimental Procedure

3.3.1 Specimen Preparation and measurement

Four samples of local mica namely (K), (MT), (MP) and (B) were used to prepare specimens by using two different methods.

1. Ceramic method
2. Flake method

3.3.1.1 Specimen Preparation for ceramic method

Mica flakes were ground and mixed thoroughly using a ball mill with ceramic balls of different sizes for 2 h. The mixture was sieved to obtain less than 75 μm particles.

(a) XRD and SEM analysis

For the observation of crystalline phases, X-ray diffraction (XRD, Rigaku Ultima IV, Cu-K_{α} radiation, Scan angle (range) =3^0 -140^0) was used. The micro structural examinations by using scanning electron microscopy (SEM, LEO, and 15 X to 300kX) were performed.

(b) Preparation of disc shaped specimens

2-3 drops of Poly Vinyl Alcohol (a binder) were mixed with sieved mica powders of less than 75 μm particles and uni- axial pressing was employed to shape the samples. Discs with 2.5 mm thickness and 10 mm diameter were shaped under the 7 bar pressure for one minute and then sintered at selected temperatures between 900°C -1240°C at the heating rate of 5°/min for 2h. Weight, thickness and diameter of each properly sintered specimen were measured.

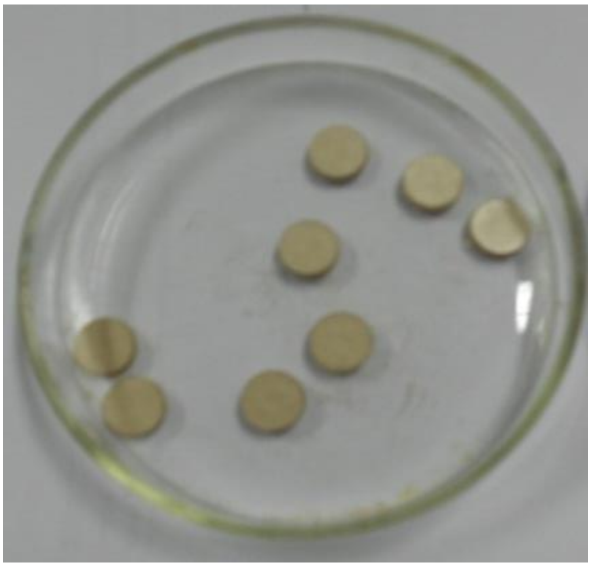


Figure 3.3: Several specimens before sintering

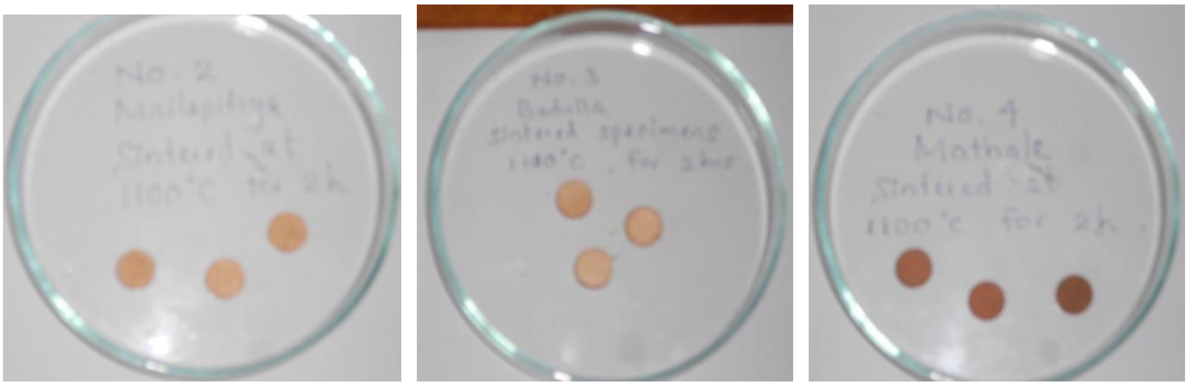


Figure 3.4: Several specimens after sintering

(Sintering cycle: 1100 ^{0} C, 2 hours, rate: 5 ^{0} C/min)

(c) Measurement of water absorption %

Water absorption test was carried out as per the method given in ISO 10545-3:1995 - Determination of water absorption for ceramic tiles.

Although all specimens were sintered at 1240 ^{0} C, only Mathale and Mailapitiya specimens have been properly sintered enough to carry out the water absorption tests. Sintered mica discs were kept in an electric oven adjusted to (110±5) ^{0}C, until constant mass is achieved. i.e. until the difference between two consecutive weighings at 24 h intervals is below 0.1%. Then the specimens were cooled in a desiccator and each specimen was weighed with an analytical balance.

Each specimen was placed in a beaker of 125 ml volume and five beakers were simultaneously placed on a hot plate maintaining a depth of 5 cm of water above the specimens. Once water boiled, boiling was continued for 2 h, then heating was stopped and specimens were allowed to cool to room temperature, still completely immersed, in 4 h + 15 min.

Dried cotton cloth was used for dabbing water on the specimens and each specimen was weighed.

Water-absorption percentage (E) was calculated by

$$E = \frac{m_2 - m_1}{m_1}$$

Where,

m_1 – mass of dry specimen;

m_2 - mass of wet specimen.

(d)Application of Silver paste

Conductive silver paste was applied on one surface of sintered disc and allowed to dry at room temperature. Then other side of the disc was silver coated. Specimens were dried in an electric oven at 150 ^{0} C for 2 hours and kept to cool at room temperature.

3.3.1.2 Preparation of flaky silver –mica specimens

Using a steel template, mica sheets of 3 cm x 3 cm were cut. Using a pointed tool individual thin layers were carefully delaminated. Flaw less squares of mica flakes having uniform thicknesses have been selected for the application of conductive silver. Thicknesses of flakes were measured using a micrometer screw gauge. Silver paste was applied on both surfaces of each mica flake, using the steel template with a cut of 1cm x 2 cm area ($200mm^2$) as shown in Figure 3.5 and a small painting brush. Specimens were dried in an electric oven at 150 ^{0}C for 2 hours and kept to cool at room temperature.

Figure 3.5: Application of silver paste on mica flakes

3.3.2 Measurement of Capacitance

3.3.2.1 Capacitance of silver coated sintered pellets

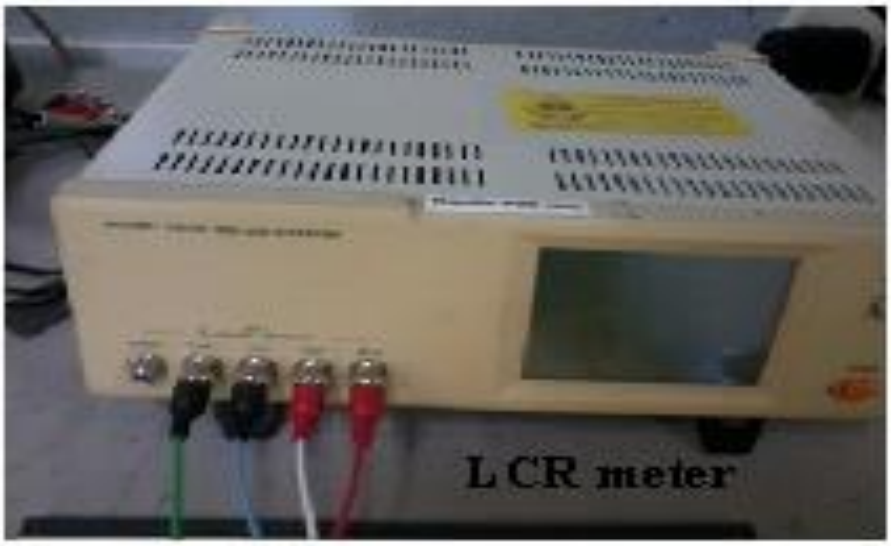


Figure 3.6: Measurement of capacitance of silver coated sintered pellets with LCR meter

One of the specimens prepared as described in 3.3.1.1 (b) was mounted on the device attached to the LCR meter as shown in Figure 3.12 and set the frequency as 10 kHz and corresponding Capacitance (C) was measured. Likewise, C values of sintered specimens of Mathale and Mailapitiya samples were measured at 10 kHz, 50 kHz, 100 kHz, 500 kHz and 1000 kHz (1 MHz), frequencies and readings tabulated were in Appendix – B.

3.3.2.2 Capacitance of silver coated mica flakes

As described in 3.3.2.1 Capacitance (C) values of silver coated mica specimens of Mathale, Mailapitiya, Badulla and Kebethigollewa samples were measured at 10 kHz, 50 kHz, 100 kHz, 500 kHz and 1000 kHz (1MHz), frequencies and readings tabulated were in Appendix – B.

4. RESULTS AND DISCUSSION

4.1 X- Ray Diffraction results

4.1.1 Mica sample -Mathale

According to the x ray diffraction data, two different phases were identified.

i. **Phlogopite 1 M - $KMg_3(Si_3Al)O_{10}(OH)_2$**

Monoclinic structure with two layers per unit cell

ii. **Phlogopite 3 T- $KMg_3(Si_3Al)O_{10}(OH)_2$**

Trigonal (hexagonal) structure with three layers per unit cell.

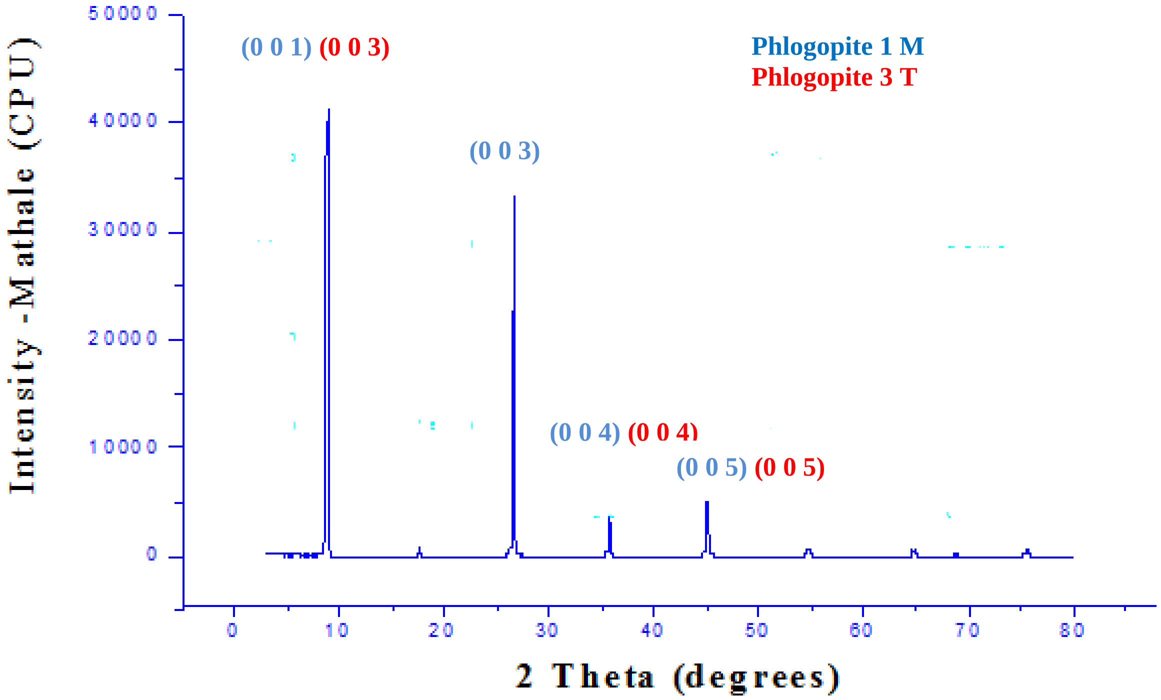


Figure 4.1: XRD Pattern of Mathale sample

4.1.2 Mica sample -Badulla

According to the x ray diffraction data, three different phases were identified.

i. Phlogopite 1 M - $KMg_3(Si_3Al)\ O_{10}(OH)_2$

ii. Hendricksite -$KZn_3Al\ Si_3O_{10}(OH)$

iii. Wustite- $Fe_{0.92}\ O$

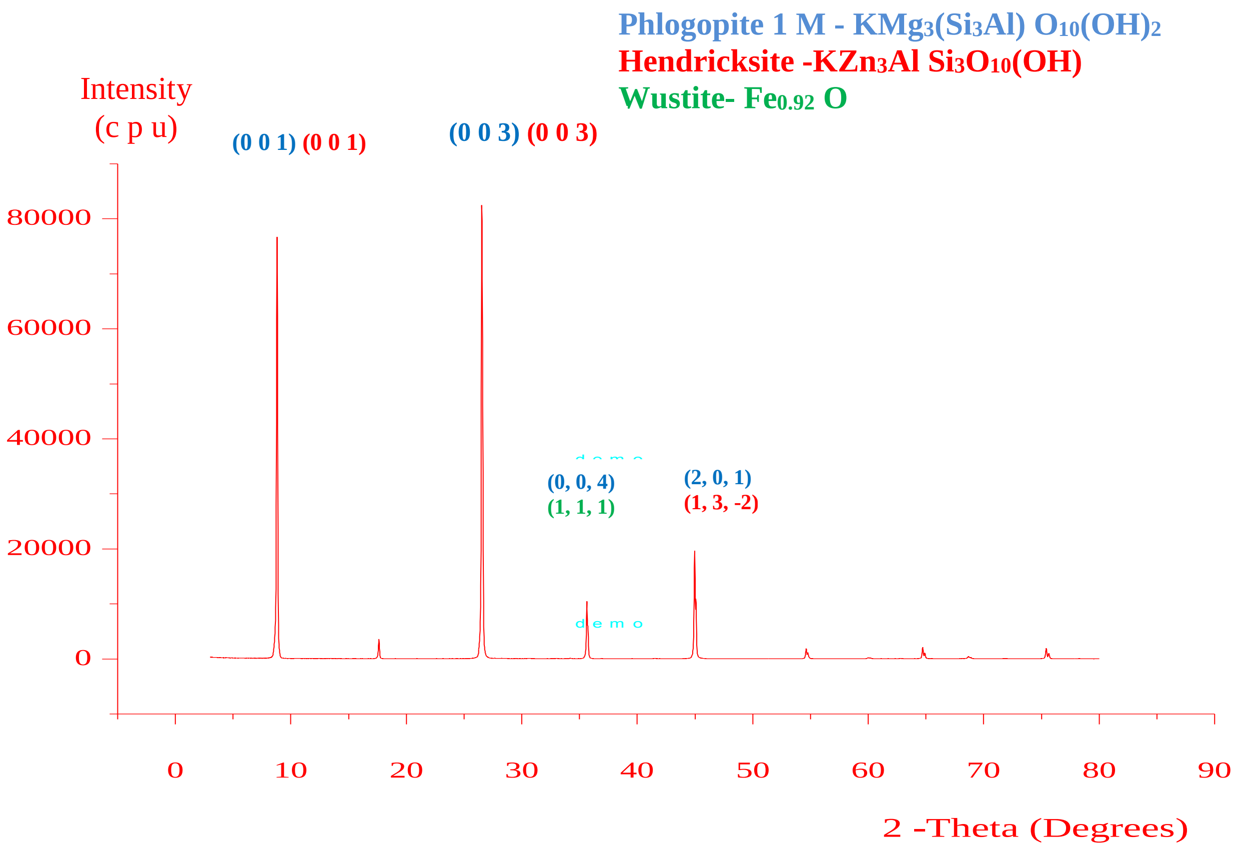


Figure 4.2: XRD Pattern of Badulla sample

4.1.3 Mica sample -Mailapitiya

According to the x ray diffraction data, two different phases were identified.

i. Phlogopite 1 M - $KMg_3(Si_3Al)O_{10}(OH)_2$

ii. Biotite -K Fe $Mg_2(Al\ Si_3\ O_{10})(O\ H)_2$

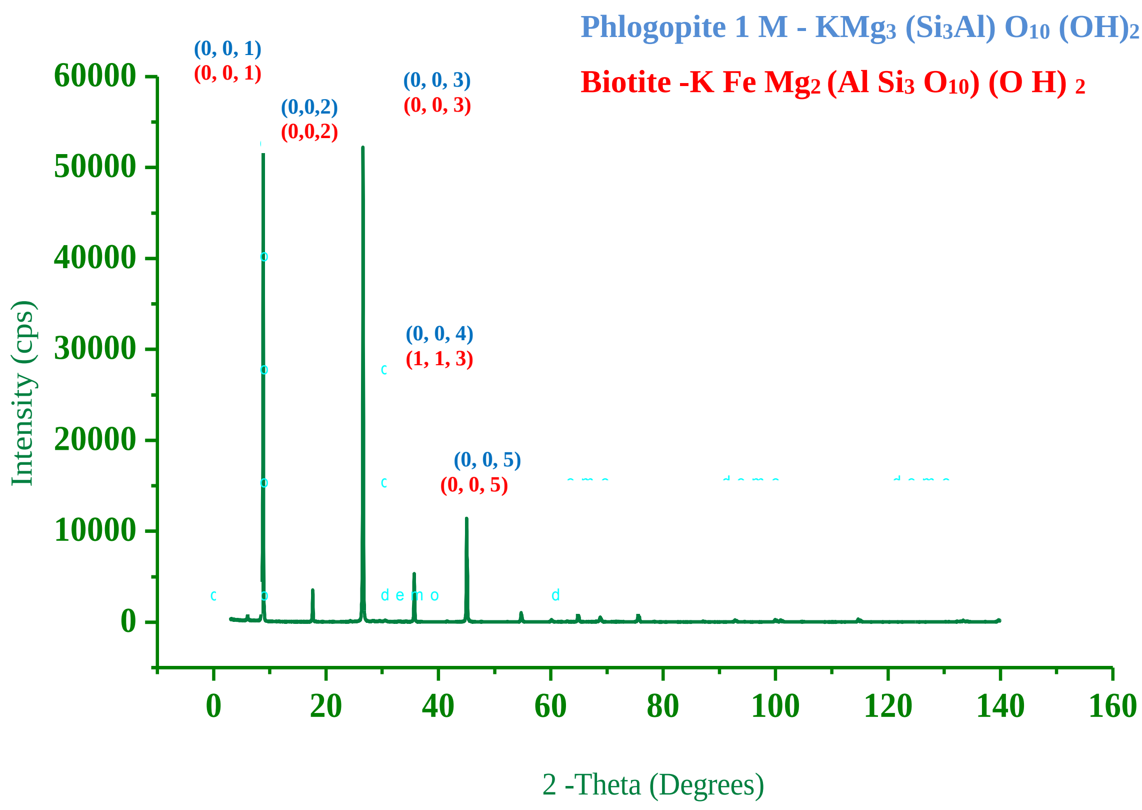


Figure 4.3: XRD Pattern of Mailapitiya sample

4.1.4. Mica sample – Kebethigollewa

According to the X- ray diffraction data, Phlogopite-3T is the most significant phase identified.

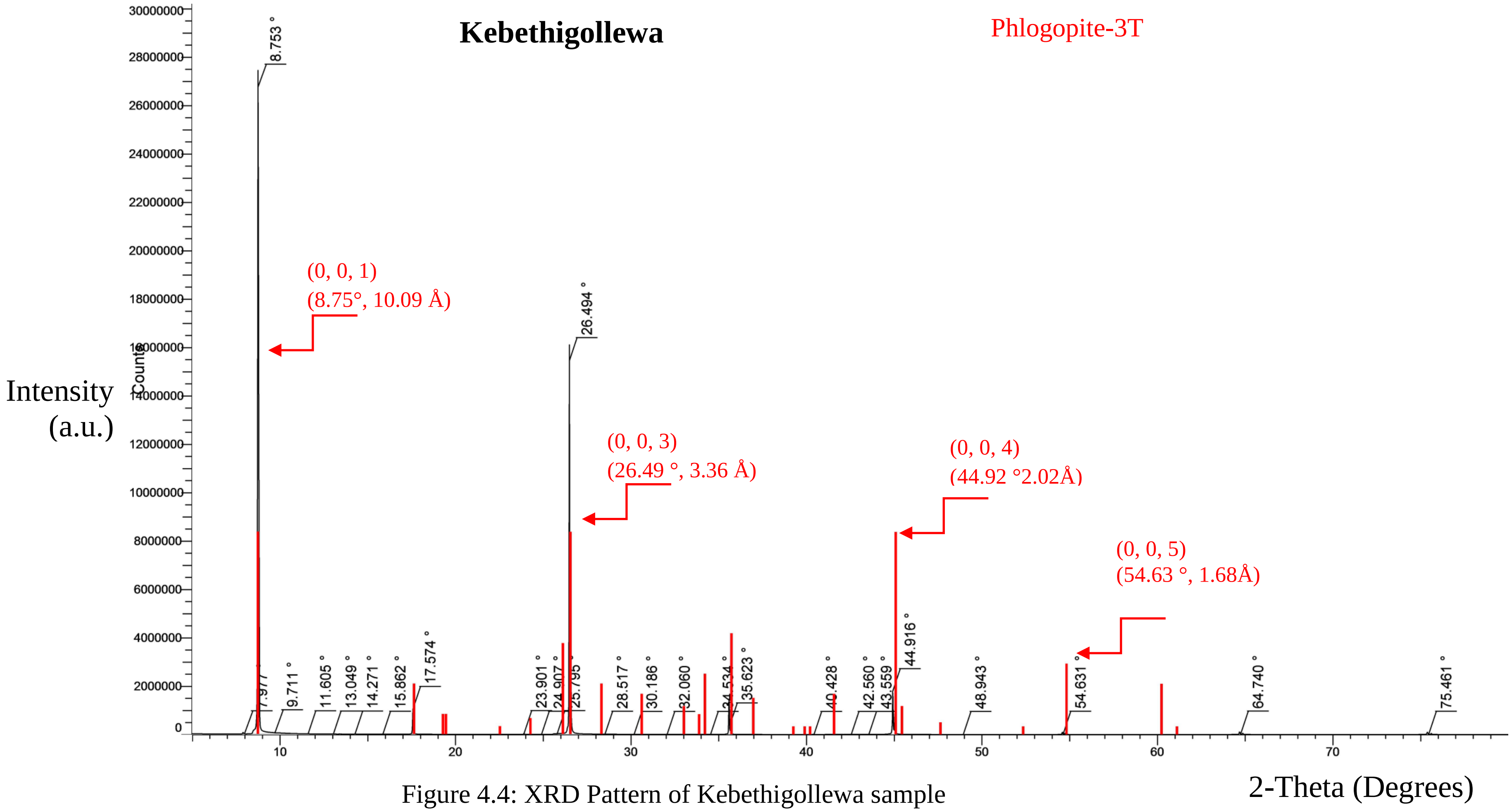


Figure 4.4: XRD Pattern of Kebethigollewa sample

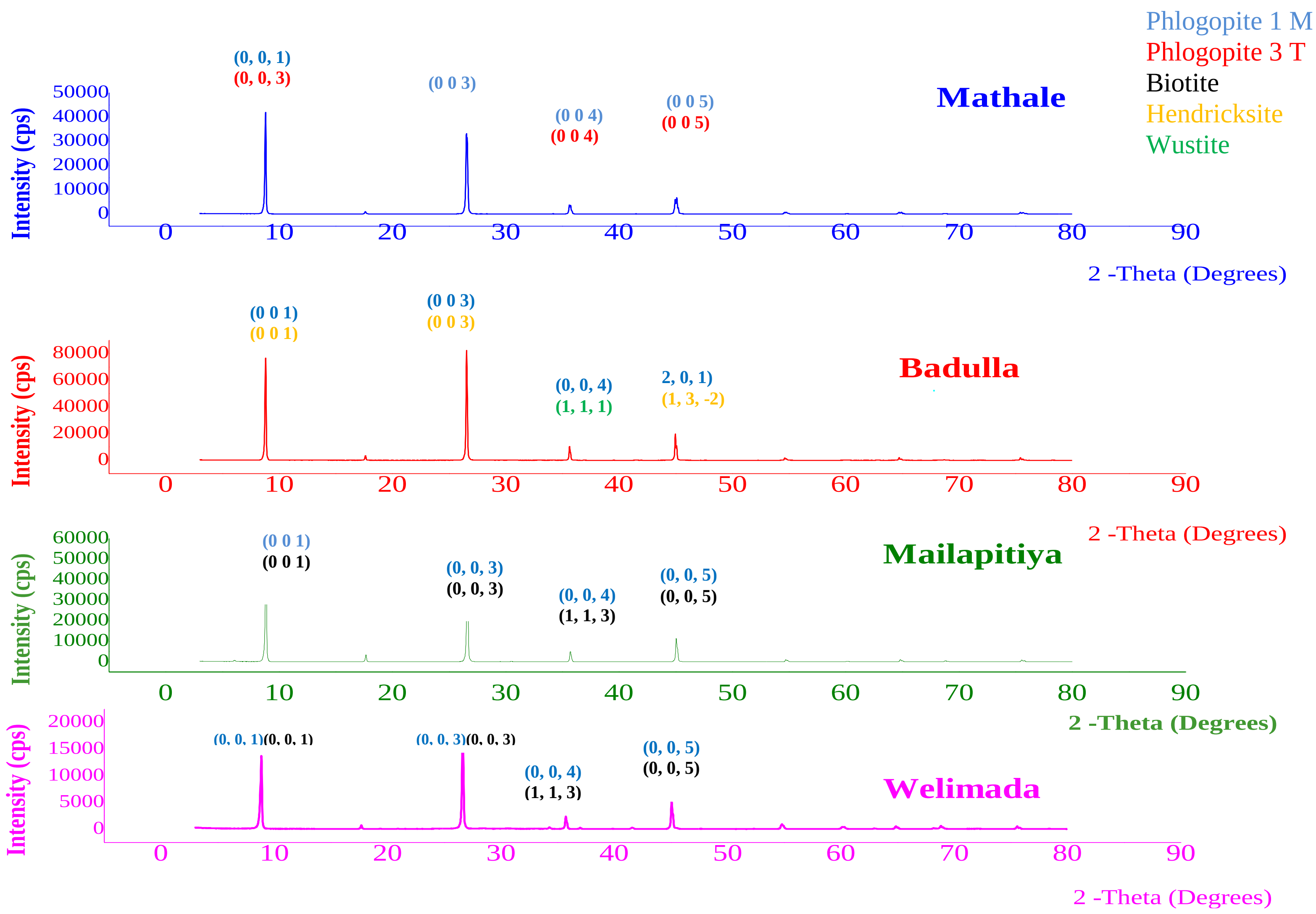


Figure 4.5: Comparison of XRD Patterns

XRDs of mica samples from different locations revealed different crystal structures and poly types. For example, Mathale phlogopite has two different phases, matched with Phlogopite - 1M and Phlogopite - 3T. XRD of Badulla mica revealed two different crystal structures, matched with the peaks of Phlogopite - 1M and another different type of mica called Hendricksite, which is having Zn, instead of Mg in the chemical structure.

XRD of Mailapitiya sample also revealed two different crystal structures, matched with the peaks of Phlogopite - 1M and Biotite, which is an Iron rich mineral. XRD of Kebethigollewa high quality mica sample reveals crystal structures, reveals Phlogopite–3T.

4.2 SEM results

The SEM micrographs (Figure 4.6 & Figure 4.7) confirm that the samples have typical mica-like structures characterized by parallel layers.

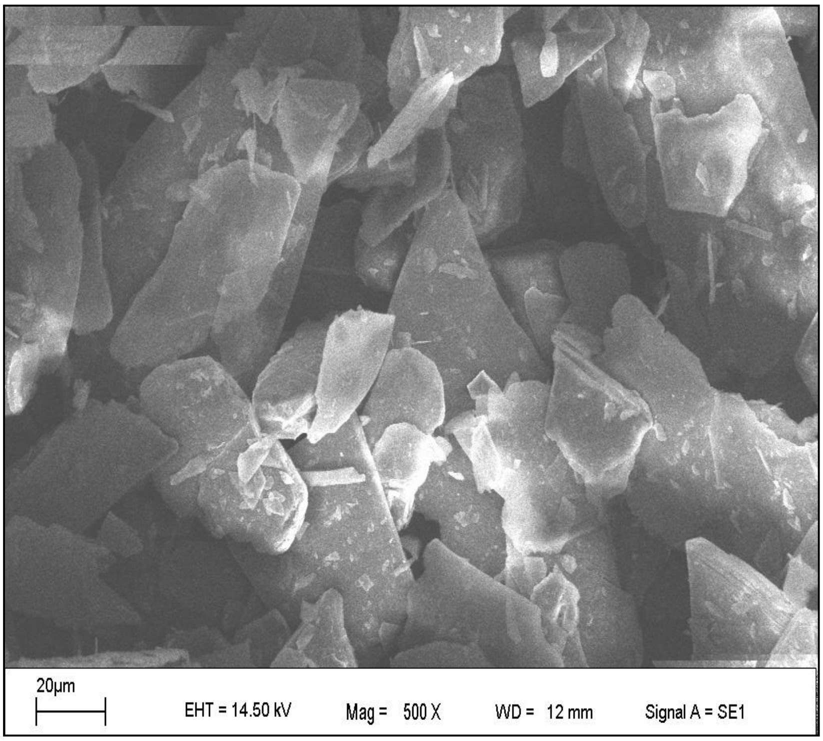


Figure 4.6: SEM micrographs of Mathale mica sample (Mag. =500 X)

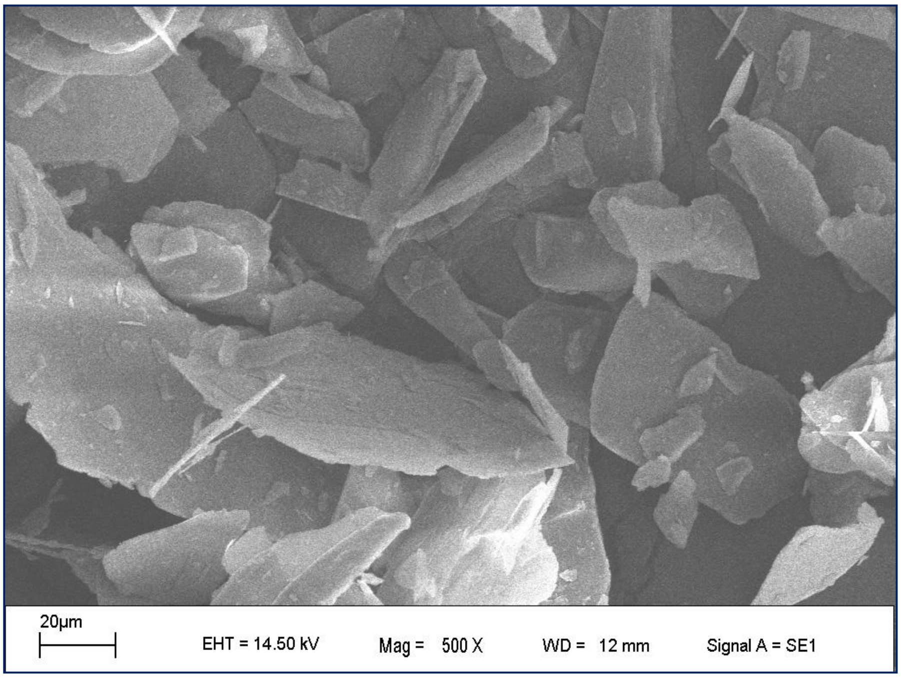


Figure 4.7: SEM micrographs of Mailapitiya mica sample (Mag. =500 X)

The SEM micrographs of Mathale and Mailapitiya samples confirmed that they have typical mica-like structures characterized by parallel layers.

Kebethigollewa sample has a different appearance when compared with other four samples. It has been popular among mica miners as “Kebethigollewa high quality golden mica”, due to its very nice golden colour appearance and considerably large sheets of similar sizes can be very easily removed from the blocks.

4.3 Results of water absorption tests

Water absorption tests carried out on sintered mica samples from Mathale and Mailapitiya showed following results.

Table 4.1: Sintered mica discs-Mathale and Mailapitiya

Specimen No.	WA%	Specimen No.	WA%
SIN-MT1	12.25	SIN-MP1	11.78
SIN-MT2	12.78	SIN-MP2	11.08
SIN-MT3	11.79	SIN-MP3	12.31
Average	**11.73**	Average	**12.28**

According to the results sintered specimens of both Mathale and Mailapitiya show higher values of water absorption. This may be an indicator of higher porosity in the structure of sintered mica discs. Although specimens of mica discs were sintered at 1260^0 C, only Mathale and Mailapitiya specimens were properly sintered. Even though specimens of Badulla and Kebethigollewa samples were sintered at this temperature, the specimens have shown broken edges and when they were touched with fingers, powder particles were removed.

4.4 Dielectric Properties versus Frequency at room temperature

Shown below is how Geyer, (1990) categorized materials according to their dielectric properties.

	dielectric constant (ε')	**loss tangent (tanδ)**
1	Low (≤4)	Low (<0.001)
2	High (≥ 10)	Low (<0.001)
3	Very high (ε' ≥ 100)	Very low (<0.0002)

Mica from different locations (Mathale, Mailapitiya, Badulla and Kebethigollewa), were investigated with dielectric measurement techniques were employed at selected frequencies. Those frequencies are typically within very low frequency, low frequency and medium frequency in radio spectrum, as defined by the International Telecommunication Union (ITU). [21]

Even though studies on chemical composition and dielectric behaviour of minerals (Jinkai, 1990) are available, literature survey shows the works on chemical composition versus dielectric properties of mica are very limited.

4.4.1 Mica Flakes

All mica flakes under study were kept at the room temperature and relative permittivity (ε_r) and loss tangent (D) were measured in the frequency range 1 kHz to 1 MHz. The results obtained are shown in Figure 4.8 to Figure 4.11. Figure 4.8 represents the behaviour of relative permittivity and loss tangent of Mathale mica against and frequency ranging from 1kHz to 1 MHz.

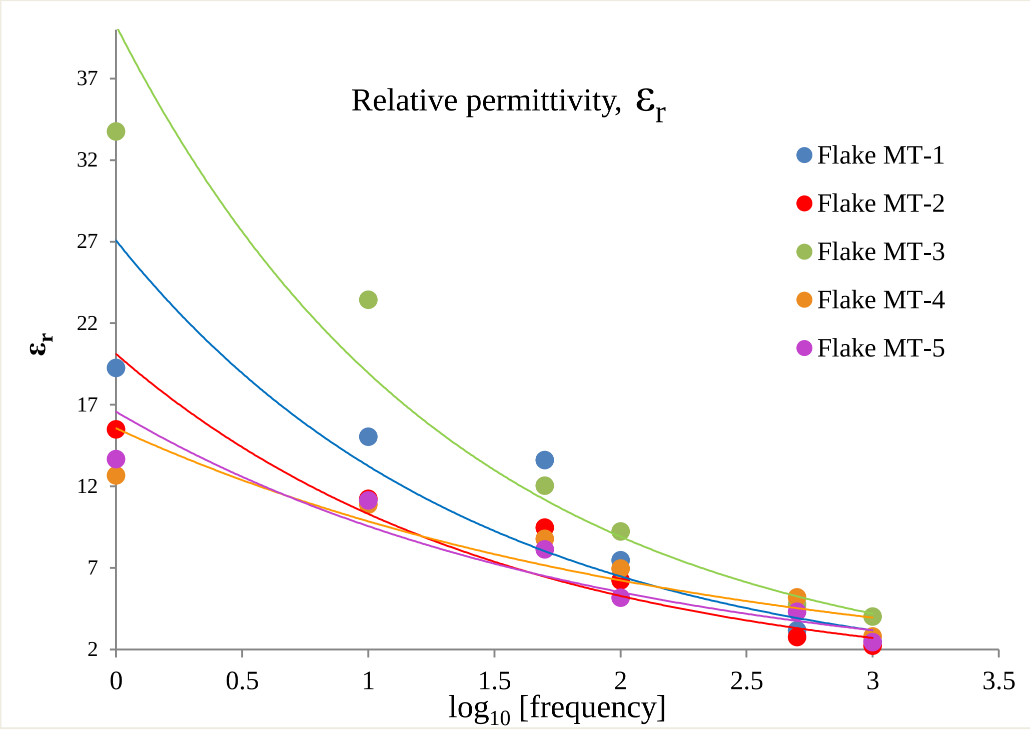
It can be noticed that the relative permittivity (ε_r) decreases with the increasing frequency, in each sample under study, at room temperature. Polarization is the phenomena behind this. Due to exchange of ions in crystals, electrons are locally shifted with the applied field. This will cause polarization. When the frequency increases, it will reach to a point where the space charge cannot bear the variation of the external field and hence the polarization decreases. Hence dielectric constant will also decrease with increasing frequency. [22]

According to Figure 4.8, relative permittivity increased and loss tangent declined with frequency starting from 1 kHz to 1 MHz.

Average Relative Permittivity, $(\varepsilon_r)_{avg}$ and Average Loss tangent, D_{avg} of all flake specimens calculated location wise are shown in Figure 4.12. It can also be noticed, gradual decrease in average relative permittivity, $(\varepsilon_r)_{avg}$ as the frequency of the applied field is increased. The dielectric dispersion occurs specially at high frequencies. This decrease of average loss tangent, D_{avg} with increasing frequency can be explained by the lag of molecules behind the alterations of the applied field.

Dielectric permittivity is how a material will response to an applied field and it varies with frequency and temperature. It also gives information on material properties. Dielectric permittivity of the materials initiates from the space charge polarization induced in that. [23]

4.1.2.1 Mathale



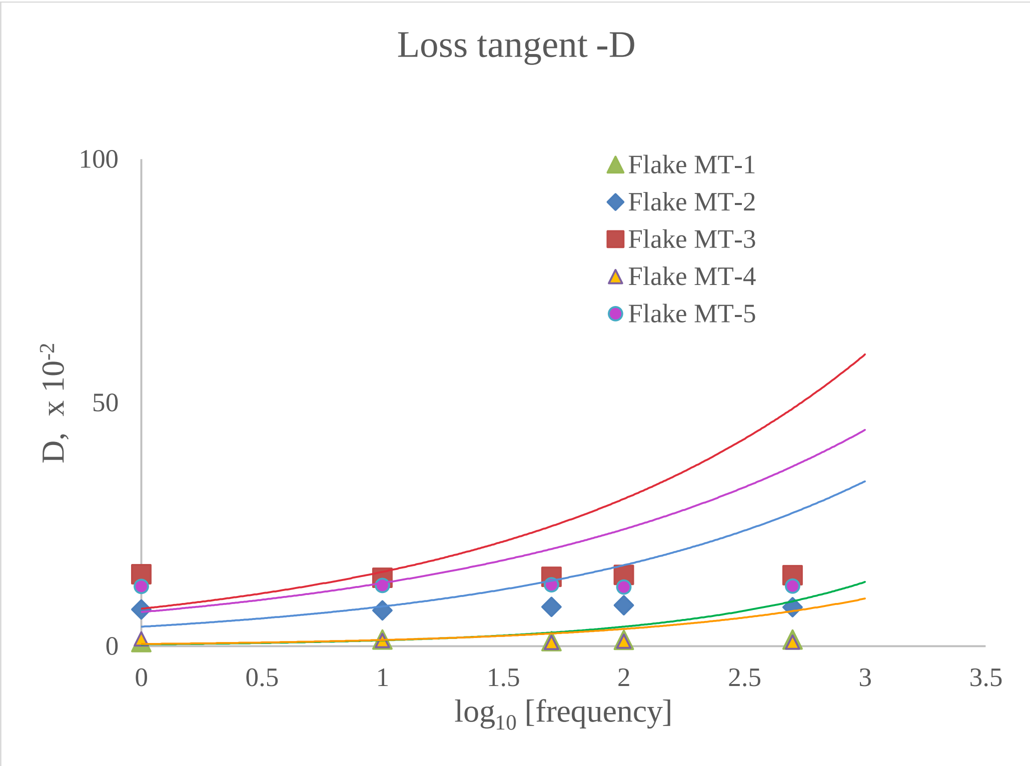
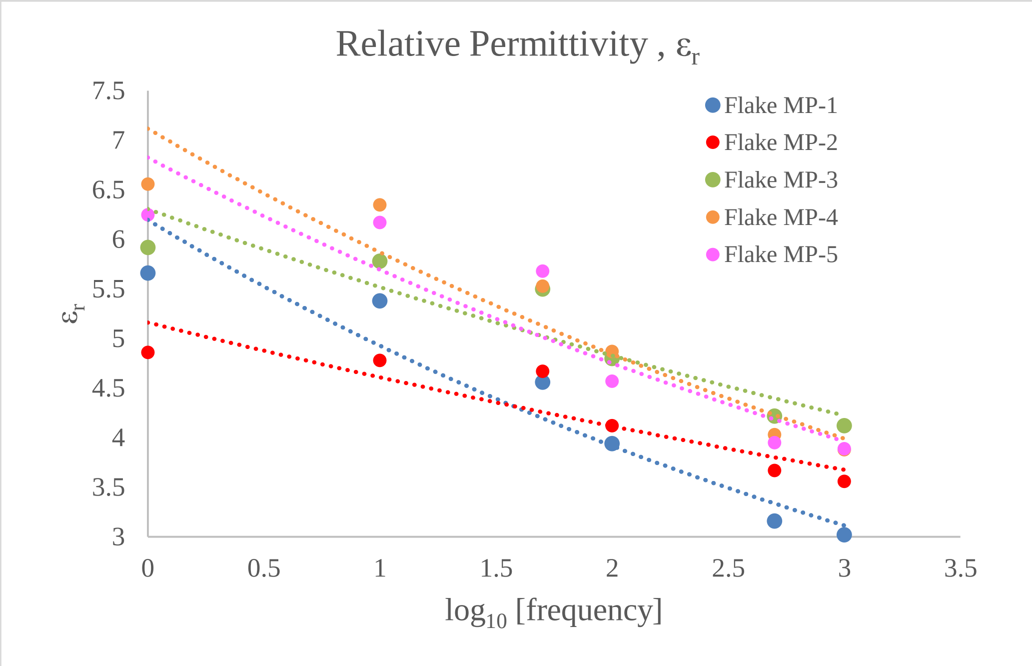


Figure 4.8: Relative permittivity (ε_r) and Loss tangent (D) of Mathale mica flakes

4.4.1.2 Mailapitiya



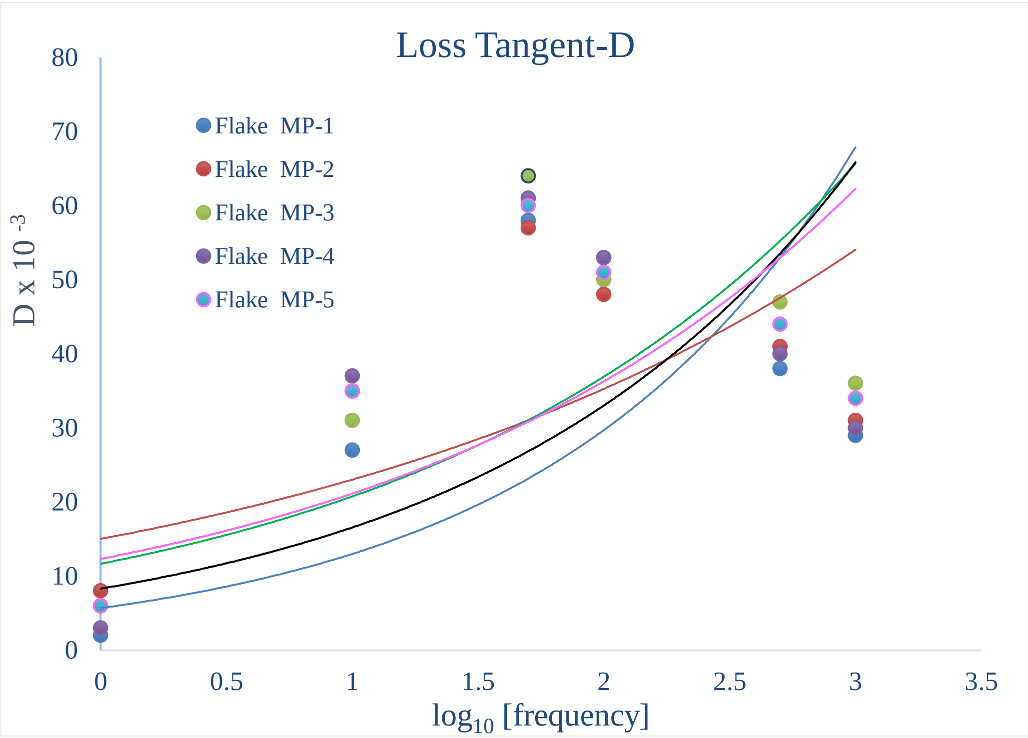


Figure 4.9: Relative Permittivity (ε_r) and Loss Tangent (D) of Mailapitiya mica flakes

4.4.1.3 Badulla

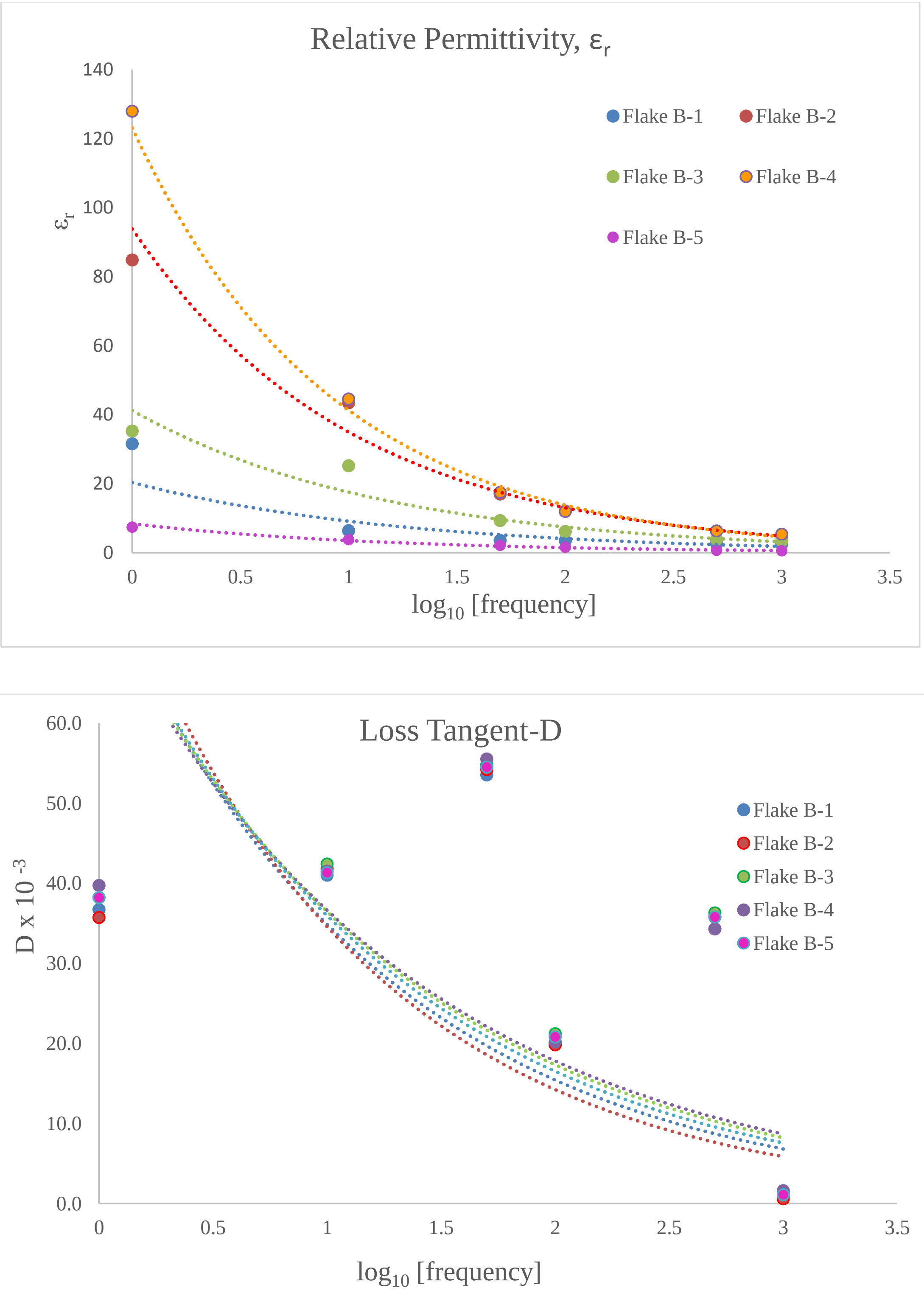
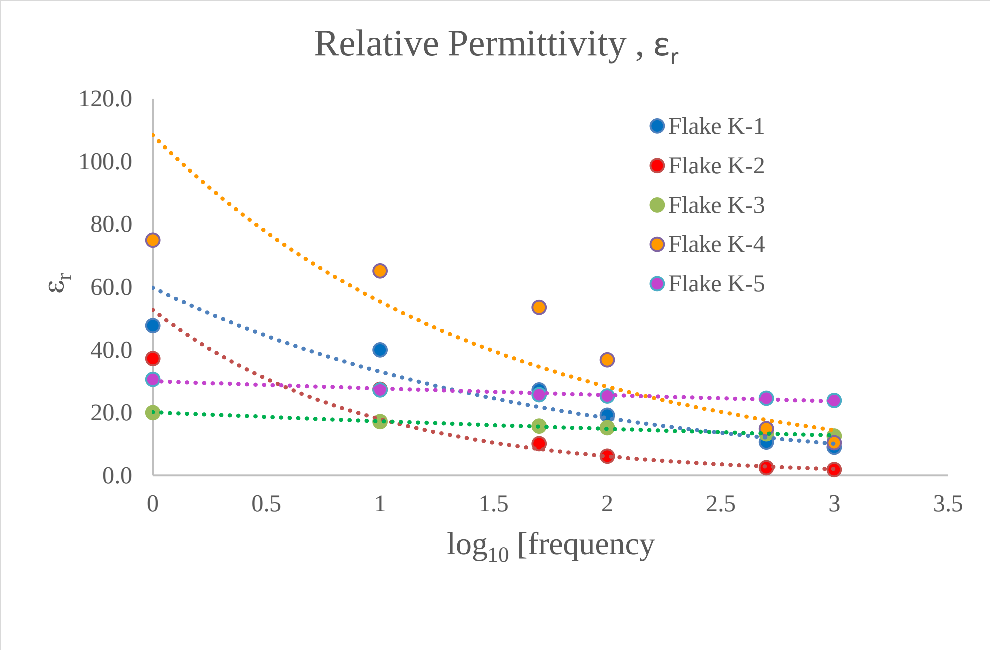


Figure 4.10: Relative permittivity (ε_r) and Loss tangent (D) of Badulla mica flakes

4.4.1.4 Kebethigollewa



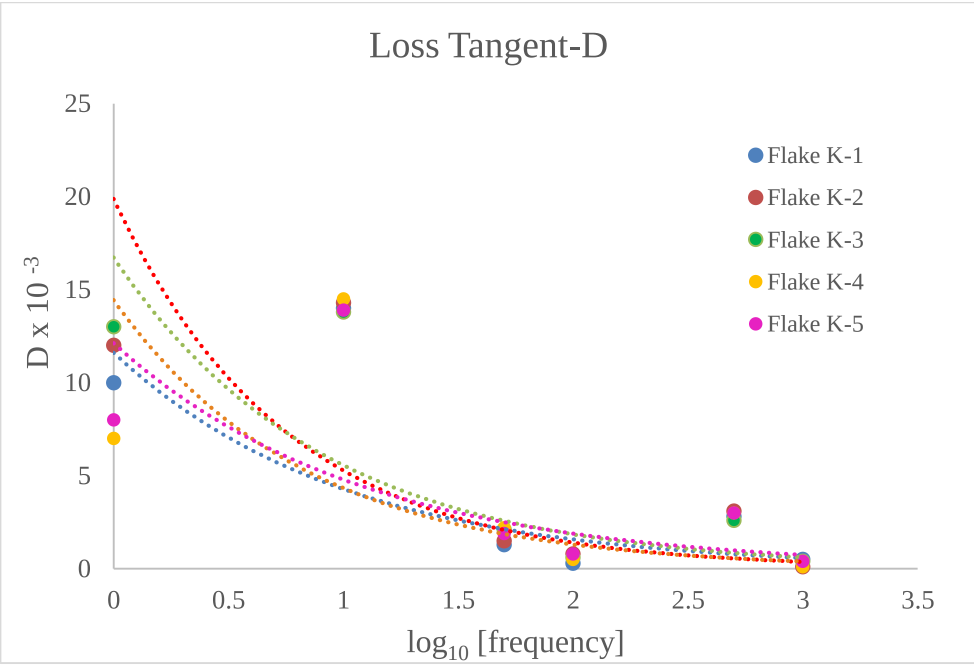


Figure 4.11: Relative permittivity (ε_r) and Loss tangent (D) of Kebethigollewa mica flakes

Mica's layered structure, anisotropic nature and complex composition, has made publications on mica very limited [24]

Figure 4.12 shows the average dielectric constant $(\varepsilon_r)_{avg}$ of Mathale and Kebethigollewa samples, that of Mathale and Mailapitiya samples and that of Mathale and Badulla samples are illustrated in Figure 4.13 and Figure 4.14 respectively.

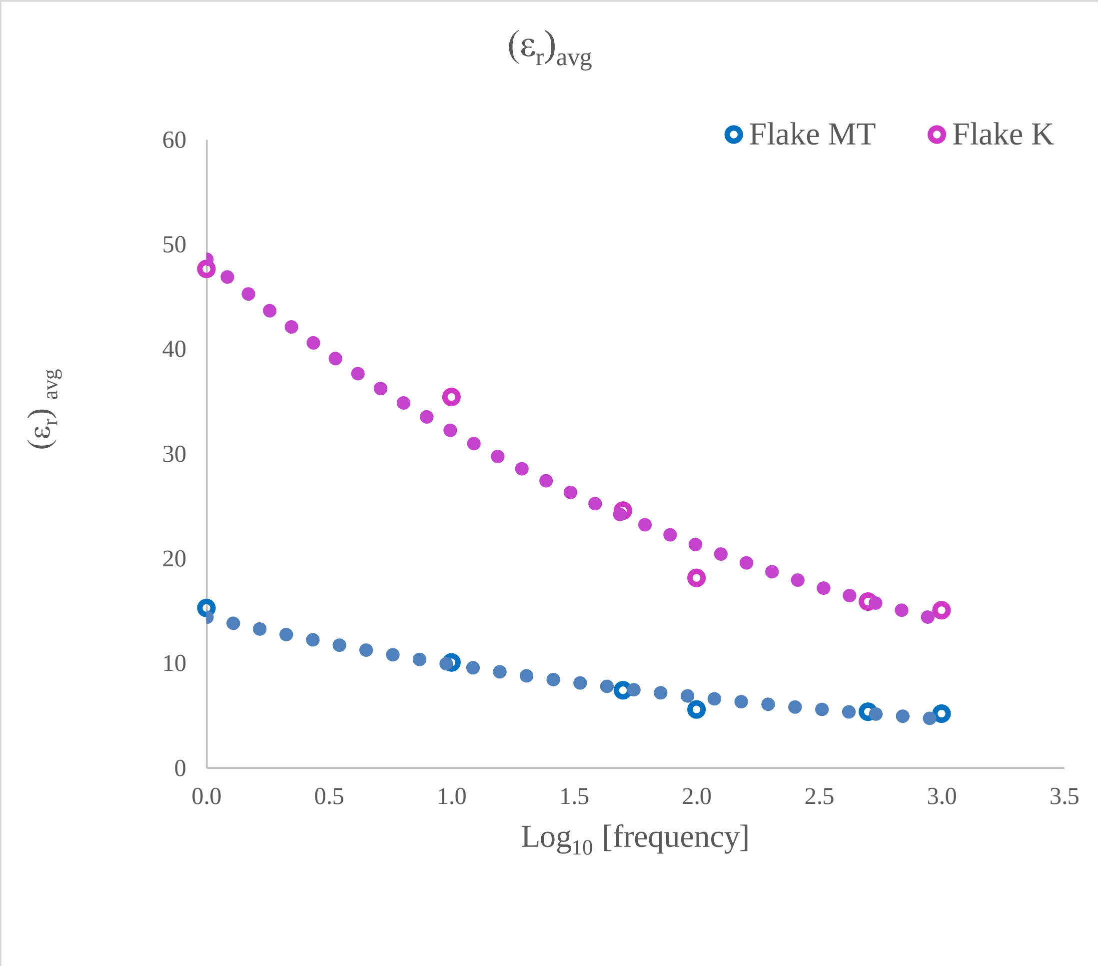


Figure 4.12: Average Relative Permittivity $(\varepsilon_r)_{avg}$ of Mathale and Kebethigollewa mica flakes

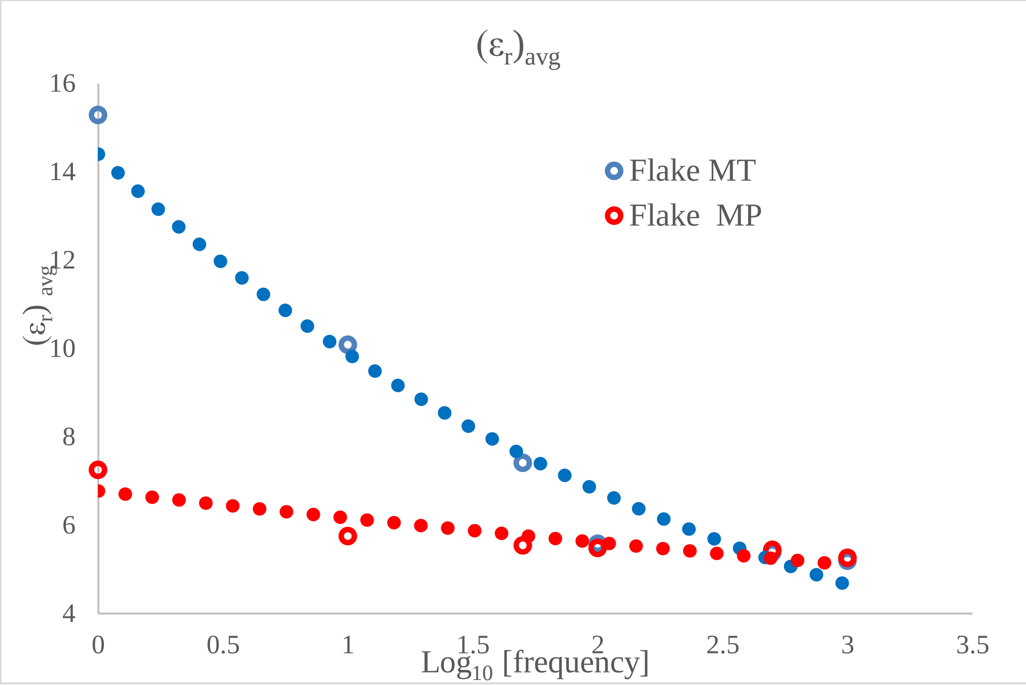


Figure 4.13: Average Relative Permittivity $(\varepsilon_r)_{avg}$ of Mathale and Mailapitiya mica flakes

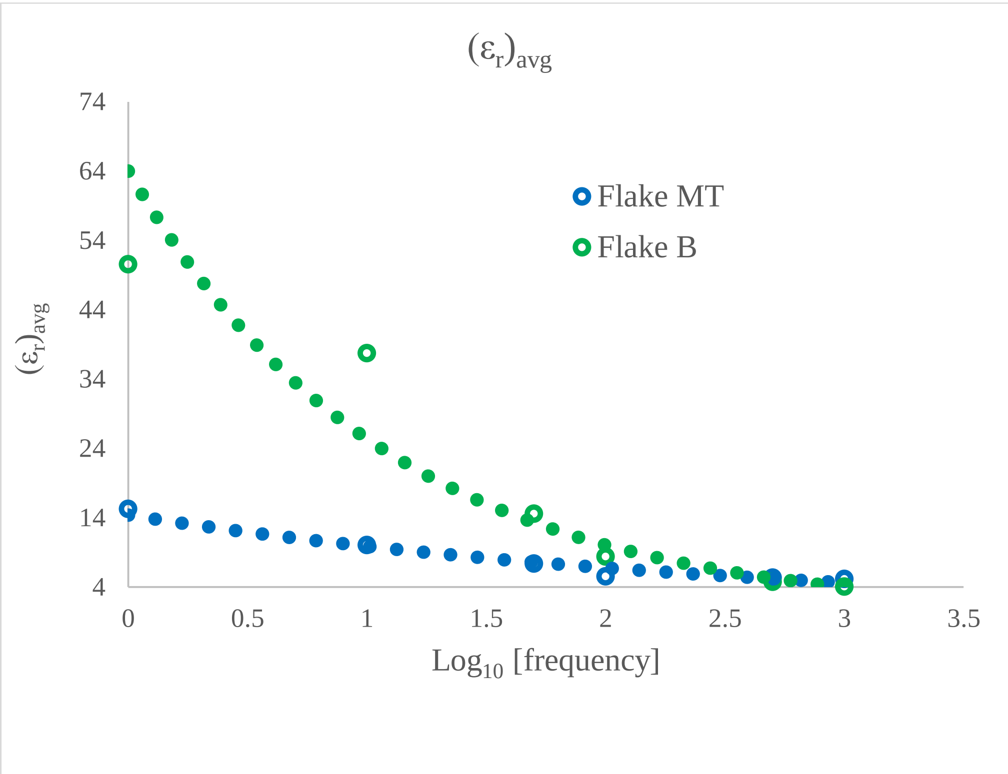


Figure 4.14: Average Relative Permittivity $(\varepsilon_r)_{avg}$ of Mathale and Badulla mica flakes

Figure 4.12 shows that Kebethigollewa sample is the one with higher ε_r at all frequencies compared to Mathale . while Figure 4.14 shows that Badulla sample also has higher ε_r than Mathale sample at same frequencies,except at 1 MHz.However,Figure 4.13 shows that Mathale has higher ε_r than the Milapitiya at all same frequencies,except at 1 MHz.The variation in the relative permitivity of these samples will be due to their varying minerological compositions. The Kebethigollewa is having higher ε_r, higher ε_r Mathale and Badulla samples when compared to the Milapitiya sample, is possibly caused by the polarization effect of ionic conduction of inter-layer cations.

As per XRD results ,Kebethigollewa,Mathale and Badulla samples have higher phlogopite content containing interlayer Mg^{2+} ions when compared to Mailapitiya sample which possesses biotite, i.e. Fe rich mica type with high interlayer Fe^{3+} ions as discussed in section 2.1.2 & 2.1.3. Since polarizing power of $Mg^{2+} < Fe^{3+}$ [25]. conductivity of biotite may be higher than that of phlogopite.This may be a reason for comparatively lowε_r values obtained for Mailapitiya sample .

Also it can be observed through XRD results that Kebethigollewa and Mathale samples are having both phlogopite 1M and phlogopite 3T,while Badulla sample contains only phlogopite 1M .This phlogopite 3T in Kebethigollewa and Mathale samples may be a reason for their comparatively higher ε_r values compared to Badulla sample.

Figure 4.15 illustrates D_{avg} of Mathale and Kebethigollewa samples from 1 kHz to 1 MHz, while Figure 4.16 and Figure 4.17 show that of Mathale and Mailapitiya samples and that of Mathale and Badulla samples respectively across the same frequency range.

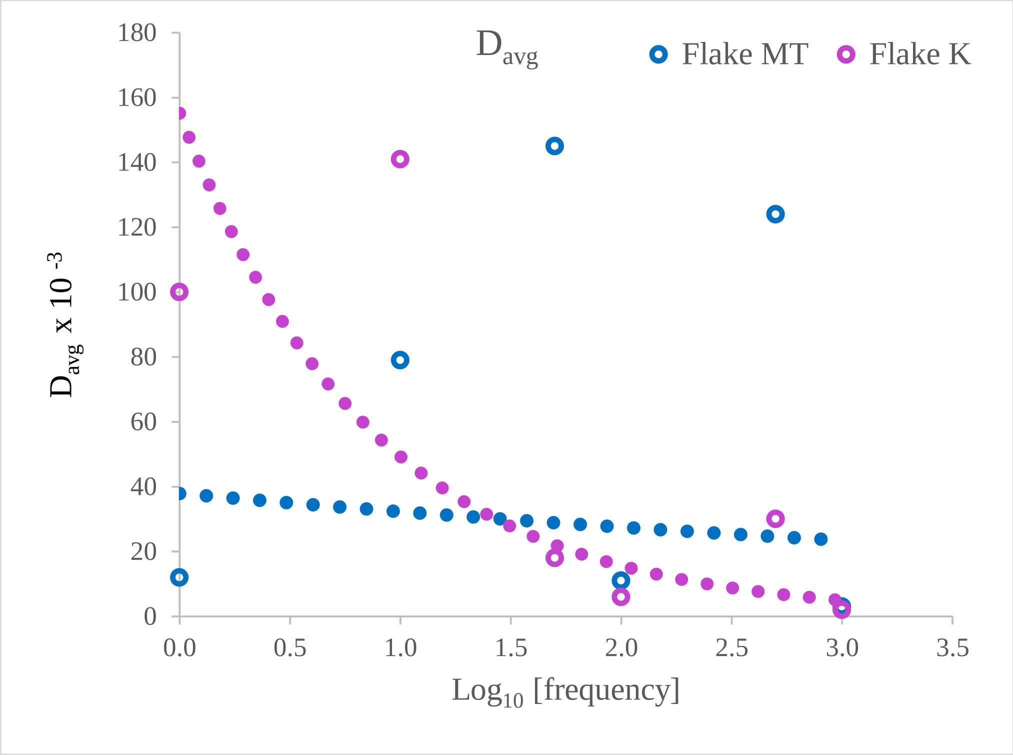


Figure 4.15: Average Loss Tangent of Mathale and Kebethigollewa mica flakes

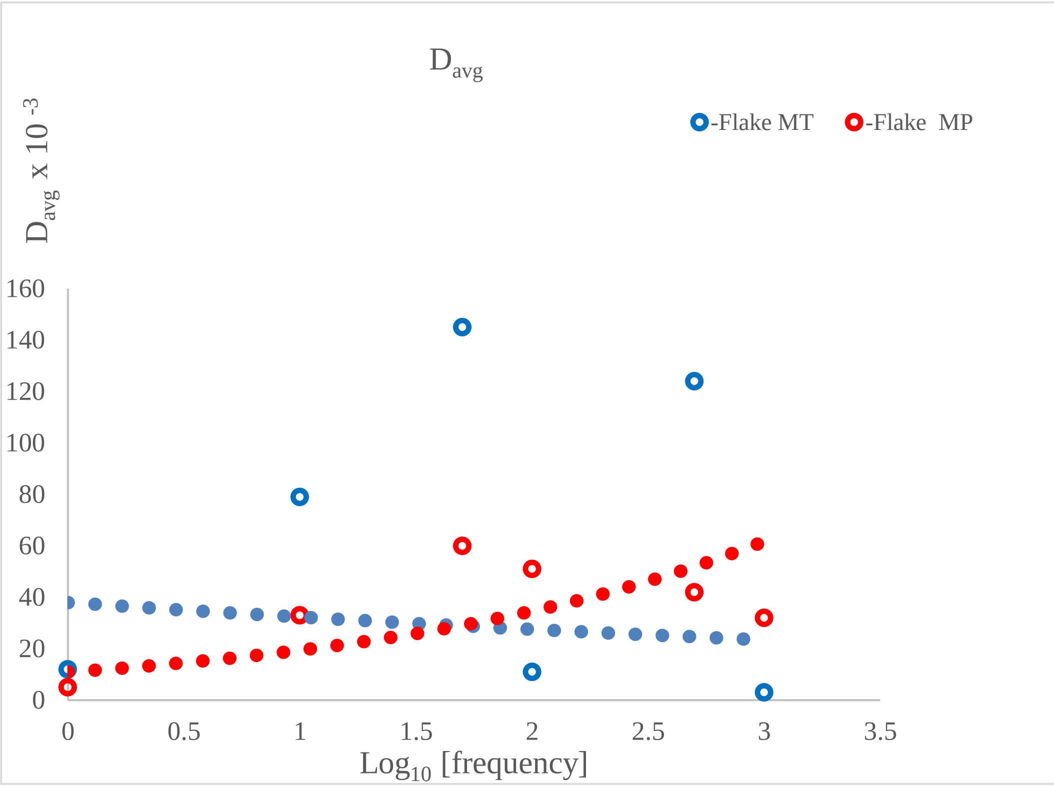


Figure 4.16: Average Loss Tangent of Mathale and Mailapitiya mica flakes

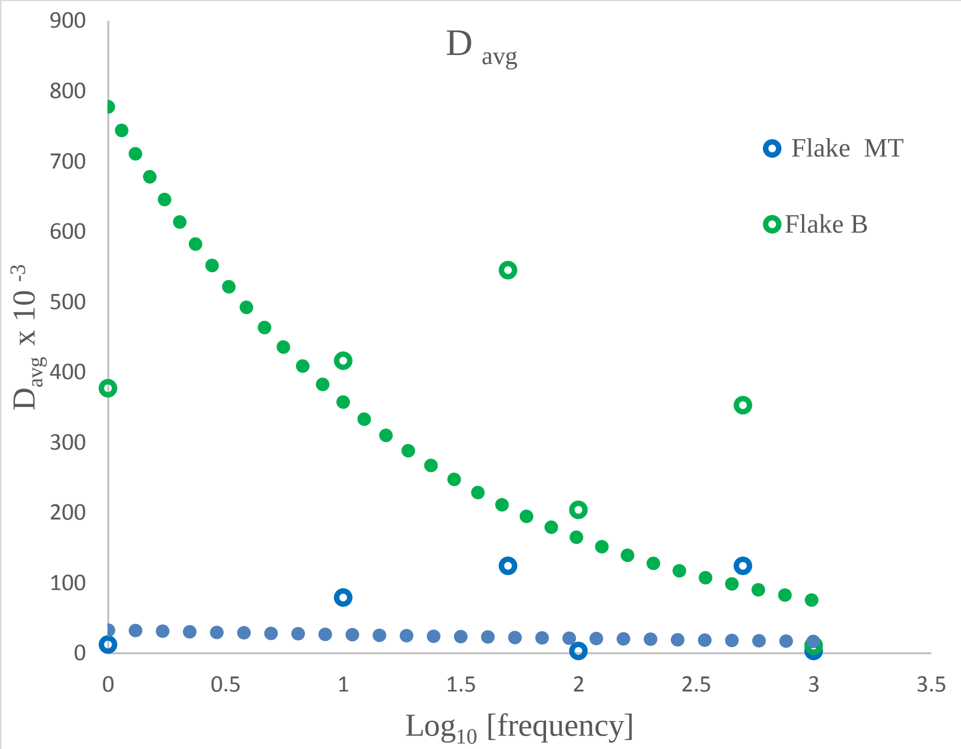


Figure 4.17: Average Loss Tangent of Mathale and Badulla mica flakes

Average Relative Permittivity, $(\varepsilon_r)_{avg}$ and Average Loss tangent, D_{avg} of all flake specimens calculated location wise are shown in Figure 4.12. It can also be noticed, gradual decrease in average relative permittivity, $(\varepsilon_r)_{avg}$ with rising frequency of the applied field. The dielectric dispersion occurs specially at high frequencies. This decrease of average loss tangent, D_{avg} with increasing frequency can be explained by the lag of molecules behind the alterations of the applied field.

How the material interacts with applied field affects its dielectric properties. Relative Permittivity (ε_r) describes how the material respond to the applied field. It also reveals properties of the material. Space charge polarization within the material affects ε_r, which comprises of two parts. Real part denotes the polarizability while imaginary part symbolizes the energy losses caused by polarization and ionic conduction. [26]

As per results Kebethigollewa mica is the most suitable dielectric applicable for capacitors. Flake mica with higher relative permittivity values (i.e. ~15-47) and low loss factors (<0.1). Even though Badulla sample also shows comparable relative permittivity values, its loss factor is high. Mathale flakes also show low loss factors, their relative permittivity values are comparatively low. The large values of ε_r at low frequency region might be attributed to the presence of space charge polarization. However, at high frequencies space charge polarization is minimal [27]

The above results agree with the studies of Sukhnandan Kaur, 2016.He has studied ε_r vs. frequency of Muscovite mica at room temperature, within the same frequency range (1-1000 kHz) and revealed that ε_r increases with increase in frequency ε_r value between 1 to 10 kHz is 10.8 to 10.5 [28]

He has also revealed that the variation of loss factor, with the increase of frequency within the same range is approximately 0.004-0.008. Roy & Pandya,2004 has investigated Phlogopite mica films coated with pure aluminum and revealed a similar pattern of ε_r -Frequency behaviour within the range of 1-1000kHz, at room temperature. Corresponding ε_r value was approx. 5.3. However, they have not studied loss factor of it. [19]

In 2008, Yun, Eui-Jang, has investigated mica as the dielectric of the capacitors and multi-layer capacitor with lead foils have been formed and capacitance (C) and Loss factor (D) were measured over 150 kHz to 50 MHz range and found a self-resonant frequency of 65 MHz and D =0.001%. [27]

Hence, Kebethigollewa flakes within the frequency region of 1-100 kHz can be recommended as capacitors with higher capacitance values, while Mailapitiya flakes within the same frequency range can be recommended for applications which require low capacitance values, together with relative permittivity of (~5-7).

4.4.2 Sintered mica samples

All Sintered mica samples under study were kept at the room temperature. The dielectric properties as the relative permittivity (ε_r) and loss tangent (D) were measured in the frequency range (1kHz to 1 MHz). The results obtained are shown in Figure 4.18 to Figure 4.21.

4.4.2.1 Mathale

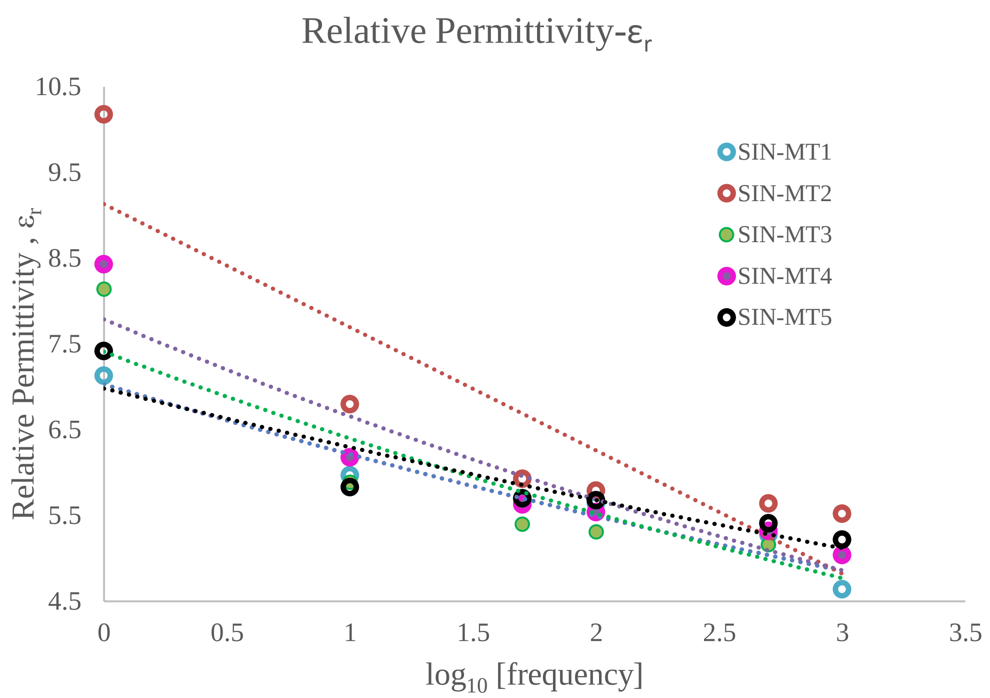


Figure 4.18: Relative permittivity (ε_r) of Mathale sintered mica

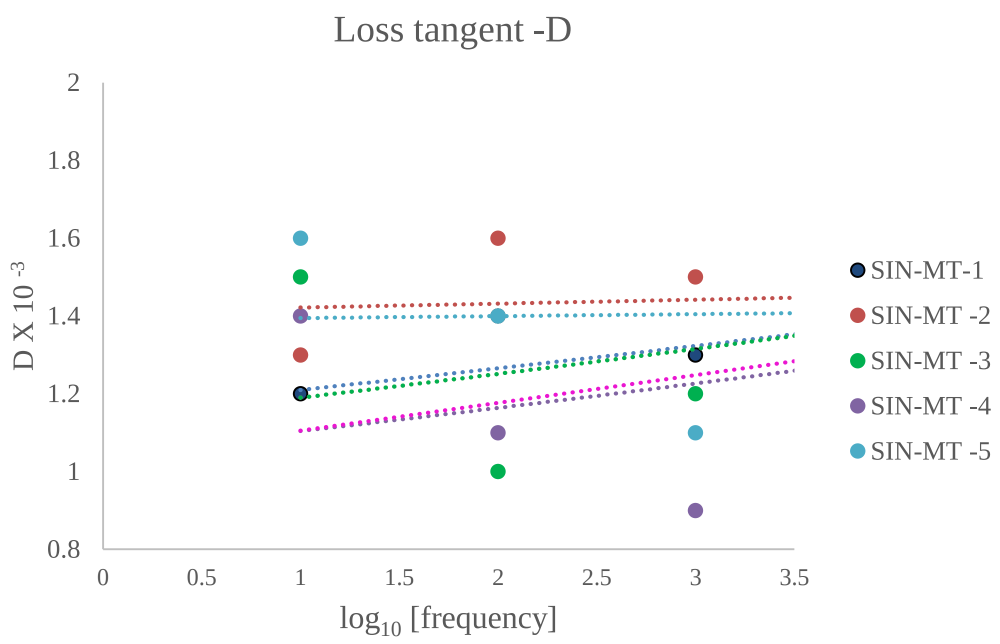


Figure 4.19: Loss Tangent (D) of Mathale sintered mica

4.4.2.1 Mailapitiya

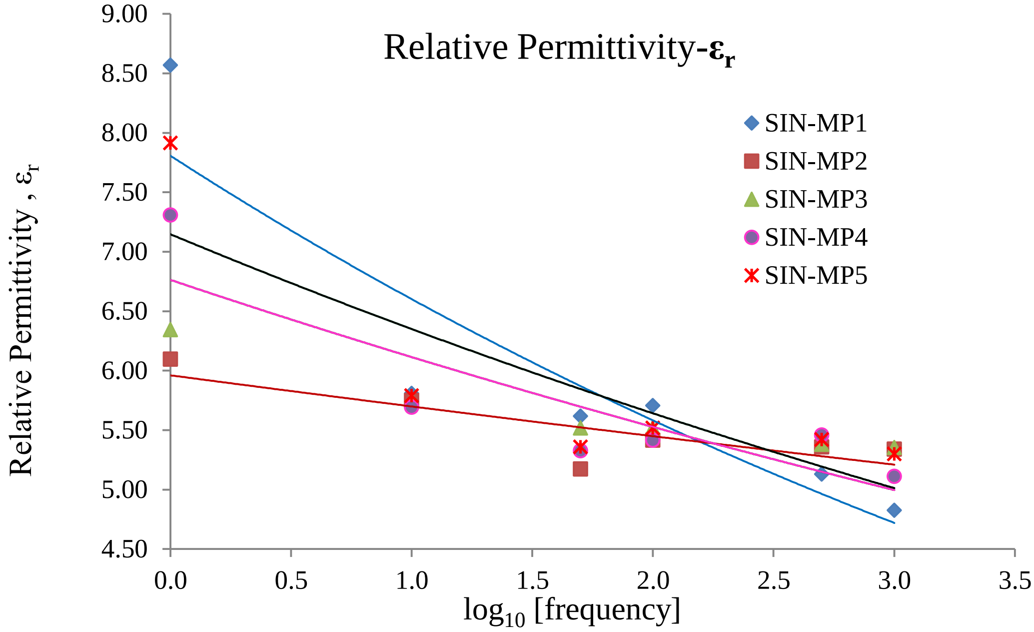


Figure 4.20: Relative permittivity (ε_r) of Mailapitiya sintered mica

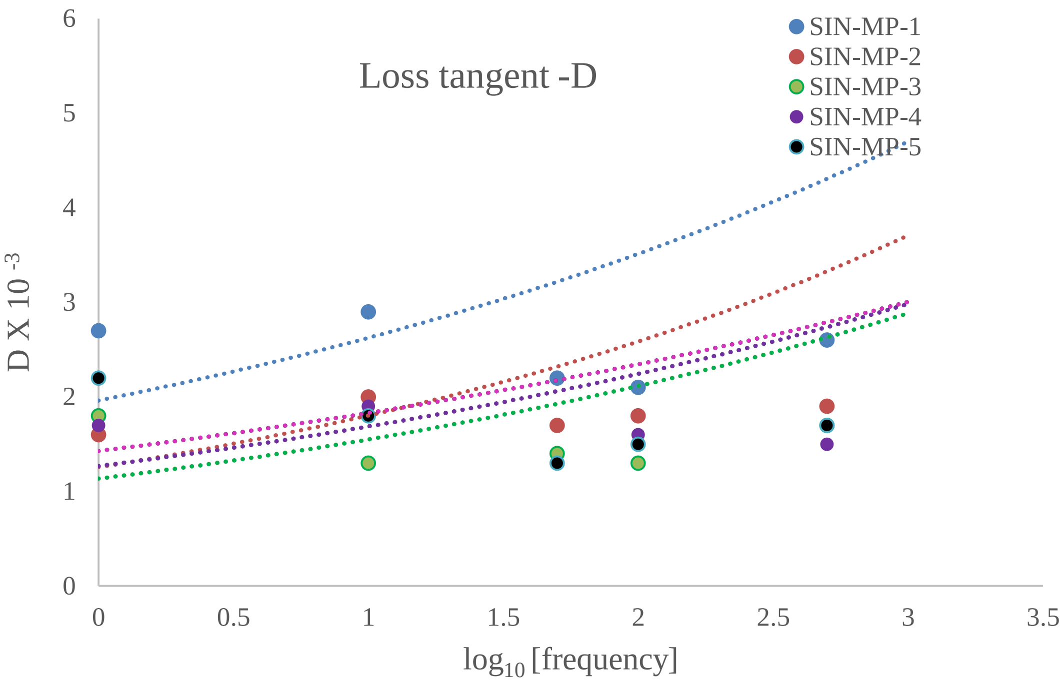


Figure 4.21: Loss Tangent (D) of Mailapitiya sintered mica

4.4.2.3 Comparison of Dielectric properties of sintered mica

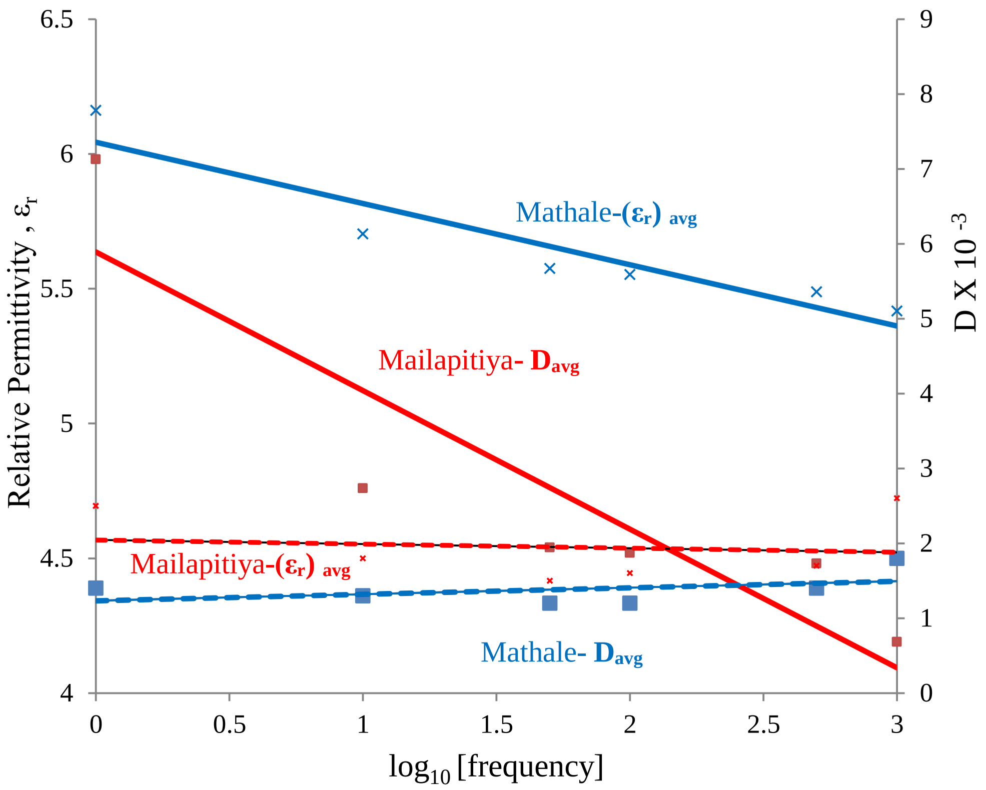


Figure 4.22: Comparison of (ε_r) avg and D avg of sintered mica

As per the results above, sintered Mathale mica shows comparatively higher values of (ε_r) avg and comparatively lower values of D_{avg} within 1-100 kHz frequency range. (ε_r) avg between 5.5 & 6.0 and D_{avg} between 0.001 & 0.002 within 1-100 kHz frequency range would be the most suitable dielectric measurements, at room temperature.

These results are also comparable with the study N. Kaur et. al. 2012 has done with phlogopite mica. Relative permittivity (ε_r) and loss tangent (D) measured at 0.1Hz–10MHz frequency range [16]. It has revealed that ε_r and D decreases with increments of frequency at low frequency region. Further within 10-50 kHz frequency range, ε_r is about 2.6-4.0 and D is less than 0.01, at a temperature close to room temperature. [28]

Ray Fred Schumeracher, 2000 has studied dielectric properties of synthetic flour mica (Phlogopite equivalent) formed by a ceramic method. Results of the ε_r values are comparable to this study and at room temperature ε_r ~7.1 and D ~ 0.0025. However, no frequency ranges were mentioned. [17]

4.4.3 Comparison of sintered specimens and flake specimens

4.4.3.1 Mathale

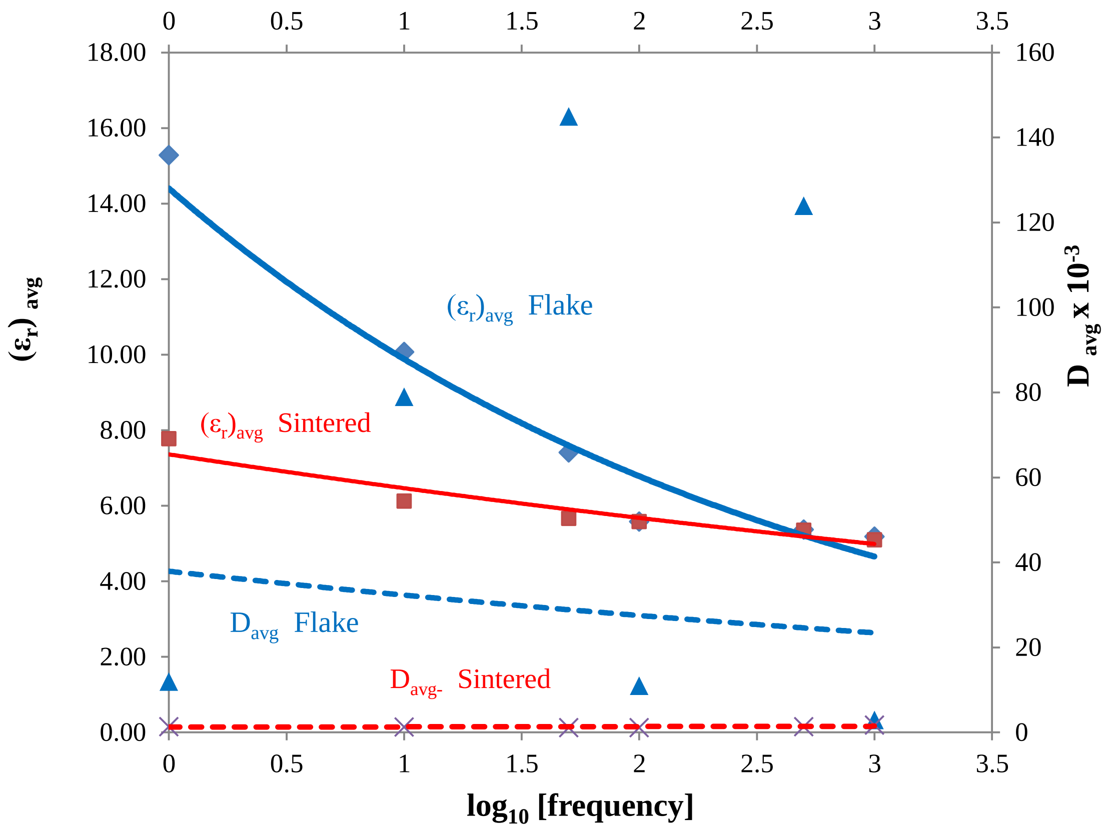


Figure 4.23: Comparison of $(\varepsilon_r)_{avg}$ and D_{avg} of flakes and sintered specimens of Mathale Mica

4.4.3.2 Mailapitiya

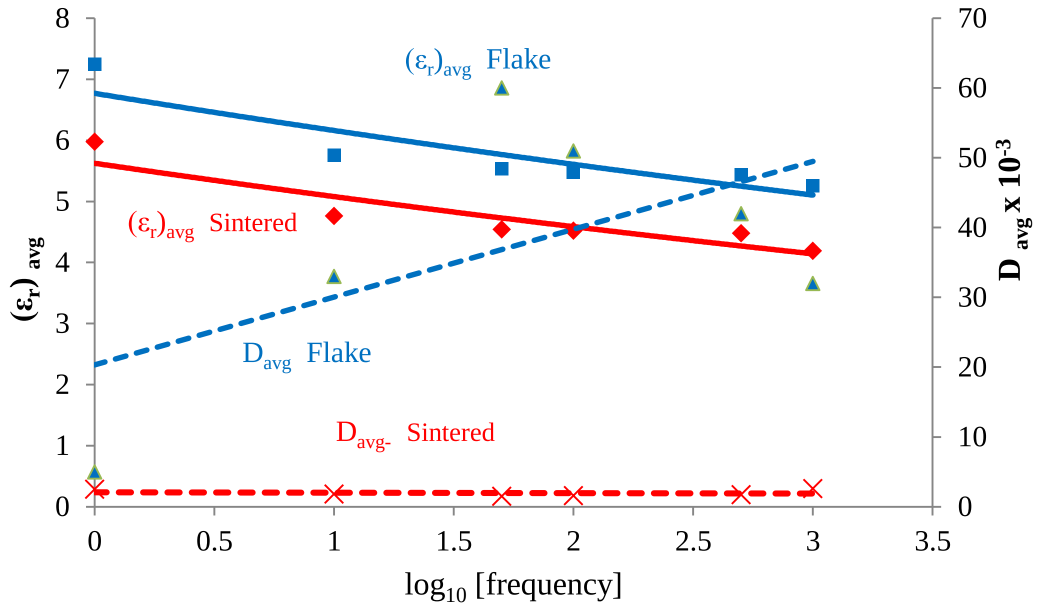


Figure 4.24: Comparison of $(\varepsilon_r)_{avg}$ and D_{avg} of flakes and sintered specimens of Mailapitiya Mica

Average Relative Permittivity, $(\varepsilon_r)_{avg}$ and Average Loss tangent, D_{avg} of both silver coated mica flakes and sintered mica discs of Mathale and Mailapitiya samples as a function of $\log_{10}$ [frequency] at room temperature are shown in Figure 4.23 and Figure 4.24 respectively.

As per Figure 4.23, at low frequency region (<500 kHz), $(\varepsilon_r)_{avg}$ of both flake and sintered mica of Mathale decrease with frequency. D_{avg} of the flakes also decrease with frequency while that of sintered sample shows no change with increasing frequency.

Figure 4.24 also shows that $(\varepsilon_r)_{avg}$ of both flake and sintered mica of Mailapitiya decrease with increase in frequency. D_{avg} of the flakes increase with increase in frequency, while no significant change can be seen with D_{avg} of sintered mica. Hence, sintered mica within 1 kHz-100 kHz frequency. As per the results above, sintered Mathale mica shows comparatively higher values of $(\varepsilon_r)_{avg}$ within 1-50 kHz frequency range and comparatively lower values of D_{avg} within 10-50 kHz frequency range. $(\varepsilon_r)_{avg}$ between 5.67 & 6.13 and D_{avg} between 0.012 & 0.013 within 10-50 kHz frequency range would be the most suitable dielectric measurements, at room temperature.

As shown in Figure 4.23, $(\varepsilon_r)_{avg}$ values of sintered samples are comparatively very lower than that of flake mica from the same source in Mathale. The reason may be due to higher porosity within the structure of the sintered specimens. The specimens sintered at higher temperatures like 1240 ^{0}C indicate water absorption values of more than 10 %. These poor characteristics may be a direct result of volatility losses during sintering at higher temperatures. These losses can be detected by doing XRF analyses before and after sintering. If these losses could be eliminated by different melting procedures, the sintered material should have much better dielectric properties. This implies that ceramic method is not a very effective method for the manufacturing of capacitors.

5. CONCLUSIONS

Mica samples from Mathale, Mailapitiya, Badulla and Kebethigollewa were characterized by using X-ray diffraction analysis (XRD) and Scanning Electron Microscopy (SEM). The XRD analysis of the four mica samples presented for mineral identification shows the presence of different mineral phases. Phlogopite 1 M, a polytype of phlogopite mica is the most significant phase in the Mathale, Mailapitiya and Badulla samples. Out of four XRD analysed samples, Kebethigollewa is the one with significant phlogopite 3 T composition, which is another polytype of phlogopite mica when compared to the other samples.

The SEM analysis reveals that all samples have typical mica-like structures characterized by parallel layers.

The dielectric characterization of samples investigated, showed that relative permittivity as well as loss tangent of mica are mineralogy and frequency dependent. All of them demonstrate a decline in relative permittivity with frequency. Reason for this is lagging of the interlayer cations behind the electric field. The relationship observed between measured relative permittivity and frequency is positive while negative relationship is there between measured loss tangent and frequency. Dipolar polarization and ionic conduction will be the main polarization techniques. At lower frequencies, due to the excitation of the interlayer cations, significant effect of ionic conduction is noticeable.

Based on the results obtained, it can be concluded that locally available mica can be applied as dielectrics for capacitors at low radio frequency range. Kebethigollewa sample was found to have a relative permittivity of 20 -50 and loss tangent of less than 0.1 within 1 kHz to 500 kHz frequency range. Even though Badulla sample was found to have a relative permittivity of 14 -64 within 1 kHz to 500 kHz, but it exhibited a loss tangent of 0.2 to 0.8 within the same frequency range.

As per the results above, sintered Mathale mica shows comparatively higher values of relative permittivity and comparatively lower values of D_{avg} within 1 kHz-100 kHz frequency range. Hence Mathale mica having $(\varepsilon_r)_{avg}$ between 5-6 and D_{avg} less than 0.01 within 1kHz-100 kHz frequency range would be the most suitable dielectric measurements, at room temperature, in terms of ceramic method.

That means even though both flake method and ceramic method can be used to manufacture capacitors, flake method is more efficient, in terms of all aspects including cost. However, for appliances which require low capacitance values, ceramic method is also applicable.

Ceramic method can be further developed by mixing suitable proportions of suitable materials and binders, to reduce porosity. Further sand casting method can be utilized As an alternative to the ceramic method.

Based on the results of this study, Kebethigollewa and Mathale are the best sources in terms of dielectric properties.

6. RECOMMENDATIONS

This research was carried out to investigate the characterization of locally available mica minerals from different locations in Sri Lanka for capacitor applications.

The dielectric properties of locally available mica were studied and how frequency and mineralogy influence these properties were investigated. The systems and methods used for testing dielectric behaviour of the mica from Mathale, Mailapitiya, Badulla and Kebethigollewa can be applied for the expansion of this study with new mica sources such as Welimada, Thalawa, Pathana etc. The following recommendations can be made for further work.

Similar to the methodology followed in this work, mineralogical characterization techniques such as XRD, SEM can be utilized to identify different mineral phases present in the minerals and to investigate how these mineral phases and chemical compositions affect dielectric properties. Extensive measurements of dielectric properties of these minerals would be carried out at different frequency ranges, including HF and VHF, to get information about the interaction of these minerals with higher frequency ranges. Further researches can be done on Kebethigollewa mica, since it has a different structure than other mica types studied.

Ceramic method can be further developed to reduce porosity and thereby reduce loss factor. Experiments can be done to investigate the modifications to improve the properties, such as investigations with sand casting method etc.

Further researches also can be done with dielectric properties of flake mica at different temperatures, at both higher temperatures as well as very low temperatures.

The outcome of this research will be beneficial to design and manufacturing of Multi Layered Silver mica capacitors, to obtain higher relative permittivity.

Currently Sri Lanka is not manufacturing mica capacitors. Future possibility of manufacturing capacitors with local mica makes value added product in view of exporting mica will make this a fruitful research.

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APPENDIX – A: INDIVIDUAL RESULTS, CAPACITANCE VALUES AND LOSS TANGENT OF SINTERED AND FLAKE MICA SAMPLES AT THE FREQUENCY RANGE OF 1KHz -1 MHz, MEASURED AT 27±2 ^{0}C.

A.1 Sintered mica discs-Mathale

Frequency 1 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MT-1	2.358	2.19	10.2	81.75	7.134	0.0012
SIN-MT -2	3.462	2.17	10.3	83.36	10.180	0.0013
SIN-MT -3	2.744	2.19	10.3	83.36	8.141	0.0015
SIN-MT -4	2.855	2.18	10.3	83.36	8.432	0.0014
SIN-MT -5	2.452	2.19	10.2	81.75	7.419	0.0016

Frequency 10 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MT-1	1.972	2.19	10.2	81.75	5.967	0.0014
SIN-MT -2	2.314	2.17	10.3	83.36	6.803	0.0016
SIN-MT -3	1.986	2.19	10.3	83.36	5.893	0.001
SIN-MT -4	2.091	2.18	10.3	83.36	6.175	0.0011
SIN-MT -5	1.926	2.19	10.2	81.75	5.828	0.0014

Frequency 50 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MT-1	1.974	2.19	10.2	81.75	5.974	0.0013
SIN-MT -2	2.018	2.17	10.3	83.36	5.933	0.0015
SIN-MT -3	1.821	2.19	10.3	83.36	5.404	0.0012
SIN-MT -4	1.906	2.18	10.3	83.36	5.630	0.0009
SIN-MT -5	1.884	2.19	10.2	81.75	5.699	0.0011

Frequency 100 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MT-1	2.358	2.19	10.2	81.75	5.639	0.0013
SIN-MT -2	3.462	2.17	10.3	83.36	5.794	0.0014
SIN-MT -3	2.744	2.19	10.3	83.36	5.314	0.0016
SIN-MT -4	2.855	2.18	10.3	83.36	5.538	0.0013
SIN-MT -5	2.452	2.19	10.2	81.75	5.679	0.0014

Frequency 500 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MT-1	2.358	2.19	10.2	81.75	5.278	0.0012
SIN-MT -2	3.462	2.17	10.3	83.36	5.643	0.0014
SIN-MT -3	2.744	2.19	10.3	83.36	5.162	0.0011
SIN-MT -4	2.855	2.18	10.3	83.36	5.320	0.0013
SIN-MT -5	2.452	2.19	10.2	81.75	5.410	0.0015

Frequency 1 MHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MT-1	2.358	2.19	10.2	81.75	4.640	0.0018
SIN-MT -2	3.462	2.17	10.3	83.36	5.519	0.0015
SIN-MT -3	2.744	2.19	10.3	83.36	5.073	0.0019
SIN-MT -4	2.855	2.18	10.3	83.36	5.041	0.0017
SIN-MT -5	2.452	2.19	10.2	81.75	5.222	0.0015

A.2 Sintered mica discs- Mailapitiya

Frequency 1 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MP-1	2.819	2.20	10.2	81.7	8.571	0.0027
SIN-MP -2	2.005	2.20	10.2	81.7	6.098	0.0029
SIN-MP -3	2.087	2.20	10.2	81.7	6.346	0.0022
SIN-MP -4	2.404	2.20	10.2	81.7	7.309	0.0021
SIN-MP -5	2.603	2.20	10.2	81.7	7.915	0.0026

Frequency 10 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MP-1	1.910	2.20	10.2	81.7	5.809	0.0016
SIN-MP -2	1.891	2.20	10.2	81.7	5.752	0.002
SIN-MP -3	1.893	2.20	10.2	81.7	5.756	0.0017
SIN-MP -4	1.872	2.20	10.2	81.7	5.694	0.0018
SIN-MP -5	1.904	2.20	10.2	81.7	5.791	0.0019

Frequency 50 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MP-1	1.910	2.20	10.2	81.7	5.809	0.0018
SIN-MP -2	1.891	2.20	10.2	81.7	5.752	0.0013
SIN-MP -3	1.893	2.20	10.2	81.7	5.756	0.0014
SIN-MP -4	1.872	2.20	10.2	81.7	5.694	0.0013
SIN-MP -5	1.904	2.20	10.2	81.7	5.791	0.0017

Frequency 100 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MP-1	1.910	2.20	10.2	81.7	5.809	0.0017
SIN-MP -2	1.891	2.20	10.2	81.7	5.752	0.0019
SIN-MP -3	1.893	2.20	10.2	81.7	5.756	0.0013
SIN-MP -4	1.872	2.20	10.2	81.7	5.694	0.0016
SIN-MP -5	1.904	2.20	10.2	81.7	5.791	0.0015

Frequency 500 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MP-1	1.688	2.20	10.2	81.7	5.132	0.0022
SIN-MP -2	1.762	2.20	10.2	81.7	5.359	0.0018
SIN-MP -3	1.770	2.20	10.2	81.7	5.383	0.0013
SIN-MP -4	1.795	2.20	10.2	81.7	5.459	0.0015
SIN-MP -5	1.782	2.20	10.2	81.7	5.420	0.0017

Frequency 1 MHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Diameter, (mm)	Area (mm^2)	ε_r	D
SIN-MP-1	1.588	2.20	10.2	81.7	4.828	0.0028
SIN-MP -2	1.756	2.20	10.2	81.7	5.341	0.0024
SIN-MP -3	1.761	2.20	10.2	81.7	5.354	0.0025
SIN-MP -4	1.681	2.20	10.2	81.7	5.113	0.0023
SIN-MP -5	1.743	2.20	10.2	81.7	5.301	0.003

A.3 Silvered mica flakes- Mathale

Frequency 1 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MT 1	656.270	0.026	100.0	19.272	0.009
Flake MT 2	596.850	0.023	100.0	15.504	0.014
Flake MT 3	478.300	0.025	100.0	33.763	0.011
Flake MT 4	488.140	0.023	100.0	12.680	0.013
Flake MT 5	550.450	0.022	100.0	13.677	0.014

Frequency 10 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MT 1	512.300	0.026	100.0	15.044	0.076
Flake MT 2	432.800	0.023	100.0	11.243	0.074
Flake MT 3	332.100	0.025	100.0	23.443	0.081
Flake MT 4	418.750	0.023	100.0	10.878	0.084
Flake MT 5	448.230	0.022	100.0	11.137	0.080

Frequency 50 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MT 1	463.780	0.026	100.0	13.619	0.148
Flake MT 2	364.370	0.023	100.0	9.465	0.141
Flake MT 3	170.770	0.025	100.0	12.055	0.143
Flake MT 4	338.000	0.023	100.0	8.780	0.147
Flake MT 5	327.700	0.022	100.0	8.143	0.146

Frequency 100 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MT 1	254.850	0.026	100.0	7.484	0.015
Flake MT 2	239.760	0.023	100.0	6.228	0.012
Flake MT 3	130.770	0.025	100.0	9.231	0.008
Flake MT 4	268.450	0.023	100.0	6.974	0.011
Flake MT 5	208.240	0.022	100.0	5.174	0.009

Frequency 500 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MT 1	107.900	0.026	100.0	3.169	0.123
Flake MT 2	106.450	0.023	100.0	2.765	0.125
Flake MT 3	67.340	0.025	100.0	4.754	0.126
Flake MT 4	200.140	0.023	100.0	5.199	0.122
Flake MT 5	173.730	0.022	100.0	4.317	0.124

Frequency 1 MHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MT 1	84.882	0.026	100.0	2.493	0.001
Flake MT 2	86.034	0.023	100.0	2.235	0.002
Flake MT 3	56.980	0.025	100.0	4.022	0.005
Flake MT 4	107.760	0.023	100.0	2.799	0.002
Flake MT 5	98.760	0.022	100.0	2.454	0.005

A.4 Silvered mica flakes- - Mailapitiya

Frequency 1 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MP 1	199.23	0.025	100.0	5.66	0.006
Flake MP2	185.95	0.023	100.0	4.86	0.003
Flake MP 3	236.80	0.022	100.0	5.92	0.005
Flake MP 4	250.99	0.023	100.0	6.56	0.007
Flake MP5	220.00	0.025	100.0	6.25	0.004

Frequency 10 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MP 1	189.38	0.025	100.0	5.38	0.032
Flake MP2	182.89	0.023	100.0	4.78	0.031
Flake MP 3	231.20	0.022	100.0	5.78	0.035
Flake MP 4	242.96	0.023	100.0	6.35	0.034
Flake MP5	217.18	0.025	100.0	6.17	0.033

Frequency 50 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MP 1	160.51	0.025	100.0	4.56	0.050
Flake MP2	178.68	0.023	100.0	4.67	0.070
Flake MP 3	220.00	0.022	100.0	5.50	0.060
Flake MP 4	211.58	0.023	100.0	5.53	0.070
Flake MP5	199.94	0.025	100.0	5.68	0.050

Frequency 100 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MP 1	138.69	0.025	100.0	3.94	0.050
Flake MP2	157.63	0.023	100.0	4.12	0.053
Flake MP 3	192.00	0.022	100.0	4.80	0.049
Flake MP 4	186.33	0.023	100.0	4.87	0.051
Flake MP5	160.86	0.025	100.0	4.57	0.047

Frequency 500 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MP 1	111.23	0.025	100.0	3.16	0.039
Flake MP2	140.42	0.023	100.0	3.67	0.040
Flake MP 3	168.80	0.022	100.0	4.22	0.041
Flake MP 4	154.19	0.023	100.0	4.03	0.047
Flake MP5	139.04	0.025	100.0	3.95	0.043

Frequency 1 MHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake MP 1	106.30	0.025	100.0	3.02	0.030
Flake MP2	136.21	0.023	100.0	3.56	0.034
Flake MP 3	164.80	0.022	100.0	4.12	0.029
Flake MP 4	148.45	0.023	100.0	3.88	0.033
Flake MP5	136.93	0.025	100.0	3.89	0.034

A.5 Silvered mica flakes- -Badulla

Frequency 1 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm2)	εr	D
Flake B 1	402.370	0.139	200	31.584	0.380
Flake B2	277.290	0.542	200	84.872	0.366
Flake B 3	119.780	0.522	200	35.309	0.382
Flake B 4	434.240	0.522	200	128.006	0.378
Flake B 5	158.370	0.083	200	7.423	0.379

Frequency 10 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake B 1	81.662	0.139	200	6.410	0.412
Flake B2	141.910	0.542	200	43.435	0.417
Flake B 3	85.636	0.522	200	25.244	0.410
Flake B 4	151.110	0.522	200	44.545	0.421
Flake B 5	80.671	0.083	200	3.781	0.420

Frequency 50 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake B 1	45.617	0.139	200	3.581	0.544
Flake B2	55.536	0.542	200	16.998	0.546
Flake B 3	31.618	0.522	200	9.320	0.542
Flake B 4	59.352	0.522	200	17.496	0.548
Flake B 5	46.229	0.083	200	2.167	0.545

Frequency 100 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake B 1	44.832	0.139	200	3.519	0.200
Flake B2	39.516	0.542	200	12.095	0.207
Flake B 3	20.779	0.522	200	6.125	0.203
Flake B 4	40.688	0.522	200	11.994	0.204
Flake B 5	34.530	0.083	200	1.618	0.206

Frequency 500 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake B 1	33.379	0.139	200	2.620	0.356
Flake B2	20.509	0.542	200	6.277	0.351
Flake B 3	13.178	0.522	200	3.885	0.352
Flake B 4	21.328	0.522	200	6.287	0.354
Flake B 5	33.379	0.139	200	2.620	0.352

Frequency 1 MHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake B 1	32.738	0.139	200	2.570	0.010
Flake B2	16.415	0.542	200	5.024	0.012
Flake B 3	11.737	0.522	200	3.460	0.013
Flake B 4	18.110	0.522	200	5.339	0.009
Flake B 5	11.880	0.083	200	0.557	0.011

A.6 Silvered mica flakes- -Kebethigollewa

Frequency 1 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm2)	εr	D
Flake K 1	262.35	0.322	200	47.705	0.100
Flake K2	187.28	0.352	200	37.228	0.120
Flake K 3	268.45	0.132	200	20.011	0.130
Flake K 4	908.83	0.192	200	206.966	0.070
Flake K 5	350.40	0.155	200	30.671	0.080

Frequency 10 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake K 1	220.000	0.322	200	40.005	0.140
Flake K2	138.320	0.352	200	27.495	0.143
Flake K 3	229.920	0.132	200	17.139	0.138
Flake K 4	693.450	0.192	200	75.188	0.145
Flake K 5	311.670	0.155	200	27.281	0.139

Frequency 50 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake K 1	149.930	0.322	200	27.263	0.013
Flake K2	51.020	0.352	200	10.142	0.015
Flake K 3	211.480	0.132	200	15.764	0.021
Flake K 4	678.250	0.192	200	73.540	0.022
Flake K 5	294.170	0.155	200	25.749	0.019

Frequency 100 kHz

Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake K 1	105.560	0.322	200	19.195	0.003
Flake K2	30.850	0.352	200	6.132	0.008
Flake K 3	204.010	0.132	200	15.207	0.006
Flake K 4	340.130	0.192	200	36.879	0.005
Flake K 5	288.910	0.155	200	25.289	0.008

Frequency 500 kHz

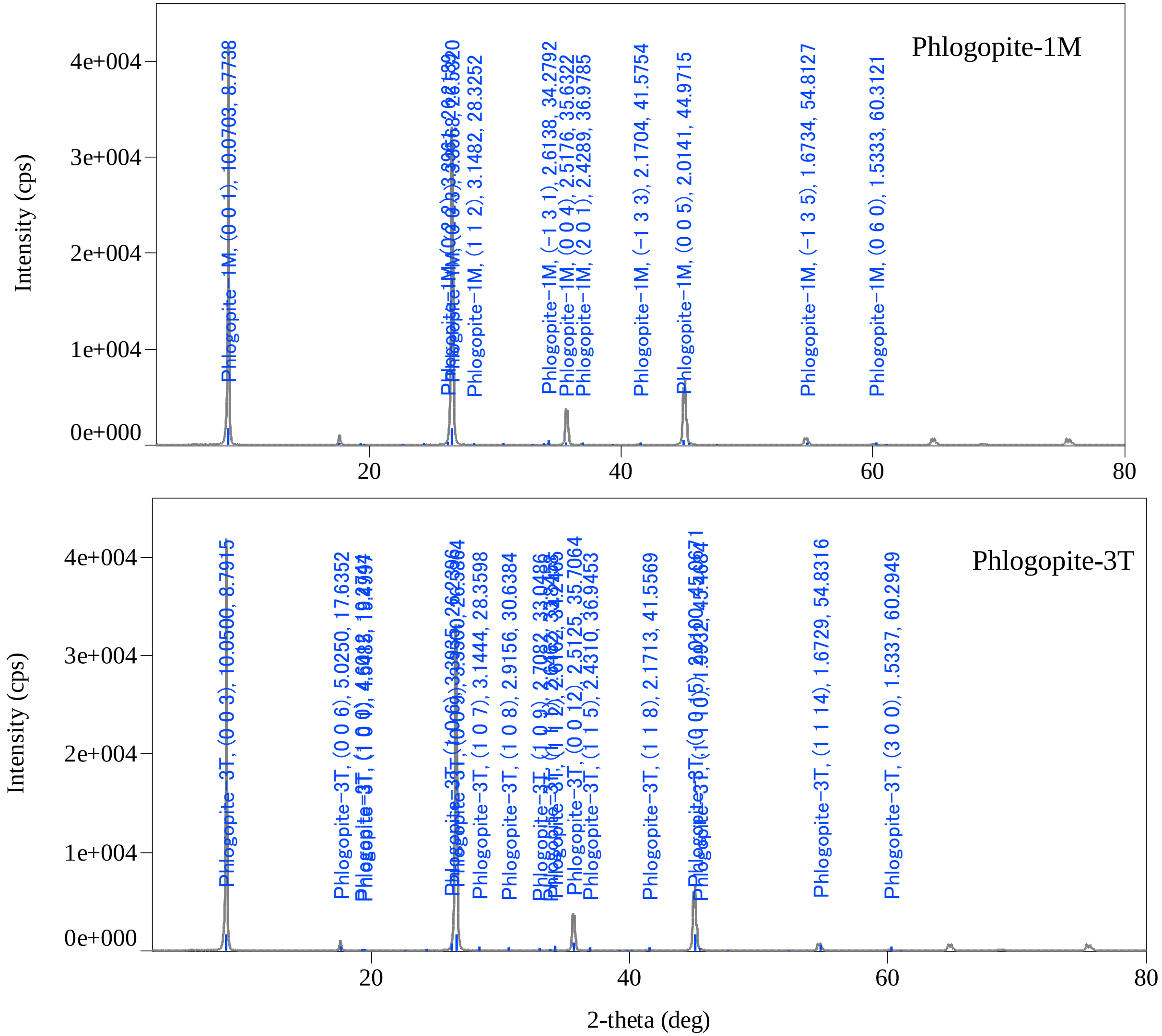
Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake K 1	58.625	0.322	200	10.660	0.028
Flake K2	12.425	0.352	200	2.470	0.031
Flake K 3	178.730	0.132	200	13.323	0.026
Flake K 4	137.600	0.192	200	14.919	0.030
Flake K 5	281.020	0.155	200	24.598	0.030

Frequency 1 MHz

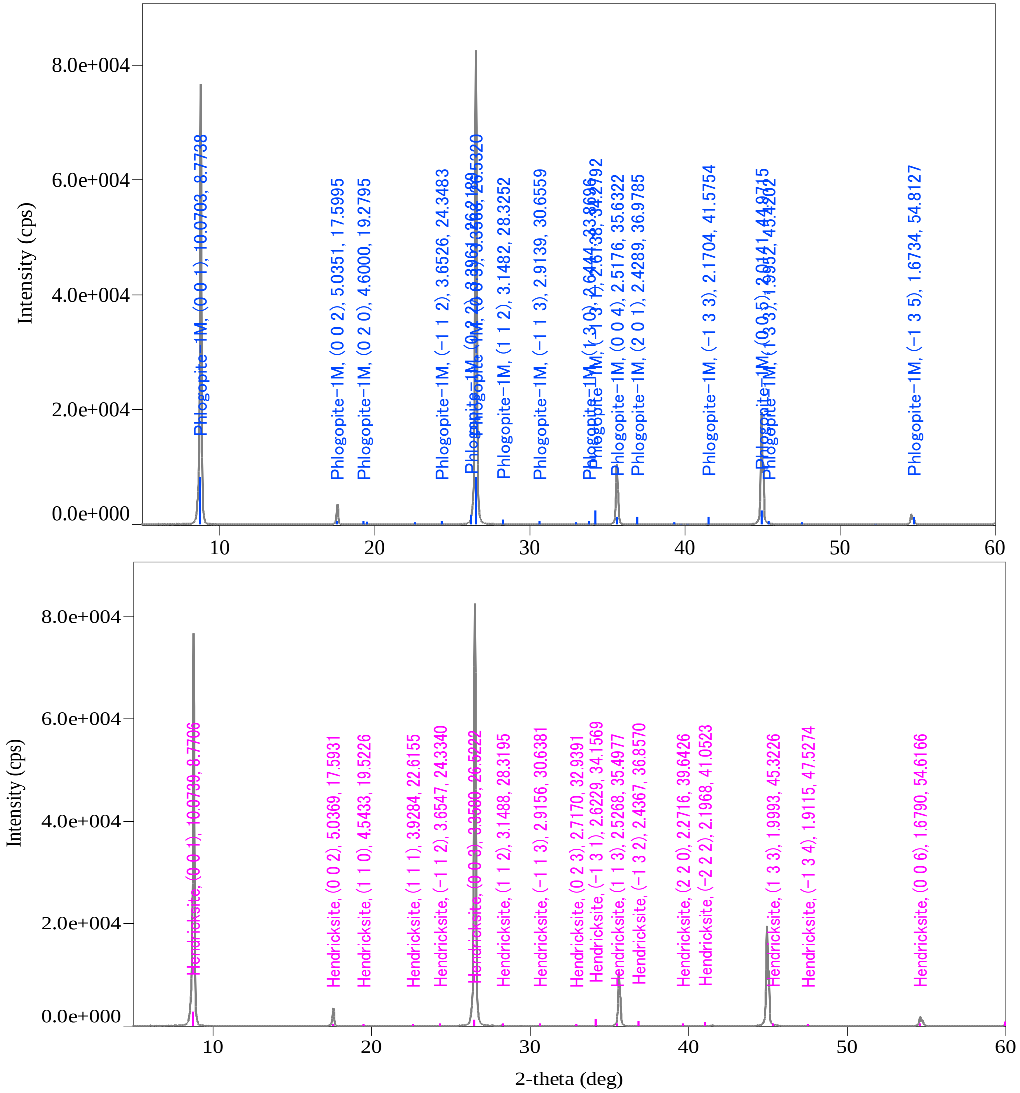
Specimen No.	Capacitance (pF)	Thickness (mm)	Area (mm^2)	ε_r	D
Flake K 1	49.823	0.322	200	9.060	0.004
Flake K2	9.363	0.352	200	1.861	0.001
Flake K 3	168.430	0.132	200	12.555	0.002
Flake K 4	96.578	0.192	200	10.472	0.001
Flake K 5	273.100	0.155	200	23.905	0.002

APPENDIX – B: X- Ray Diffraction results

Sample ID: Mathale Mica



Sample ID: Badulla Mica



Sample ID: Mailapitiya Mica