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X-밴드 주파수의 마이크로파를 이용한 자유공간에서의 모래수분측정

Sand Moisture Measurement with Microwave Technique in Free Space at X-Band Frequency

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요 약

건축연구에서의 수분측정 방법을 개선하기 위하여 비파괴적인 수분측정기술을 응용하였다. 본 실험은 연속적이고 비파괴적인 측정에서의 핵심요소로서 자유공간에서의 혼 안테나를 사용하여 실험하였으며 사용한 기술은 마이크로파 브릿지 장치로서 9.5 GHz의 주파수에서 함수율이 1~12 % 범위의 모래수분을 측정하였다. 이로부터 대표적인 교정곡선을 구하였다. 이를 바탕으로 마이크로파를 이용한 석탄, 제지, 식품 및 건축재료 등과 같은 비금속내의 수분측정이 가능함을 보였다.

Abstract

A nondestructive moisture measurement technique has been applied to improve the previous moisture measurement method in the building research. The experiment was done in free space using horns since it is the key element for continuous and non-destructive measurement. For this purpose a microwave bridge type analyzer at the frequency of 9.5 GHz was used to determine the moisture content of sands in the range of 1~12 %. From this, the representative calibration curves were obtained. This shows that moisture measurement technique using microwave is applicabe to the measurement of moisture in non-metallic materials such as coal, pulp, foods, building materials, etc.

I. Introduction

Water is abundant in our environment and has more peculiar properties than other substances, to which many scientists are attracted. Studies have been made on the interaction of electromagnetic waves with water and aqueous materials[1], the interaction of water with solid surfaces[2], and the moisture transport properties of wet porous media[3],[4]. Since water is mostly in liquid form in the temperature range of our daily experiences and has strong polar nature, it is easily

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condensed and absorbed into surrounding materials. It has been important to understand its transport mechanism, the state of absorbed water, and to determine the amount of water absorbed. Therefore several techniques to measure the moisture content in various materials in agricultural, industrial and manufacturing fields have been developed.

These methods are divided into two groups based on their nature: primary and secondary. Primary methods are those which yield absolute amount of water and include oven-drying method, vacuum drying method, Karl Fischer and distillation methods. Oven-drying method using weight change before and after drying a moist material is being applied to the moisture detection of wide ranges of solid and powder type materials. However this can not give total amount of water, rather it gives total amount of free water.

Secondary methods including infrared, microwave techniques utilize various physical nature of the interactions of the probe with water molecules.

In IR method, the amount of water is determined by measuring and comparing reflectivities of two light beams with different wavelengths; one is strongly absorbed by water and the other is not. But its measurement is done only on the surface of the sample. Therefore its accuracy is dependent on the condition of surface. Microwave, which is the electromagnetic wave in GHz frequency range, strongly interacts with polar molecules such as water via dipole relaxation process. Microwave can efficiently distinguish a moist material from many dry materials because of the large permittivity differences. A microwave technique has more advantages compared to IR since microwave signals represent the average of moisture content in large volume and IR signal is limited to signal from relatively small area of a sample. In this paper a microwave bridge system was built using waveguides with other passive components and sand moistures from 1 % mc to 12 % mc were measured. The obtained data were compared with the results from the oven-drying method to get the calibration curves. Our experimental data shows that a microwave technique is suitable for moisture detection in the building material.

Ⅱ. Experimental Method

2-1 Principle

Microwave, the electromagnetic wave in the frequency range of 0.3 to 300 GHz (equivalent to 1 m to 0.1 cm of wavelength) is located between radio and infrared wave in the spectral range. When microwave passes through a dielectric medium (a moist material, in this case), it is attenuated and its wavelength is reduced due to the interaction with the medium. If a plane wave is incident normally on an infinite plane-parallel plate of homogeneous dielectric medium, the system can be described in relatively simple terms. Now consider a system as shown in Fig. 1.

Here γ_0 and γ_1 are the propagation coefficients of the electromagnetic wave in free space and a dielectric medium, respectively. R_0 and T_0 are the amplitude of reflection and transmission coefficients. From Maxwell equations with boundary conditions, following

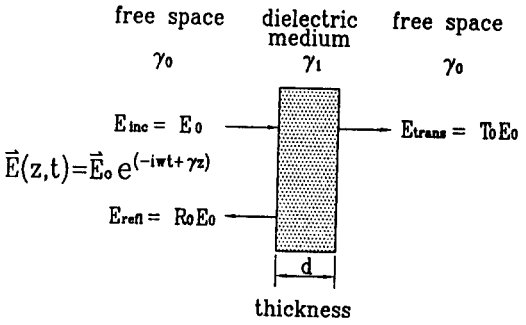

Fig. 1. A theoretical model for determining R_0 and T_0.

equations can be obtained[15],

$$R_0=\frac{(\gamma_0^2-\gamma_1^2)e^{-\gamma_1 d}-(\gamma_0^2-\gamma_1^2)e^{\gamma_1 d}}{(\gamma_0+\gamma_1)^2e^{-\gamma_1 d}-(\gamma_0-\gamma_1)^2e^{\gamma_1 d}} \quad (1)$$

$$T_0=\frac{4\gamma_1\gamma_0}{(\gamma_0+\gamma_1)^2e^{-\gamma_1 d}-(\gamma_0-\gamma_1)^2e^{\gamma_1 d}} \quad (2)$$

$$\gamma_0=i\frac{2\pi}{\lambda_0}, \qquad \gamma_1=i\frac{2\pi}{\lambda_0}\sqrt{\varepsilon}=\alpha+j\beta \quad (3)$$

$$\varepsilon=\varepsilon'-j\varepsilon', \qquad \tan\delta=\varepsilon'/\varepsilon' \quad (4)$$

where λ_0 is the wavelength in free space; d, the thickness of the dielectric medium; ε, the relative complex permittivity; ε', the dielectric constant; ε'', the loss factor; α, the attenuation coefficient and β, the phase coefficient, respectively.

Power transmission and reflection,

$$P_{refl}=R\cdot P_{inc}, \qquad P_{trans}=T\cdot P_{inc} \quad (5)$$

where, the power reflection coefficient, $R=|R_0|^2$, and the power transmission coefficient, $T=|T_0|^2$. Therefore if R_0 or T_0 is determined, the permittivity ε, of the dielectric medium can be calculated. R_0 can be determined from SWR (Standing Wave Ratio) measurement. T_0 can be determined from measuring the attenuation ΔA(in dB) and the phase shift $\Delta\phi$ (in deg.) which are caused by the presence of the dielectric medium in the path of electromagnetic wave transmission. Then T_0 can be expressed as follows,

$$T_0=10^{-\frac{\Delta A}{20}}\exp\left(j\frac{2\pi}{360^\circ}\Delta\phi\right) \quad (6)$$

$$=10^{-\frac{\Delta A}{20}}\exp\left(j\frac{2\pi}{360^\circ}(\Delta\varphi+n\cdot 360^\circ)\right) \quad (7)$$

where $\Delta\phi=\Delta\varphi+n\cdot 360^\circ$ and $\Delta\varphi$ is a measured phase shift.

Since we can measure angle only within the range of 360°, n, an integer number, has to be determined to get the total phase shift caused by the presence of the medium. This will be discussed later in detail. α and β are determined numerically by iteration from measured transmission coefficients and equation (2). Once α and β are determined, ε' and ε'' can be calculated using the following equation,

$$\varepsilon'=\left(\frac{\lambda_0}{2\pi}\right)^2(\beta^2-\alpha^2)+\left(\frac{\lambda_0}{\lambda_c}\right)^2 \quad (8)$$

$$\varepsilon''=\left(\frac{\lambda_0}{2\pi}\right)^2 2\alpha\beta, \quad (9)$$

where λ_0 is the cut-off wavelength of the waveguide.

To simplify the process above equations are rearranged, and with the approximation of $\tan^2\delta \ll 1$, followings can be obtained[6].

$$\varepsilon' \cong \left[1+\frac{\Delta\phi\,\lambda_0}{360^\circ \cdot d} \right]^2 \tag{10}$$

$$\varepsilon'' \cong -\frac{\Delta A\lambda_0\sqrt{\varepsilon'}}{8.686\pi d}, \tag{11}$$

where d is the sample thickness and in cm unit.

These approximate equations are useful for the estimation of dielectric constant values from the measured attenuations and phase shifts.

A moisture content is usually defined as

$$m.c. = \Psi = \frac{m_{water}}{m_{dry}+m_{water}}, \tag{12}$$

where m_{water} and m_{dry} are the weights of water and dry material of samples, respectively. This is the ratio of water to total mass. Therefore it is called wet-base method.

A moist material can be modelled as a compound with two constituents, water and dry material, even though dry material may consist of more than two components. In terms of complex permittivity, it can be expressed as

$$\varepsilon = \varepsilon(\rho_d, \Psi) = \varepsilon'(\rho_d, \Psi) - j \cdot \varepsilon''(\rho_d, \Psi) \tag{13}$$

where ρ_d is the packing density of dry material. For the most dry materials, $\varepsilon'' \approx 0$.

In equation (13), frequency and temperature dependencies are not included. The measured permittivities should be calibrated against moisture content determined by a primary method such as oven-drying.

A model describing frequency dependency of polar molecule is proposed by Debye[7]. For pure water, the loss factor ε'' is maxima at near 20 GHz and decreases as frequency is either increasing or decreasing. At about the same frequency, the rate of change of the dielectric constant ε' against frequency change is also maximum and the slope is negative around at this range. Temperature dependency has been studied experimentally.

Buckmaster[8],[9] and his colleagues have extensively studied on temperature dependency of the permittivity of pure water near 9.4 GHz from 0 to 40 ℃. Temperature effect on microwave moisture content measurement is done by few groups[10],[11].

To select optimal frequency to use, several factors should be considered. As frequency increases toward 20 GHz, the attenuation increases also. This may increase the sensitivity, but decreases the penetration efficiency of microwave to the sample. This will cause poor phase shift data. On the otherhand, decreasing the frequency down to 1~3 GHz will increase the penetration depth. However the ionic conductivity effect might override the dielectric attenuation effect. Therefore X-band (8.2~12.4 GHz) seems to be appropriate to use and 9.5 GHz frequency is used for this experiment.

The state of water in the moist material is also very important. Bound water, which is chemisorbed, and ice have dispersion curves different from free water due to loss of free rotational motion of water molecule. The loss factors of those are maxima at much lower

frequencies, i. e. KHz order. Therefore mositure content measured by microwave is not the total water, rather reflect the total free water.

Moisture dependency of permittivity can be separated from density dependency. It is known experimentally that the quantity $(\varepsilon'(\rho_d, \Psi)-1)/\varepsilon''(\rho_d, \Psi)=f(\Psi)$ is independent of the density[12]. Calibration equation which relates Δ A and $\Delta\varphi$ to moisture content can be established and applied to determine arbitrary moisture content from Δ A and $\Delta\varphi$ measurements[13]. These calibration curves do not need informations on the sample density or thickness.

2-2 Experiment

A typical bridge circuit shown in Fig. 2 is constructed. Extensive studies have been done on sands. Conditioning hard solid material to the proper moisture level is difficult and takes long time. But powder-like material such as sand is much easier to do conditioning. Therefore sands are chosen in this experiment for easier conditioning. Kraszewski also has done microwave moisture measurement experiment

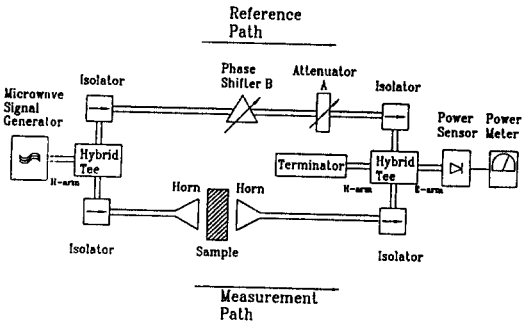

Fig. 2. The experimental set-up.

of sand from 1 % mc to 8 % mc and his results have good correlation with moisture content[14]. But the density of sands he used is much higher than what we normally can achieve in Korea. This suggests that the characteristics of sands may be different from place to place. Sand is obtained from a ordinary building material supplier. It is washed and drained several times to remove organic materials and salt. Then it is dried completely in the air flowing oven at 105 ℃ for more than 8 hours. Water with known weight is added to dried sands and mixed throughly by hands, observing the change of contrast. Small amount of four to five patches are taken randomly from the mixture and their moisture contents are determined by oven drying method. Variation of water concentration in the mixture is less than 0.1 % mc, suggesting that water is very well mixed. Then for microwave measurement mixed samples are placed in the containers of the known volumes with sample thicknesses of 2 cm, 4 cm and 8 cm, respectively. Δ A and $\Delta\varphi$ are determined by the bridge circuit after that. The containers for sands are made of plexiglas. The thickness of the container wall is determined to minimize the container's multiple reflection effect. This can be accomplished if the thickness is close to $\lambda_m/2=\lambda_0/2\sqrt{\varepsilon_m'}\approx 9.7mm$ with $\varepsilon'_m=2.65$ for Plexiglas. A 10 mm thick wall has been chosen in the experiment. To avoid for the diffracted portion of microwave reaching the receiving horn, the container is desinged to be about five times larger than the horn. The distance between horns is maintained at a fixed value as much as possible. It was briefly mentioned previously that the necessitiy of the determi-

nation of integer number n for absolute phase shift due to the sample. n can be determined from different methods depending on the situations.

1) If the medium is not dispersive in the frequency range used,

$$\varepsilon'(f_1) = \varepsilon'(f_2)$$

2) In the case that two different thicknesses of the sample are used,

$$\varepsilon'(d_1) = \varepsilon'(d_2)$$

3) In the case that dielectric constant value of the sample are known.

Methods 2 and 3 are used in this experiment.

Since a datum obtained from one experiment differs from another because of the slight density differences of the samples at each time, data are normalized to the density of 1.34 g/cm³ and to the thickness of d=2 cm. These calibrated data are compared to Kraszewski's results and are shown in Fig. 3.[14] Linear relationships between both attenuation and phase shift and the moisture content can be expressed as,

$$\Delta A = 95.91 \cdot \Psi - 0.44, \qquad r = 0.988 \qquad (14)$$

$$\Delta \Phi = 2113.7 \cdot \Psi + 111.4, \qquad r = 0.991 \qquad (15)$$

where r is the linear correlation coefficient. ΔA is in dB unit, $\Delta \Phi$ in degree, Ψ in decimal number.

Phase shift data are more reproducible than

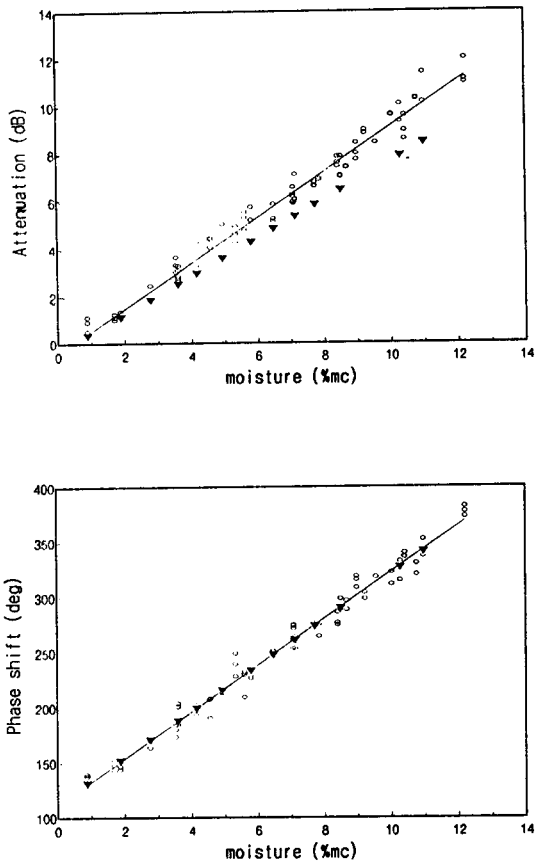

Fig. 3. Data from sand moisture measurement at 9.5 GHz. (○) Data are normalized to ρ= 34 g/cm³ and to the thickness of 2 cm. The line is the least square fit to our data. These data are compared to the fit results of the reference 14 (▼).

attenuation data and agree well with the result of Kraszewski's experiment. The reason for disagreement of our attenuation data with reference 14 is not well understood.

The dielectric constants and the loss factor of moist sands are calculated using equations (10) and (11), and are shown in Fig. 4. It should be noted that, in low moisture range,

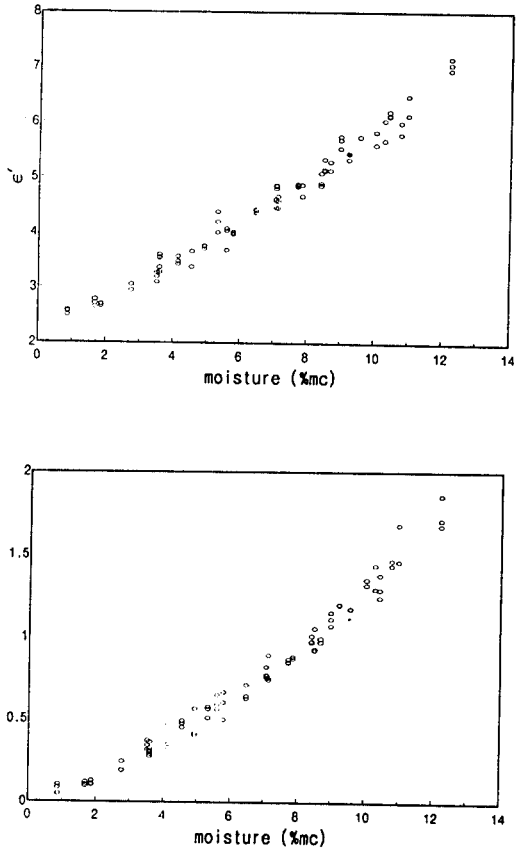

Fig. 4. The dielectric constant and the loss factor calculated from above data using equations (10) and (11).

the loss factor approaches to zero asymptotically. Experiment done by Meyer and Schilz on tobacco clearly shows that the curvature of the loss factor in low moisture content range becomes nearly parallel to the abscissa and intersects the ordinate about 0.01[12].

The loss factor of moist sands deduced from the above concept varies as much as 200 times as the moisture content increases from dry state to 12 % mc. Meanwhile the dielectric constant ε' changes only by 10 times.

Ⅲ. Discussion

We have obtained attenuation and phase shift data as a function of moisture content in sand and corresponding calibration curves were calculated. They are compared to known results and found that using phase shift for moisture determination is better than using attenuation or using both since attenuation data are relatively poor. It needs to be improved further in future but our data suggest that microwave method can be applied to moisture content measurements as a non-contacting probe since measurement can be done in free space. With some modifications this can be applied for continuous on-line moisture sensor system for various non-metallic materials such as coal, pulp, food, building materials and so on. Due to experimental difficulties to maintain homogeneous temperature and moisture distribution at the same time in free space measurement, data for our experiment had been taken under the environment of relatively constant room temperature in the range of ±1.5 ℃ around 25 ℃.

For the proper experiment two factors are important. First frequency. Second the state of water.

Since multiple reflections from other sources can influence measurements, we have checked the measurement system briefly by changing the distance between horn antennas and the location of empty container between them. There were some scatters in certain data but not to the extent as a major error contributers. Moreover our samples attenuate the microwave signal by more than 10 dB in certain

moisture ranges, for example, over 3 % mc with 8 cm thick samples and this should reduce its effect on the data. From this, we can conlcude that it should have contributed to our result by some extent, but not as a major error sources. For future experiment, modifications to the measurement system, such as measuring SWR for various frequencies, averaging data for several locations between horns, sweeping frequencies and tilting the sample container with respect to transmission axis, should improve data further. Diffraction effect can be avoided either by using samples larger than horn or filling empty space with dielectric medium, which allow direct transmission through free space. Sample position between horns may cause variations between data points. Taking average of readings at several different positions or fixing the position at a certain point will reduce the effect. Uncertainties due to temperature variations are yet to be studied. Inhomogeneous distribution of sample and/or moisture does not need to be greatly concerned about because large transmission area (about 100 cm^2) will average out inhomogeneity. Other factors such as the presence of conductive object, uncertainties in density measurement and the false estimation of absolute moisture content in oven-drying method etc. should also be considered.

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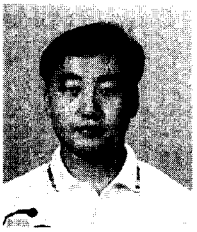

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