Diterbitkan di Malaysia oleh
Bahagian Komunikasi Korporat.
Universiti Putra Malaysia
43400 UPM Serdang
Selangor, Malaysia

Tel : 603-8946 6003
Fax : 603-8948 7273
e-mail: cco@admin.upm.edu.my

ISBN 967-960-174-9

INAUGURAL LECTURE

PROF. DR. KAIDA KHALID

Microwave Aquametry:
A Growing Technology

24 April 2004

DEWAN TAKLIMAT
TINGKAT 1, BANGUNAN PENTADBIRAN
UNIVERSITI PUTRA MALAYSIA

KAIDA BIN KHALID

Dr. Kaida bin Khalid was born on July 8 1952 in Chukai, Kemaman Trengganu. He attended early education at SRK Chukai, Kemaman and SMK Padang Midin, Kuala Trengganu, Terengganu and completed his secondary school education at Sultan Abdul Halim Secondary School in Jitra, Kedah. He entered National University of Malaysia and received B.Sc. (Hons) in Physics and was awarded the Intan Zaharah Gold Medal for Best Physics Student in 1976. In the same year, he joined Universiti Pertanian Malaysia* as a tutor at the Physics Department, Faculty of Science and Environmental Studies (FSES). He obtained his MSc in Solid State Physics from Bedford College, University of London in 1978 and returned to Malaysia, to serve as a lecturer. Because of his interest in Microwaves, he had to shift from Physics to Engineering which offers more facilities and expertise in the area. In 1986, he obtained his Ph.D in Electronic and Electrical Engineering from University of Birmingham, in the area of microwave sensor.

He was appointed as a lecturer in 1979, Associate Professor in 1991 and Professor in Physics in August 2000. He has already served more than 28 years with UPM and in recognition of his excellent services; the university has honoured him with Excellent Service Awards in 1991, 1994 and 1997. In administration he was appointed twice as Deputy Dean of FSES from 1997-1999 for Research and Development affair and 2002-2004 for Development and Financial affair. Before this, from 1992-1994 he was appointed as Head of Physics Department. Among the contributions he has made during his tenure as Deputy Dean was to serve as Management Representative for the development of Quality Management System, MS ISO 9001:2000.

For the past 24 years he has embarked in research in the field of Microwave Aquametry, Dielectric Physics and Solid State Physics. In 1982, his first invention, Microwave Transmission Type Latexometer was judged as the best entry in the international competition on Dry Rubber Content (DRC) determination organized by the Malaysian Rubber Research and Development Board. In 1987 he further intensified his research in the development of Microwave Reflection Type Latexometer and Moisture Meter and this instrument was awarded first prize in the Malaysian Invention and Design Competition (General Technology category) in 1990. This product was patented in Malaysia (MY-106441-A) in 1995 under the title" *Apparatus and Method for the determination of DRC of hevea latex*". Other contribution of this project is the development of microstrip and conductor-backed coplanar waveguide (CBCPW) moisture sensors and microwave wood densitometer.

Since 1982 more than 100 papers related to these fields have been published in journals and proceedings and about 20 exhibitions and demonstrations have taken place in order to promote this product locally and internationally. In recognition of his work on microwave aquametry, the Third World Academy of Science had awarded him the 1992 TWAS National Young Scientist Award in Physics. Although latexometer is still at the prototype stage, 30 units of this product has already been used by various agencies such as Rubber Research Institute, MINTS, Rubberflex and RISDA for quality assessment and field-testing.

He has been a visiting scientist at the Centre for Theoretical Physics, Trieste Italy (1988), King's College, Univ. of London (1993), Marpet Enterprises Inc., Boston USA(1996), SAIREM-company, Lyon France (2002), Milestone-Microwave Lab. System, Bergamo, Italy(2003) and guest of honour at the 11th Khrazmi International Science Festival – The Islamic Republic of Iran (1998).

Dr. Kaida is a member of the editorial board of the International Journal of Subsurface Sensing Technologies and Applications USA, Inst. of Electrical and Electronic Eng., Inst. of Physics Malaysia, member of Malaysian Invention and Design Society (MINDS), life member of Malaysian Solid State and Technology Society and Malaysian Society for Non-Destructive Testing. He has served in the committee which collaborated with Dewan Bahasa and Pustaka for the preparation of the Bahasa Melayu terminology and dictionary in the field of Physics. To date this committee has published 2 books on Physics terminology and 10 dictionaries in various sub-areas of Physics.

In 2000 he was awarded the Pingat Kesatria Mangku Negara (KSN) by Seri Paduka Baginda Yang di-Pertuan Agung XI.

MICROWAVE AQUAMETRY: A GROWING TECHNOLOGY

ABSTRACT

A rapid growth of microwaves system has taken place after the Second World War in the area of telecommunication and navigation in both civilian and military. However, industrial, scientific, medical and domestic applications have developed at a slower pace. By far, the most popular application of microwave power is in microwave oven for domestic and commercial cooking. On the other hand, a greater variety of industrial applications of high microwave power has been demonstrated including applications in various industries such as rubber, food, textiles, plastics, foundry, building materials, paper, pharmaceuticals, cosmetics, and coal. The main advantage of microwave power in processing of materials are increased rate of production, improved product characteristics, uniform processing and controllability of the process.

Low-intensity microwaves have found industrial, scientific and medical application in a non-destructive testing and monitoring of material, objects and people. These include microwave aquametry and mechanical parameters monitoring and the first known patent was granted in Sweden in 1945. Microwave methods have also been used in medical diagnosis such as cancer detection and monitoring of respiratory systems. It was only recently that the measurement of dielectric properties has been applied to microwave aquametry for on-line process control in the manufacturing industries. However, the measurement and use of dielectric properties has been a concern of the physical sciences for almost a decade ago. In past years, two Nobel Prizes have been awarded to scientists Debye (1936) and Onsager (1968) for their work involving dielectric theory and the application of Maxwell's electromagnetic theory.

The objective of this paper is to expose the growing technology of microwave aquametry and highlight its most interesting and successful applications. In organising and presenting the material, an attempt was made to meet four goals. First to show the dielectric properties of water and moist substances, second the state of the art of microwave aquametry system, third to show the development of microwave sensors and instrumentation for that could benefit our agriculture and manufacturing industries and fourth the current development of microwave aquametry for various applications. This work highlights the findings of research over the past 23 years especially in the application of microwave aquametry in rubber and oil palm industries.

INTRODUCTION

Aquametry is a new branch of metrology deals with the measurement of water content or moisture content (MC) in solid or liquid, in a similar way as hygrometry is a branch of metrology devoted to measurement of water vapour in gases. It is formed from a combination of a Latin word aqua- water and a Greek word metre – I measure[Kraszewski, 1980].

The adjective microwave in the title of this paper indicates that the measurements of MC are done by using microwave techniques. Microwave is electromagnetic radiation with a free space wavelength between 1 mm to 1 metre, corresponding to frequencies of 300 MHz to 300 GHz. It is longer than infrared and shorter than radiowave. The recent advancement in microwave fields are in the area of microwave drying and heating, microwave chemistry, stellar applications, civil and army communications, e-weapon and solar power satellite.

Specifically, microwave aquametry can be defined as a branch of metrology that investigates solid or liquid dielectric materials containing water by identifying their properties at microwave frequency. [Kraszewski, 1980]

As we know, our planet earth is a watery place with about 70% of the its surface is water-covered, also exists in the air as water vapour and in the ground as soil moisture and in aquifers. This water is constantly moving from one place to another and from one form to another to form the water cycle. Human body consists of 60% water, the brain is composed of 70% water, blood is 82% water and the lungs are nearly 90%. Consider as a humble material, colourless, odourless and tasteless, but it is not at all simple and plain and it is vital for all life on earth. Where there is water there is life, and where water is scarce life has to struggle.

It is also mentioned in the Alquran from surah Al Anbiyaa (30)— *We made from water every living* thing and Surah Al-Mukminun (18-19) — *and We send down water from the sky according to (due) measure, and We cause it to soak in the soil and We certainly are able to drain it off. With it We grow for you garden of date palms and vines: in them have ye abundant fruits: and of them ye-eat(and have enjoyment)* [Yusuf Ali, 1994]

The importance of water is symbolised in UPM's logo as a water droplet showing the commitment of the University in preserving the environment. Water is also fundamental in life, as is knowledge in the quest for progress in human development.

SCIENCE AND TECHNOLOGY BENEFITS

Since water exists in the majority of materials encountered in nature whether being present naturally or being introduced there on purpose during specific processes. The water content

to a large extent, affect physical, chemical, mechanical and thermal properties of many dielectric or non- metallic materials in nature.
MC is often a quality criterion of solid or liquid substances and is used in the industrial process . Some examples are as follows

- During the drying processes, MC measurements can help save energy and thus prevent pollution of the environment
- MC determination of soil is required in agriculture when using certain machine, when applying fertilizer and during sowing and spraying.
- Most natural substances are sold by weight, hence the exact determination of MC will help to fix the true value of the product such as hevea rubber latex, milk, grain etc. Latex collected by smallholders is sold to a collector who pays according to the dry rubber content (DRC) or Total Solid Content (TSC) which is closely related to MC. [Chin, 1979]
- MC of grain is a very important quality characteristic not only during the harvesting, purchase and sale but also during transportation and storage and is define by standard – Long term storage is safe 13-14 % (free from microbial degradation). However overdrying the grain can decrease its nutritional and reproductive values and contribute to the increased breakage during handling -input and output grain control for silos and grain elevators.[Nelson et al, 1999]
- MC and temperature are essential characteristics for biological decomposing process during composting and on waste disposals.
- Water is a main contaminant of many liquid such as crude oil, gasoline and jet engine fuel, Thus routine monitoring of MC is necessary in various stages of product pumping, processing, storage and trade.
- The MC of snow is important for predicting avalanches and introducing steps of prevention. By continuously controlling soil MC landslides and mud streams can be forecasted and /or prevented in high mountain region. [Brandelik et al, 1999]
- The manufacture of sugar products from either cane or sugar beet requires the constant regulation of processes that involve either wetting or drying of raw materials and intermediates.
- Palm oil is obtained from mesocarp of the oil palm fruits and oil quantity is determined by the quality of fruits during harvesting or amount of oil, water and free fatty acid (FFA) in the fruit. Normally the amount of moisture content in fresh mesocarp is about 85% at 14-15 weeks after anthesis and decreases rapidly to about 30% in ripe fruits at about 20-24 weeks after anthesis [Thomas et al, 1971] . The close relationship between moisture content and stage of ripeness gives a possibility of using this parameter to gauge the ripeness of the fruit.
- A good technique to monitor concrete hardening process and predict the anticipated concrete strength in order to fulfil design requirements.

MOISTURE CONTENT AND ITS MEASUREMENT

MC is ratio of water to the total mass of wet material and may be defined on a wet basis as a ratio of mass of water m_w, to mass of the moist material, m_m

$$M_w = m_w/m_m = m_w/(m_w+m_d) \qquad (1)$$

or on dry basis as a ratio of the mass of water in the material to the mass of dry material, m_d

$$M_d = m_w/m_d = (m_m+m_d)/m_d \qquad (2)$$

Quite often both quantities are expressed in percentage which is known as gravimetric moisture. Throughout this paper the author will use wet basis as the scale for moisture content or otherwise stated.

Most standard methods of MC determination are direct method, based on the definitions of equations and performed in the laboratory according to the rule of analytical chemistry. For most materials, these methods are accurately described in formal documents constituting professional, national or international standards. These methods are static, providing an accuracy of a few tenths of 1% MC and usually involving much time to complete.

For rapid MC determination and monitoring, indirect methods, calibrated against the standard methods, have been used for many years. An indirect method is based on finding a property of a material that is related to its moisture content for examples based on the effects of ultrasonic, X-ray, chemical, optical and electrical. Among this method , those based on strong correlations between MC and electrical properties play an increasingly important role. Moisture meter based on dc conductance measurements was developed in the beginning of 20th century. As measuring technique developed, they were superseded by AC meters measuring conductance of samples and later their dielectric constant at radio frequencies. Finally, parallel to the development of microwave techniques and devices during the World War II, microwave radiation was applied to MC measurement [Nyfors et al, 1989].

Performing fast, accurate moisture content measurements is of great importance in the manufacturing, agriculture, processing, storing and trading of most products and raw materials. Microwave methods and techniques have attracted a lot of interest in industry for measuring MC because they possess many interesting capabilities and offer many attractive technical and economical possibilities. The following unique features of microwave radiation make it useful for MC Measurement.[Kraszweski, 1996]

- Waves propagate along straight lines and reflect from metal surface, obeying the laws of optics

- Microwave can propagate through free space; thus , a physical contact between the equipment and material under test is not required, allowing remote sensing to be accomplished.
- Many solid dielectric materials are opaque to light and infrared radiation but transparent to microwaves which permit the probing of the whole volume of materials.
- The effect of dc conductivity decreases with frequency and is much smaller at microwave frequencies than at radio frequencies, which makes moisture content measurement easier and less dependent upon the material composition.
- Microwave radiation does not alter or contaminate the material under test as do some chemical methods, enabling fast, non-destructive, and continuous monitoring.
- In contrast to ionizing radiation, microwave methods are much safer and very fast
- Microwave radiation is relatively insensitive to environment conditions, thus dust and water vapour do not affect the measurement, in contract to infrared methods.

WATER, MOIST MEDIUM AND DIELECTRIC PROPERTIES

Chemical description for water is H_2O. The hydrogen atoms are attached to one side of oxygen atom resulting in a water molecule having a positive charge on the side where the hydrogen atoms are and a negative charge on the other side where the oxygen is. This molecule possesses a permanent electric dipole moment μ that is directed along the two-fold axis of symmetry, the bisector of the H-O-H angle, and points from the oxygen atom to the region between the hydrogen atoms. Under the influence of electric field this dipole tends to reorient, thus giving rise to dipolar or orientation polarization. Other source of polarizations is electronic polarization, atomic polarization and interfacial polarization or Maxwell-Wagner polarization . Dipolar polarization and interfacial polarization, together with the DC conductivity are the main mechanisms causing dissipation of the electromagnetic energy in dielectric materials exposed to high-frequency fields. At microwave frequencies (normally above 1 GHz) dipolar polarization is the dominant effect.

A measure of the polarization which material interacts with applied electromagnetic field is known as permittivity and for non-magnetic material it is presented by the complex permittivity or dielectric properties of material, $\varepsilon^* = \varepsilon' - j\varepsilon''$. The real part, ε', which is known as dielectric constant expresses the ability of material to store energy and directly related to strength of polarization and the imaginary part, e'', known as dielectric loss factor, is a measure of the energy absorbed from the applied field. The permittivity of materials is often normalized to the permittivity of a vacuum and is referred ad the relative permittivity:

$$\varepsilon^*_r = \varepsilon^*/\varepsilon_o = \varepsilon'/\varepsilon_o - j\varepsilon''/\varepsilon_o = \varepsilon'_r - j\varepsilon''_r \quad (3)$$

where the permittivity of free space is $\varepsilon_o = 8.854 \times 10^{-12}$ F/m. The relative dielectric constant and loss factor are thus dimensionless quantities, and the word 'relative' is often omitted and ε'_r is referred to as the dielectric constant ε'. The relative loss factor is a function of the material conductivity :

$$\varepsilon''_c = \varepsilon''/\varepsilon_o = \sigma/(2\pi f \varepsilon_o) \qquad (4)$$

Generally the loss factor is written as ε'' and is meant to contain losses caused by all possible mechanisms. Since all those mechanisms show frequency dependence, the definition of an effective loss factor is

$$\varepsilon'' = \varepsilon''_d(w) + \varepsilon''_e(w) + \varepsilon''_a(w) + \varepsilon''_i(w) + \varepsilon''_c(w) \qquad (5)$$

where subscripts *d, e, a, i* and *c* refer to dipolar, electronic, atomic, interfacial polarizations and conductive losses. Loss mechanisms due to atomic and electronic polarizations occur at frequencies in the infrared and visible parts of the electromagnetic spectrum, and as such, play no role of interest from the microwave aquametry point of view. The loss factor is shown schematically as a function of frequency in Figure 1 in terms of loss factors contributing to the effective loss factor of the moist material. In water ε'' varies with frequency to give dispersion which is known as a Debye dispersion . As the frequency of the applied field increases the molecules are unable to reorient completely before the field reverses. This type of relaxation is called dipolar relaxation.

The water properties of wet materials in nature which are generally hygroscopic are different from those of pure water. Many different structures of porous, granular, fibre, liquid and powdered materials can bind water in many different ways depending upon material structure and density, temperature, chemical and physical composition. Thus the relaxation frequency of liquid water (or free water) at temperature between 20 and 30°C occurs at 17-22 GHz, whereas bound water relaxes at much lower frequencies , a few megahertz to several hundred megahertz. At present situation its rather complicated to describe bound water . Several forces can bind water e.g. Coulomb-, Van der Walls-, capillary-force etc. There is a great possibility to use dielectric aquametry as a new definition for bound water which we can relate to the change in its dielectric permittivity.

We call water as " bound water" if the dielectric constant is less than that of free water at same frequency and temperature [Brandelik et al., 1996] . Binding of water molecule is strongest in an ice crystal with $\varepsilon' = 3.2$ compared to $\varepsilon' = 80$ in case for free water.

The frequency dependence of the loss mechanisms is presented in Figure 1 in terms of loss factor of the moist materials. In the radio and microwave frequencies, the most important phenomena contributing to the loss factor is dipolar loss .Specifically the complex dielectric spectrum for pure water at 30°C is displayed in Figure 2.

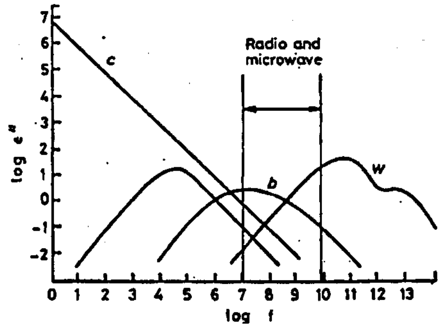


Figure 1 : Mechanism contributing to the effective loss factor as a function of the frequency in Hz. i, Maxwell-Wagner effect; b, bound water relaxation; c, d.c. conductivity: w, dipolar polarization of free water. [Metaxas et al., 1983]

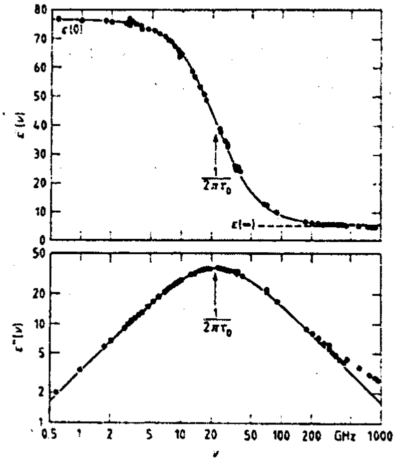


Figure 2 : Dielectric constant ε' and dielectric loss ε'' of water at 30°C plotted versus frequency.[Kaatze, 1996]

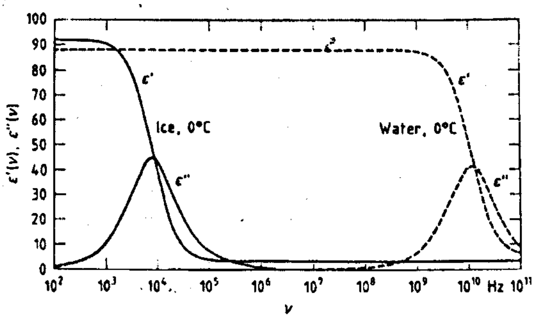


Figure 3 : Complex dielectric spectrum of ice (full circle) and water (dashed curve) [Kaatze, 1996]

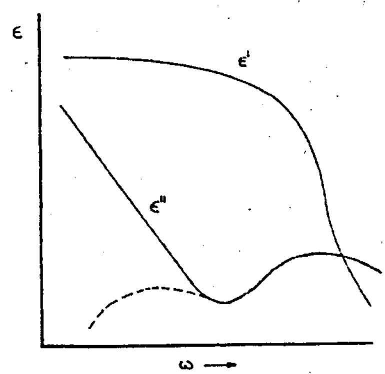


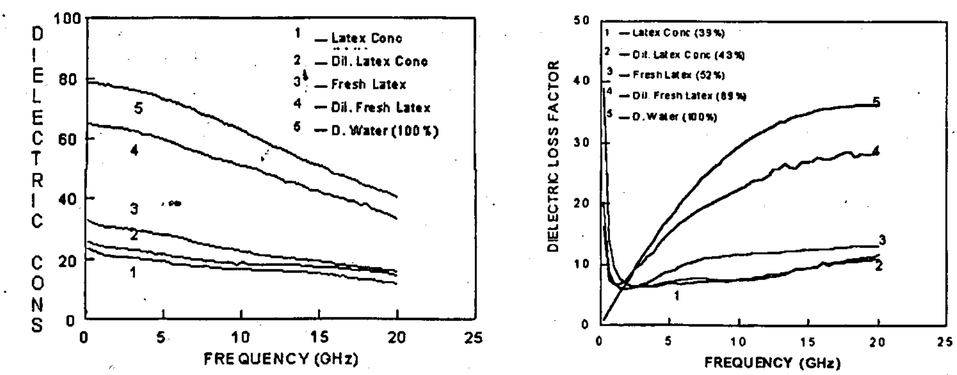
Figure 4 : The permittivity of a heterogeneous dielectric exhibiting dipolar polarization losses and conductive losses at lower frequency. The dashed line is the dipolar losses of water bound to the matrix of the material bound [Nyfors et al., 1989].

As shown in Figure 3, dielectric relaxation in frozen water (ice at 0°C) is about six orders of magnitude lower than liquid water at the same temperature.

The typical loss factor for heterogeneous material containing water versus frequency are shown in Figure 4. Dipolar polarization is clearly shown and the rise at the lower frequencies is attributed by the dc conductivity by the material. Possible relaxation of bound water (dotted line) may be overshadowed by the dc conductivity. These phenomena can be clearly seen in the hevea rubber latex and mashed oil palm mesocarp.

Figure 5 shows the dielectric spectrum of hevea latex from various samples such as fresh field latex, diluted fresh latex, latex concentrate, and diluted latex concentrate. [Khalid et al., 1997] The dielectric constant ε' for almost all samples follows the trend of deionized water and their magnitudes are found to decrease as the MC in the latex decreases. For the frequency range between 0.2 GHz and 20 GHz, the loss factor ε'' can be divided into two regions. For frequency less than 2.5 GHz, ε'' is dominated by conductive loss while in the upper region (> 2.6 GHz) the loss mechanism is dominated by the dipole orientation of water molecules in the latex. The effect of conductive loss can be seen clearly in Figure 5.(b)

It was stated earlier that the hevea rubber latex is conductive for frequencies less than about 2 GHz. However, solidified latex at temperatures less than 1°C shows a dielectric phenomenon which is almost similar to ice [Khalid et al., 1997]. Figure 6 shows the dielectric spectrum of fresh latex and latex concentrate with frequency ranging from 10^{-2} Hz to 10^{6} Hz and at a temperature of –30°C. The relaxation peak is shifted to a higher value as the water content in the latex decreases.



(a) (b)

Figure 5 : Dielectric properties of hevea rubber latex as a function of frequency. **a** Dielectric constant. **b** Dielectric loss factor. (See [Khalid et al., 1997])

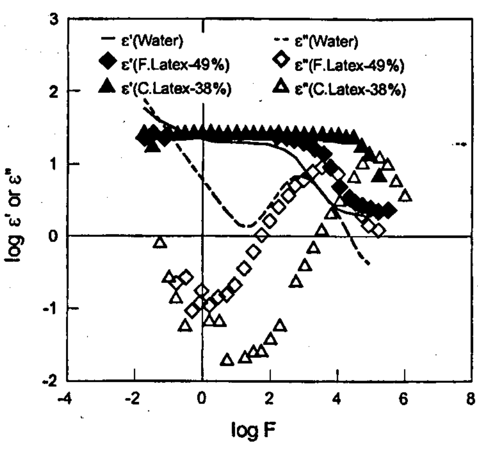


Figure 6 Variation of Dielectric Properties of solidified latex at lower frequencies ranging from 10^{-2} Hz to 1 MHz and at temperature of -30°C. (See [Khalid et al. , 1977]

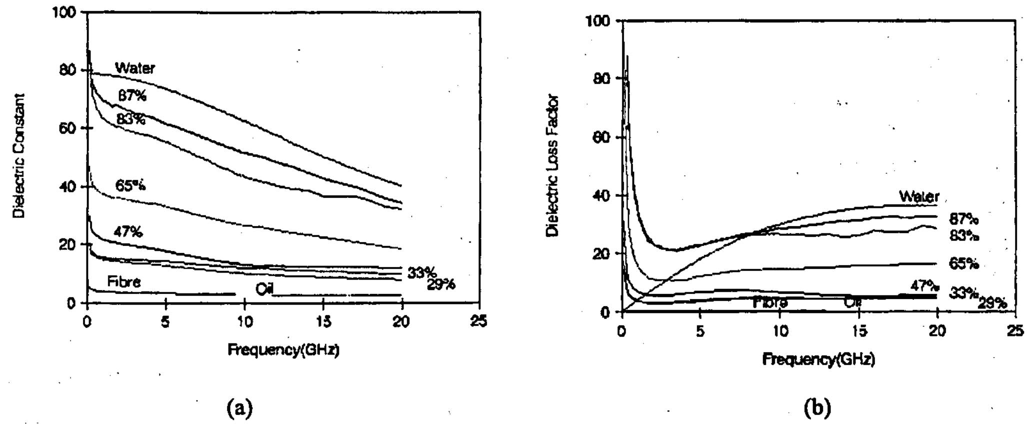


Figure 7 : Dielectric spectrum of mashed mesocarp from 0.2 GHz to 20 GHz at various moisture contents. **a** Dielectric constant. **b** Dielectric loss. (See [Khalid et al., 1996a])

Figure 7 shows the dielectric spectrum of mashed mesocarp at various stages of maturity and mesocarp constituents such as water, fiber and oil [Khalid et al.,1996a]. The ε' for most samples follows the trend of water and their magnitudes decrease as the MC in the mesocarp decreases. In the frequency range of 0.2 GHz to 20 GHz, the loss factor can be divided into two regions. For frequencies less than 3 GHz, dielectric loss is dominated by conductive loss, while in the upper region the loss mechanism is dominated by the dipole orientation of the water molecule. Dielectric properties of the fiber and oil are about the same and their values are about 2.6 – j0.02 and almost constant throughout the frequency of measurement

MOISTURE CONTENT DEPENDENCE

The variation of ε' and ε'' with moisture content at 0.2 GHz and 10 GHz are shown in Figure 8. [Khalid et al., 1994]. At 0.2 GHz, ε'' spreads depending on the strength of ionic species in the latex. For latex concentrate, the higher value of ε'' at a particular MC is due to ammonium ions associated with ammonium added to the latex concentrate acting as a preservative. However, at 9.3 GHz, no spreading of ε'' was observed·This implies that the contribution from the conductive loss is small and ε'' is merely dominated by the dipolar orientation of water molecules. A close relationship between dielectric properties and MC at this frequency, regardless of the types of latex, gives important information on the state of the art of the development of microwave moisture meter for latex.

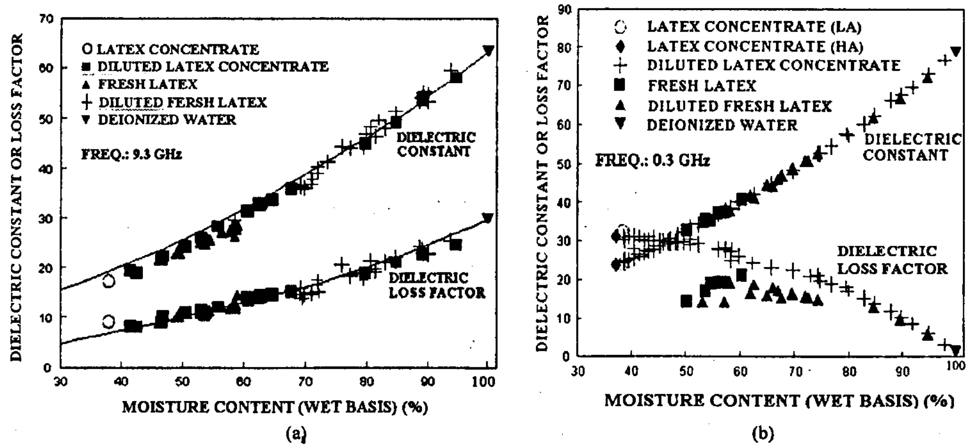


Figure 8 : Dielectric properties of hevea rubber latex versus MC (wet basis) at 26°C: **a** 9.3 GHz; **b** 0.3 GHz. (See [Khalid et al., 1992b])

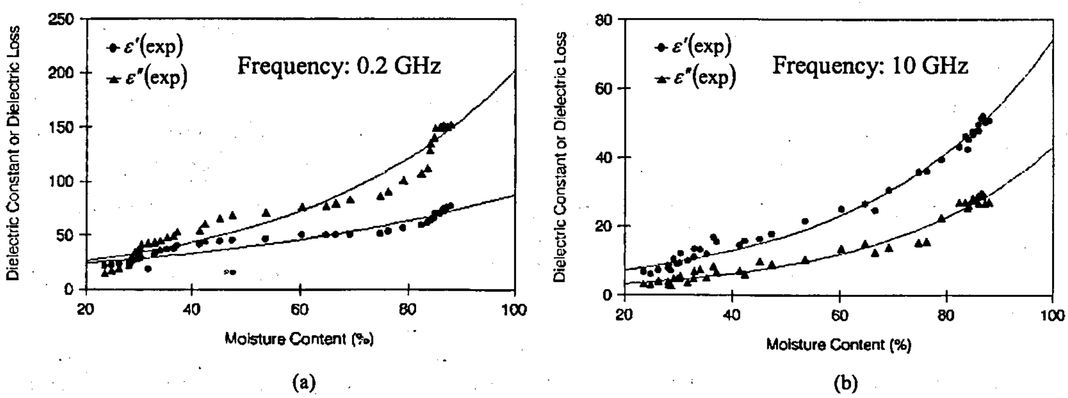


Figure 9 : Variation of dielectric properties of mashed mesocarp with respect to MC at **a** 0.2 GHz and **b** 10 GHz (See [Khalid et al., 1996a])

The variation of dielectric properties of oil palm mesocarp, ε' and ε'', with moisture content at 0.2 GHz and 10 GHz are shown in Figure 9 [Khalid et al., 1996a]. Throughout these figures both ε' and ε'' demonstrate a good relationship with moisture content . The same data can be plotted as the variation of dielectric properties with day of anthesis (Figure 10). As expected the ε' and ε'' almost follow the same pattern as moisture content. With moisture content ranging from 25% to 85% the ε' at 2 GHz varies from 11 to 61 and the ε'' varies from 2.1 to 24.6 at 10GHz . A significant variation of ε' and ε'' at 2 GHz and 10 GHz respectively (see Figure 10) make it suitable to form a maturity index as suggested by Nelson et al., [Nelson et al., 1995]. It is clear that water rapidly decreases in the mesocarp from approximately 15 to 20 weeks after anthesis. After the 20th week, there is a further small decrease in moisture content until full ripeness. Although the optimum time to harvest the fruit is 21 to 22 weeks after anthesis, time must be allowed for most of the fruits of the bunch to ripen. [Hartley, 1977] [Khalid et al., 1996a].

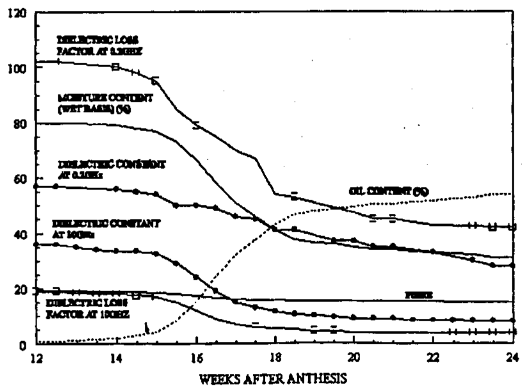


Figure 10 : Variation of microwave dielectric properties of mashed mesocarp, oil content, fibre content and moisture content as a function of development time of oil palm fruit. [Khalid et al., 1996a].

Water is present in wood in two forms, one as free water in the cell cavities and pores and the other as bound water in cell walls [Torgovnikov, 1993]; [Nyfors, 1989] . The free water is held by capillary forces whereas bound water is chemically bonded to the cell walls. When the wood is dried, the first water to be removed is the free water, and eventually a stage is reached when the cell cavities and pores are empty but the ce'l wall is still saturated. This is the fiber saturation point (FSP), generally ranging from 10% to 35% depending on the species. This means that the moisture in wood contributes to the dielectric properties in two ways: one below FSP and the other above FSP (Figure 11). The MC below the FSP constitutes bound water whereas the MC above the FSP constitutes as free water plus bound water.

The comparison between dielectric mixture model of Weiner (k=1) with experimental results for dielectric properties of wooden cross-arm (chengal wood) versus moisture content at 10.7 GHz are shown in Figure 11 [Khalid et al., 1999]. The FSP is about 17% moisture content and dielectric parameters display small increment with moisture content which is due to the lower rotational mobility of binding water while above FSP a higher slope is obtained which is due to the free water.

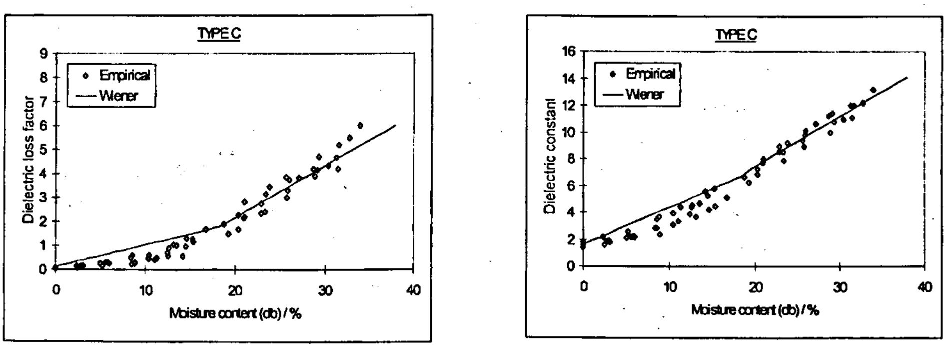


Figure 11 : Comparison of the experimental dielectric data for wooden cross-arms with mixture model data at 10.7 GHz and 26°C for type C (See [Khalid et al., 1999])

TEMPERATURE DEPENDENCE

The orientation of water molecules is considerably affected by thermal agitation and the corresponding dielectric properties of water are therefore temperature dependence. The temperature dependence of ε' and ε'' of hevea latex at 0.6 GHz and 10 GHz is shown in Figure 12 [Khalid et al., 1996b]; [Hassan et al., 1997, 2003]. Three different states exist in the temperature range of -30°C to 50°C. These are the frozen (solid) state (-30°C to -3°C), the transition state (-3°C to 3°C), and the liquid state (above 3°C). In the transition region both ε' and ε'' show a steep increase as phase of the latex changes from solid to liquid. This may be due to a change in the physical state of water molecules from bound water to free water. In the frozen state, both ε' and ε'' at 0.6 GHz show a spreading in their values with temperature and this may be due to the effect of conducting phases in the samples. In the liquid state region and at 0.6 GHz, the increase in temperature raises the mobility of ions in the solution resulting in an increase in ε''. At 10 GHz, ε'' decreases as temperature increases, which is similar to the trend of deionized water. The shapes of the latex curves show a depression, which may be due to the water binding by dissolved ions.

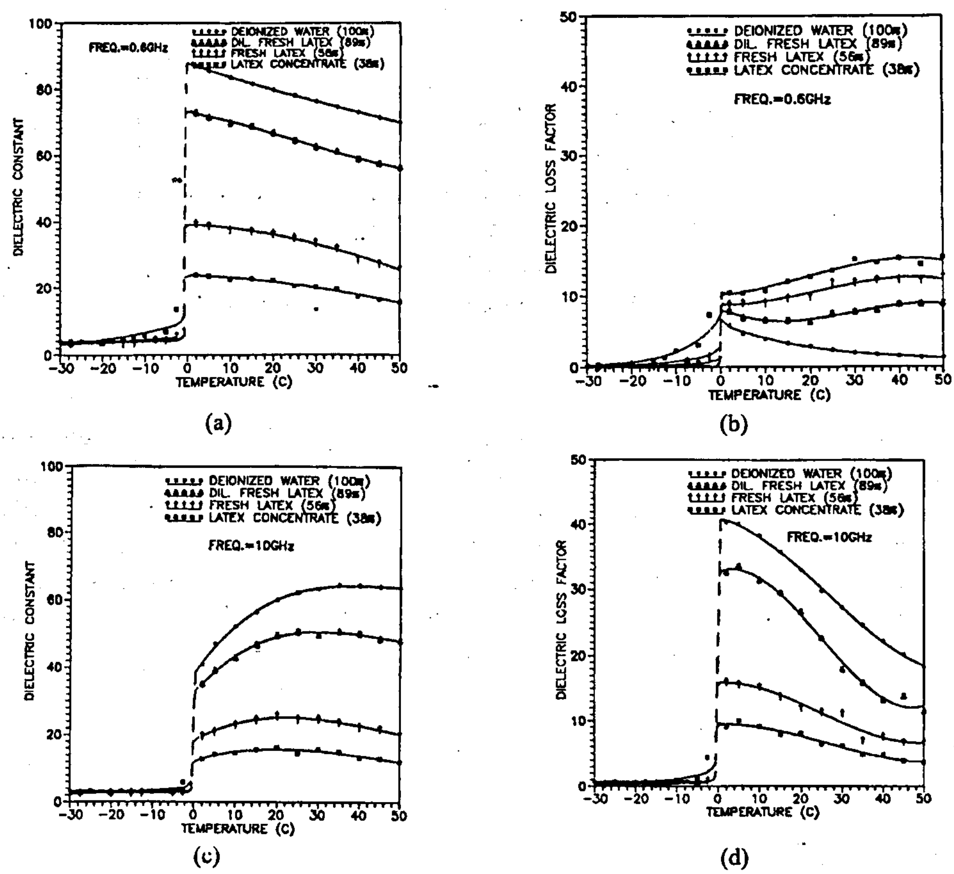


Figure 12 : Dielectric properties of hevea rubber latex with respect to temperature (a) dielectric constant at 0.6 GHz (b) dielectric loss at 0.6 GHz (c) dielectric constant at 10 GHz (d) dielectric loss at 10 GHz (see [Khalid et al., 1996b]).

SOME OTHER APPLICATIONS OF DIELECTRIC PROPERTIES

(i) SNOW

The dielectric properties can be distinguished easily between the dry snow and the wet snow phase. In the dry snow phase there is a constant increase of the dielectric constant which is due to compaction of snow for higher density. A sharp rise in the dielectric constant can be seen around the 135th day at the beginning of the melting season. (see Figure 13). When liquid water is formed in the snow, microwave absorption is drastically increased. The snow property parameter is a key parameter for global warming and is interested by avalanche and flood warning authorities and hydro-power stations operator as well. [Brandelik et al., 1999]

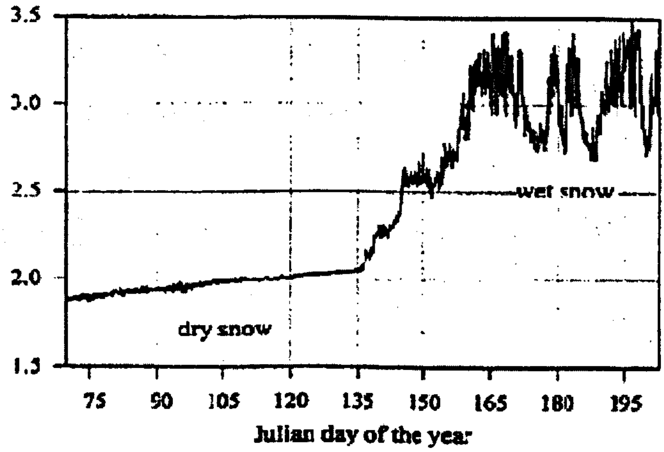


Figure 13 : Dielectric constant of a snow cover versus time

(ii) SEED

The Argand diagram (Figure 14) is used to show the dielectric behaviour for wheat at two frequencies (11.3 and 18.0 GHz). Moreover, all four variables i.e. frequency, bulk density, moisture content and temperature, can be included and their respective effect analyzed. From dielectric properties viewpoint, it implies that moisture content and temperature are interchangeable. The normalized dielectric properties with respect to density for given moisture content at higher temperature are those for virtual higher moisture content at lower temperatures. [Nelson et al.,1999]

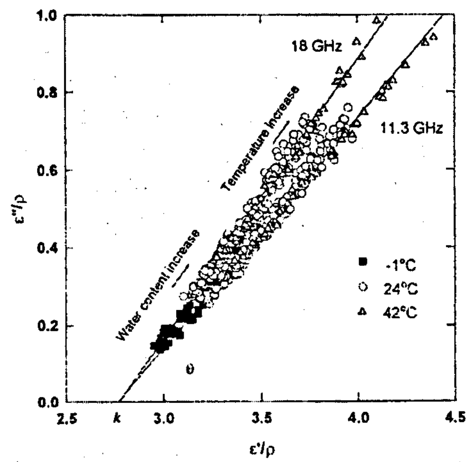
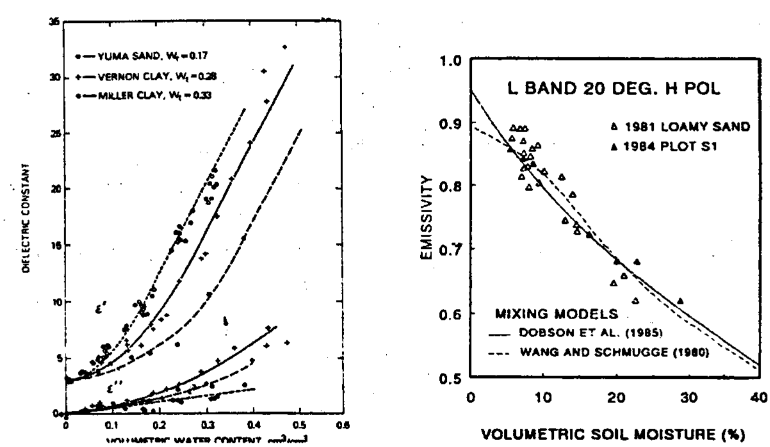


Figure 14 : Argan diagram of a normalized relative complex permittivity for wheat at 11.3 and 18.0 GHz and three temperatures, -1, 24, and 42°C.

(iii) SOIL

The dielectric constant of soil increases from about 3 when dry to almost 30 when wet. While the range of variation is about the same for almost soils. except at lower MC. This is due to textural differences or soil particles sizes. At lower MC water is tightly bound to the soil particles while at higher MC water begin to behave like free water. This behaviour is shown in Figure 15(a) for sand and clay soils [Schmugge et al, 1999]. The ability to observe the variations of MC with the soil's microwave emissivity has been verified by radiometers operating on the tower, aircraft and satellite platforms. It becomes a useful tool for observing the spatial and temporal variations of surface soil moisture which have important hydrological, agricultural and meteorological applications. An example of the results from a field tower is given in Figure 15(b) which illustrates the observed and predicted emissivities versus soil moisture in the 0-2cm layer for a bare smooth loamy sand soil.



(a) (b)

Figure 15 : (a)Dielectric properties for sand and clay soils. (b)Observed and predicted emissivities versus soil moisture in the 0-2 cm layer for a bare smooth loamy sand soil. [Schmugge et al., 1999].

(iv) FISH

The relationship between the water content and oil content of the herring can be seen in Figure 16 [Kent, 1990]. It is widely know that the water content of pelagic species is complementary to the oil content. The reason for this is basic and arises from the need of the fish to maintain a density slightly greater than that of water. The fat content can vary slightly in these species depending on the season and so the water content also varies.

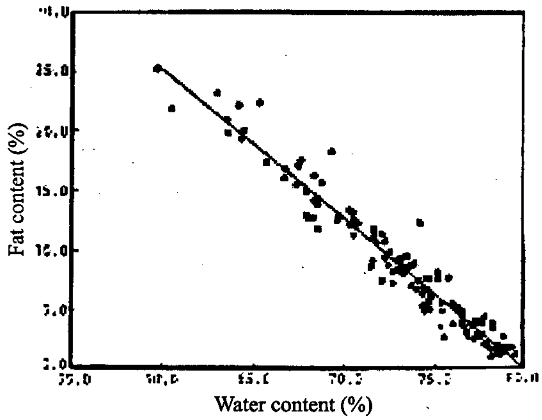


Figure 16 : Correlation between fat content and water content of the herring.

(v) CONCRETE

The overall quality and strength of concrete are dependent upon the water content in the concrete mixture. Detection of completion of the curing process is critical prior to application of surface finish or coating. Figure 17 shows the variation of reflection power from microstrip antenna during the curing process as the moisture content in the concrete drops.[Mat Yassin, 2001]

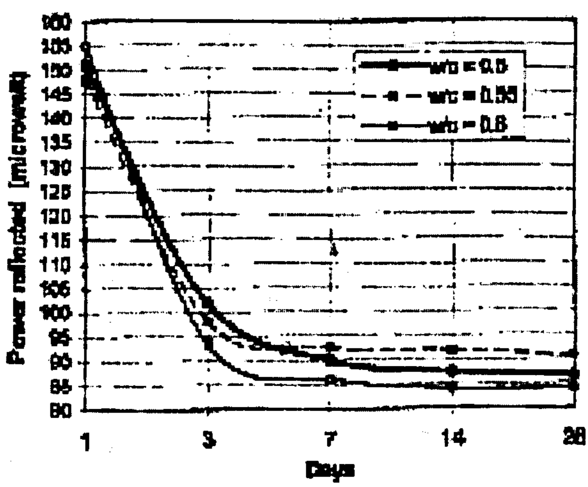


Figure 17 : Power reflected by concrete versus curing time at three different water/concrete ratios, 0.5, 5.5, and 0.6

MIXTURE MODEL

A functional dependence between dielectric properties and its moisture content is very complex. The formulation is derived in terms of volume fraction, shape of the inclusion particles and permittivity of the mixture. In this section, a formula for the permittivity of the hevea latex as a function of its MC is derived.

In these formulas, hevea latex is treated as a biphase liquid, consisting of water and solid rubber. In Wiener's upper bound formula [Suresh et al., 1967] the relative dielectric permittivity of the mixture is written as

$$\varepsilon = (1 - \delta)\, \varepsilon_s + \delta\, \varepsilon_w \qquad (6)$$

where ε_w and ε_s are the dielectric constants for water and solid materials respectively, and δ is the water volume fraction. In this expression, it is assumed that the water molecule (dipole) is an ellipsoid with the major axis parallel to the direction of the applied field and the dipole is free to orientate.

A previous study has shown that for the frequency range 2 to 20 GHz, the dielectric properties of a liquid are strongly dependent upon the geometrical shape of the ellipsoid. For a spheroid with three main axes *a, b,* and c with $a \neq b = c$ the equation for ε which are based on the Bruggemann model [Bruggeman, 1935] may be written as [Boned et al., 1983]

$$(1-\delta) = \left[\frac{\varepsilon_s}{\varepsilon}\right]^{3d} \frac{(\varepsilon_w - \varepsilon)}{(\varepsilon_w - \varepsilon_s)} \left[\frac{\varepsilon_s(1-3A) + \varepsilon_w(2-3A)}{\varepsilon(1-3A) + \varepsilon_w(2-3A)}\right]^K \qquad (7)$$

where

$$d = \frac{A(1-2A)}{(2-3A)} \text{ and}$$

$$K = \frac{2(3A-1)^2}{(2-3A)(1-3A)}$$

A is known as the depolarization factor, d is the volume fraction, and the value of e may be obtained from Eq. 7 by the numerical root-seeking method. Kraszewski et al. have developed a simple model based on the relation between the propagation constants and relative dielectric permittivity [Kraszewski et al., 1976] and is written as

$$\varepsilon^{1/2} = \delta\, \varepsilon_w^{1/2} + (1 - \delta)\, \varepsilon_s^{1/2} \qquad (8)$$

The volume fraction d is related to the MC by

$$\delta = M_w\, [\, M_w + D_s / D_w)] \qquad (9)$$

M_w is the MC, D_w and D_s are the relative density of the water and solid rubber respectively and are considered to be constant with $D_w = 1.0$ and $D_s = 0.94$.

Figure 18 shows the variation of ε' and ε'' with MC at 10.9 GHz and at 26°C. The experimental data are shown by the point symbols and the lines are the theoretical values predicted from mixture equations given by Eq. 6, 7 (with a/b = 0.01), and 8. Throughout these figures ε' and ε'' demonstrate a good relationship with the MC and are almost independent of the type of solution.

The experimental results of Figure 18 [Khalid et al., 1994] are very close to the predicted values of Brugemann's model with *a/b* = 0.01 (prolate spheroid) and well below and close to the upper limit of Wiener's model. These results suggest that the water molecules in hevea latex are loosely bound together and are easily aligned by the electric field, and the shape of the water molecules is probably close to that of prolate spheroid.

The model from Kraszewski et al., is also suitable to predict the variation of ε' and ε'' with MC with the average deviation from measured values of within 5-7% as compared with that of Brugemann's model of about 3%.

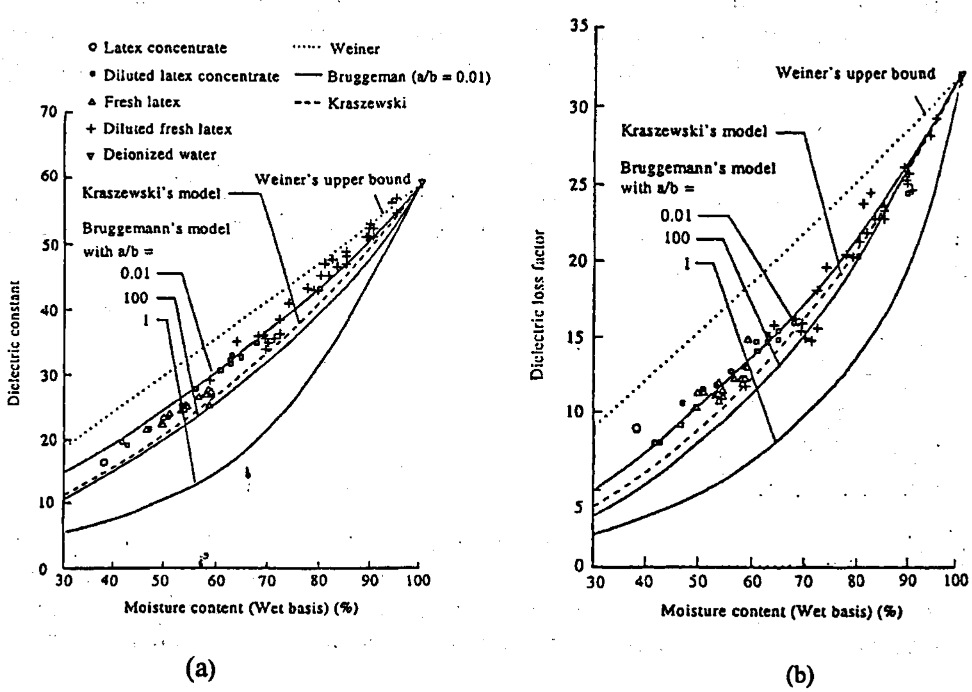


Figure 18 : Comparison between experimental dielectric data for hevea latex with theoretical data calculated from mixture model at 10.9 GHz and 26°C (a) dielectric constant (b) dielectric loss (see [Khalid et al., 1994])

STATE OF THE ART

The basic physical phenomena utilized in relating moisture content to electrical quantities at microwave frequencies are usually presented based on transduction principles [Stuchly et al., 1972]. A general scheme of microwave transducers used for measuring moisture content can be presented using a block diagram as display in Figure 19. The first block represents conversion of a measured moisture content M_w to an electromagnetic quantity E. In our case E is much related to the complex permittivity ε and in the first block involves with the determination of the functional dependence between material's permittivity and moisture content.

$$\varepsilon = f_1 \ (M_w) \tag{10}$$

f_1 is directly related to the contribution of the polarization of water dipole which is affected by the operating frequency, temperature and chemical compositions.

The second block stands for the microwave sensor which converts complex permittivity to the microwave electromagnetic parameter E_m such as reflection coefficient, attenuation, resonant frequency, phase shift, time domain reflection etc. Therefore this section involves with the determination of functional relationship between E_m and ε given by

$$E_m = f_2 \, (\varepsilon) \tag{11}$$

where f_2 is normally affected by the changes of the measuring condition, displacement of measured object in measuring region, material density in the test zone , wave impedance etc. Many forms of microwave sensors are used for example waveguide, coaxial line, microstrip, coplanar line configurations.

The third block is the microwave transducer which converts the microwave signal into electrical signal, V such as DC or low frequency voltage current.

The functional relationship between E_m and V can be written as follows:

$$V = f_3 \, (E_m) \tag{12}$$

f_3 is affected by the noise, stability of microwave detector, and non-linearity.

In simple microwave instrument a square law detectors are most frequently used. However, some advanced meters use heterodyne or homodyne detectors.The last few blocks are signal processing units, which contains amplifiers, interfacing unit, digital processing and control and display unit. The performance of these units are affected by the electronic noise and electromagnetic interference. The above scheme enables us to find out or to predict the accuracy, precision, dynamic range, sensitivity and the effects of unwanted factors or interferences.

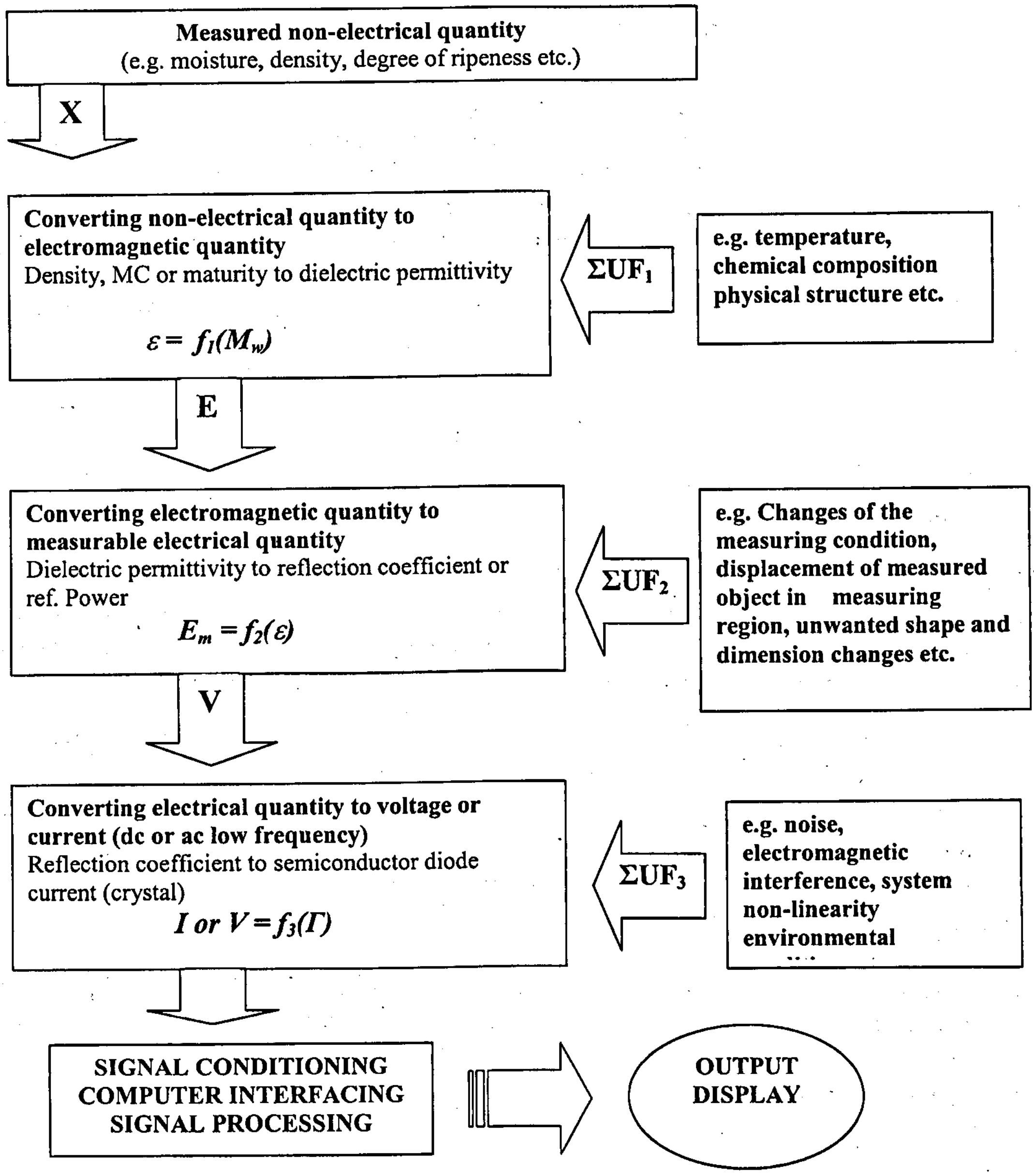


Figure 19: State of the art of the development of microwave aquametry system.

PRESENT TECHNOLOGY OUTLOOK

MRT – Latexometer

Based on the basic dielectric properties of hevea rubber latex as mentioned earlier, we have developed a simple, portable, easy to use and cheap latexometer which can be used for MC or DRC measurement of hevea rubber latex. [Khalid, 1982]; [Khalid et al., 1983]. The first Latexometer developed is based on the transmission method (see Figure 20). This instrument won the best entry in the international competition on Dry Rubber Content (DRC) determination organized by the Malaysian Rubber Research and Development Board in 1981. Although the technique is capable of giving an accuracy of about 1% unit DRC as compare to the Standard lab Method, it has some drawbacks such as bubbles trapping in the container and a small container make it difficult to wash.

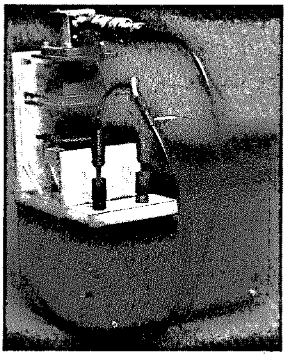


Figure 20: Microwave Transmission Type Latexometer. [Khalid, 1982]

A new meter was proposed which is based on the reflection method. Basically, the sensor consists of microwave transmitter and receiver, non-lossy protective cover, detector, signal conditioning and display unit (see Figure 21(a)). The analysis of the propagation of wave through this multi-layer system is very complex and it can be simplified by using signal flow graph (Figure 21(b)) and Mason's non-touching loop rules [Warner, 1977]. The details of the analysis, structure of the sensor and prediction of reflection power can be referred to the previous works [Khalid et al., 1994, 2002].

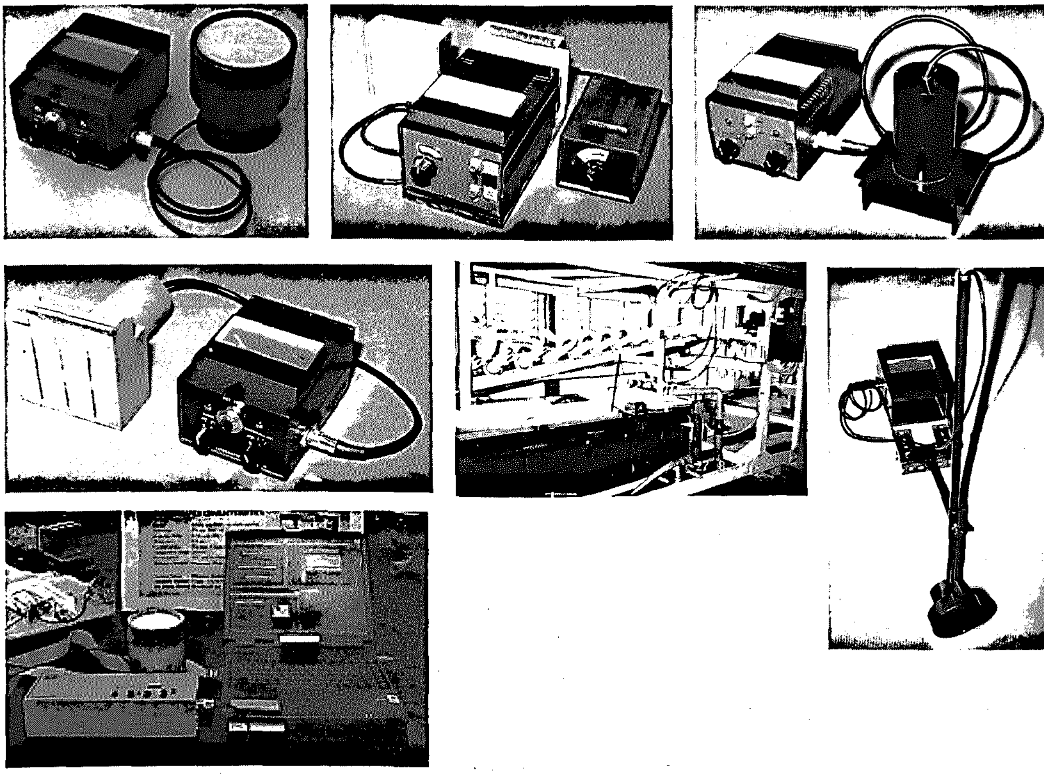


Figure 22: Various models of MRT-Latexometer and its application in rubber glove industry.

Some of the various versions of latexometer shown in Figure 22 are fixed container version, dipped version, removable container version and digital version. In the rubber glove industry, this meter is suitable for the preparation of latex with correct MC or TSC for dipping process and for monitoring of MC. Normally it takes more than one hour for the initial preparation of the latex solution since MC is determined by drying the sample in the oven. Figure 22 shows the installation of the latexometer at rubber glove factory and normally the initial MC of the latex solution for latex dipping process is around 70%.

The variation of the detected current of the meter with moisture content and TSC is shown in Figure 23. It is clearly shown that a relationship between MC and detected current is excellent. Over the temperature range of 25°C to 45°C the variation in MC is less than 1%. The performance characteristic of the latexometer is shown in Table-1. Meter of this kind is suitable to be used at latex collecting center and process control at latex dipping industries. With proper calibration this instrument is also suitable for determination of MC in various lossy liquids such as fresh milk, coconut milk, soya sauce, tomato ketchup and water-based paint.

Table-1: The performance characteristics of the MRT- Latexometer

Range	: 0-60% unit DRC : 40-100% unit MC
Accuracy	:1% unit DRC :0.5% unit MC
Reproducibility	: 0.5% unit DRC & MC
Warm-up	: 2-5 Sec.
Operating time	: less than 5 minutes
Temperature range	: 20-45oC
Volume of sample	: 150 ml

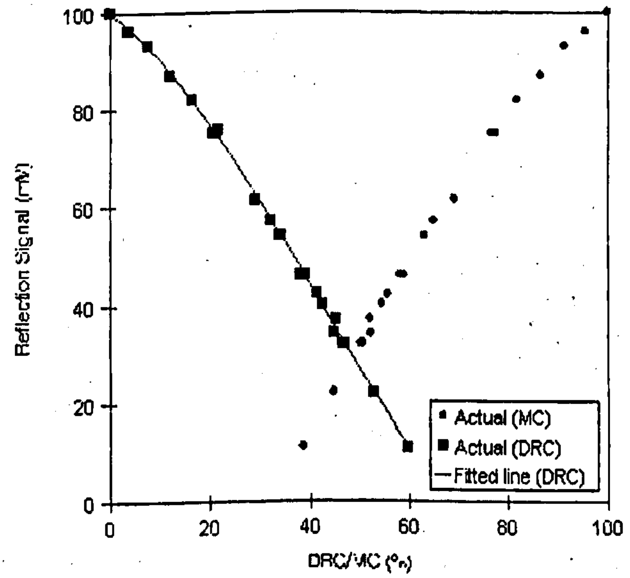


Figure 23: Variation of reflection signal in form of detected current versus DRC and MC of hevea latex. [Khalid et al., 2002]

Microstrip and conductor-backed coplanar waveguide(CPCPW) sensors for liquid and oil palm fruits

U-shaped Microstrip moisture sensors [Khalid, 1988] have been developed to measure the variation of moisture content in various liquids and Linear Microstrip and CBCPW moisture sensors for oil palm fruit [Khalid et al., 1988, 1992a, 1996a]. [Khalid et al., 1998] By knowing moisture content in palm fruit we can subsequently predict the level of its maturity. Both structures as shown in Figure 24 consists of input and output, sensing area and stripline or coplanar line. The sensing area consists of a substrate, a protective layer and a sample with semi-infinite thickness (see Figure 25) .The transmission and reflection phenomena in the structure can be analyzed using signal flow graph and Mason's non-touching loop rules. The scattering parameter S_{21} or attenuation can be predicted based on the dielectric properties of the sample. The detailed analysis of these structures can be referred to the previous works [Khalid et al., 1996c, 1998, 1994].

Figure 26(a) shows the attenuation of microstrip sensor against the moisture content for sucrose solution and for various thickness of protective layer [Khalid et al., 1988]. The results show that the sensitivity is drastically affected by the thickness of the protective layer. The performance of CBCPW sensor [Khalid et al, 1998] is shown in Figure 26(b) with a sensing area length of about 1.6 cm, small gap size (b-a)/h = 0.3 and s/h ratio (or SPH) equals to 0.0, 0.04, 0.08, 0.13, 0.18 and 0.22. The sensitivity for SPH=0.08 is about 0.15 dB/% MC.

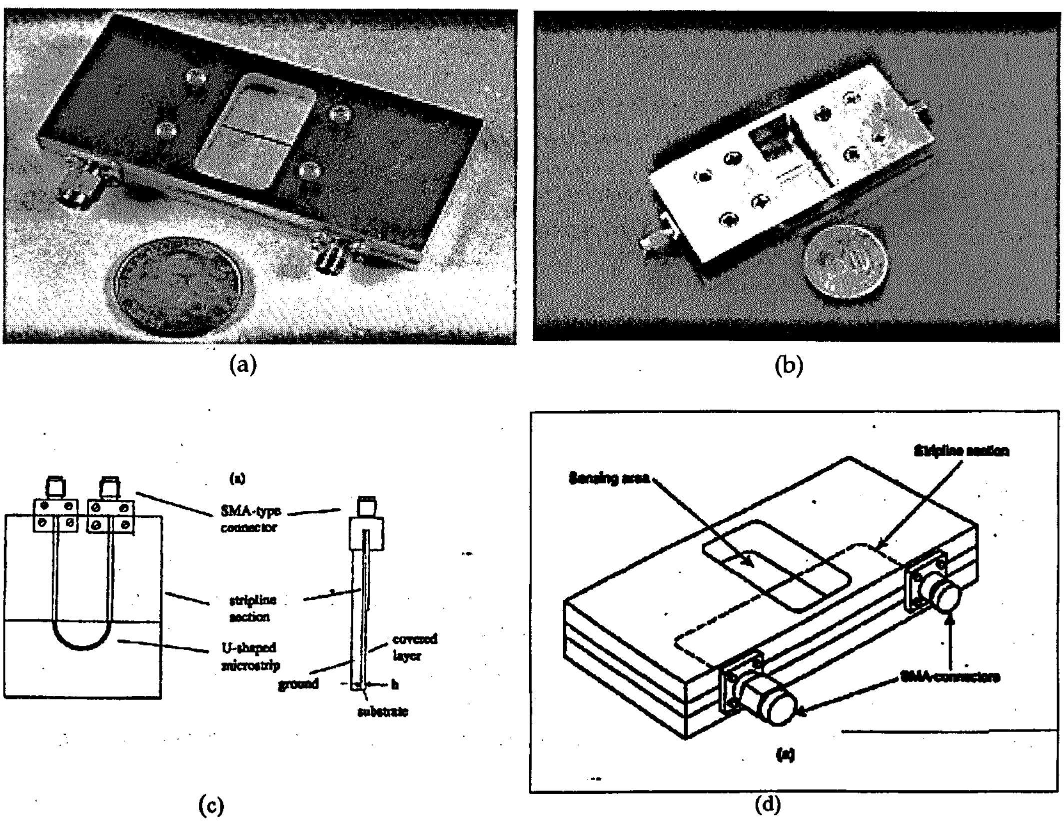
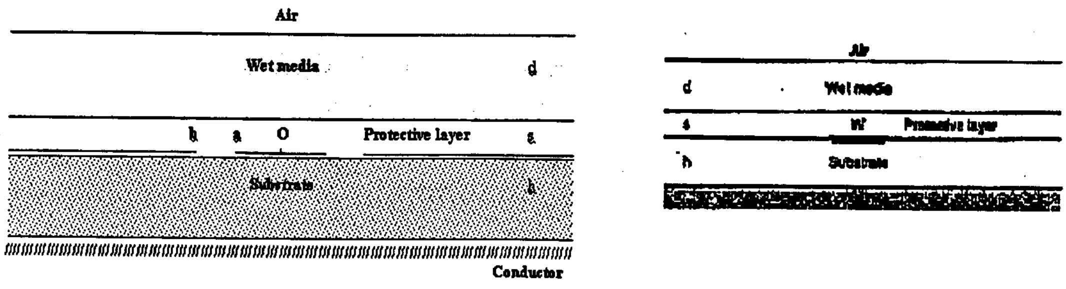
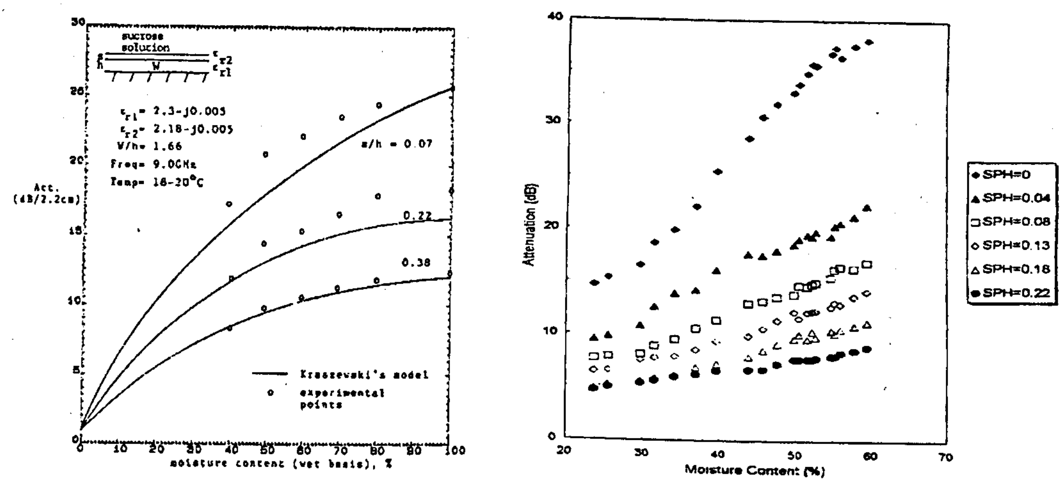


Figure 24 : Various types of planar moisture sensors (a) linear microstrip sensor (b) CBCPW sensor (c) U-shapes microstrip sensor (d) detailed structure of linear microstrip sensor.



(a) (b)

Figure 25 : Cross-section of test structure (a) CBCPW sensor (b) Microstrip sensor



(a) (b)

Figure 26 : Variation of Attenuation or insertion loss with moisture content (a) U-shaped microstip sensor for measuring MC in the sucrose solution at various s/h ratios (b) CBCPW sensor for oil palm mesocarp.

A prototype for ripeness indicator using microstrip sensor is shown in Figure 27 . The detected current from the meter is related to the moisture content of mashed mesocarp and finally the stage of the ripeness can be determined. A single test of the sample is adequate for predicting the optimum time of harvesting by applying the profile of ripeness. This method is found suitable for assessing the quality of the fruit that reaches the factory.

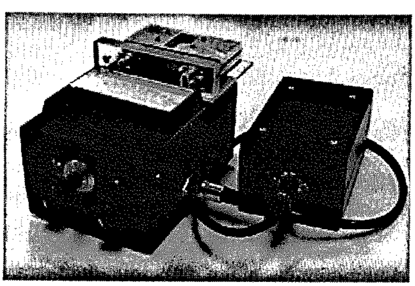


Figure 27: A prototype of ripeness meter for oil palm fruit.

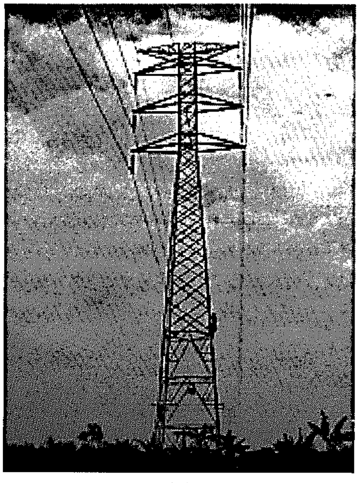
Wood Meter

This paper shows the development of a simple microwave wood meter based on the variation of dielectric properties of wood with moisture, density and stage of decay [Khalid et al, 1999, 2000, 2001].

In Malaysia more than 90% of the cross-arms of the 275 KV and 132 KV transmission lines used chengal wood (see Figure 28). As a result of natural weathering the wood is degraded and decayed. For this reason there is a need for a portable, easy, light, small and accurate sensor for decay detection especially to be used by maintaining staffs. The stages of decay can be classified as sound wood, partly decayed and severely decayed (see Figure 29).

The characteristic of detected current at receiver with moisture content for decayed and sound wood is shown in Figure 30. In actual condition especially during rainy season, the maximum moisture content that can be absorbed by sound wood is about 15% while for decayed wood it is about 35%. There is a possibility of using moisture content and its corresponding detected current as the indicator of decay. For example, if the detected current for that particular sensor is more than 50 mAmp, the wood is considered already decay. However, the measurement has to be done immediately after the rain and it is not recommended as far as safety of the operator is concerned.

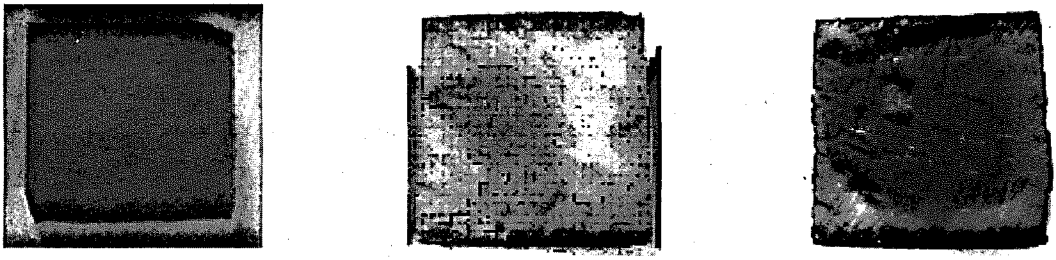
Looking back at Figure 30, it is found that at environmental moisture content (EMC) of about 10% there is quite a reasonable difference in the detected current between decayed wood and sound wood. This property gives the possibility for the detection of decay while the wood is dried or at EMC.



(a)

(b)

Figure 28: (a) High power transmission lines pylon (b) Close view of the pylon which showing wooden cross arms .



(a) (b) (c)

Figure 29: Various stages of decay of wooden cross-arms : (a) sound wood (b) partly decayed (c) severely decayed wood

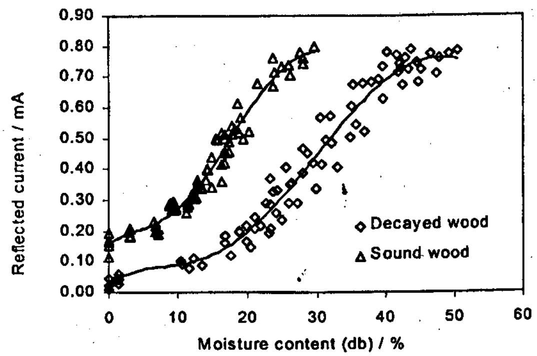


Figure 30 : The profile of the current detected from microwave detector with moisture content for decayed and sound wood.

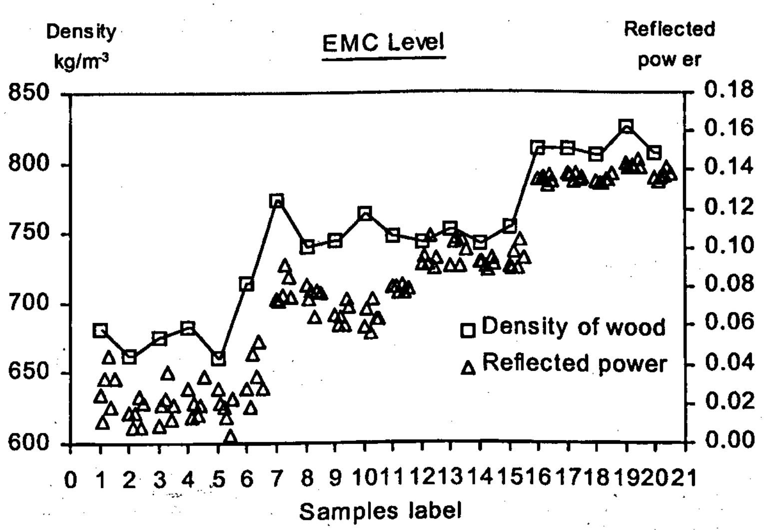


Figure 31 : Variation of density and reflected power for 20 samples of dried wood from different stages of decay.

It is clearly shown in Figure 31 the variation of density and reflection power for 20 specimens of wood including sound wood, partially decays and decayed wood (the measurement of each specimen is repeated 5 times). The reflection power from decay wood is quite low (close to zero) while sound wood gives the reflection power of about 0.14. Their corresponding density varies from 670 kg/m^3 for decayed wood to about 800 kg/m^3 for sound wood.

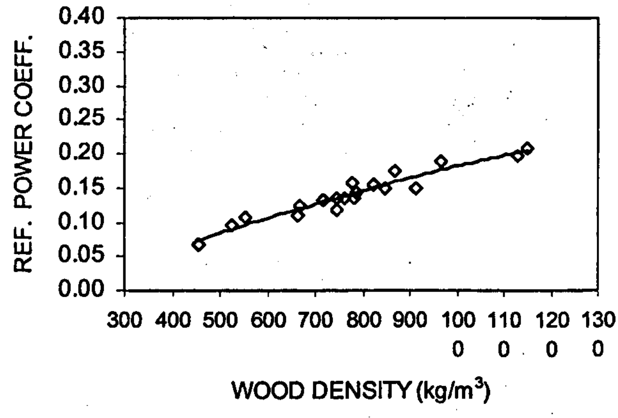


Figure 32 : Dependence of reflected power coefficient with wood density

The measurement results of the variation of the microwave reflection power coefficient with density of the wood with respect to the protective cover of thickness of 1 cm are shown in Figure 32. It is found that there is a good relationship between reflection coefficient and wood density and the sensitivity is about 2.7e-4/kgm^{-3}. This means that a simple, portable and accurate wood densitometer can be developed which covers the wood density ranging from 30kgm^{-3} to 1200 kgm^{-3}. This range covers most of the wood species originated from tropical regions.

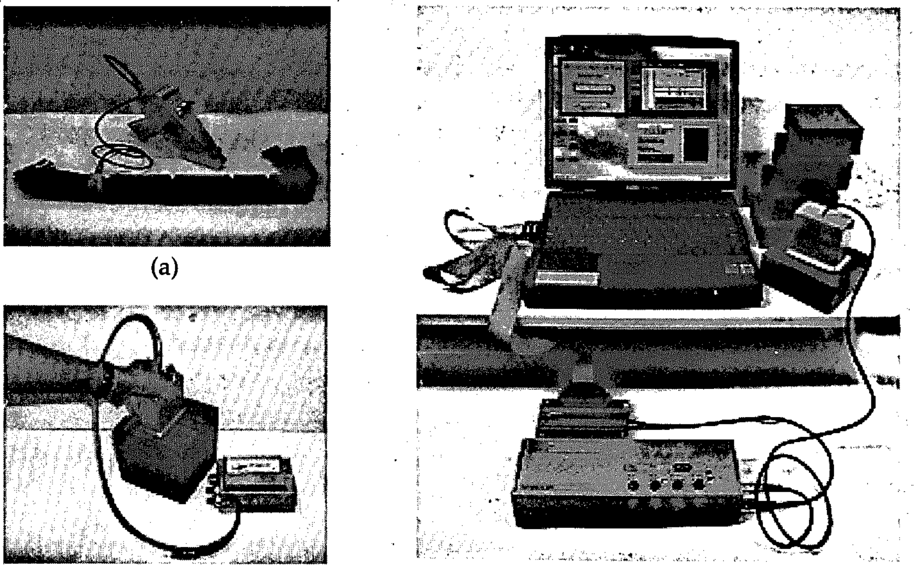
Various microwave wood meter (see Fig. 21) have been developed and all designs are taken under consideration for portability, ease of use, cheap and acceptable accuracy. Further information of each version is described as follows [Khalid et al., 2001].

(i) MRT-wood moisture meter and decay level detection.

This instrument is suitable for routine inspection of the stage of decay of wooden cross-arms based on the moisture content in the sample. The dynamic range of moisture content is about 0% to 40% for decay wood and 0% to 30% for sound wood. The accuracy of the moisture content is about 2% to 5% (dry basis).

(ii) MRT-Wood densitometer.

This instrument is used to measure the density of wood with the thickness more than 5cm and the density ranging from 400 kg/m^3 up to 1200 kg/m^3. The accuracy of the meter is about ± 5 kg/m^3 and the measurement is operated at EMC condition.



(a) (b) (c)

Figure 33: Various types of wood meter (a) wood moisture meter and decay level detection in wooden cross-arm (b) wood densitometer (c) computer-assisted wood densitometer (see ref [Khalid et al., 2001])

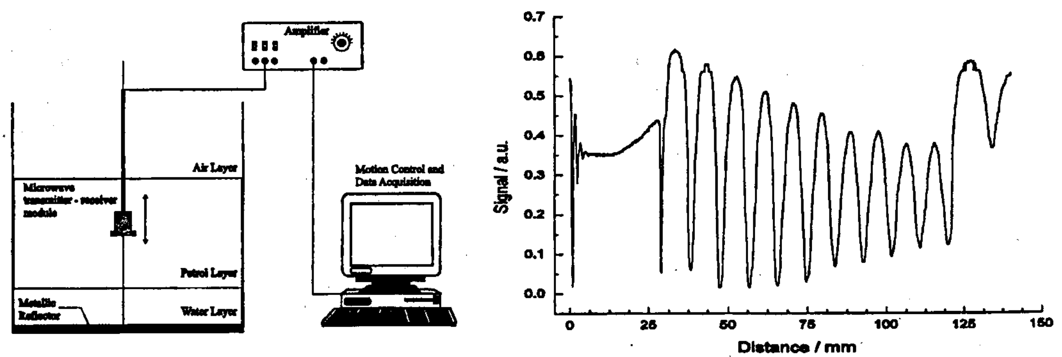
(iii) Computer-assisted MRT-wood meter

This instrument is for measurement of density, moisture and stage of decay of the wood. It is designed for multipurpose measurements and averaging technique base on Lab View package is applied in order to reduce the error due to the inhomogeneity of the samples. The possible species of the wood corresponding to the measured density can be display on the screen.

Detection of Water in The Fuel Tank

Water is often present in the fuel tanks due to night and day temperature changes resulting in a build up of condensed water within the inner surface of the tank. The expectancy of the water infiltration in the fuel tanks is even higher in the flooding prone areas. Water settlement at the bottom of the tank causes internal corrosion. In this work, a simple, low cost and accurate microwave reflection type system for detection of water in the fuel tanks has been developed. Figure 34(a) shows a module containing by a microwave generator and a detecting diode is used to measure the microwave reflection coefficient at various position through the fuel tank. In the course of the study, a motion control and data acquisition system has been developed. A software written using the LabVIEW programming language is used to control the movement of the sensor and for the data acquisition. [Khalid et al., 2003a]

At microwave frequencies (~10 GHz), the loss factor and dielectric permittivity of water ($\varepsilon_w = 60\text{-}j31$) are always higher than the solid inclusions of most wet materials and fuel oil ($\varepsilon_f = 2.24\text{-}j0.07$). Therefore there is a wide different between the reflection and absorption of microwave signal due to water as compare to fuel. Figure 34(b) shows the experimental results of the reflected value in terms of voltage detected by the microwave detector as we move the sensor in the top-down movement passes through air, fuel and water. The level of water and petrol for this measurement are about 30mm and 95mm respectively and the measurement is up to 15 mm above the petrol level. Experimental results show the capability of the system to detect the presence of a water level down to 1 mm thickness.



(a) (b)

Figure 34 : Detection of water in fuel tank (a) Schematic diagram of the microwave reflection measurement system (b)Experimental result for reflected power as sensor is moving through 30 cm water, 95 cm petrol and 15 cm above the petrol level (see [Khalid et al., 2003b]).

PRESENT DEVELOPMENT OF MICROWAVE AQUAMETRY TECHNOLOGY

The interest in the microwave aquametry was growing in the seventies. One of the main reason for this was the availability of inexpensive solid state devices and monolithic microwave integrated circuit used for generation, modulation, switching and detection of microwave signal. As a result, reliable microwave equipment, capable of operating in the field and in industrial environment became available and competitive with that of capacitance and nuclear radiation meters. Another factor stimulating the development of microwave aquametry in recent years has been the growing interest in modernizing and automating the measurement system by applying electronic embedded technology and computer aided instrumentation. The finding of research over the past 15 years have established the bases for several new techniques and eventually find practical use as new sensors or a new generation of microwave moisture meter.

The total number of microwave moisture meters manufactured during the last ten years throughout the world is unknown. However as we search through the internet we can easily find more than 50 companies manufacturing various kind of microwave moisture meter for various applications. Some of the meters are listed in Table –2.

Further development of microwave aquametry depends upon the needs and the requirements of the industry and upon the ability and inventiveness of microwave scientists and microwave engineers.

CONCLUSIONS

It has indeed been about 100 years of achievement since the development of dielectric theory and Maxwell's electromagnetic theory, growing an era rich in technology discovery and innovation. We are in the pursuit of ways to create practical instrumentation and system for our daily life and one of the fascinating area is microwave aquametry. Since water appears in many materials, the concern about precise measurement of its existence will continuously become an important agenda for serious scientists and engineers.

From the above discussion, it is clearly that technology from microwave aquametry offers many important advantages such as non-contact bulk measurement, non-destructive technique, independent of ionic conductivity, fast, no radiation hazards and acceptable average accuracy of about 0.5 to 2%. This technology is expanding from year to year offering a new reliable, robust and better accuracy to be used for MC monitoring and measurement in the laboratory, field and industries. However, there are still some limitations in the application of microwave methods. Among the set-backs are microwave components remain much more expensive then their lower-frequency counterparts, sensitive to temperature and density, requirement for higher precision for certain application and inaccuracy at low moisture levels due to bound water and low reflection or attenuation.

Some of the technical and scientific problems in microwave aquametry can be solved by deeply study the interaction of electromagnetic wave with the wet material, modelling transmission and reflection phenomena in the sensing region, decreasing the effect of temperature and density by applying dual frequency system, multivariate statistical analysis, and artificial neural networks. The development of microwave aquametry should be hand in hand with the development of new materials, hyperperformance real time signal processing, nanotechnology and interdisciplinary knowledge. It is possible in near future to develop a computer-assisted microwave reflection type instrument for multi-tasking measurement of various parameters related to the assessment of the quality of our commodities.

Table 2: Present Microwave Aquametry Equipment

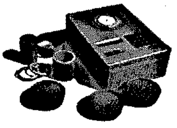
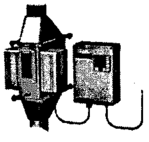
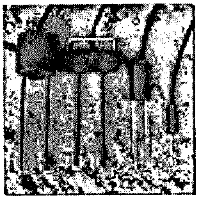
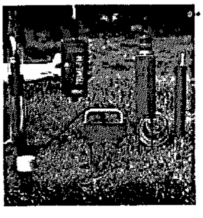
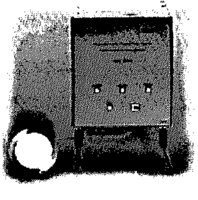
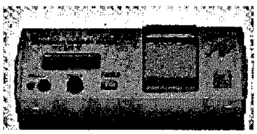
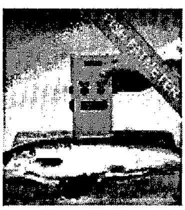
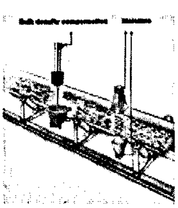
Name of Instrument	Application	Operating Principle	Accuracy
Microradar – 101,2 moisture meter  	analysis of water contentin powders and granules,resonator, via the fringing and provides-insensitive to variations in bulk density. Suitable for grinded coffee, cocoa powder,milk poweder, salts, sugar tea, grains powders etc.	based on an open-ended fields from the open resonator to the sample cup.	Range of moisture; within 0.01 to 16% Resolution, in % moisture: 0.01%
Trime  	Measuring MC in soil and offer excellent spatial resolution with a high penetration depth allowing for excellent measurement precision even at high salinity soils.	based on the Time-Domain-Reflectometry), and was developed to measure the MC of a material. The metal rods, stripes or plates are used as wave-guides for the transmission of the TDR-signal. The device generates a high-frequency-pulse (up to 1GHz) picoseconds (10^{-12}s)! (0.20mA).	0-90% volumetric water content Universal calibration allow a measuring accuracy of up to ± 1% independent of material type, temperature, texture and bulk soil electrical conductivity up to 2 dS/m.
Gre Con 	suitable to measure MC for wood chips and fibers.	worked according to the microwave resonance method. A harmonic, electromagnetic resonance field (microwave field) is generated by means of the planar sensor.	MC range: 0.1% to 85% in selectable sub-domains Accuracy: ± 2% of the measuring range

Table 2 (cont.): Present Microwave Aquametry Equipment

Name of Instrument	Application	Operating Principle	Accuracy
microwave moisture meter MBBM- 9 	designed for nondestructive field and laboratory measurements of grain-moisture content of 7 types of seeds: wheat, barley, rye, oats, beans, sunflower and maize.	based on the measurement of the attenuation, due to moisture in the grain, at microwave frequencies.	MC range: 5-32 % in selectable sub-domains Accuracy: ±1-5% of the measuring range
Fish fat meter  	Measurement of fat content of various fish such as salmon, herring, mackerel trout and sprats.	The device responds mainly to the water present and in the fish tissue not fat , in fish these are highly correlated [ ]. Measurement is based on the variation of insertion loss of microstrip sensor with water content.	Accuracy is about 2.5%. Variability: Skin thickness, distribution of fat below the skin, surface moisture and temperature.
Berthold on-line moisture analyser 	On line moisture measurement of wood chips.	microwaves are transmitted via horn antenna through the wood chips and received by the other antenna at the opposite side.	Accuracy ± 1.5% Moisture range : up to 55% MC

ACKNOWLEDGEMENT

The author would like to thank Universiti Putra Malaysia, Ministry of Science, Technology and the Environment, and Tenaga Nasional Research and Development Sdn. Bhd. for funding his research projects. Thanks are also due to all staff and his postgraduate students of Physics Department, Faculty of Science and Environmental Studies for their support and generous assistance. Finally, his sincere gratitude and appreciation will be preserved to his wife and children for their love, constant support and encouragement.

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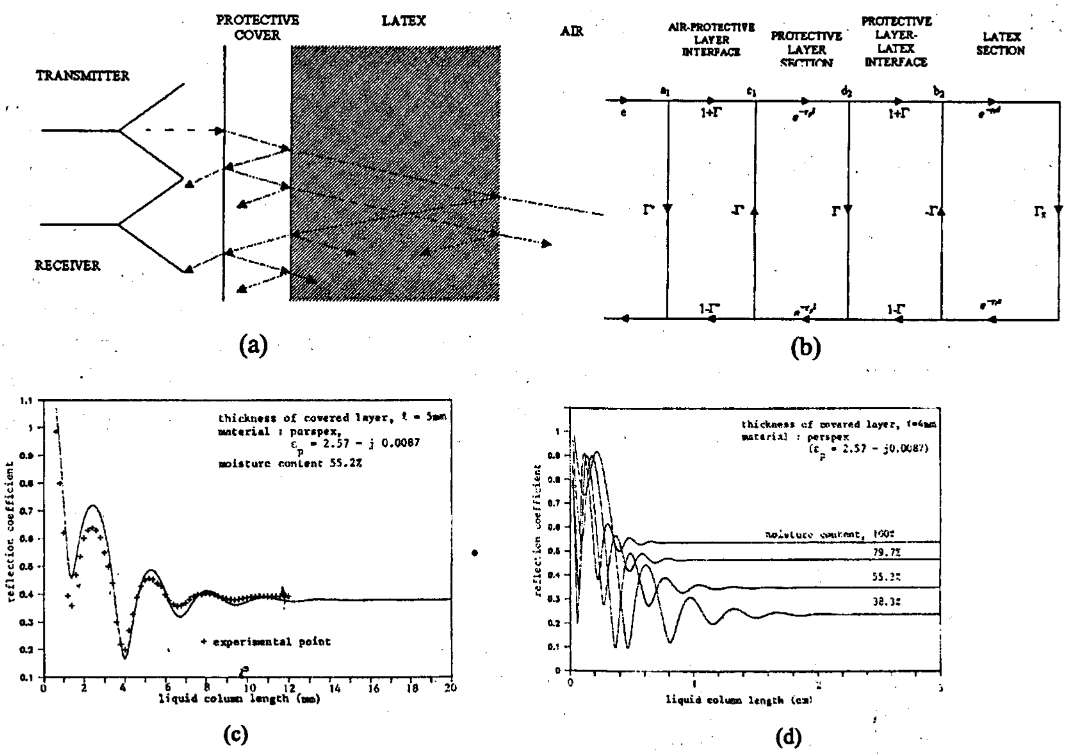

Figure 21: Structure of MRT- Latexometer : (a) Reflection and transmission phenomena in the sensing structure (b) A corresponding signal flow graph of sensing structure (c) The profile of reflection coefficient at various liquid coulomn lengths (d) A profile of reflection coeff. at various latex concentrations.

The prediction and experimental values for the reflection coefficient profile for hevea latex with varying moisture content are shown in Figure 21(c). The profile exhibits successive maximum and minima due to interference phenomena and tends towards a final value for the reflection coefficient R_∞ at the semi-infinite length, d_∞ of the liquid column. At d_∞, the reflected power is only due to the reflection at the protective cover-lossy liquid interface.

Figure 21(d) shows the profiles of various hevea latex solutions with different moisture contents. Since water is more lossy than latex, its d_∞ value is smaller than that of the latter and for a liquid sample with ~ 40% moisture content the value of d_∞ is about 2.5 cm. This means, minimum thickness of the liquid sample in order to avoid any interference phenomena should be greater than d_∞.