UNIVERSITY OF MANITOBA

DIELECTRIC PROPERTIES OF WHEAT AND ITS DERIVATIVES- DENSITY EFFECTS

by

B.D. TRAPP

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ABSTRACT

The effect of density on the dilectric constant and loss factor of wheat, ground wheat and flour was determined at selected frequencies between 75 kHz and 10 MHz. Tests were performed on samples at oven dry state and at moisture contents above and below normal storage moisture content. The density was varied from the natural bulk density of a given material to a density about two times larger.

A parallel plate capacitor was constructed to contain the samples during testing and a hydraulic press was employed to compress the samples. Electrical measurements were made using a Q-meter with a supplementary voltmeter and frequency counter. The effect of pressure, if any was not investigated.

The experimental results showed that the relationship between the dielectric constant and loss factor and the density was almost perfectly linear throughout the range investigated.

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SYMBOL

A_j	depolarization factors along the major axes of a dielectric particle
a	area in square meters
C	capacitance in farads
d	electrode separation in meters
ε	permittivity in farad/meter
ε_o	permittivity of free space
ε'	real part of the permittivity (dielectric constant)
ε''	loss factor
emf.	electromotive force in volts
f	frequency in hertz
i,I	current in amperes
j	operator = $\sqrt{-1}$
L	inductance in henrys
MEC	micrometer electrode capacitor
q	electric charge in esu
Q	quality factor (ratio of reactance to resistance)
R	resistance in ohms
σ	conductance in mhos
τ	time constant in seconds
v	electromotive force in volts
υ	volume filling factor
ω	angular frequency in radians/second
X	reactance in ohms
MC	percent moisture content (wet base)

CHAPTER I

INTRODUCTION

1.1 Purpose of the study and choice of materials

Eight hundred million bushels of grain are harvested, stored, bought and sold each year in Canada. Each operation demands an accurate measure of the moisture content of the grain. Since the dielectric properties of grains are strongly dependent on their moisture content, several electrical moisture meters are in use in the grain trade which evaluate moisture content by measurement of dielectric properties. However, factors other than moisture content affect the dielectric properties of grain. These factors include the frequency at which measurement is made, the temperature, type of grain and the density of the grain sample.

Since grain is a mixture of grain particles surrounded by air, measurement of the dielectric properties is more difficult than if it were a homogeneous substance consisting of grain only. If the grain to be measured for moisture content could be reduced to a homogeneous medium by some simple means, it is expected that the accuracy and simplicity of the measurement methods would be improved. Appreciable errors in measurement result from density fluctuations between repetitive samples due to bridging of the particles. This effect is more pronounced in testing powdery materials such as flour.

It was decided to investigate the feasibility of compressing grain samples to the point where all air spaces were displaced and to measure the effect of density on the dielectric constant and loss factor.

Since a large number of tests were to be performed on each type of material, it was necessary to limit the variety of materials to be tested. Wheat was chosen because it is one of Canada's most common and important crops. Flour and ground wheat were chosen to examine the applicability of the measurement technique to fine powdery materials.

1.2 State of the art

1.2.1 Dielectric properties

A dielectric is defined as a material which will support an electric field. Nearly all materials except ferro-electrics and including biological materials belong to this class. Dielectric properties are expressed in terms of the permittivity ε ,and conductivity σ.

From the early days of electrostatic experimentation it was realized that a dielectric medium placed between the plates of a capacitor had the ability to increase the charge storage capability of the capacitor. To specify this property, the parameter dielectric constant was defined, usually noted by the symbol ε and ε_o for the free space value.

Consider a capacitor consisting of parallel plates of an area a (meters^2) each, separated by a distance d (meters) in vacuum. The capacitance of this capacitor (farads) is then given as

$$C_o = (\varepsilon_o a)/d \qquad (1.1)$$

where the permittivity of free space = 8.85x 10 F/m.

If a dielectric medium was placed between the plates of the capacitor, the capacitance (farads) would then be

$$C = (\varepsilon a)/d \qquad (1.2)$$

It is often convenient to express the permittivity of materials relative to the free space value. This gives a relative permittivity defined as $\varepsilon_r = \varepsilon/\varepsilon_o$. In practice the subscript r and the term relative are often omitted. Relative values may be differentiated from absolute values since relative permittivity is generally a number greater than unity, while absolute values include a negative power of ten.

In the previous example of a parallel plate capacitor with capacitance C_o in vacuum the insertion of a dielectric material of relative permittivity ε_r would increase its capacitance to $C = \varepsilon_r C_o$.

If an alternating electromotive force (emf) v is applied across the capacitor, an alternating current i will flow, its value being

$$i = j\omega\varepsilon_r C_o v$$

If losses occur there will be a resistive element of current in phase with the voltage, as well as the reactive element.

To account for the losses within the dielectric a complex permittivity is introduced as

$$\varepsilon = \varepsilon' - j\varepsilon''$$

where ε' is the real part of the permittivity often called the dielectric constant, and ε'' is the loss factor. It is impossible to separate losses due to conductivity and losses due to permittivity (Harrington, 1961). Therefore it has become customary to express all losses by the loss factor.

In order to fully understand dielectric phenomena, it is necessary to examine the processes that contribute to energy storage and losses.

1.2.2 Mechanisms of polarization

Polarization is the process of alignment of electrical dipoles within a dielectric medium placed in an electric field. Molecules of a dielectric medium though electrically neutral may have unequal distribution of positive and negative charges. These equal but opposite charges (q), separated by a distance (d) are called dipoles. When charges are expressed in esu, distances in angstroms (A), dipole moments (qd) are in debyes.

When a dielectric medium is placed in a capacitor connected to a battery, the dipoles align along the lines of the field existing between the plates. The result is the phenomena called polarization, ie. the formation of chains of alternating positive and negative charges from one plate to the other. The charges at the ends of the chains (at the plates of the capacitor) neutralize some of the charges on the plates of the capacitor, allowing a greater charge to be stored on the plates.

Many substances and compounds, known as dipolar materials have permanent dipoles arising from asymmetries in the molecular structure. Under the influence of the external electric field, these permanent dipoles will attempt to align along the field by rotation. This is known as orientational polarization. As the temperature rises, increased thermal agitation lessens the alignment possible, and the contribution of orientational polarization to the dielectric constant decreases.

Dipoles may be created under the influence of an applied field by the shifting of electrons relative to the nucleus (electronic polarization), or by a displacement of atoms within the molecule (atomic polarization). These two forms are known as induced, or distortional polarization.

Interfacial polarization occurs when free charge carriers, such as ions, build up along defects and interfaces in the structure of the dielectric material. The effect may be quite large at low frequencies (below a few kilohertz) but usually diminishes rapidly with increasing frequency.

The mechanisms of polarization are frequency dependent since a finite time is required for the realignment of the dipoles in the applied alternating field. As the frequency increases the alignment of the dipoles begins to lag. The contribution to polarization of the dielectric decreases and losses occur. This decrease in the dielectric constant is termed dispersion, while the increase in losses is called dielectric absorption.

Interfacial polarization is the first mechanism to be affected by increasing frequency. Respectively the next mechanisms to be affected are orientational, atomic and electronic polarization.

Materials are classified according to the polarization mechanisms they display under an applied field. Non-polar materials, usually pure elements, show electronic polarization with dispersion at optical frequencies. Polar materials have a polar moment induced under an applied field (molecular polarization) with dispersion in the infrared as well as the optical region. Dipolar materials which have permanent polar moments exibit orientational polarization as well as the other two forms.

1.2.3 Dielectric properties related to grain and water

Grain as a dielectric medium exibits all four types of polarization. The relative magnitude of the effect depends greatly on the moisture content of the grain.

Water in biological materials exists as either bound or free water, having different physical and dielectric properties. Bound water is tightly held by the molecules of starch, protein and other components of grain and forms part of the physical though not chemical structure of the molecules. The dielectric constant of bound water is similar to that of ice. At low moisture contents almost all of the water in grain may be bound water, while at higher moisture contents free water predominates.

Free water is found in capillary pores and other interstitial spaces between the plant molecules. This water will act as a solvent and thus will allow conduction of electricity due to movement of dissolved ions. At low frequencies the value of the dielectric constant of free water is close to 80 while that of bound water is in the order of 4.5 to 5.0.

It is known that interfacial polarization, which requires the presence of free charge carriers, is generally weak if bound water predominates, while the effect may be quite large if much free water is present.

Although water is a dipolar substance characterized by a high polar moment, in the bound form it is restricted in its rotation in an alternating field. As a result bound water shows only a small contribution to orientational polarization. This is the reason for the large difference in the dielectric constants of the two forms of water.

1.2.4 Unwanted factors in moisture measurement

As an ideal indicator of moisture content, the dielectric properties would be affected only by the amount of water contained in the material. Since this is not the case several other factors need to be considered in the determination of moisture content.

Measurements of the dielectric properties of grain give values representing a mixture of plant material, water and air, not just the water. Calibration charts are usually required to arrive at the moisture content since the measured values depend in part on the host material. Separate charts must be provided for each type of grain, obtained by comparing readings of the dielectric properties of grain samples with the moisture content of the same sample as determined by one of the standard methods (AOAC,1965).

The majority of electric moisture meters in use today measure the dielectric constant of the grain as an indication of its moisture content. Most of the contribution to the dielectric constant of grains results from orientational polarization of the free water contained in the kernels. Since increased thermal agitation of the water molecules reduces orientational polarization, the dielectric constant of grains is temperature dependent. This means that the temperature must be held constant or be compensated for when making measurements.

Another problem observed with electric moisture meters is that grain samples of similar moisture content as determined by oven methods, may not give similar results when tested by dielectric meters. This has been noted for samples of similar species and variety of grain but grown in different localities or crop years. Zeleny (1962) suggests that the small differences observed may be due to samples with the same moisture content having different ratios of free and bound water.

1.2.5 Considerations of density

Granular and powdery materials are subject to large density fluctuations due to bridging of the particles when placed in sample holders for moisture content determinations. This effect is magnified when samples having different particle sizes, such as different grinds of flour are being compared.

Most of the grain moisture meters in use employ a dumping hopper to minimize variations in the loading process of the sample holder. Samples of constant weight were found to give smaller variations than samples of constant volume, but both methods are used in practice to lessen density fluctuations.

Measurements of the dielectric properties of powders are more critical because of potentially larger variations in their bulk density than those in grains. A determination of the moisture content of such materials without a correction for density is subject to errors as large as 10 percent (Yevstigneyev,1939). Density corrections may be achieved by measuring the volume of a sample of known weight while it is contained in the test cell, or by compressing the sample in some reproducible way.

1.2.6 Previous work in the field

Many excellent reference texts containing background information on dielectric materials and their properties are available, such as Hill et al.(1969), Von Hippel (1954), Bottcher (1952), Anderson (1964), and Calderwood (1971). Topics include permittivity, conductivity, mechanisms of polarization and measurement techniques. The work of Debye, Cole, Kirkwood, Onsager, Frolich and other early investigators is presented and discussed.

DeLoor (1968) investigated heterogeneous mixtures with emphasis on materials containing water. Grant (1969) gave a simplified discussion on the use of dielectric methods in the study of biological materials.

Several researchers have investigated the dielectric properties of agricultural products. Nelson (1971) reviewed experimental data of electrical properties for a wide range of products including wood, textiles, grains, seeds, fruits, vegetables and meat and dairy products. A summary of properties of grains and seeds in the frequency range of 1 to 50 MHz was published by Nelson (1965). Stetson and Nelson (1970) presented the experimental results of tests made on several grains and seeds at audio frequencies.

Measurements of the dielectric properties of grains at higher frequencies have been made by several researchers. These include Nelson (1972) who covered the entire frequency range from 250 Hz to 12.2 GHz for wheat and rice weevils, Hamid et al. (1968) for wheat and flour at 10.93 GHz, and Chugh (1973), who made measurements of wheat at 2.45 and 9.4 GHz.

Very little research has been done with grains regarding the effect of large density changes on their dielectric properties. Nelson (1972) made measurements on wheat at 9.367 GHz, using a press to compress the samples.

A few experiments have been done to investigate the effect of pressure and density on the dielectric properties of other materials. Mopsik (1967) made measurements on n-hexane, Chan et al. (1965) measured the effect of pressure on the dielectric constant and loss factor of ice, and Scaife (1967) studied the effect of pressure and density on the dielectric properties of eugenol.

1.2.7 Measurement of permittivity

Experimental methods for the measurement of permittivity are discussed in several references including Hill et al. (1969), Anderson (1964), Grant (1969) and Von Hippel (1964).

The equipment used to measure permittivity is usually determined by the frequency range and the material to be investigated. Since the frequency range of interest in this study was from 75 kHz to 10 MHz, either a bridge or resonant circuit could be used. Bridge circuit methods have an upper frequency limit of approximately 10 MHz. Beyond this limit, measurement is impaired by the effects of residual impedance of leads and stray capacitances to ground. Difficulties may be encountered below this upper limit.

Resonant circuits are employed to minimize the effects of stray capacitances. Resonance is indicated with a transistor voltmeter and is therefore a deflection method rather than a null method as with bridge circuits. Since resonant circuits are used in a wide range of frequencies a Q-meter provides a convenient solution.

CHAPTER II

MATERIALS AND METHODS

2.1 Equipment

The Q-meter used was a Marconi model T1245A fed from a Marconi model TF1246 oscillator, having a frequency range of 40 kHz to 50 MHz. The Q-meter contained a variable air capacitor and a built in VTVM, but in order to increase the accuracy of measurement a General Radio type 1690 micrometer electrode capacitor (MEC) (Hartshorn, Ward,1936) was used as a standard capacitor and a Hewlett Packard model 427A TVM was utilized for voltage measurement. Test frequencies were monitored with a Monsanto model 105A digital frequency counter.

Since pressures up to 7.84 kPa were to be used to compress the samples, the sample holder (test cell) had to be specially constructed. In order to facilitate loading and unloading of the test cell, it was decided to employ a parallel plate capacitor with a surrounding collar of insulating material. The final test cell is shown in Fig. 2.1.

A Nylon-6 insulating cylinder was press fitted into a steel collar and then bored out smooth. The base and plunger were machined from steel and electoplated with copper in such a way that a sliding fit was obtained with the Nylon-6 cylinder.

The test cell was fitted into a Carver model B

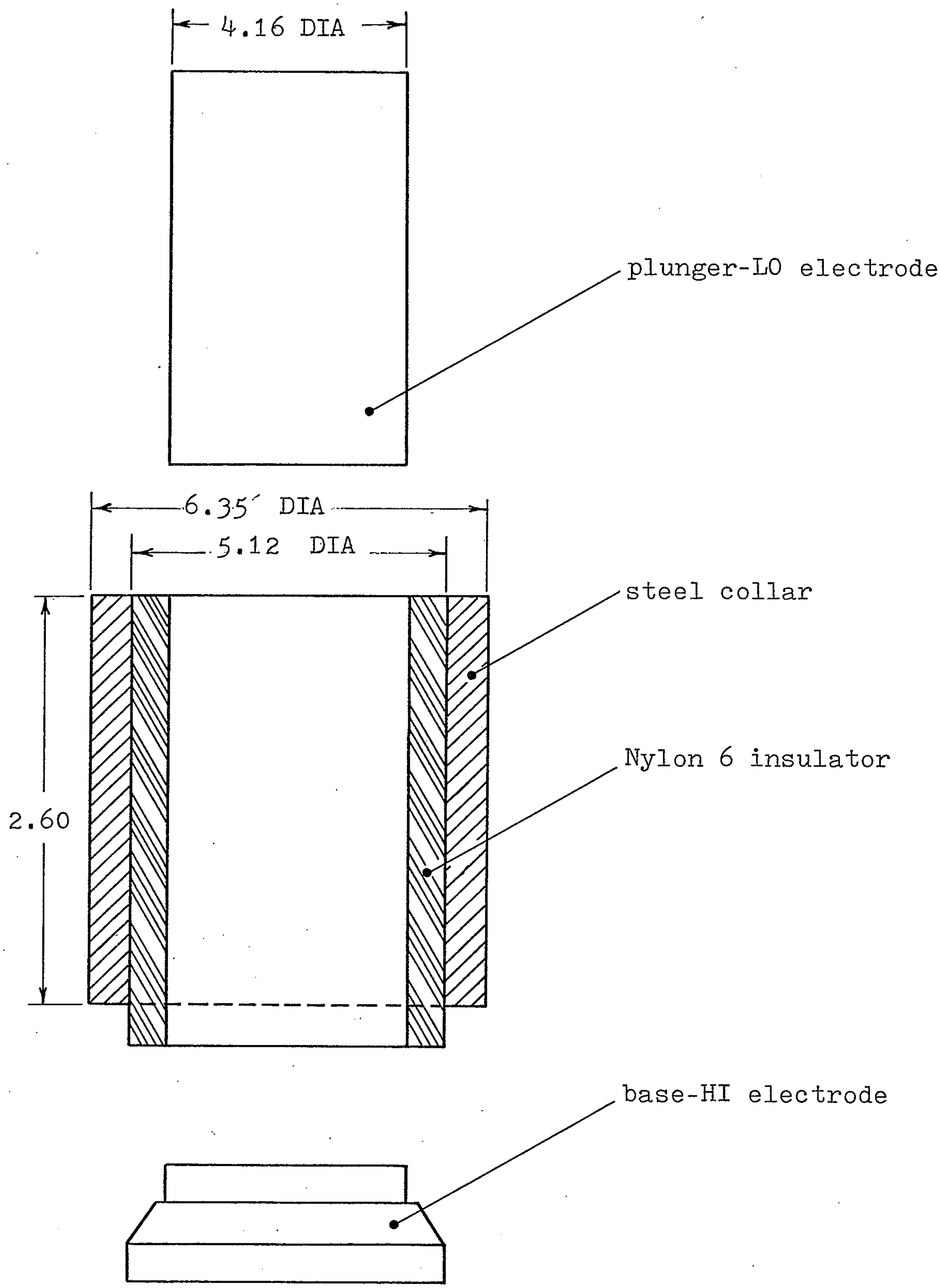


Fig. 2.1 Test cell. Base and plunger are copper-plated steel. Dimensions in cm.

laboratory press slightly modified to suit the testing procedure. Keeping all leads as short as possible to minimize lead inductance, the test cell, MEC and TVM were connected in parallel with the Q-meter variable capacitor. Two additional low-loss ceramic capacitors were added to the circuit as plug-in components. These were necessary as the capacitance increments of the MEC were not large enough for measurements made on samples of high moisture content. A Mitsubishi dial gauge with a range from 0 to 1 in. and resolution of 0.001 in. was used to measure the plate separation of the test cell.

A calibrated, deformable plastic strip normally used to measure the clearance in automotive journal bearings ("Plastigage", Perfect Circle Ltd.) was used to check the parallelism between the base and the plunger. Plastigage is a soft plastic wire that deforms nonelastically under pressure. By measuring the width of the flattened wire, the clearance between the parts may be determined quite accurately. During the test procedure the Plastigage wire was also used to check the calibration of the dial gauge.

The photograph, Fig. 2.2, shows the assembled equipment. Shown are the oscillator, Q-meter, micrometer electrode capacitor (MEC), transistor volt meter (TVM), test cell, hydraulic press and the dial gauge. The frequency counter is just out of sight to the upper left.

2.2 Sample description and preparation.

Samples were drawn from a single clean batch of Manitou

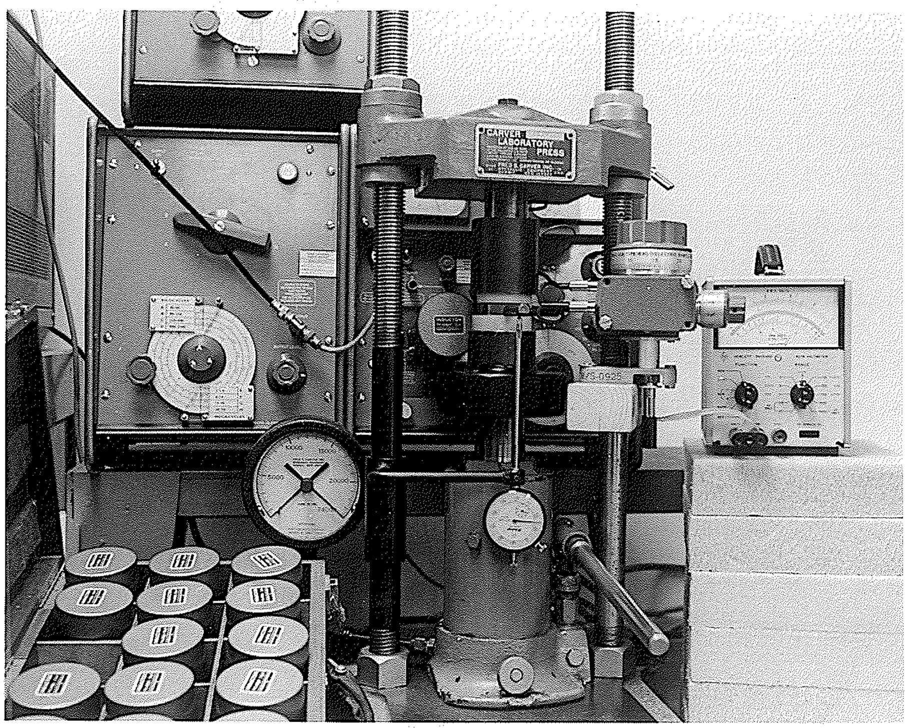


Fig. 2.2 - Photograph of the test equipment.

variety red spring wheat graded number 1 C.W. Flour samples were processed by a laboratory-size flour mill. Ground wheat samples were processed by the same mill but were not screened to remove the other elements from the flour.

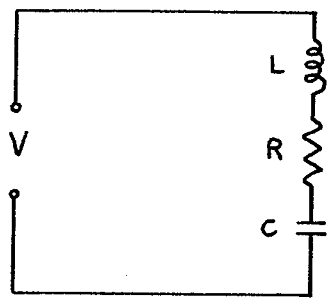
Conditioning of the samples to the desired moisture content was achieved by either putting them over water in a closed container, or by placing them in an air oven at 100°C. After conditioning, the samples were allowed three days to come to equilibrium before they were tested. The exceptions to this were the oven dry samples which were heated at 130°C for three hours, cooled, and then tested immediately in order to minimize any uptake of moisture.

The moisture content of all samples was evaluated by standard methods (AOAC, 1965). Sample size was kept as uniform as possible with wheat kernel samples being 8.0 g within one kernel weight, while flour and ground wheat samples were weighed out to 8.000 ± 0.001 g. All moisture contents as given in the text are percent wet base.

2.3 Q-meter theory and operation

2.3.1 The Q-meter

A Q-meter is normally used to measure the performance characteristics of coils and capacitors. By definition the Q-factor of a component is the ratio of its reactance to its resistance. The measurement principle depends on the characteristics of a series resonant circuit at the point of resonance. The following conditions are then true



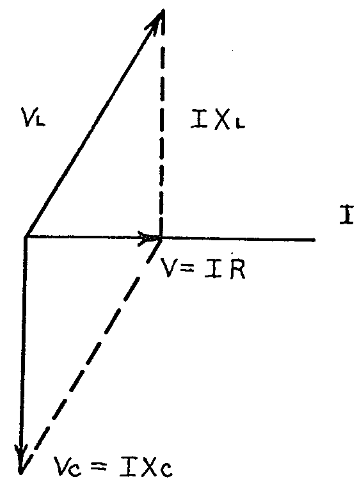


Fig. 2.3 Series resonant circuit.

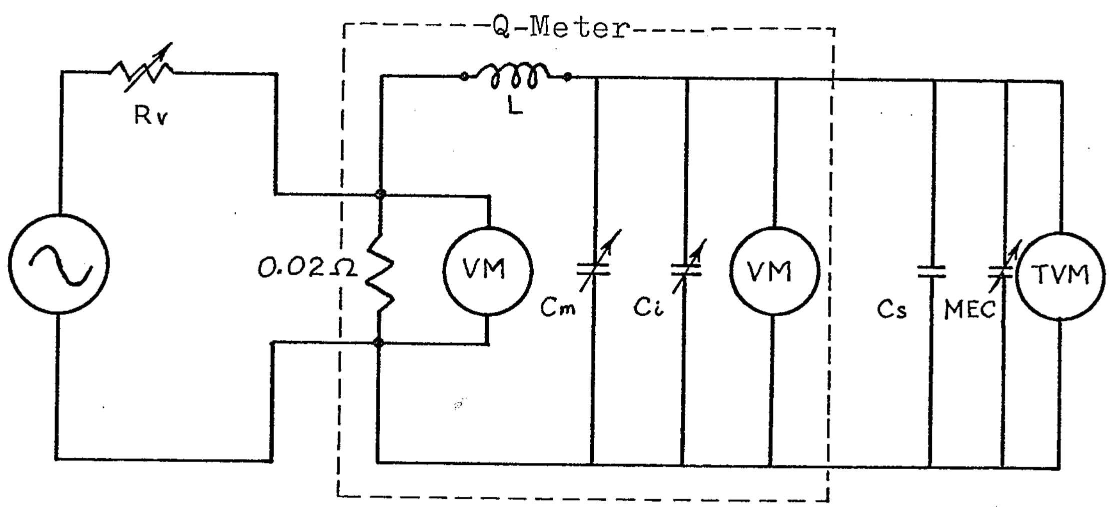


Fig. 2.4 Schematic of measurement circuit.

$$X_c = X_L$$
$$V = IX_c = IX_L = \text{maximum}$$
$$V = IR$$

Where X_c and X_L are the capacitive and inductive reactances, V_c is the voltage across the capacitor, R is the circuit resistance, and V is the applied emf. See Fig. 2.3.

by definition $Q = X/R$

$$= (IX_c)/(IR)$$
$$= V_c/V$$

Therefore if V is maintained at a constant and known level a voltmeter connected across the capacitor to indicate resonance may be calibrated directly in terms of the circuit Q-factor.

The series resonant circuit of the Q-meter is well adapted to the measurement of the dielectric constant and the loss factor of a specimen held in a test cell connected in parallel with the variable capacitor of the Q-meter. This method has been used by Hartshorn, Ward (1936), Nelson et al. (1963), and Nelson (1972).

2.3.2 Measurement of dielectric properties with the Q-meter.

The Q-meter used in this research employs an external oscillator connected to the Q-meter by means of a 0.02Ω shunt resistor. The voltage across this shunt corresponds to a voltage source with very low internal resistance. An external plug-in inductor (L) together with the variable capacitors (Cm and Ci) of the Q-meter form a series resonant circuit. The sample holder (Cs), MEC and TVM are all connected in parallel with these capacitors. (Fig. 2.4)

With an inductor selected for a given test frequency and with the sample contained in the test cell, the circuit is tuned to resonance. This is done by adjusting the variable capacitor (Cm) contained in the Q-meter, until resonance is indicated by the external voltmeter (TVM). The sample is then removed from the test cell, and the circuit is retuned to resonance by adjusting the MEC.

Since the two resonant conditions occur at the same frequency, the total circuit capacitance must be the same in both situations. Therefore, the change in capacitance due to the removal of the sample is equal to the change in capacitance between the initial and final setting of the MEC. If Cx is this change in capacitance, and C_o is the capacitance of the empty sample holder, then the dielectric constant of the sample is given by

$$\varepsilon' = (Cx + C_o)/C_o \qquad (2.1)$$

Calculation of the loss factor by the susceptance variation method relies on the fact that the width of the resonant curve is a measure of losses occuring in the circuit. The circuit is tuned to resonance by Cm. The resonant peak voltage (V_m) and the setting of the MEC are noted. The circuit is then detuned on either side of resonance by the MEC to new settings C_1 and C_2 corresponding

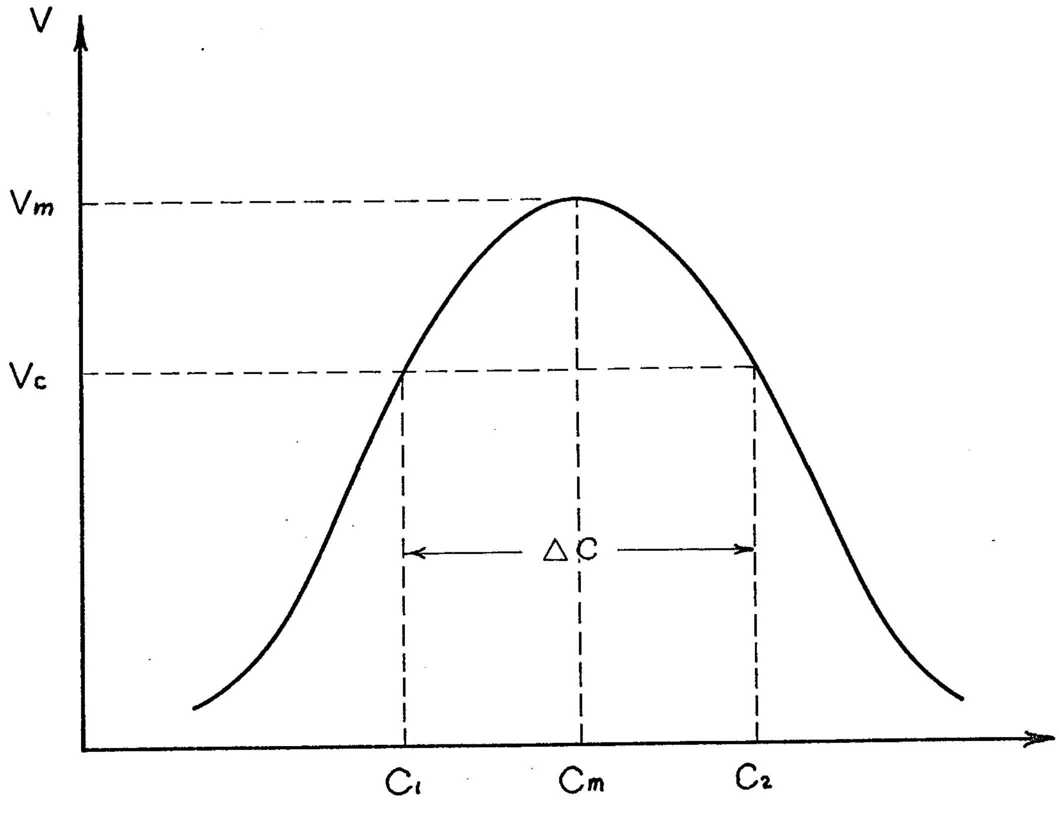


Fig. 2.5 Characteristic resonant curve.

to a lower voltage V_c as indicated by the TVM. (Fig. 2.5)

The process is repeated for the empty test cell to give ΔC_s and ΔC_H for the sample in and out conditions respectively.

It can be shown that the loss factor may be calculated from the following relations (Nelson, 1972).

$$\varepsilon'' = \frac{\varepsilon'}{2C_x}\left(\frac{\Delta C_s}{\sqrt{\left(\frac{V_m}{V_c}\right)_S^2 - 1}} - \frac{\Delta C_H}{\sqrt{\left(\frac{V_m}{V_c}\right)_H^2 - 1}} \right)$$

for $V_c = 0.707\ V_m$, the expression simplifies to

$$\varepsilon'' = \varepsilon' \left(\frac{\Delta C_s - \Delta C_H}{2C_x} \right) \qquad (2.2)$$

2.4 Experimental procedure

Five frequencies were used in the frequency range under investigation. These frequencies were chosen so that the circuit could be resonated with the variable capacitor of the Q-meter set to a minimum value, since accuracy in measuring the loss factor decreases as the total circuit capacitance increases (Von Hippel, 1954).

The assembly of components was devised to reduce lead lengths as much as possible in order to minimize errors due to lead inductance. The assembly was also arranged to have identical lead lengths for the sample in and sample out conditions.

Seven samples at a time were weighed out from a batch of desired moisture content, one sample for each of the five test frequencies and two for moisture content determination. The samples that were not tested immediately were placed in a small air-tight container.

The proper inductor was installed in the Q-meter, the test frequency was set, and the circuit was tuned to resonance by Cm of the Q-meter, with the sample holder empty. Then with a sample in the holder and the plates in contact with the specimen, the circuit was tuned to resonance by the MEC. The output level of the oscillator was adjusted to give a scale reading convenient to calculate 0.707 Vm on the TVM. A change in the output level of the oscillator usually affected the frequency as well, and therefore the frequency was adjusted to the desired value. The MEC was then used to detune the circuit to 0.707 V_m on each side of the resonant peak. Readings of the MEC plate separations were recorded along with the plate separation of the sample holder. The capacitance setting of the MEC corresponding to Vm cannot be found as accurately as the settings corresponding to 0.707 V_m since with losses in the circuit the peak of the resonant curve is quite broad. Since the resonant curve is symmetrical, the value of the capacitance of the MEC at resonance may be more accurately determined by taking the value for Cmax as the average of C_1 and C_2 (see Fig. 2.5) This method became imperative for samples at high moisture content and large density.

After the readings were recorded the press was used to compress the samples to greater density. Then the pressure was released such that the plates just maintained contact with the sample. The procedure of tuning to resonance and then detuning to measure the width of the resonant peak was repeated and settings of the MEC and test cell recorded. This process was continued until measurements had been made at seven densities, the last being about twice natural bulk density. The temperature was also recorded. It varied from 21° C to 23°C.

After these measurements had been made, the sample holder was emptied, cleaned and replaced in the circuit. The measurement procedure outlined above was then carried out to obtain values for the empty sample holder at the plate separations used during the sample in condition.

The values of C_1 and C_2 obtained at 0.707 V_m for the sample in and sample out conditions were used to calculate ΔC_S, ΔC_H and Cx for insertion in eq. (2.1) and (2.2)

It can be shown that

$$\Delta C_S = C_{S2} - C_{S1} \qquad \text{for sample in}$$

$$\Delta C_H = C_{H2} - C_{H1} \qquad \text{for sample out}$$

$$C_x = 0.5(C_{S1} + C_{S2} - C_{H1} - C_{H2})$$

C_o is calculated from eq. (1.1)

The micrometer electrode capacitor (MEC) used as a standard capacitor is a parallel plate capacitor with one moveable plate controlled by a micrometer screw (Hartshorn, Ward, 1936). A calibrated dial attached to the screw gives readings in terms of plate separation. These readings are converted to capacitance by means of eq. (1.1).

A computer program was written to calculate the dielectric constant and loss factor for the samples from eq. (2.1) and (2.2), respectively. The same program was used to calculate the capacitances for different plate separations of the sample holder and the MEC from eq. (1.1). The values of capacitance were corrected for fringe capacitance according to Kirchhoff's formula (Scott, Curtis, 1939).

CHAPTER III

RESULTS

Measured values of the dielectric constant (ε') and the loss factor (ε'') for wheat at 121 kHz and at 10 MHz are shown in tables 3.1 and 3.2 respectively. These results are fairly typical for the data collected.

DEGC is degrees Celsius, MC is the moisture content (wet base), T is the sample thickness in thousandths of an inch, DENS is the density in g/cm^3, E' is the dielectric constant and E" is the loss factor. O.D. indicates samples that were oven dried for three hours at 130°C.

The hydraulic press was used to bring the sample to a given density, then pressure was released such that the electrodes just maintained contact with the sample. The samples were not tested under pressure. The data contained in tables 3.1 and 3.2 is shown plotted in Fig. 3.1 and 3.2.

It is evident that at both frequencies shown, the two parameters, the dielectric constant and the loss factor, increase linearly with sample density. A computer program was used to fit curves to the measured points by least squares regression, and to compute the corresponding linear correlation coefficient. An analysis of the correlation coefficients showed that the assumption of a linear relationship is valid at the one percent level of significance.

The experimental results of all tests made on wheat

Table 3.1 - Calculated values of the dielectric constant and loss factor of Manitou variety red spring wheat at 121 kHz.

MANITOU WHEAT WHOLE 23DEGC MC=O.D. 121KHZ

T MILS	DENS GM/CC	E'	E"
303.0	0.744	3.10	0.15
277.0	0.814	3.43	0.15
265.0	0.851	3.56	0.17
244.0	0.924	3.86	0.21
219.0	1.030	4.37	0.24
204.0	1.106	4.75	0.24
192.0	1.175	5.11	0.29

MANITOU WHEAT WHOLE 23DEGC MC=10.28 121 KHZ

T MILS	DENS GM/CC	E'	E"
290.0	0.776	4.58	0.25
267.0	0.843	5.30	0.34
255.0	0.883	5.79	0.44
225.0	1.001	7.10	0.59
199.0	1.131	8.42	0.69
177.0	1.272	10.16	0.87
169.0	1.332	10.80	0.96

MANITOU WHEAT WHOLE 22DEGC MC=13.4 121 KHZ

T MILS	DENS GM/CC	E'	E"
303.0	0.743	5.50	0.69
270.0	0.833	7.40	1.25
252.0	0.893	8.46	1.54
221.0	1.018	10.73	2.02
198.0	1.137	12.80	2.61
179.0	1.257	15.08	3.04
174.0	1.293	16.18	3.18

MANITOU WHEAT WHOLE 23DEGC MC=14.19 121 KHZ

T MILS	DENS GM/CC	E'	E"
301.0	0.747	6.19	1.32
264.0	0.852	8.48	2.41
236.0	0.953	10.64	3.90
212.0	1.061	12.42	4.31
188.0	1.197	15.05	4.82
171.0	1.316	17.67	5.52

MANITOU WHEAT WHOLE 23DEGC MC=15.82 121 KHZ

T MILS	DENS GM/CC	E'	E"
308.0	0.731	7.13	3.58
263.0	0.856	10.79	6.56
243.0	0.926	12.82	7.71
208.0	1.082	16.92	10.71

Table 3.2 - Calculated values of the dielectric constant and loss factor of Manitou variety red spring wheat at 10 MHz.

MANITOU WHEAT WHOLE 23 DEGC MC=O.D. 10 MHZ

T MILS	DENS GM/CC	E'	E"
295.0	0.762	2.54	0.25
277.0	0.812	2.69	0.29
266.0	0.845	2.80	0.30
245.0	0.918	2.97	0.37
222.0	1.013	3.26	0.42
199.0	1.130	3.64	0.45
190.0	1.183	3.81	0.48

MANITOU WHEAT WHOLE 23 DEGC MC=10.28 10 MHZ

T MILS	DENS GM/CC	E'	E"
293.0	0.768	3.49	0.37
267.0	0.843	4.07	0.49
255.0	0.882	4.35	0.53
227.0	0.991	5.11	0.70
199.0	1.131	6.20	0.96
179.0	1.257	6.93	1.02
168.0	1.339	7.68	1.25

MANITOU WHEAT WHOLE 22 DEGC MC=13.38 10 MHZ

T MILS	DENS GM/CC	E'	E"
299.0	0.753	4.06	0.40
266.0	0.847	5.06	0.65
248.0	0.908	5.74	0.77
220.0	1.024	7.11	1.04
195.0	1.155	8.56	1.29
174.0	1.294	10.37	1.51
169.0	1.333	10.72	1.58

MANITOU WHEAT WHOLE 23 DEGC MC=14.19 10 MHZ

T MILS	DENS GM/CC	E'	E"
300.0	0.750	4.35	0.46
257.0	0.876	5.89	0.75
239.0	0.942	6.72	0.97
210.0	1.072	8.25	1.24
188.0	1.197	9.93	1.52
172.0	1.309	11.35	1.84
167.0	1.348	12.06	2.01

MANITOU WHEAT WHOLE 23 DEGC MC=15,82 10 MHZ

T	DENS	E'	E"
312.0	0.721	4.80	0.57
261.0	0.862	6.85	0.95
237.0	0.950	8.19	1.25
210.0	1.072	9.98	1.59
189.0	1.191	11.68	1.87
176.0	1.279	13.07	2.15
171.0	1.316	13.76	2.32

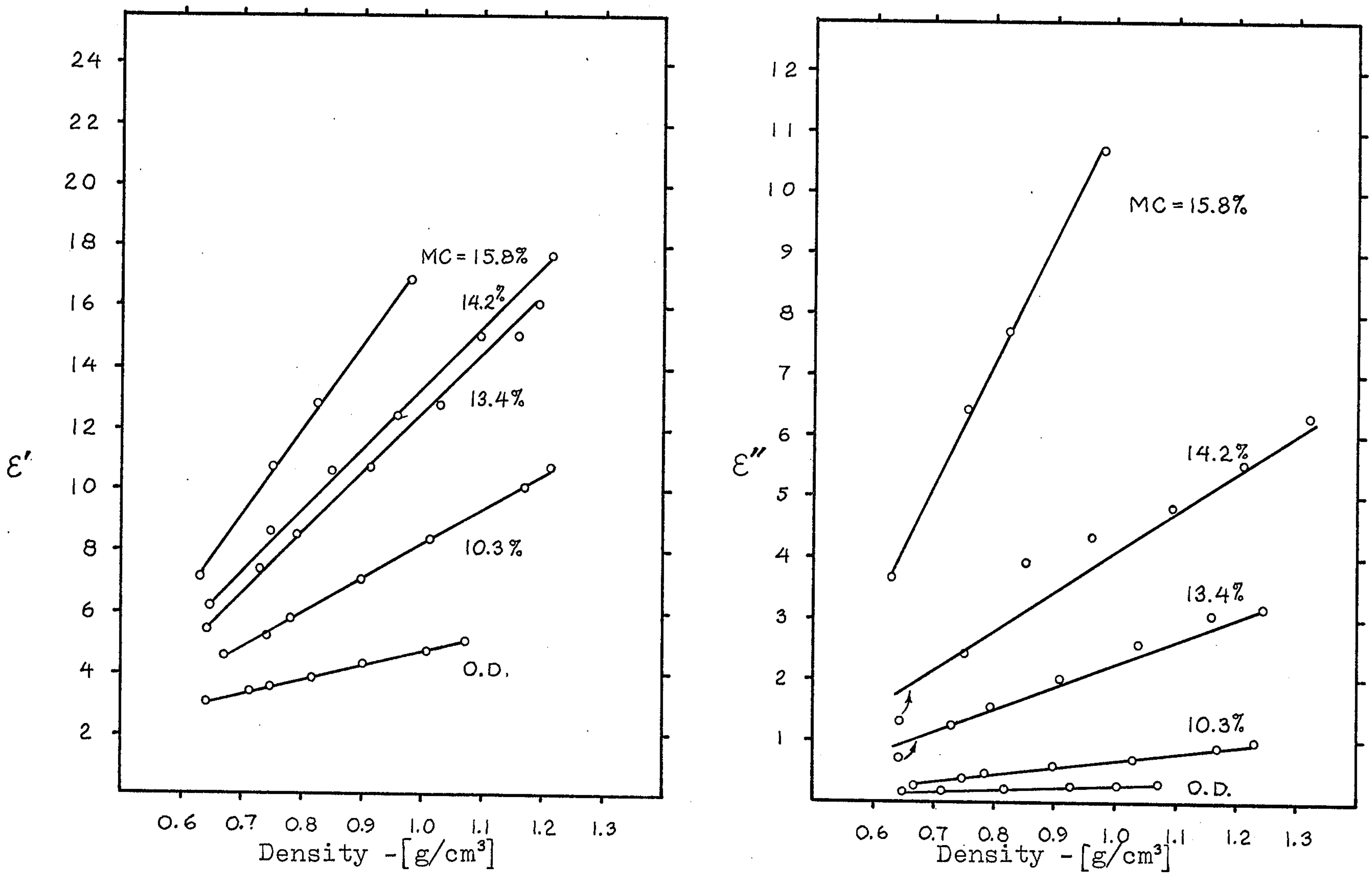


Fig. 3.1(a,b) Variation of ε' and ε" with density for Manitou wheat at 121 kHz and indicated moisture content.

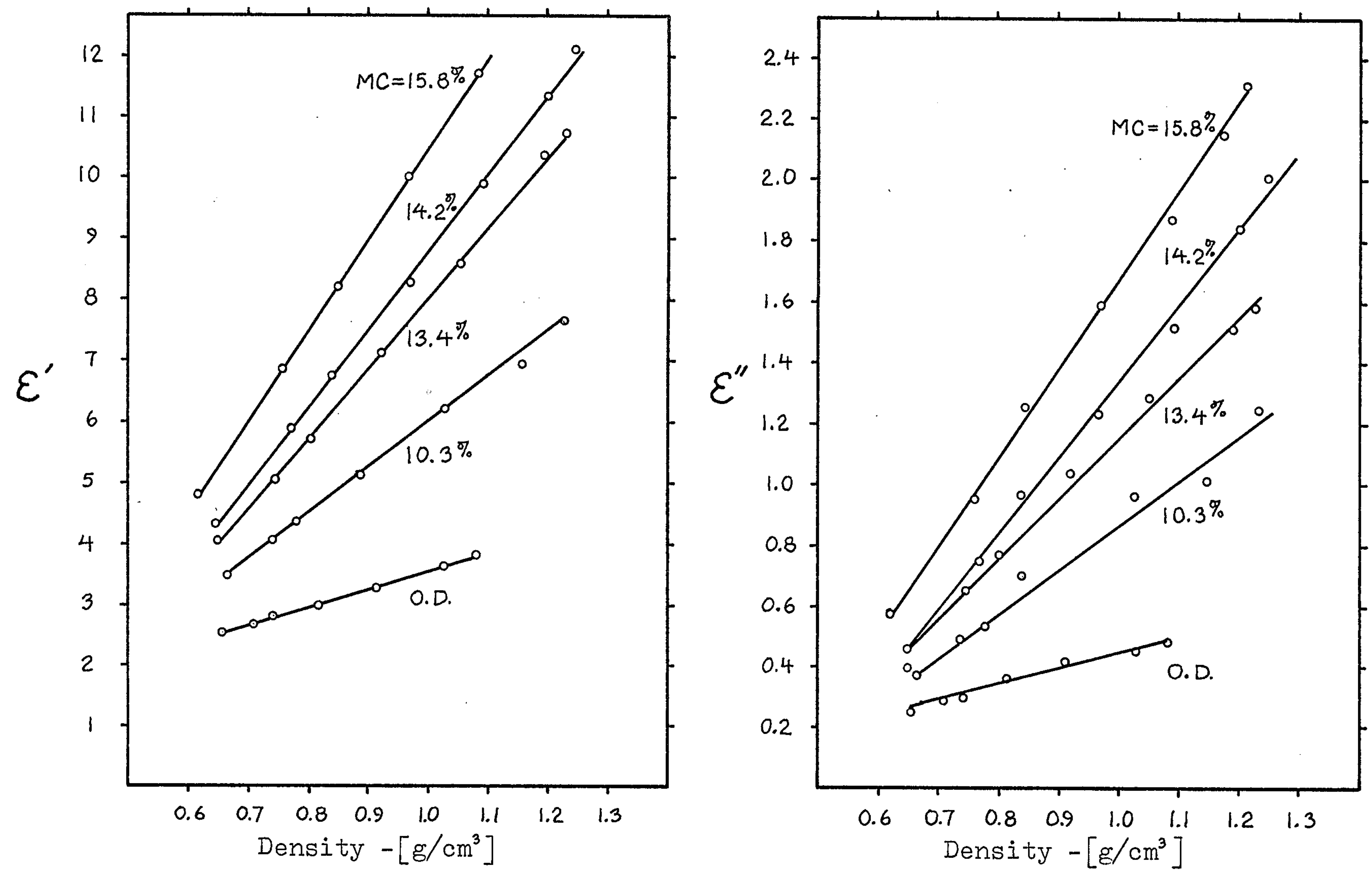


Fig. 3.2(a,b) Variation of ε' and ε" with density for Manitou wheat at 10 MHz and indicated moisture content.

kernels, ground wheat and flour are contained in table A.1 of the appendix. The results of these tests are similar to those presented above. The dielectric constant and the loss factor increase linearly with increasing sample density, while increasing the moisture content increased the slope of the curves. The linear correlation coefficients of the ground wheat and flour samples were generally lower than those of the wheat kernel samples, although they were still above the one percent level of significance. Fig. 3.3 presents the results of the measurements performed on samples of wheat kernels, ground wheat and flour at a frequency of 121 kHz. Since the samples were conditioned separately to the desired moisture contents, it was not possible to compare the permittivities of these materials at identical moisture contents.

The results were similar at all of the test frequencies, with only minor differences between the properties of the three materials. At moisture contents above 14 percent, wheat kernels had higher values of the dielectric constant and loss factor than either ground wheat or flour samples. Flour proved to be less compressible and exibited a greater elasticity at low moisture contents than did the other materials.

Values were interpolated from the measured points and plotted to show the variation of the dielectric constant and loss factor with moisture content of the sample. Fig. 3.4 and 3.5 show the plotted values for wheat kernels at 121 kHz

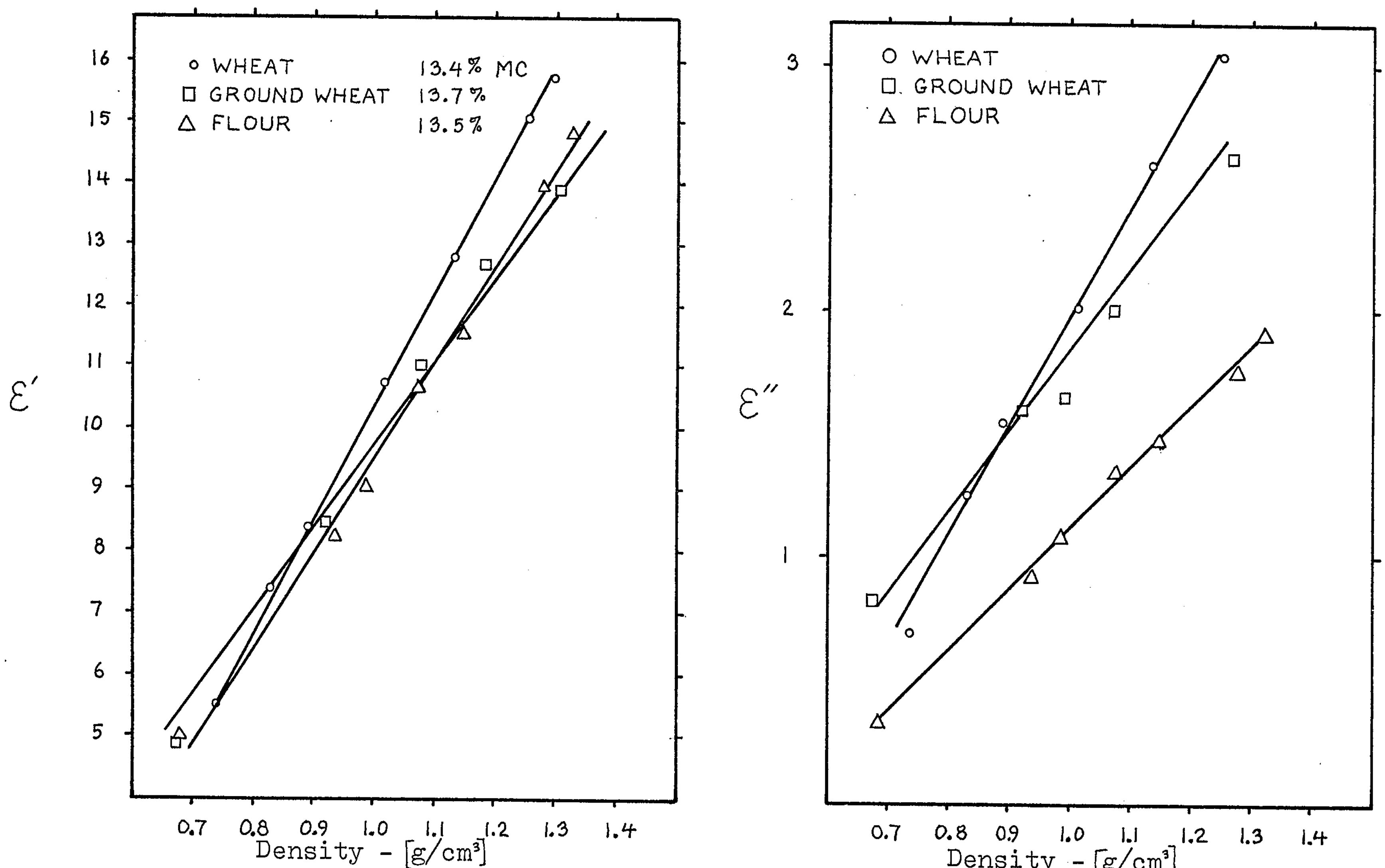


Fig. 3.3(a,b) Comparison of the variation of ε' and ε" with density at 121 kHz for the three materials tested.

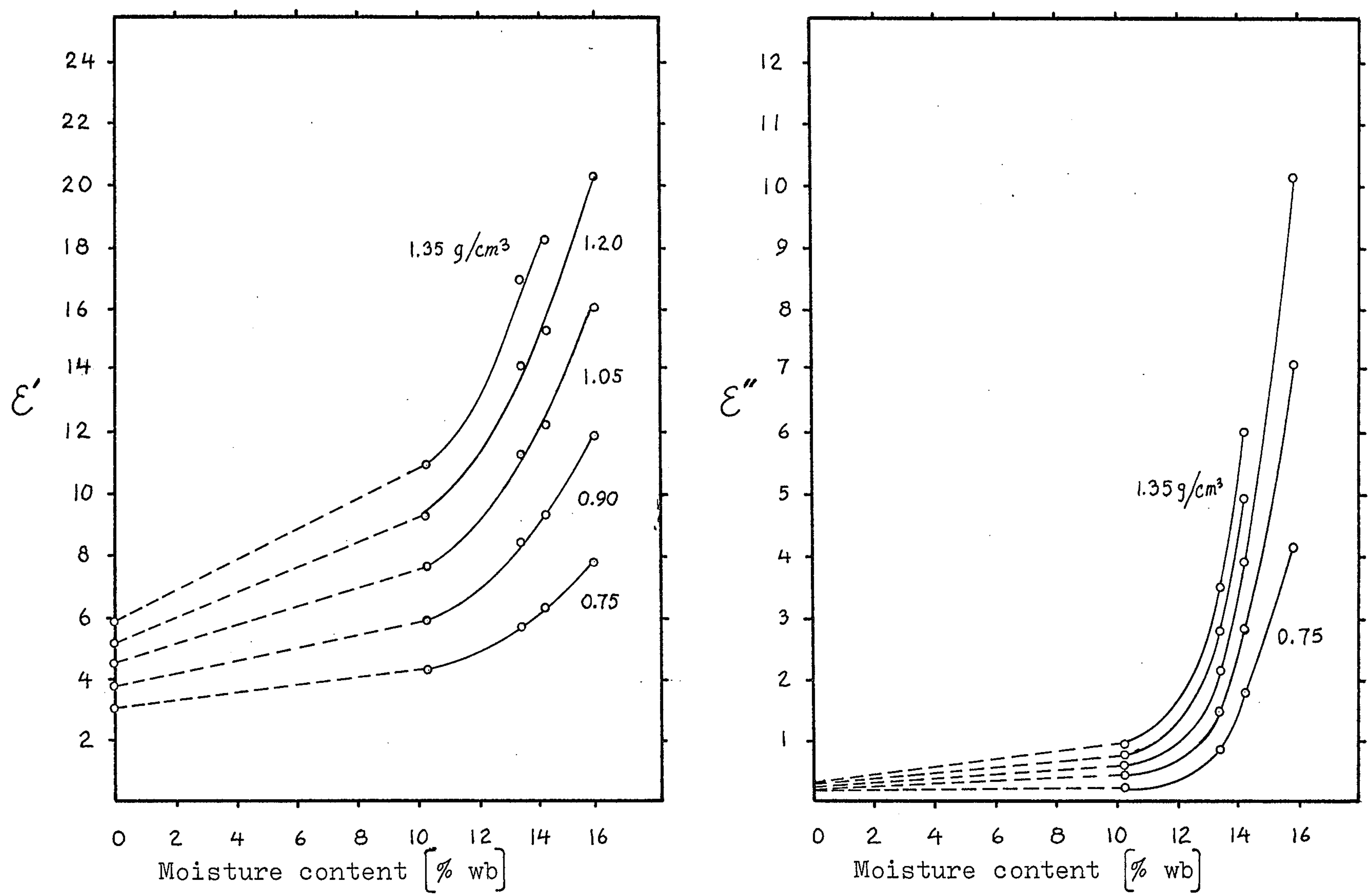


Fig. 3.4(a,b) Variation of ε' and ε" with moisture content for Manitou wheat at 121 kHz and indicated sample density.

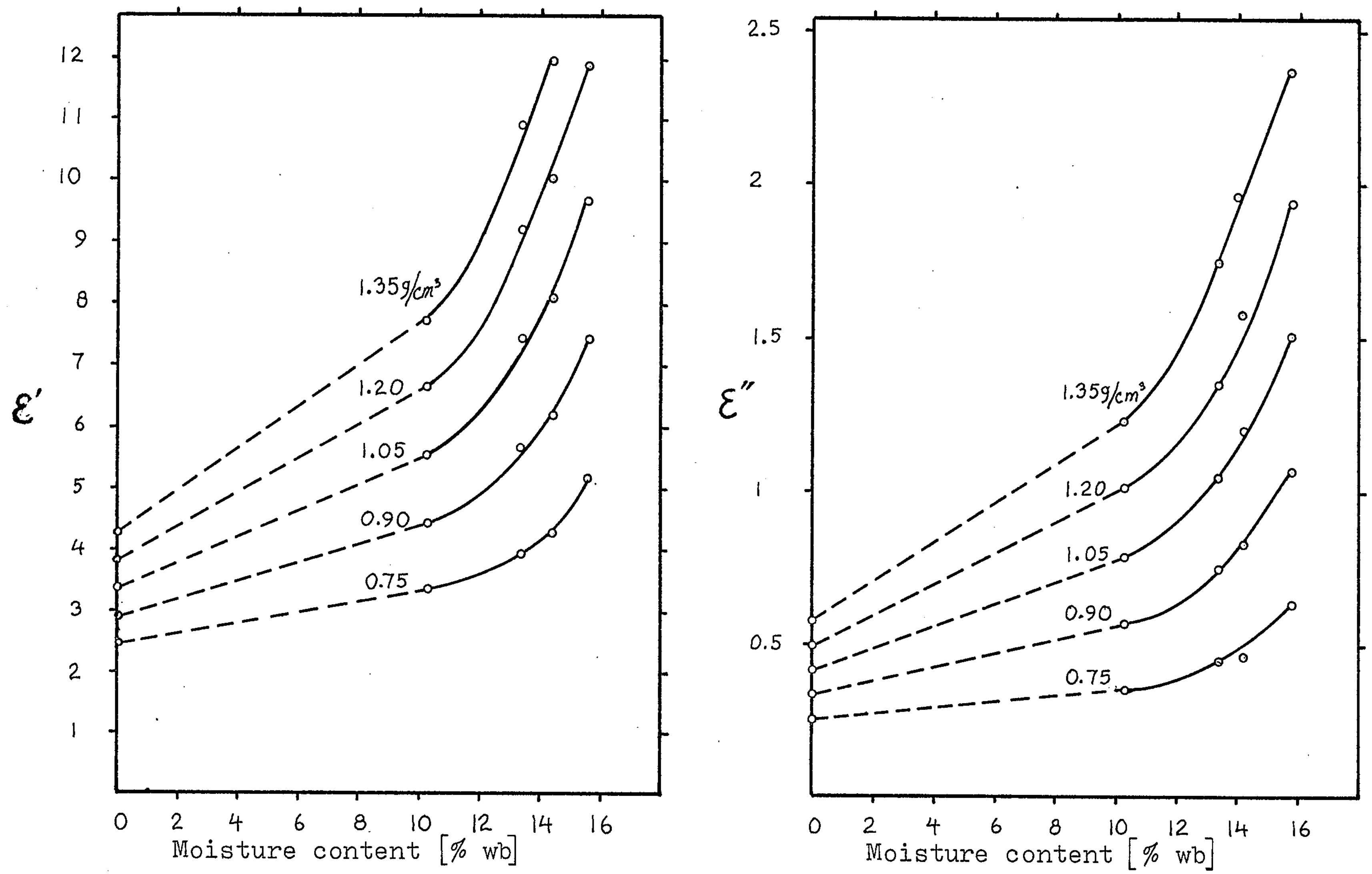


Fig. 3.5(a,b) Variation of ε' and ε" with moisture content for Manitou wheat at 10 MHz and indicated sample density.

and 10 MHz respectively.

Dashed lines on Fig. 3.4 and 3.5 indicate the expected behavior between the oven dry state and the next measured point. At both frequencies the dielectric constant and loss factor increase slowly with moisture content up to about 10 percent MC. In the range 10 to 13 percent MC, the increase is much faster, while for MC above 13 percent the increase is very great and appears to be almost linear. The curves were fitted to the interpolated points by drawing a smooth line through them.

Fig. 3.6 illustrates the frequency dependence of the dielectric properties. The curves were fitted by drawing a smooth line through the points measured at the indicated frequencies. A region of dispersion is indicated below 75 kHz but measurements were not performed in this range so that it is not possible to confirm the exact shape of the curves. The shape does indicate however that the peak in the loss factor curves may be shifting to higher frequencies as the density of the sample increases.

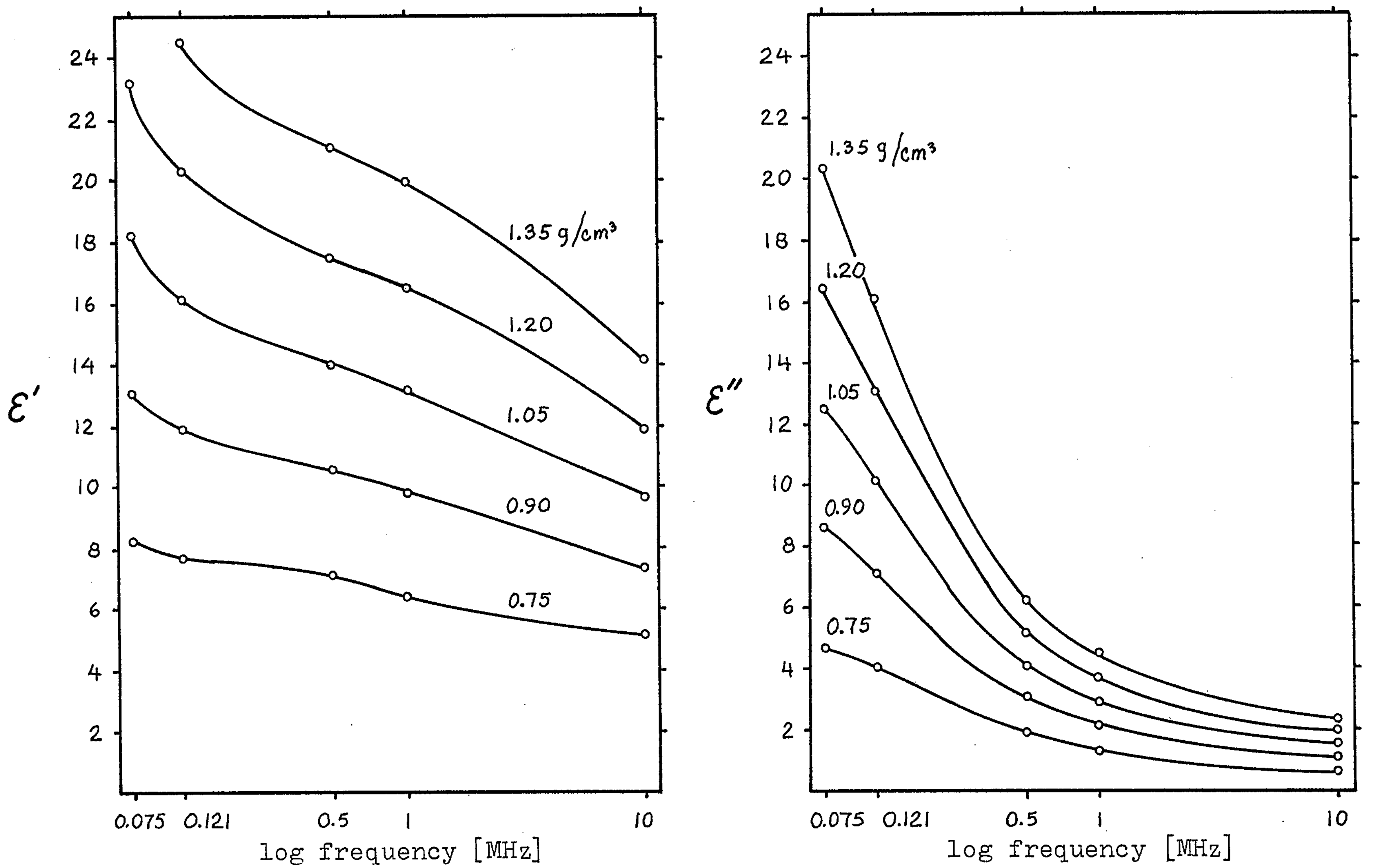


Fig. 3.6(a,b) Frequency dependence of Manitou wheat for samples of 15.8% MC and indicated density.

CHAPTER IV

DISCUSSION

4.1 Frequency dependence of the dielectric properties.

The decrease of permittivity with increasing frequency is caused by the effect of frequency on the various mechanisms of polarization. The total polarization of a dielectric is made up of contribution from electronic and atomic polarization, orientational polarization and interfacial or Maxwell-Wagner polarization.

At low frequencies the dipoles can follow the applied field and the contribution to polarization and, therefore permittivity is maximum. At very high frequencies the applied field alternates too fast for the dipoles to rotate and there is a smaller contribution to polarization. At some point between these extremes the polarization begins to lag the applied field, losses occur and the contribution of that polarization mechanism begins to decrease. Interfacial polarization is the first mechanism to be affected by increasing frequency. Orientational polarization is the next to be affected, followed by atomic and electronic polarization. Atomic and electronic polarization are affected only at very high frequencies above 10^{13} Hz.

This decrease in permittivity is termed dielectric dispersion and has been studied by a large number of researchers, such as Debye, Cole, Frolich, Kirkwood and Onsager. Presentation and discussion of their work may be found in many references including Hill et al. (1969), Bottcher (1952), and Von Hippel (1954).

Debye suggested that for orientational polarization of dipolar substances, the dielectric properties are described by the following equations

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2 \tau^2} \qquad (4.1)$$

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\,\omega \tau}{1 + \omega^2 \tau^2} \qquad (4.2)$$

Where ε_s is the low frequency value of the permittivity, ε_∞ is the value of permittivity above the region of dispersion, τ is the relaxation time associated with the molecular rotations, and ω is the angular frequency. A graphical presentation of eq. (4.1) and (4.2) is shown in Fig. 4.1.

The Debye equations are based on the assumption that there is only a single relaxation time involved. This is true only for a few homogeneous materials (Hill et al.,1969). Due to the bonding forces of various types of water contained in agricultural products there may be a wide range of relaxation times present.

Heterogeneous systems containing free charge carriers exibit Maxwell-Wagner effects arising from interfacial polarization. Interfacial polarization results from free charge carriers piling up along interfaces in the structure of the dielectric medium. This causes an accumulation of localized centers of positive and negative charges. An

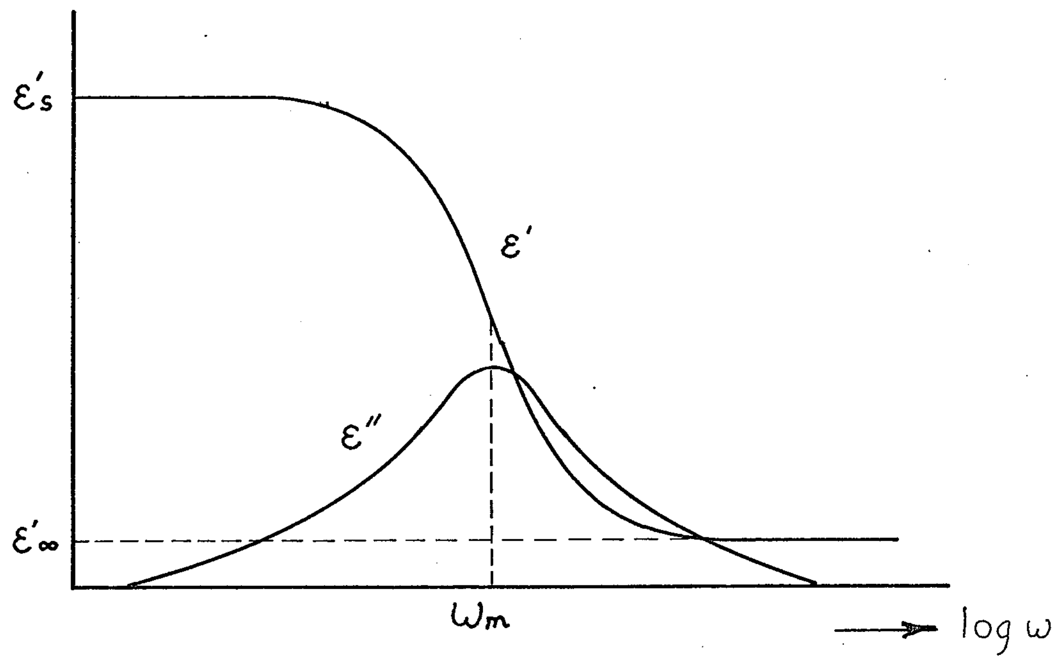


Fig. 4.1 Dispersion and absorption curves for a polar material following the Debye relaxation process.

increase in conductivity will increase the magnitude, and alter the frequency response of the effect. To better understand these effects researchers have utilized several theoretical and experimental models that give results similar to those found with practical materials.

An experimental model of a biological system as used by Hamon was reported by Van Beek (1967). Hamon coated lumps of paraffin wax with a conducting powder and then pressed them into a solid mass. The experimental curves of log ε'' against log frequency were found to decrease over several decades of frequency without any maximum. At high concentrations of the conducting powder the loss curve approached a straight line indicating the existence of conducting paths. Many biological systems exibit a frequency response very similar to this.

Other systems exibiting Maxwell-Wagner losses may have a peak in the loss factor, and a dispersion region that closely follows the Debye equations (Van Beek, 1967).

4.2 The effect of moisture on dielectric properties.

The dielectric properties of grains are strongly dependent on both the moisture content of the grain, and the manner in which the water is held. As mentioned in 1.2.4 Zeleny (1962) suggested that some differences noted during moisture testing may have been due to differences in the ratios of free water to bound water between samples.

Free water is considered to be water contained in large capillary pores and other interstitial spaces within the grain. Its properties are close to those of water in bulk in that it may contain dissolved ions and has a static dielectric constant of 80 at 20°C. Bound water on the other hand, is tightly held to the grain molecules in such a way that it forms part of the mechanical structure of the molecule. As such it cannot dissolve ions and thus cannot conduct electricity. Bound water is regarded as having a static permittivity in the range from 4.5 to 5.0.

The effect of moisture on the dielectric properties is clearly shown in Fig. 3.1, 3.2, 3.3 and 3.4. Fig. 3.1 and 3.2 show the dielectric constant and loss factor of wheat kernels at five moisture contents, versus sample density. As the moisture content increases the slope of the curves also increases.

The effect of increasing sample moisture content is even more clearly illustrated in Fig. 3.4 and 3.5, where the dielectric properties of wheat kernels are plotted versus moisture content. The data plotted in Fig. 3.1 and 3.2 were interpolated to show the effect of moisture content at five sample densities. Below 10 percent MC, bound water predominates in the sample as evidenced by the small slope of the curves. In the range 10 to 13 percent MC there appears to be a transition region with some of the additional water being stored in both forms of water. Above 13 percent MC the rapid rise in dielectric properties indicates that nearly all of the added moisture is stored as free water.

The effect of the ratios of bound and free water is caused by more than the differences in their static dielectric constants. Free water, due to dissolved ions contributes to Maxwell-Wagner losses, while bound water cannot. Pierce, as reported by Van Beek (1967), made measurments on suspensions of sea water in oil. He found that the high conductivity of sea water shifted the frequency at which the maximum Maxwell-Wagner losses occured into the mega hertz region. Maxwell-Wagner effects are usually not appreciable above a few kilo hertz.

This shift to higher frequencies of Maxwell-Wagner effects was also reported by Stetson and Nelson (1970), who performed tests on a number of seeds in a frequency range of 250 Hz to 20 kHz. Nebraska grown, Gage hard red winter wheat of 14.0 percent MC showed a peak in the loss factor at about 500 Hz, while a sample of 15.8 percent MC had a loss peak at 1.5 kHz. Samples of 12 and 10 percent MC showed a gradual decline in the loss factor from 250 Hz to 20kHz with no peak. Similar results were observed for other seeds tested by the same researchers.

No tests were carried out in this study below 75 kHz. However, Fig. 4.6 indicates that an increase in sample density is causing a similar shift in the loss factor versus log frequency curves.

4.3 The effect of density.

Agricultural products such as grain and flour are heterogeneous mixtures of particles in air, and have been investigated as such as early as 1821. The problem of the dielectric properties of mixtures composed of different substances has been studied for a variety of materials.

De Loor (1968) showed that by considering granular particles of dielectric constant ε_i, dispersed in air of dielectric constant ε_o, derivations of dielectric properties may be made analagous to those given by Debye (1929) for dipolar liquids. An effective internal dielectric constant ε^* is attributed to the immediate surroundings of the particles to account for interactions with surrounding material.

Assuming the particles to be ellipsoids of similar size and shape, De Loor (1968) stated that the macroscopic dielectric constant (ε_m) could be expressed in the form

$$\varepsilon_m = \varepsilon_o + \frac{v_i}{3}\left(\varepsilon_i - \varepsilon_o\right)\sum_{j=1}^{3} \frac{1}{1 + A_j\left(\left(\varepsilon_i/\varepsilon^*\right) - 1\right)} \qquad (4.3)$$

Where v_i is the volume filling factor of the granules, and A1, A2, A3 are the depolarization factors along the main axes of the granule. These factors are determined by the shape of the granules. For spherical particles A1= A2 =A3 =1/3 and (4.3) can be written

$$\varepsilon_m = \varepsilon_o + 3 v_i \,(\varepsilon_i - \varepsilon_o)\,\varepsilon^* / \,(2\varepsilon^* + \varepsilon_i) \qquad (4.4)$$

De Loor stated that ε^* always lies between ε_o and ε_m and thus limits for εm may be estimated. When the shape of the particles is not known, limits can still be estimated by substituting Aj = 0, 0, 1 (disk shaped particles) with $\varepsilon^* = \varepsilon_m$, and Aj = 1/3, 1/3, 1/3 (spherical particles) with $\varepsilon^* = \varepsilon_o$. Fig. 4.2 from De Loor (1968) illustrates the variation of the dielectric constant with filling factor.

Since eq. (4.3) is asymmetric in $\mathcal{V}_i$, several regions are apparent in Fig. 4.2. For filling factors near 0.5, a form of eq. (4.4), known as Bottcher's formula is often used. Since the particles are surrounded by the mixture rather than one of the constituents, ε^* is replaced by ε_m. Another formula that often gives results that agree well with exprimmental values was derived by Looyenga (reported by Van Beek, 1964) as

$$\varepsilon_m = (\varepsilon_o^{1/3} + \quad (\varepsilon_i^{1/3} - \varepsilon_o^{1/3}))^3 \qquad (4.5)$$

Examination of the experimental results showed that the dielectric constant and loss factor varied linearly with density in the range tested. However, since the curves did not intersect $\varepsilon_m' = 1$ at $\mathcal{V}_i = 0$, it became apparent that they were probably not linear outside the range of densities examined.

Assuming that the highest density reached during the testing was equivalent to a filling factor of 0.95, a value of ε_i' was extrapolated from the data. This value was used in eq. (4.5) for a rough check of ε_m'. It was found that

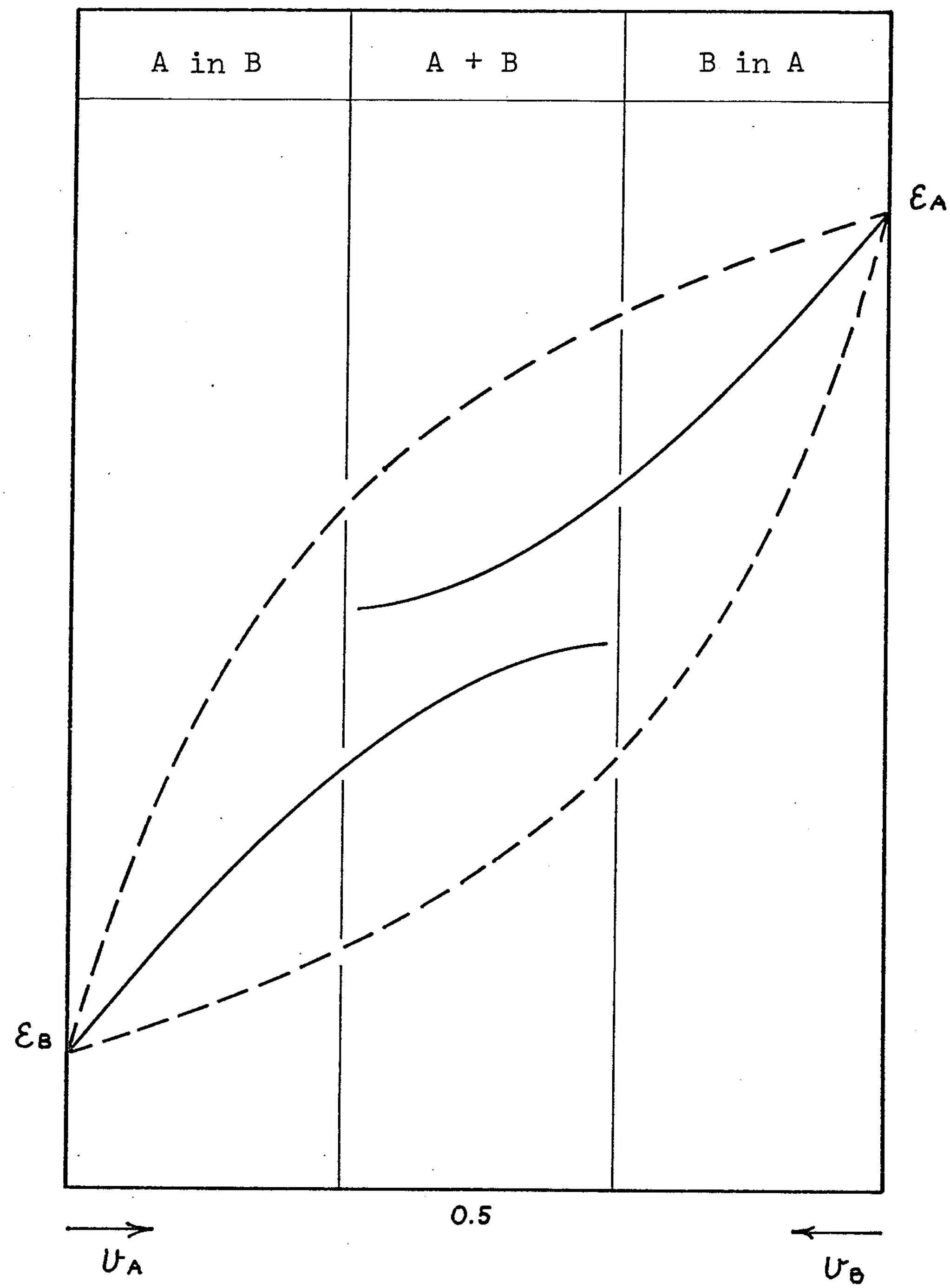


Fig. 4.2 Different regions for heterogeneous mixtures from eq 4.3.

above a filling factor of 0.6, the results obtained by eq. (4.5) were within a few percent of the measured values.

In sections 4.1 and 4.2, the effects of conductivity on the frequency response of the Maxwell-Wagner absorption and the effect of moisture and of conductivity was discussed with respect to experimental and theoretical models. Since compression of a sample increases its conductivity, it is expected that the sample density will affect the frequency response of the dielectric in a manner similar to the effect of an increase in conductivity. This is illustrated in Fig. 3.6.

Stetson and Nelson (1970) showed that an increase of moisture content from 14.0 to 15.8 percent in a sample of wheat shifted the critical frequency of the Maxwell-Wagner absorption from 0.5 kHz to 1.5 kHz. At the same time the curve of the loss factor vs. log ω was more sharply peaked. Fig. 3.6 indicates that a similar shift is caused by an increase in sample density although the tests were not done at sufficiently low frequencies to establish the exact shape of the curves. The results shown are similar to those reported for the model mentioned in section 4.1, consisting of lumps of paraffin coated with a conducting powder. Tests on this model showed a steady decline of the loss factor over several decades of frequency with no apparent peaks.

4.4 Special problems encountered.

The main problem encountered during assembly of the equipment involved the construction of a suitable test cell. The pressures to be used precluded the use of brittle materials such as glass or ceramics. After some trials a Nylon-6 cylinder with a surrounding steel collar was constructed and proved adequate.

There were inconsistencies in measurement during trial runs that were eliminated by relatively minor changes in the test cell. Surface conductivity of the cell was reduced by chamfering the base and cutting back the bottom of the steel collar (see Fig. 2.1). It was also found that cleaning the walls with an ethyl alcohol solution before each test lowered the losses of the empty test cell. Some of the random fluctuations in measured values were eliminated by grounding the steel collar to the LO terminal of the Q-meter. These changes greatly improved the reliability and repeatability of the tests.

Since samples released from pressure tended to have a slow rebound, it was necessary to make electrical measurements as quickly as possible. The Monsanto frequency counter used to monitor frequency showed that changes in sample loss caused by compression often caused appreciable changes in the frequency of operation. Often this resulted in readings being made in a series of steps. The circuit was adjusted to resonance with the MEC, the frequency was reset if it had varied, and if so the circuit had to be retuned. In the meantime the sample had rebounded and changed the plate separation of the sample holder. The changes in frequency were quite large and frequency monitoring was considered very important.

At frequencies beyond those investigated (above 10 MHz), severe problems were encountered with hand capacitance. Slight movements of the body near the testing components resulted in fluctuating readings on the TVM. Since the volume of data obtained was already quite large, testing was terminated at 10 MHz. The problem of hand capacitance could be alleviated however, by the use of styrofoam extensions for the the knobs of the variable capacitors. This allowed settings to be made with the hands kept at a distance from the test components.

The wall of the test cylinder was scored by the drier material during testing. If a large number of tests were to be made on very dry samples, it would be expected that the sample holder would have a rather short life. As the wall became scored it was much more difficult to keep the wall clean, and surface conductivity became apparent.

4.5 Mechanical properties of the test materials.

It was noted during the tests that the deflection versus pressures curves were very consistent at all moisture content levels and provided an excellent rough indication of sample moisture content. During the writing of this thesis, a report was received describing the development of a moisture indicator for farm use that employs this principle (University News, 1974)

The flour samples proved to be more elastic and showed a greater rebound than either the ground or kernel wheat. There were only minor differences between the compressibility of the kernels and the powdery materials.

4.6 Verification of reliability

An analysis of errors was made by the method of uncertainies presented by Kline and McClintock (1953), as given by Holman (1971). This method takes into account the relative effect of the uncertainy of each measured variable.

The probable uncertainy of a calculated value is given as the square root of the sums of the squares of the estimated uncertainies of each measured variable times the partial deriative of the defining equation with respect to that variable. The dielectric constant is defined by eq. (2.1) and the loss factor by eq. (2.2). If d_i are the uncertainies in the measured values, then the probable uncertainy in the dielectric constant is

$$d\mathcal{E}' = \left[\left(\frac{\partial \mathcal{E}'}{\partial C_x} \; dC_x \right)^2 + \left(\frac{\partial \mathcal{E}'}{\partial C_o} \; dC_o \right)^2 \right]^{1/2}$$

$$= \left[\left(\frac{1}{C_o} \; dC_x \right)^2 + \left(\frac{C_x}{C_o} \; dC_o \right)^2 \right]^{1/2}$$

dividing by $\varepsilon' = (C_x + C_o)/C_o$ (2.1)

$$\frac{d\mathcal{E}'}{\mathcal{E}'} = \left[\left(\frac{C_x}{C_x + C_o} \; \frac{dC_x}{C_x} \right)^2 + \left(\frac{C_x}{C_x + C_o} \; \frac{dC_o}{C_o} \right)^2 \right]^{1/2} \qquad (4.6)$$

for low loss materials $C_x/(C_x + C_o)$ has a minimum value of approximately 0.66 and a maximum of 0.95 for high loss materials. The estimated values of dC_x/C_x and dC_o/C_o are 0.03 and 0.01 respectively. Inserting these values in (4.6)

$d\varepsilon'/\varepsilon' = 0.02 = 2\%$ for low loss materials

$d\varepsilon'/\varepsilon' = 0.03 = 3\%$ for high loss materials

The probable uncertainy in the loss factor is

$$d\varepsilon'' = \left[\left(\frac{\partial \varepsilon''}{\partial \varepsilon'} \, d\varepsilon' \right)^2 + \left(\frac{\partial \varepsilon''}{\partial \Delta C_S} \, d\Delta C_S \right)^2 + \left(\frac{\partial \varepsilon''}{\partial \Delta C_H} \, d\Delta C_H \right)^2 + \left(\frac{\partial \varepsilon''}{\partial C_X} \, dC_X \right)^2 \right]^{1/2}$$

$$= \left[\left(\frac{\Delta C_S - \Delta C_H}{2C_X} \, d\varepsilon' \right)^2 + \left(\frac{\varepsilon'}{2C_X} \, d\Delta C_S \right)^2 + \left(\frac{\varepsilon'}{2C_X} \, d\Delta C_X \right)^2 + \left(\frac{\varepsilon'(\Delta C_S - \Delta C_H)}{2C_X} \, dC_X \right)^2 \right]^{1/2}$$

dividing by $\varepsilon'' = \varepsilon'(\Delta C_S - \Delta C_H)/2C_X$ (2.2)

$$\frac{d\varepsilon''}{\varepsilon''} = \left[\left(\frac{d\varepsilon'}{\varepsilon'} \right)^2 + \left(\frac{d\Delta C_S}{\Delta C_S - \Delta C_H} \right)^2 + \left(\frac{\Delta C_H}{\Delta C_S - \Delta C_H} \right)^2 + \left(\frac{dC_X}{C_X} \right)^2 \right]^{1/2} \quad (4.7)$$

Estimated values for $\Delta C_S/(\Delta C_S - \Delta C_H)$ are 0.05/1 for low loss materials, and 1/40 for high loss materials. Estimated values for $\Delta C_H/(\Delta C_S - \Delta C_H)$ are 0.05/1 for low loss materials and 0.05/40 for high loss materials. Inserting these values and the values for $d\varepsilon'/\varepsilon'$ and dC_X/C_X in eq. (4.7) gives

$d\varepsilon''/\varepsilon'' = 0.079 = 7.9\%$ for low loss materials

$d\varepsilon''/\varepsilon'' = 0.044 = 4.4\%$ for high loss materials

The estimated uncertainies for the measured values are the maximum expected. A further check was made of accuracy by measuring the dielectric constant and loss factor of Teflon discs held in the sample holder. The results of these tests are contained in table 4.1. Manufacturers data for the samples gives a value for the dielectric constant of 2.03 to 2.04 and a value for the loss factor of 0.0. The maximum error in the dielectric constant was 3.5 percent, with an average error of 1.5 percent. The maximum error in the loss factor was 0.05 with an average error of 0.015.

Table 4.1 - Calculated values of the dielectric constant and loss factor of Teflon discs held in the sample holder.

TEFLON AT 75 KHZ

T MILS	E'	E''
255.0	2.04	0.02
216.0	2.00	-0.00
111.0	1.99	-0.01
58.5	2.06	-0.01

TEFLON AT 121 KHZ

T MILS	E'	E''
217.0	1.99	0.03
113.0	2.03	-0.00
55.0	1.97	-0.01

TEFLON AT 500 KHZ

T MILS	E'	E''
219.0	2.05	-0.02
111.0	2.00	-0.01
57.0	2.02	-0.01

TEFLON AT 1 MHZ

T MILS	E'	E''
220.0	2.04	0.01
113.0	2.05	-0.02
58.0	2.05	0.02

TEFLON AT 10 MHZ

T MILS	E'	E''
254.0	2.07	-0.01
216.0	1.95	0.05
58.0	1.99	-0.01

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

1. The variation of the dielectric constant and loss factor with density of wheat kernels, ground wheat and flour samples was found to be linear within the range of moisture content, density and frequency investigated. However, since the extrapolated curves, with the exception of the oven dry samples do not intersect $\varepsilon' = 1$ for density equal zero, it appears that the relation is non-linear at densities less than those tested. Densities below natural bulk density however, have little practical significance and can only be achieved with the use of a filler material such as, for example, styrofoam beads.

2. Differences between materials, and in some cases between moisture contents of the same material, were more noticeable in the loss factor values than in the values of the dielectric constant.

3. The difference in capacitance between samples of different moisture content is increased by compression such that there should be an increase in the accuracy of the measurement of moisture content by compressing the samples.

4. Increased sample density shifted the Maxwell-Wagner effects towards higher frequencies due to an increase in the sample conductivity.

5. For practical moisture meters the measurement frequency should be higher than 1 MHz to be free from any interference from Maxwell-Wagner effects.

6. Pressures required to compress samples to a filling factor of 1 are not practical for a commercial moisture meter.

7. Extreme pressures scored the wall of the test cell when used with dry samples, and increased the losses of moist samples such that measurements were made difficult.

8. The procedure is unsuited for the testing of oilseeds due to the expulsion of oil from the samples under compression.

9. Further examination should be made of the feasibility of measuring moisture content by measuring the deflection of the sample versus the applied pressure.

CHAPTER VI

SUMMARY

Samples of wheat, ground wheat and flour were tested to determine the effect of density on the dielectric constant and loss factor of the materials. With the use of a specially constructed test cell, it was possible to compress samples to about twice the natural density. Tests were made on samples at oven dry state and at moisture contents above and below normal storage levels. The frequencies at which measurements were made are 75 kHz, 121 kHz, 500 kHz, 1 MHz and 10 MHz. Electrical measurements were made by the resonance method, using a Q-meter.

An introduction to the dielectric properties is given along with a review of previous investigations. Various polarization mechanisms are discussed with reference to theories of early researchers in the field. Since the dielectric properties are greatly affected by the test frequency and the moisture content of the sample, a discussion of these effects with respect to the mechanisms of polarization is presented.

The results of all tests made, as calculated by a computer program, are contained in the appendix. Typical curves of the variation of the dielectric properties with density, with moisture content, and with frequency are shown for wheat samples. A comparison of the dielectric properties of the three materials at a frequency of 121 kHz and a moisture content of about 13 percent is also given. It was not possible to compare samples of identical moisture content since samples were conditioned separately.

The dielectric constant and loss factor were found to vary almost perfectly linearly with density. With increasing moisture content the dielectric constant and loss factor rose slowly from 0 to 10 percent MC, then faster, while beyond 13 percent MC the rise was very steep. Increasing the sample density increased the slope of the curves.

The dielectric constant declined slowly with increasing frequency. The loss factor, especially for wet samples, declined rapidly in the frequency range from 75 to 500 kHz, and declined more slowly from that point. For a sample of wheat at 14.19 percent MC (w.b.) at a frequency of 75 kHz, the increase in the dielectric constant with density was from 6.14 at a density slightly higher than natural bulk density, to 15.46 at a density 1.5 times that. The corresponding loss factors increased from 1.69 to 5.31 in this range. At 10 MHz for the same moisture content the dielectric constant increased from 4.35 to 12.06 for an increase in density from slightly greater than natural bulk density to a density 1.8 times as great. The corresponding loss factors increased from 0.46 to 2.01. There were shifts made in the loss factor versus log frequency curves which indicated that increased sample density made the effects of Maxwell-Wagner absorption felt at higher frequencies.

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APPENDIX

Table A-1

The following pages contain all of the data that was collected during the course of the project. WHOLE WHEAT is Manitou variety red spring wheat in the kernel form. T is the sample thickness in mils (thousandths of an inch), DENS is the density of the sample in g/cm^3, E' is the dilectric constant and E" is the loss factor. O.D. indicates samples that were oven dried for 3 hours at 130° C. All moisture contents given are percent wet base.

MANITOU WHEAT WHOLE 23 DEG MC= O.D. 75 KHZ

T MILS	DENS GM/CC	E'	E''
306.0	0.736	3.24	0.10
283.0	0.795	3.57	0.19
271.0	0.831	3.61	0.14
246.0	0.915	4.01	0.17
222.0	1.014	4.49	0.20
205.0	1.098	4.85	0.24
195.0	1.154	5.17	0.25

MANITOU WHEAT WHOLE 23 DEGC MC= 10.28 75 KHZ

T MILS	DENS GM/CC	E'	E''
294.0	0.766	4.34	0.28
267.0	0.844	5.31	0.36
254.0	0.887	5.83	0.44
227.0	0.992	7.06	0.56
199.0	1.132	8.62	0.72
180.0	1.251	9.84	0.90
171.0	1.317	10.87	0.96

MANITOU WHEAT WHOLE 22DEGC MC=13.69 75KHZ

T MILS	DENS GM/CC	E'	E''
303.0	0.742	5.58	0.82
271.0	0.830	7.39	1.47
253.0	0.889	8.57	1.76
223.0	1.008	10.67	2.50
198.0	1.136	13.03	3.06
178.0	1.263	15.14	3.25
173.0	1.300	16.36	3.68

MANITOU WHEAT WHOLE 23 DEGC MC=14.19 75 KHZ

T MILS	DENS GM/CC	E'	E''
303.0	0.744	6.14	1.69
269.0	0.838	8.59	2.83
245.0	0.920	10.05	3.39
213.0	1.058	12.92	4.50
191.0	1.180	15.46	5.31

MANITOU WHEAT WHOLE 23DEGC MC=15.82 75 KHZ

T MILS	DENS GM/CC	E'	E''
312.0	0.721	7.04	3.53
264.0	0.853	11.72	8.28
242.0	0.930	14.46	9.38
212.0	1.062	18.37	12.59

MANITOU WHEAT WHOLE 23DEGC MC=O.D. 121 KHZ

T MILS	DENS GM/CC	E'	E''
303.0	0.744	3.10	0.15
277.0	0.814	3.43	0.15
265.0	0.851	3.56	0.17
244.0	0.924	3.86	0.21
219.0	1.030	4.37	0.24
204.0	1.106	4.75	0.24
192.0	1.175	5.11	0.29

MANITOU WHEAT WHOLE 23DEGC MC=10.28 121 KHZ

T MILS	DENS GM/CC	E'	E''
290.0	0.776	4.58	0.25
267.0	0.843	5.30	0.34
255.0	0.883	5.79	0.44
225.0	1.001	7.10	0.59
199.0	1.131	8.42	0.69
177.0	1.272	10.16	0.87
169.0	1.332	10.80	0.96

MANITOU WHEAT WHOLE 70 DEG MC=13.40 121 KHZ

T MILS	DENS GM/CC	E'	E''
303.0	0.743	5.50	0.69
270.0	0.833	7.40	1.25
252.0	0.893	8.46	1.54
221.0	1.018	10.73	2.02
198.0	1.137	12.80	2.61
179.0	1.257	15.08	3.04
174.0	1.293	16.18	3.18

MANITOU WHEAT WHOLE 23DEGC MC=14.19 121 KHZ

T MILS	DENS GM/CC	E'	E''
301.0	0.747	6.19	1.32
264.0	0.852	8.48	2.41
236.0	0.953	10.64	3.90
212.0	1.061	12.42	4.31
188.0	1.197	15.05	4.82
171.0	1.316	17.67	5.52

MANITOU WHEAT WHOLE 23DEGC MC= 15.82 121 KHZ

T MILS	DENS GM/CC	E'	E''
308.0	0.731	7.13	3.58
263.0	0.856	10.79	6.56
243.0	0.926	12.82	7.71
208.0	1.082	16.92	10.71

MANITOU WHEAT WHOLE 23DEGC MC=O.D. 500 KHZ

T MILS	DENS GM/CC	E'	E''
305.0	0.737	2.98	0.22
280.0	0.803	3.20	0.23
265.0	0.849	3.37	0.24
242.0	0.929	3.76	0.28
221.0	1.017	4.12	0.32
202.0	1.113	4.59	0.37
192.0	1.171	4.90	0.42

MANITOU WHEAT WHOLE 23DEGC MC= 10.28 500 KHZ

T MILS	DENS GM/CC	E'	E''
293.0	0.768	4.31	0.26
267.0	0.842	5.09	0.36
252.0	0.892	5.51	0.38
226.0	0.995	6.63	0.50
198.0	1.136	8.06	0.68
179.0	1.256	9.34	0.77
169.0	1.331	10.07	0.86

MANITOU WHEAT WHOLE 23DEGC MC=14.19 500 KHZ

T MILS	DENS GM/CC	E'	E''
302.0	0.745	5.50	0.70
263.0	0.856	7.55	1.23
243.0	0.926	8.62	1.44
212.0	1.062	11.08	1.93
191.0	1.179	13.08	2.25
172.0	1.309	15.70	2.78
168.0	1.340	16.25	2.82

MANITOU WHEAT WHOLE 23DEGC MC= 15.82 500 KHZ

T MILS	DENS GM/CC	E'	E''
312.0	0.721	6.34	1.54
265.0	0.849	9.68	2.89
243.0	0.926	11.32	3.35
211.0	1.067	14.48	4.23
190.0	1.185	17.09	5.03
175.0	1.286	19.51	5.82
172.0	1.309	20.09	5.89

MANITOU WHEAT WHOLE 23DEGC MC=O.D. 1 MHZ

T MILS	DENS GM/CC	E'	E''
305.0	0.739	2.90	0.19
280.0	0.805	3.16	0.24
267.0	0.844	3.30	0.23
242.0	0.931	3.65	0.33
220.0	1.024	4.07	0.40
202.0	1.116	4.49	0.45
192.0	1.174	4.76	0.49

MANITOU WHEAT WHOLE 23DEGC MC= 10.28 1 MHZ

T MILS	DENS GM/CC	E'	E''
295.0	0.763	4.20	0.27
270.0	0.834	4.85	0.34
252.0	0.893	5.42	0.42
225.0	1.000	6.52	0.58
199.0	1.131	7.75	0.69
179.0	1.257	8.94	0.82
169.0	1.332	9.74	0.92

MANITOU WHEAT WHOLE 22 DEGC MC=13.19 1MHZ

T MILS	DENS GM/CC	E'	E''
299.0	0.753	5.08	0.41
269.0	0.837	6.39	0.64
250.0	0.901	7.28	0.75
219.0	1.028	9.21	1.05
198.0	1.138	11.00	1.23
178.0	1.265	13.03	1.53
171.0	1.317	13.68	1.60

MANITOU WHEAT WHOLE 23 DEGC MC=14.19 1 MHZ

T MILS	DENS GM/CC	E'	E''
302.0	0.746	5.21	0.55
261.0	0.863	7.24	1.03
240.0	0.939	8.48	1.25
211.0	1.068	10.65	1.61
188.0	1.199	12.80	2.03
172.0	1.310	14.62	2.31
167.0	1.350	15.09	2.34

MANITOU WHEAT WHOLE 23 DEGC MC= 15.82 1 MHZ

T MILS	DENS GM/CC	E'	E''
311.0	0.723	5.95	1.05
264.0	0.852	8.78	2.06
238.0	0.945	10.87	2.68
211.0	1.066	13.33	3.21
189.0	1.190	16.04	3.45
176.0	1.278	18.17	4.04
172.0	1.307	19.41	4.34

MANITOU WHEAT WHOLE 23 DEGC MC=O.D. 10 MHZ

T MILS	DENS GM/CC	E'	E''
295.0	0.762	2.54	0.25
277.0	0.812	2.69	0.29
266.0	0.845	2.80	0.30
245.0	0.918	2.97	0.37
222.0	1.013	3.26	0.42
199.0	1.130	3.64	0.45
190.0	1.183	3.81	0.48

MANITOU WHEAT WHOLE 23 DEGC MC=10.28 10 MHZ

T MILS	DENS GM/CC	E'	E''
293.0	0.768	3.49	0.37
267.0	0.843	4.07	0.49
255.0	0.882	4.35	0.53
227.0	0.991	5.11	0.70
199.0	1.131	6.20	0.96
179.0	1.257	6.93	1.02
168.0	1.339	7.68	1.25

MANITOU WHEAT WHOLE 22DEGC MC=13.38 10 MHZ

T MILS	DENS GM/CC	E'	E''
299.0	0.753	4.06	0.40
266.0	0.847	5.06	0.65
248.0	0.908	5.74	0.77
220.0	1.024	7.11	1.04
195.0	1.155	8.56	1.29
174.0	1.294	10.37	1.51
169.0	1.333	10.72	1.58

MANITOU WHEAT WHOLE 23 DEGC MC= 14.19 10 MHZ

T MILS	DENS GM/CC	E'	E''
300.0	0.750	4.35	0.46
257.0	0.876	5.89	0.75
239.0	0.942	6.72	0.97
210.0	1.072	8.25	1.24
188.0	1.197	9.93	1.52
172.0	1.309	11.35	1.84
167.0	1.348	12.06	2.01

MANITOU WHEAT WHOLE 23 DEGC MC= 15.82 10 MHZ

T MILS	DENS GM/CC	E'	E''
312.0	0.721	4.80	0.57
261.0	0.862	6.85	0.95
237.0	0.950	8.19	1.25
210.0	1.072	9.98	1.59
189.0	1.191	11.68	1.87
176.0	1.279	13.07	2.15
171.0	1.316	13.76	2.32

MANITOU WHEAT GROUND 23 DEGC MC=O.D. 75 KHZ

T MILS	DENS GM/CC	E'	E''
348.0	0.647	2.83	0.12
265.0	0.849	3.50	0.11
250.0	0.900	3.69	0.15
232.0	0.970	3.94	0.21
217.0	1.037	4.14	0.25
198.0	1.137	4.54	0.26
187.0	1.203	4.76	0.26

MANITOU WHEAT GROUND 21 DEGC MC=10.73 75KHZ

T MILS	DENS GM/CC	E'	E''
255.0	0.882	5.57	0.34
213.0	1.057	7.44	0.58
203.0	1.109	8.02	0.66
193.0	1.166	8.68	0.68
182.0	1.236	9.39	0.79
171.0	1.316	10.55	0.92
165.0	1.364	11.02	0.96

MANITOU WHEAT GROUND 23 DEGC MC= 13.16 75 KHZ

T MILS	DENS GM/CC	E'	E''
321.0	0.701	5.84	1.08
242.0	0.930	9.46	2.24
223.0	1.009	10.90	2.68
206.0	1.092	12.33	3.04
192.0	1.172	14.19	3.51
177.0	1.271	15.82	3.98
171.0	1.316	16.74	4.11

MANITOU WHEAT GROUND 23 DEGC MC= 13.75 75 KHZ

T MILS	DENS GM/CC	E'	E''
322.0	0.699	5.36	0.82
241.0	0.934	9.13	1.97
225.0	1.000	10.10	2.11
206.0	1.092	11.97	2.57
189.0	1.191	13.68	3.10
173.0	1.301	15.66	3.58
167.0	1.348	16.06	3.69

MANITOU WHEAT GROUND 23 DEGC MC= 15.61 75 KHZ

T MILS	DENS GM/CC	E'	E''
335.0	0.672	6.25	2.50
238.0	0.946	12.05	5.43
221.0	1.018	13.69	6.40
199.0	1.131	16.26	8.02
183.0	1.230	18.23	9.20

MANITOU WHEAT GROUND 23 DEGC MC=O.D. 121 KHZ

T MILS	DENS GM/CC	E'	E''
345.0	0.652	3.11	0.12
264.0	0.852	3.78	0.17
250.0	0.900	3.94	0.18
231.0	0.974	4.25	0.24
216.0	1.042	4.49	0.25
198.0	1.137	4.94	0.29
189.0	1.191	5.10	0.33

MANITOU WHEAT GROUND 22 DEGC MC= 10.73 121 KHZ

T MILS	DENS GM/CC	E'	E''
271.0	0.830	5.24	0.31
221.0	1.018	7.31	0.54
213.0	1.057	7.74	0.59
203.0	1.109	8.42	0.62
193.0	1.166	9.28	0.76
182.0	1.236	10.43	0.87
177.0	1.271	10.95	0.88

MANITOU WHEAT GROUND 22DEGC MC=12.6 121KHZ

T MILS	DENS GM/CC	E'	E''
332.0	0.678	4.84	0.08
254.0	0.886	7.16	0.75
236.0	0.954	7.97	0.85
209.0	1.077	10.06	1.08
198.0	1.137	10.87	1.23
182.0	1.236	12.44	1.46
176.0	1.279	13.58	1.60

MANITOU WHEAT GROUND 23DEGC MC= 13.75 121 KHZ

T MILS	DENS GM/CC	E'	E''
333.0	0.676	5.40	0.83
244.0	0.922	8.48	1.60
228.0	0.987	9.59	1.62
208.0	1.082	11.02	2.00
190.0	1.184	12.67	2.40
173.0	1.301	13.88	2.63
165.0	1.364	13.73	2.32

MANITOU WHEAT GROUND 23DEGC MC=15.61 121 KHZ

T MILS	DENS GM/CC	E'	E''
347.0	0.649	6.41	1.84
238.0	0.946	11.66	4.23
221.0	1.018	13.28	4.80
202.0	1.114	15.10	5.68
185.0	1.216	17.21	6.93
173.0	1.301	17.35	6.33
166.0	1.356	17.53	6.25

MANITOU WHEAT GROUND 23DEGC MC=O.D. 500 KHZ

T MILS	DENS GM/CC	E'	E''
349.0	0.645	2.77	0.19
267.0	0.843	3.36	0.29
251.0	0.897	3.53	0.30
232.0	0.970	3.82	0.28
217.0	1.037	4.04	0.33
203.0	1.109	4.24	0.37
194.0	1.160	4.43	0.39

MANITOU WHEAT GROUND 22DEGC MC= 10.73 500 KHZ

T MILS	DENS GM/CC	E'	E''
261.0	0.862	5.31	0.29
216.0	1.042	7.05	0.52
208.0	1.082	7.46	0.57
197.0	1.142	8.16	0.63
186.0	1.210	8.95	0.74
173.0	1.301	9.87	0.85
169.0	1.332	9.97	0.82

MANITOU WHEAT GROUND 23 DEGC MC= 13.75 500 KHZ

T MILS	DENS GM/CC	E'	E''
336.0	0.670	4.99	0.45
241.0	0.934	8.06	0.91
225.0	1.000	8.83	1.02
206.0	1.092	10.30	1.21
190.0	1.184	11.58	1.42
173.0	1.301	13.37	1.74
167.0	1.348	13.70	1.71

MANITOU WHEAT GROUND 23 DEGC MC=15.61 500 KHZ

T MILS	DENS GM/CC	E'	E''
339.0	0.664	5.61	0.95
239.0	0.942	9.87	1.97
223.0	1.009	10.94	2.20
202.0	1.114	12.56	2.55
184.0	1.223	14.01	2.90
171.0	1.316	14.50	2.90
164.0	1.372	14.58	2.90

MANITOU WHEAT GROUND 23 DEGC MC=O.D. 1MHZ

T MILS	DENS GM/CC	E'	E''
349.0	0.645	2.72	0.16
266.0	0.846	3.30	0.29
251.0	0.897	3.52	0.31
234.0	0.962	3.72	0.36
219.0	1.028	3.90	0.38
206.0	1.092	4.07	0.44
191.0	1.178	4.44	0.45

MANITOU WHEAT GROUND 22 DEGC MC= 10.73 1 MHZ

T MILS	DENS GM/CC	E'	E''
265.0	0.849	4.99	0.36
215.0	1.047	6.82	0.62
208.0	1.082	7.15	0.67
197.0	1.142	7.66	0.73
186.0	1.210	8.25	0.78
171.0	1.316	9.34	0.93
166.0	1.356	9.52	0.94

MANITOU WHEAT GROUND 22 DEGC MC=12.39 1MHZ

T MILS	DENS GM/CC	E'	E''
313.0	0.719	4.51	0.29
250.0	0.900	6.46	0.54
232.0	0.970	7.25	0.64
211.0	1.067	8.42	0.79
194.0	1.160	9.39	0.86
179.0	1.257	10.87	1.08
174.0	1.293	11.27	1.12

MANITOU WHEAT GROUND 23 DEGC MC= 13.75 1 MHZ

T MILS	DENS GM/CC	E'	E''
349.0	0.645	3.56	0.34
241.0	0.934	6.94	1.02
228.0	0.987	8.06	0.81
208.0	1.082	9.20	0.88
191.0	1.178	10.59	1.12
175.0	1.286	11.83	1.35
168.0	1.339	12.31	1.36

MANITOU WHEAT GROUND 23 DEGC MC= 15.61 1 MHZ

T MILS	DENS GM/CC	E'	E''
347.0	0.649	5.12	0.69
241.0	0.934	9.12	1.51
225.0	1.000	9.99	1.72
202.0	1.114	11.82	2.08
184.0	1.223	13.25	2.41
168.0	1.339	13.78	2.30
162.0	1.389	14.04	2.37

MANITOU WHEAT GROUND 23 DEGC MC= O.D. 10 MHZ

T MILS	DENS GM/CC	E'	E''
343.0	0.656	2.40	0.30
266.0	0.846	2.96	0.37
251.0	0.897	3.01	0.39
232.0	0.970	3.20	0.37
217.0	1.037	3.40	0.45
205.0	1.098	3.59	0.49
188.0	1.197	3.77	0.53

MANITOU WHEAT GROUND 22DEGC MC= 10.73 10MHZ

T MILS	DENS GM/CC	E'	E''
267.0	0.843	4.14	0.61
217.0	1.037	5.43	0.68
209.0	1.077	5.69	0.77
198.0	1.137	6.03	0.83
186.0	1.210	6.62	0.99
175.0	1.286	7.25	1.11
168.0	1.339	7.43	1.15

MANITOU WHEAT GROUND 23DEGC MC=12.39 10 MHZ

T MILS	DENS GM/CC	E'	E''
340.0	0.662	3.58	0.35
252.0	0.893	5.29	0.65
233.0	0.966	5.88	0.77
216.0	1.042	6.66	0.92
196.0	1.148	7.71	1.14
182.0	1.236	8.66	1.31
174.0	1.293	9.23	1.42

MANITOU WHEAT GROUND 23 DEGC MC= 13.75 10 MHZ

T MILS	DENS GM/CC	E'	E''
353.0	0.637	3.70	0.38
246.0	0.915	5.93	0.80
228.0	0.987	6.60	0.94
211.0	1.067	7.32	1.06
191.0	1.178	8.38	1.28
174.0	1.293	9.15	1.27
167.0	1.348	9.25	1.22

MANITOU WHEAT GROUND 23 DEGC MC= 15.61 10 MHZ

T MILS	DENS GM/CC	E'	E''
333.0	0.676	4.46	0.47
238.0	0.946	7.17	1.04
222.0	1.014	7.87	1.20
201.0	1.120	9.09	1.29
183.0	1.230	10.10	1.51
168.0	1.339	10.95	1.68
162.0	1.389	11.00	1.67

MANITOU WHEAT FLOUR 23 DEGC MC= O.D. 75 KHZ

T MILS	DENS GM/CC	E'	E''
358.0	0.629	3.11	0.12
260.0	0.866	3.79	0.19
245.0	0.919	4.04	0.21
231.0	0.974	4.12	0.20
215.0	1.047	4.49	0.26
206.0	1.092	4.58	0.28
194.0	1.160	4.91	0.31

MANITOU WHEAT FLOUR 23 DEGC MC=11.71 75 KHZ

T MILS	DENS GM/CC	E'	E''
362.0	0.622	3.96	0.15
246.0	0.915	6.81	0.41
229.0	0.983	7.69	0.57
208.0	1.082	8.98	0.68
192.5	1.169	10.11	0.78
183.0	1.230	10.64	0.84
175.0	1.286	11.32	0.91
169.0	1.332	11.80	0.95

MANITOU WHEAT FLOUR 23 DEGC MC= 13.48 75 KHZ

T MILS	DENS GM/CC	E'	E''
312.0	0.721	5.57	0.56
244.0	0.922	8.52	1.16
228.0	0.987	9.62	1.32
212.0	1.061	10.83	1.52
193.0	1.166	12.91	1.99
176.0	1.279	14.73	2.30
170.0	1.324	15.12	2.30

MANITOU WHEAT FLOUR 23 DEGC MC= 14.59 75 KHZ

T MILS	DENS GM/CC	E'	E''
328.0	0.686	5.94	0.87
247.0	0.911	9.76	1.93
231.0	0.974	10.51	1.88
212.0	1.061	12.88	2.89
195.0	1.154	14.75	3.44
179.0	1.257	17.22	4.11
175.0	1.286	18.14	4.01

MANITOU WHEAT FLOUR 23 DEGC MC=O.D. 121 KHZ

T MILS	DENS GM/CC	E'	E''
340.0	0.662	2.94	0.06
258.0	0.872	3.86	0.19
245.0	0.919	4.02	0.19
231.0	0.974	4.23	0.21
215.0	1.047	4.54	0.27
202.0	1.114	4.88	0.28
194.0	1.160	5.02	0.30

MANITOU WHEAT FLOUR 21DEGC MC=11.69 121 KHZ

T MILS	DENS GM/CC	E'	E''
359.0	0.627	2.42	0.17
250.0	0.900	7.15	0.52
234.5	0.960	7.98	0.61
219.0	1.028	8.84	0.69
203.0	1.109	10.37	0.90
187.0	1.203	12.06	1.06
179.0	1.257	13.56	1.54

MANITOU WHEAT FLOUR 23DEGC MC= 13.48 121 KHZ

T MILS	DENS GM/CC	E'	E''
328.0	0.686	5.07	0.33
240.0	0.938	8.26	0.93
228.0	0.987	9.05	1.08
208.0	1.082	10.65	1.35
195.0	1.154	11.53	1.41
175.0	1.286	13.99	1.75
169.0	1.332	14.80	1.92

MANITOU WHEAT FLOUR 23DEGC MC= 14.59 121 KHZ

T MILS	DENS GM/CC	E'	E''
328.0	0.686	5.62	0.68
244.0	0.922	9.32	1.49
229.0	0.983	10.50	1.72
210.0	1.072	12.15	2.08
193.0	1.166	13.91	2.55
174.0	1.293	16.18	2.95
168.0	1.339	16.76	3.13

MANITOU WHEAT FLOUR 23 DEGC MC= O.D. 500 KHZ

T MILS	DENS GM/CC	E'	E''
344.0	0.654	2.88	0.16
258.0	0.872	3.70	0.29
244.0	0.922	3.84	0.33
230.0	0.978	4.05	0.38
215.0	1.047	4.36	0.47
202.0	1.114	4.58	0.43
195.0	1.154	4.81	0.46

MANITOU WHEAT FLOUR 22DEGC MC=10.82 500KHZ

T MILS	DENS GM/CC	E'	E''
388.0	0.580	3.38	0.21
250.0	0.900	5.91	1.06
237.0	0.950	6.93	0.52
222.0	1.014	7.70	0.63
206.0	1.092	8.68	0.73
193.0	1.166	9.67	0.80
184.0	1.223	10.82	0.95

MANITOU WHEAT FLOUR 23 DEGC MC= 13.48 500 KHZ

T MILS	DENS GM/CC	E'	E''
337.0	0.668	4.88	0.30
240.0	0.938	7.91	0.71
230.0	0.978	8.42	0.75
208.0	1.082	9.98	0.94
194.0	1.160	11.08	1.07
174.0	1.293	13.42	1.39
169.0	1.332	14.18	1.43

MANITOU WHEAT FLOUR 23DEGC MC= 14.59 500 KHZ

T MILS	DENS GM/CC	E'	E''
327.0	0.688	5.25	0.38
245.0	0.919	8.68	0.91
231.0	0.974	9.59	1.04
210.0	1.072	11.65	1.35
197.0	1.142	12.80	1.49
180.0	1.250	14.92	1.81
176.0	1.279	15.99	1.92

MANITOU WHEAT FLOUR 23DEGC MC= O.D. 1 MHZ

T MILS	DENS GM/CC	E'	E''
308.0	0.731	4.71	0.20
257.0	0.876	4.42	0.30
243.0	0.926	4.47	0.34
231.0	0.974	4.47	0.40
216.0	1.042	4.53	0.43
206.0	1.092	4.60	0.46
197.0	1.142	4.79	0.50

MANITOU WHEAT FLOUR 22 DEGC MC=12.23 1MHZ

T MILS	DENS GM/CC	E'	E''
318.0	0.708	4.34	0.27
244.0	0.922	6.37	0.51
227.0	0.991	7.04	0.60
210.0	1.072	7.84	0.88
197.0	1.142	8.76	0.79
182.0	1.236	9.79	0.90
172.0	1.308	10.73	1.04

MANITOU WHEAT FLOUR 23 DEGC MC= 13.48 1 MHZ

T MILS	DENS GM/CC	E'	E''
329.0	0.675	4.83	0.03
236.0	0.942	7.68	0.52
220.0	1.010	8.48	0.63
203.0	1.095	9.55	0.75
186.0	1.195	10.88	0.92
169.0	1.315	12.56	1.18
162.0	1.372	13.30	1.28

MANITOU WHEAT FLOUR 23 DEGC MC= 14.59 1 MHZ

T MILS	DENS GM/CC	E'	E''
331.0	0.680	4.89	0.38
241.0	0.934	8.01	0.91
228.0	0.987	8.86	0.93
209.0	1.077	10.10	1.12
192.0	1.172	11.69	1.39
172.0	1.308	13.37	1.58
168.0	1.339	13.43	1.53

MANITOU WHEAT FLOUR 23 DEGC ,MC=O.D. 10 MHZ

T MILS	DENS GM/CC	E'	E''
340.0	0.662	2.42	0.19
258.0	0.872	3.02	0.35
245.0	0.919	3.11	0.43
232.0	0.970	3.23	0.48
218.0	1.032	3.43	0.47
205.0	1.098	3.62	0.47
193.0	1.166	3.90	0.56

MANITOU WHEAT FLOUR 23 DEGC MC= 11.14 10 MHZ

T MILS	DENS GM/CC	E'	E''
306.0	0.735	3.67	0.41
243.0	0.926	5.19	0.71
230.0	0.978	5.49	0.78
213.0	1.057	6.20	0.94
199.0	1.131	6.76	1.04
176.0	1.279	8.03	1.35
172.0	1.308	8.40	1.38

MANITOU WHEAT FLOUR 23DEGC MC= 13.48 10 MHZ

T MILS	DENS GM/CC	E'	E''
325.0	0.692	3.99	0.42
239.0	0.942	6.13	0.83
226.0	0.996	6.67	0.94
206.0	1.092	7.56	1.11
191.0	1.178	8.70	1.33
174.0	1.293	10.02	1.59
169.0	1.332	10.76	1.58

MANITOU WHEAT FLOUR 23DEGC MC=14.59 10 MHZ

T MILS	DENS GM/CC	E'	E''
327.0	0.688	4.21	0.43
243.0	0.926	6.61	0.88
229.0	0.983	7.26	0.98
210.0	1.072	8.34	1.20
192.0	1.172	9.79	1.39
177.0	1.271	11.39	1.71
173.0	1.301	11.79	1.78