Paper

An Experimental Study on the Calculation of the Complex Permittivity for Building Materials from the Reflection Loss by Free Space Measurement

Ken-ichi Kimura* Non-member
Osamu Hashimoto** Member

This paper describes the proper calculation of the complex permittivity for general building materials from the magnitude of the reflection loss measured by the free space measurement. Most building materials are very inhomogeneous, due to (among other factors) varying thickness, rough surface condition, water content and distribution. In this paper the free space measurement is chosen to determine complex permittivities, as the sample preparation is relatively easy and precision machining of materials to be tested is not required.

Iterative calculation for the complex permittivity deduces by using four measured data, which come from measurements of samples backed by a metal plate from front side (front-short), samples only from front side (front-open), samples backed by a metal plate from back side (back-short), and samples only from back side (back-open), under the condition that the frequency variation of the standard deviation of the complex permittivity is small.

This paper also presents the relation of the complex permittivites to water contents for three kinds of building materials (fiber reinforced cement boards, calcium silicate boards and mortar boards) in the frequency range between 1.55 GHz to 6.5 GHz, which is agree to the other past analytical work.

Keywords: Complex Permittivity, Free Space Measurement, Water Content, Reflection Loss, Building Materials

1. Introduction

In recent years, it has been increasingly important to correctly estimate the electromagnetic environments around and/or inside buildings or infrastructures. This is due largely to the proliferation of wireless communication (Wireless LAN, PHS, mobile phone and so on). One of the key parameters for the correct estimation of the electromagnetic environments is the complex permittivity for the materials from which the building (or structure) is constructed, such as concrete, mortar, glass, and board (typically non magnetic materials).

Various methods have been reported[1]~[5] for the determination of the complex permittivity of non magnetic materials: 1) Resonator methods: The sample is inserted into a closed or open resonator. The resulting shift of the resonance frequency and charge of Q factor is measured. By means of these methods, the relative permittivity and loss tangent of non magnetic samples can be determined quite accurately. The major disadvantage of these methods are the expensive preparation and critical positioning of the sample. 2) Waveguide methods: The sample is inserted into a hollow guide and the scattering parameters are measured. These methods give accurate values for complex permittivity and permeability up to 10 GHz. For higher frequencies, the reproducible sample preparation gets very difficult, because of decreasing size of the hollow guide. 3) Free Space methods: The planar material sample is inserted into free space transmission and/or reflection path between a transmitting and a receiving horn antenna, and transmission and/or reflection coefficient is measured versus the angle of incidence.

The main advantage of the free space methods for electrical property measurement over resonator and wave guide methods are as follows, a) Materials such as ceramics, composite *etc.*, are inhomogeneous due to variations in manufacturing process. Because of inhomogeneity, the unwanted higher order modes can be excited at an air dielectric interface in the wave guide or resonator. b) Dielectric measurements using free space methods are nondestructive, contact less and easy. c) In the wave guide method or resonator, it is necessary to machine the sample so as to fit the wave guide cross section with negligible air gaps. This requirement will limit the accuracy of the measurement for the materials which can not be machined precisely.

It is also necessary to consider other conditions; diversity or variety of the building materials for the proper measurement, such as difficulty in controlling thickness, variety of water content, multi-layering, and so on.

Some works[6][7] have been conducting to reduce inaccuracy for the measurement of the complex permittivity, and some investigations[8][9] of electrical properties for concrete, as a typical exterior building materials, have also been performed. However, only few works conducted for the other materials besides concrete for microwave frequency range.

In this paper, we present one type of free space measurement suitable for correct estimation of the complex permittivity for building materials, which are inhomogeneous and diverse. And the complex permittivities for some building materials besides concrete with differing water content are also estimated experimental for the frequency range between 1.55GHz to 6.5GHz, while some works (experimental[10] and analytical[11]).

2. Calculation Method for Complex Permittivity

2.1 Measuremnment System A box-type free space reflection loss system was constructed[12] with the frequency range

* Technology Development Division, Fujita Corporation
2025-1 One, Atsugi, 243-0125 Japan
** College of Science and Engineering, Aoyama Gakuin University
5-10-1 Fuchinobe, Sagamihara, 229-8558 Japan

from 1 GHz to 18 GHz, with incident angles from 8.5 to 60 degrees and 50 dB of the dynamic range. The antennas are connected to Vector Network Analyzer and Signal Source.

Because of the geometry, the system has three advantages, less unnecessary reflection wave around the measured sample, constant distance between the antenna and the surface of the sample, and compact size. Fig. 1 shows the outline of the system.

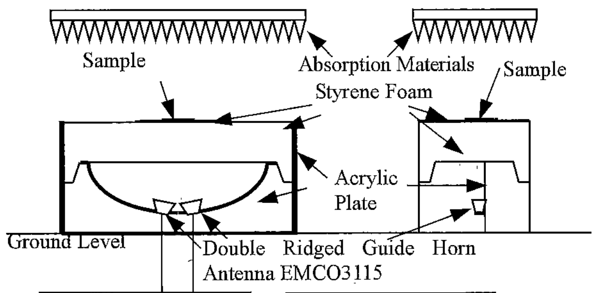

Fig. 1. Outline of the measurement system.

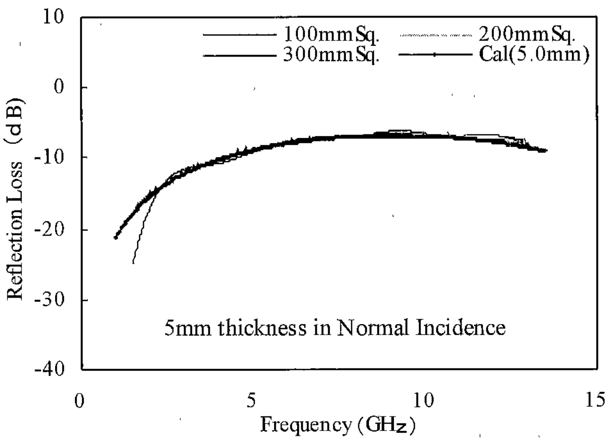

Fig. 2. Reflection Loss for the 5mm thickness acrylic plate (Normal Incidence).

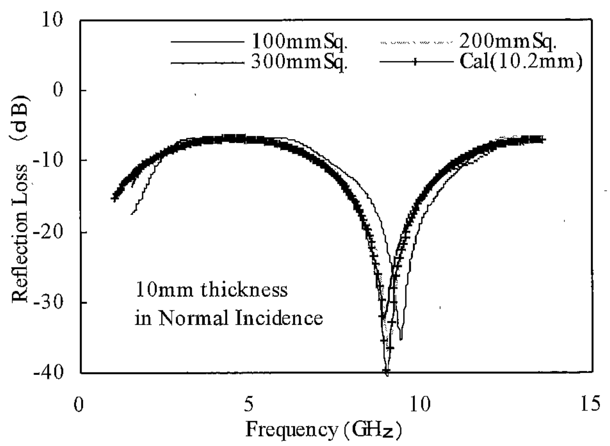

Fig. 3. Reflection Loss for the 5mm thickness acrylic plate (Normal Incidence).

2.2 Size of the Samples One of the advantages for the free space measurement is its accommodation of inaccuracies in the size of the samples. From the supplements point of view, smaller samples are better, but larger samples may help to give more accurate measurements. Therefore, it is very important to determine the size of sample for the particular measurement.

Fig.2 and Fig.3 show the magnitude of the reflection loss for the acrylic plates alone (*i.e.* not backed by a metal plate) at 5mm and 10 mm thickness respectively. The sizes of the samples were 100 mm by 100 mm (100mmSq.), 200 mm by 200 mm (200mmSq.) and 300 mm by 300 mm (300mmSq.). Frequency range of these measurements is 1 to 13.5 GHz for the TE wave. In order to avoid unnecessary reflection wave, we used time domain method and gating method[13].Calculated values are also shown in these figures by using equations as below with measured thickness and complex permittivity of the acrylic from the reference values 2.69-0.0214j (at 1 GHz) and 2.68-0.00310j (at 10 GHz)[14],

$$Zo = \mathrm{Zcte}\cdot\frac{Z_0/\cos\theta + Zcte\cdot\tanh\gamma\ d}{Zcte + Z_0/\cos\theta\cdot\tanh\gamma\ d} \quad \cdots\cdots (1)$$

$$Z\mathrm{cte} = \frac{Z_0}{\sqrt{\varepsilon\text{-}\sin^2\theta}} \quad \cdots\cdots (2)$$

$$\gamma = j\frac{2\pi}{\lambda}\sqrt{\varepsilon - \sin^2\theta} \quad \cdots\cdots (3)$$

$$\Gamma o = \frac{Z\mathrm{te} - Z_0/\cos\theta}{Z\mathrm{te} + Z_0/\cos\theta} \quad \cdots\cdots (4)$$

where, Zo is input impedance for TE wave, Zcte is the response impedance for the material, d is the thickness of the material, θ is the incident angle, ε is the complex permittivity for the material, and Γ_o is the reflection loss measured the acrylic plate only, respectively.

For these figures, the reflection loss of 200mmSq. and 300mmSq. samples are similar to the calculated values (within ± 1dB in the range up to -25 dB). For the 100mmSq. sample, reflection loss is again similar to the calculated values (within ± 1dB in the range up to the –10 dB). However, the difference of the reflection loss between the calculated value and measured value for the 100mmSq. samples increased below -10 dB. So we concludes the minimum size of the sample is 200mmSq. in the range from 1.5 GHz frequency for these measurement.

2.3 Calculation Method Using the measured reflection loss and equations (1) to (4), we may be able to calculate the complex permittivity analytically under the some conditions. However the results can not be vaild, because various uncertainty make difficult for the calculation.

Reflection measurement may not achieve very accurate results in some cases, because of antenna coupling, multiple scattering in the sample or too low loss of samples. In particular, the phase of the reflection loss by measurement may include a large inaccuracy. On the other hand, the magnitude of the reflection loss can be accurate under this measurement system as shown at Fig.2 and Fig.3 in the section 2-2. So, multiple magnitude measurement data make more accurate estimation of the complex permittivity.

The reflection loss for the non magnetic materials backed by a metal plate (short) for vertical incident wave were calculated as a function of the complex permittivity as below,

$$\Gamma s = \frac{\frac{1}{\sqrt{\varepsilon' - j\varepsilon''}} \tanh j \cdot \frac{2 \cdot \pi \cdot \sqrt{\varepsilon' - j\varepsilon''}}{\lambda} - 1}{\frac{1}{\sqrt{\varepsilon' - j\varepsilon''}} \tanh j \cdot \frac{2 \cdot \pi \cdot \sqrt{\varepsilon' - j\varepsilon''}}{\lambda} + 1} \quad \cdots\cdots (5)$$

$$= |\ \Gamma s\ | \cdot \exp(j \cdot \phi) \quad \cdots\cdots (6)$$

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad \cdots\cdots (7)$$

where, Γs is the magnitude of the reflection loss for backed by a metal, ϕ is the phase of the reflection loss, ε' is the real part of complex permittivity, and ε'' is the imaginary part of the complex permittivity.

The equation for the refrection loss calculation from the complex permittivity for non-magnetic materials only (open, no metal on the back) is already shown (1) to (4).

So, the complex permittivity can be deduced from iterative calculation (by short and open measured data) by multiple measurements of samples backed with different materials, (*e.g.* backed by a metal plate and nothing). The iterative calculation starts with the initial estimated complex permittivity, ε_{ini}, and continues until a reasonable minimum difference value $\Delta|\Gamma|$ is achieved for the complex permittivity under the calculation condition that the standard deviation of $\varepsilon(f)$ is less than σ_{set}.

$$\Delta|\ \Gamma\ | = \left[\sum_{f=f_1}^{f_2} \left\{ |\Gamma o|_m^f - |\Gamma o|_l^f \right\}^2 + \sum_{f=f_1}^{f_2} \left\{ |\Gamma s|_m^f - |\Gamma s|_l^f \right\}^2 \right]^{1/2} \quad \cdots\cdots (8)$$

$$\varepsilon(f) = \varepsilon(f)' - j\varepsilon(f)'' \quad \cdots\cdots (9)$$

where $|\Gamma s|_m^f$ and $|\Gamma o|_m^f$ are the magnitude of the reflection loss from short and open measurement at f frequency, $|\Gamma o|_l^f$ and $|\Gamma s|_l^f$ are the magnitude of the reflection loss calculated by equation (5) and equation (1) to (4) with the initial estimated complex permittivity at f frequency, $f1$ and $f2$ are the start frequency and stop frequency for the calculation, and σ_{set} is the value of the calculated complex permittivity set as the calculation condition.

For low loss materials or building materials, variety of the value of the complex permittivity (both the real part and the imaginary part) can be small in the frequency range of 1 to 10 GHz. So the above iterative calculation can be deduced under the condition of small standard deviation for $\varepsilon(f)$.

Especially, the complex permittivity of the acrylic plate can be calculated under the condition of zero standard deviation ($\sigma_{set} = 0$), because the standard deviation of the acrylic plate is negligibly small for this frequency range from the reference[14]. In this case, the calculation can be simple (so called the initial calculation for later).

Table 1 shows the calculated complex permittivities for the different size of the acrylic plates (100mmSq., 200mmSq., and 300mmSq.) with the value $\Delta|\Gamma|$ by the initial calculation. The thickness of the materials are 2 mm, 5 mm, 7 mm, and 10 mm respectively, in 2.1 GHz to 12.0 GHz frequency range and 0.1 GHz step. Summation of the calculated theoretical difference value $\Delta|\Gamma|_{th}$ also listed in the table by putting the reference complex permittivity into equation (9) for the each sample. The comparison of summations of the $\Delta|\Gamma|_{th}$ for sets of the different size samples indicates that the calculated permittivities for 200mmSq. samples are more accurate than those for 300mmSq. and 100mmSq. samples. The value $\Delta|\Gamma|$ for each sample by the initial calculation also figure out the provability of the calculation for 200mmSq. samples, rather than 300mmSq. and 100mmSq. samples in comparison to the reference value.

So 2.69-0.00391j is the calculated value as the complex permittivity of the acrylic plate in the frequency range between 2.1 GHz to 12.0 GHz, and that value is good agreement to the average of the reference value ε_{ref} listed in Table 1. So, the propriety of this method is confirmed.

2.4 Determination of the Calculation Factors For the achievement of the efficient and reasonable final results, calculation factors, ε_{ini}, and σ_{set} should be determined properly and adaptive threshold value for $\Delta|\Gamma|$ can be existed.

The value of ε_{ini} is set as a constant value in equation (9) in order to achieve a minimum value of $\Delta|\Gamma|$ from the initial calculation by using equation (8). The value of σ_{set} can be conducted from the frequency variation, typically indicated in references.

Fig.4 shows the relation of $\Delta|\Gamma|$ to $\Delta\varepsilon'/\varepsilon_{ref}'$ under increasing standard deviation σ_{set}. The incresing step is determined by the standard deviation for the frequency characteristic from the reference[14](σ_{ref}: 0.04 for the real part and 0.03 for the imaginary part of the complex permittivity). Four different calculations performed under the standard deviations of 5* σ_{ref}, 10* σ_{ref}, 20* σ_{ref}, and 30* σ_{ref}, in the frequency range from 2.1 GHz to 12.0 GHz (0.1 GHz step, 100 points from the measurement in the frequency range from 1 GHz to 13.5 GHz, 0.025 GHz step, 501 points) for 100mmSq., 200mmSq., and 300mmSq. sample sets (the thickness of the sample are 2 mm, 5 mm, 7 mm and 10 mm respectively). ε_{ref}' is the average value of the real part of the complex permittivity from the reference[14]. The first part of the symbol in Fig.4 means the size of the sample and second part means the thickness of the sample (i.e. 200-5 means 200mmSq. and 5 mm thickness sample). The point of the right edge shows the value of $\Delta|\Gamma|$ from the initial calculation (marked as bold font in the figure), and the point of the left edge shows the calculation result under σ_{set} = 30* σ_{ref} for an each sample.

Table 1. Calculated complex permittivity for acrylic plate.

Sample	Average		2mm Thickness			5mm Thickness			7mm Thickness			10mm Thickness			Summation of $\Delta\|\Gamma\|_{th}$
	ε'	ε"	ε'	ε"	Δ|Γ|	ε'	ε"	Δ|Γ|	ε'	ε"	Δ|Γ|	ε'	ε"	Δ|Γ|	
100mm sq.	2.64	2.71E-02	2.65	1.42E-03	7.05	2.71	5.90E-02	17.9	2.62	0.00E+00	26.6	2.58	4.78E-02	84.5	770
200mm sq.	2.69	3.91E-02	2.66	6.18E-02	1.09	2.71	5.17E-02	1.91	2.70	9.40E-03	0.96	2.70	3.34E-02	12.5	55.4
300mm sq.	2.73	1.10E-01	2.70	2.48E-01	3.84	2.72	6.95E-02	10.9	2.71	3.88E-02	19.4	2.80	8.35E-02	42.4	705
Reference[14]	2.68	2.79E-02	2.69	2.14E-02	@1GHz				2.68	3.10E-02	@10GHz				

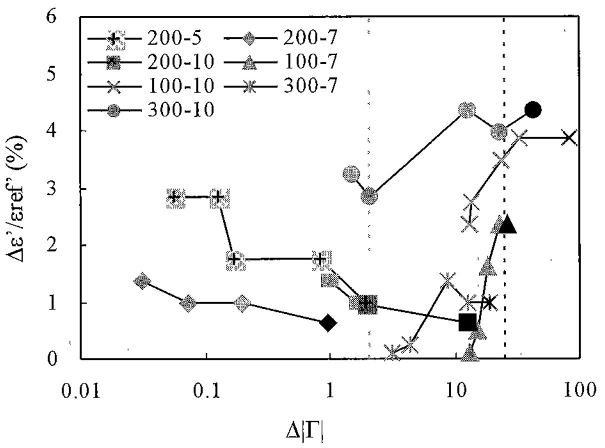

Fig. 4. Characteristics of the calculated Δ|Γ| to $\Delta\varepsilon'/\varepsilon_{ref}'$ for the acrylic plate under the various standard deviations.

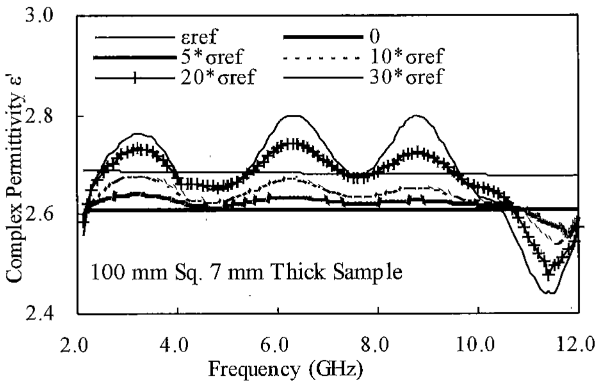

Fig. 5. Frequency distribution of the calculated ε' under the various standard deviations of the calculation for the acrylic plate (100mmSq. 7mm thickness).

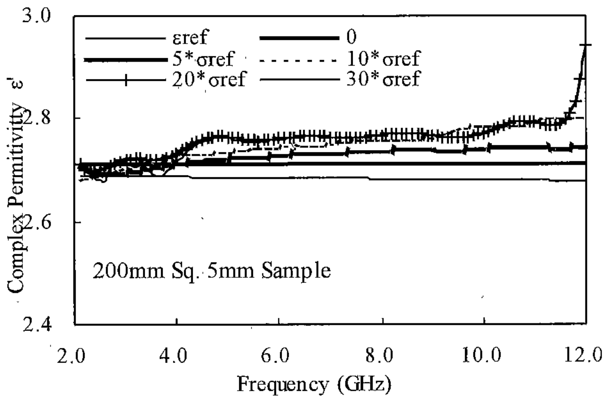

Fig. 6. Frequency distribution of the calculated ε' under the various standard deviations of the calculation for the acrylic plate(200mmSq. 5mm thick).

The $\Delta\varepsilon'/\varepsilon_{ref}'$ are tend to decrese for the calculations under the increasing standard deviation, when the value of Δ|Γ| from initial calculation is higher than 25 (100-7, 100-10 and 300-10 samples). However, the $\Delta\varepsilon'/\varepsilon_{ref}'$ are tend to increase even under the increasing standard deviation, when the value of Δ|Γ| from initial calculation is lower than 25 (200-5, 200-7 and 200-10 samples). So, Fig.4 shows different tendency for the curves depending on values of Δ|Γ| from initial calculations.

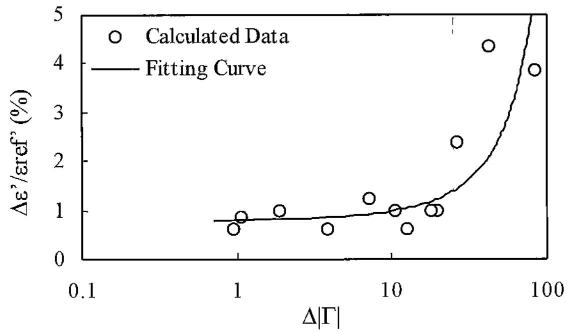

Fig. 7. Characteristic of the calculated Δ|Γ| to $\Delta\varepsilon'/\varepsilon_{ref}'$ for acrylic plate sample by the initial calculation.

Fig.5 and Fig.6 show the frequency distribution for ε' calculated from 100mmSq. and 7mm thickness sample as a representative for the former group, and that from 200mmSq. and 5 mm thickness sample as a representative for the latter group, under the various standard deviations with the frequency distribution curve for reference data ε_{ref}', respectively. Fig.5 indicates that increasing standard deviation as a condition of the calculation makes the calculated distribution curves get closer to the curve of ε_{ref}', and makes larger vibration. However, increasing standard deviation σ_{set} makes the calculated distribution curves be apart from the curve of ε_{ref}' with still getting larger vibration in Fig.6.

For the equation (8), it should achieve to reasonable value of Δ|Γ|, when the condition of the standard deviation for the calculation is zero under the proper measurement (measurement geometry, equipment, sample size, and so on) for the materials with no frequency deviation. So, the calculated value of Δ|Γ| should be less than certain value to achieve proper estimation of the complex permittivity. On the other hand, it should not be valid that the value of Δ|Γ| is zero, because the measurement system also should include some uncertainty. Finally, in a case that Δ|Γ| is higher than that value, iteration calculation may be conducted, but the value of Δ|Γ| should not be less than lower limit value for reasonable results.

Fig.4, Fig.5, and Fig.6 indicate the effective complex permittivity can be obtained when the value of Δ|Γ| from the initial calculation is lower than 25 (a bold broken line in Fig.4). In the case that the value of Δ|Γ| is higher than that, further iteration calculations are needed to achieve proper results. However, those calculations should not exceed under the condition that the value of Δ|Γ| is lower than about 2 (a broken line in Fig.4).

On the other hand, the proper size of the sample for this measurenment system is concluded as 200 mm by 200 mm in the former section and the summation of the $\Delta|\Gamma|_{th}$ for the acrylic plate samples are listed in Table 1. So, the values of $\Delta|\Gamma|_{th}$ from the 200mmSq. samples indicate accuracy for the measurement, therefore minimum value (2 from 2mm and 7mm thickness samples) and maxmam value(25 from 10mm thickness sample) can be used for the lower and higher value of the certain range for propar calculation results.

Fig. 7 shows the relation of Δ|Γ| to $\Delta\varepsilon'/\varepsilon_{ref}'$ from the initial calculation. The samples shown in the figure are 100mmSq., 200mmSq., and 300mmSq. of the acrylic plates (the thickness of the sample are 2 mm, 5 mm, 7 mm and 10 mm respectively), with fitting curve and the range defined above. The figure indicates that calculated real part of the complex permittivities, ε', have good agreement to reference data within 1.5 %, while the calculated value of $\Delta|\Gamma|$ from the initial calculation is lower than 25.

So, the range of the value of $\Delta|\Gamma|$ conducted 25 as a upper limit and about 2 as a lower limit, from the three investigation results shown Fig.4, Fig.7 and summation of the $\Delta|\Gamma|_{th}$.

3. Calculation for the Complex Permittivity of Building Materials

Most of building materials are inhomogeneous, and it is difficult to achieve uniform sample thickness in samples of the order of less than 1 mm (and to also make rigid shape for the measurement). It is also difficult to maintain very smooth surface of materials for the measurement. In addition they contain free water in their matrix, and water content of materials can vary easily in the surround environment.

For the situation above, the iterative calculation by short and open measured data is a better way to estimate the complex permittivity for building materials described section 2-3.

Because of the inhomogeneity for most of building materials, four measurements will be needed to achieve accurate estimation for the iterative calculation by using equation (10), instead of the two measured data. Measurements of samples backed by a metal plate from front side (front-short), samples only from front side (front-open), samples backed by a metal plate from back side (back-short), and samples only from back side (back-open) will conduct the four measured data.

$$\Delta|\Gamma| = \frac{\left[\begin{array}{l}\sum_{f=f_1}^{f_2}\left\{|\Gamma of|_m^f - |\Gamma o|_t^f\right\}^2 + \sum_{f=f_1}^{f_2}\left\{|\Gamma sf|_m^f - |\Gamma s|_t^f\right\}^2 \\ + \sum_{f=f_1}^{f_2}\left\{|\Gamma ob|_m^f - |\Gamma o|_t^f\right\}^2 + \sum_{f=f_1}^{f_2}\left\{|\Gamma sb|_m^f - |\Gamma s|_t^f\right\}^2\end{array}\right]}{4} \quad \cdots\cdots (10)$$

where, $|\Gamma sf|_m^f$ and $|\Gamma sb|_m^f$ are the magnitude of the reflection loss from the measurement of the sample backed by a metal plate from front side (front-short) and from back side (back-short) at f frequency,

$|\Gamma of|_m^f$ and $|\Gamma ob|_m^f$ are the magnitude of the reflection loss from the measurement of the sample only from front side (front-open) and from back side (back-open) at f frequency, $|\Gamma o|_t^f$ and $|\Gamma s|_t^f$ are the magnitude of the reflection loss calculated by the equation for open and short at f frequency.

Fiber reinforced cement boards, mortal boards, and calsium silicate boards are mesured and calculated for the complex permittivity as typical interior building materials, listed in Table 2 with the thickness, density at absolute dry condition, and symbol for samples, respectively.

The complex permittivities are calculated for these samples at the various water content. Therefore, the samples are put under the various temperature and humidity in certain days in order to make samples homogeneous with respect to water content by using humidifier and dry oven. Table 3 shows the description of the typical preparation condition for fiber reimforced cement boards with the symbol for each condition.

Fig. 8 show the characteristics for $\Delta|\Gamma|$ to $\Delta\varepsilon'/\varepsilon_{ave}'$ and ε" under increasing standard deviation σ_{set} for the calculation of fiber reinforced cement boards by equation (10) in 1.55 GHz to 6.5 GHz frequency range, as a representative case. The value of ε_{ave} is the average of the complex permittivity from the initial calculation for each preparation condition. The standard deviation for the calculation σ_{set} are set as a function of the standard deviation of the complex permittivity obtained from the initial calculation (maximum deviation are set 0.25 %, 0.5 %, and 5 % of the real and the imaginary part of the obtained complex permittivity), while 0.25 % of the complex permittivity are similar to the frequency standard deviation for the mortar in the reference(10). The captions in Fig.8 mean the sample name for the first three

Table 2. Description of measured building materials.

Material	Thickness (mm)	Number of samples	Symbol	*Density (g/cm3)
Fiber reinforced cement board	4.07 mm	4	F4	1.58
Calcium Silicate Board	6.01 mm	2	C6	0.89
	6.76 mm	1	C7	1.44
Mortar Board	9.27 mm	2	M9	1.86

* Density and thickness are average value respectively

Table 3. Preparation conditions for fiber reinforced cement boards.

Condition	Temperature	Humidity	Name of Samples
C1	Set in Dry Oven 105℃		F41 to F44
C2	45℃	80%	F41 to F44
C3	60℃	99%	F41 to F42
C4	20℃	60%	F41 to F44
C5	50℃	90%	F41 to F42
C6	15℃	40%	F41 to F44

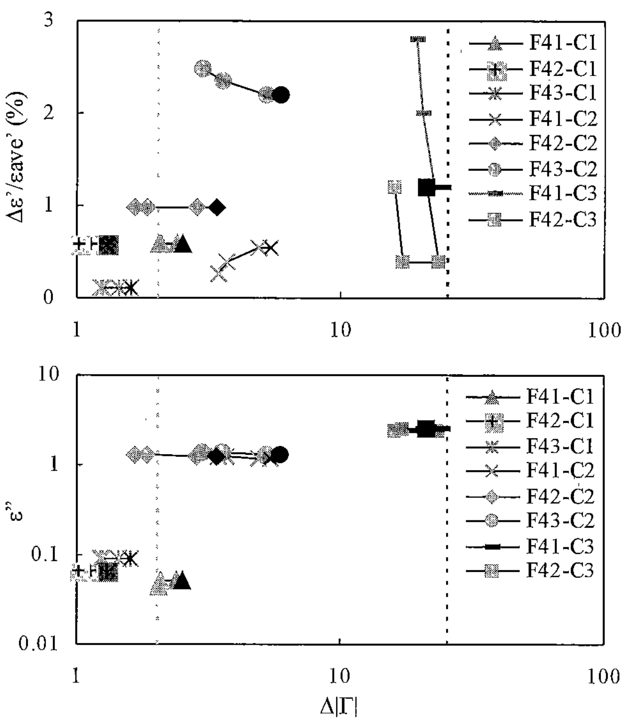

Fig. 8. Characteristic of the calculated $\Delta|\Gamma|$ to $\Delta\varepsilon'/\varepsilon_{ref}'$ and ε" for Fiber Reinforced Cement Board under the various standard deviation.

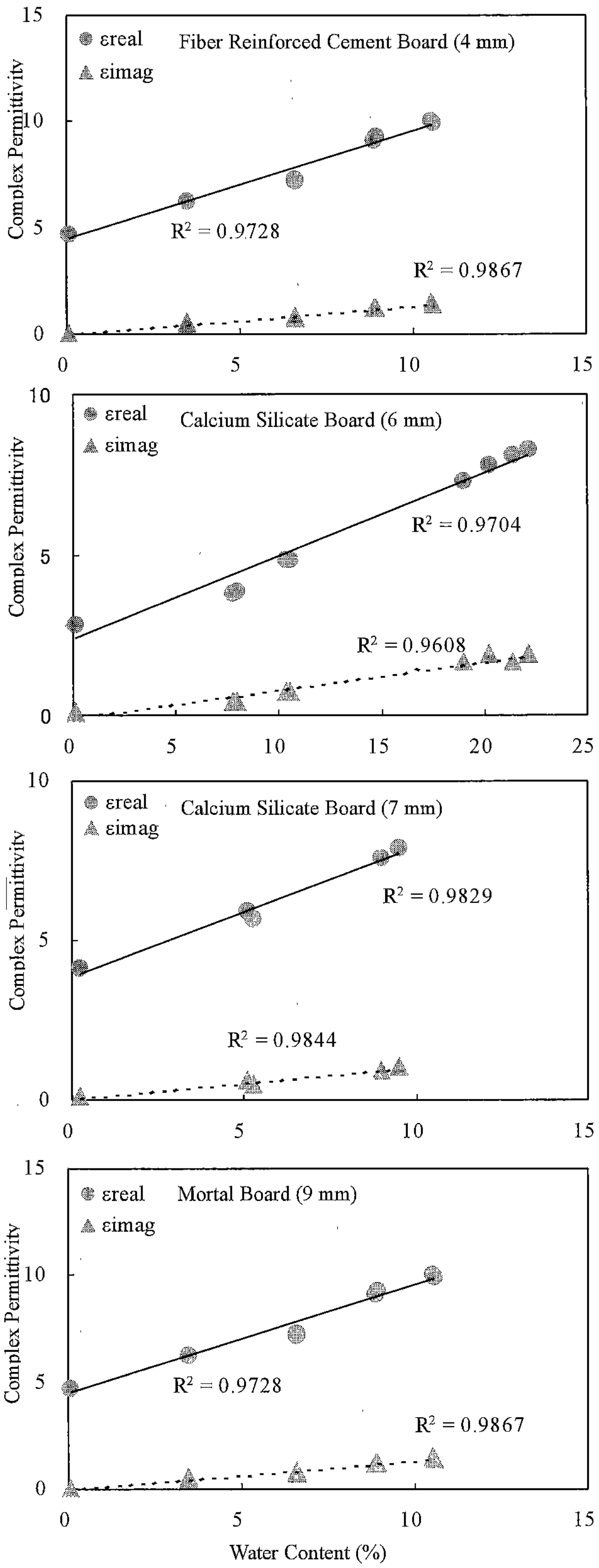

Fig. 9. Distribution of the complex permittivity of the building materials for various water content.

character and a kind of condition for the last two character listed in Table 3, respectively. The values $\Delta|\Gamma|$ calculated from the initial calculation are marked bold, and the range discribed section 2-4 is also described as a break line in the figure (25 as a higher value and 2 as a lower value).

Fig.8 indicates that the value of the real part of the complex permittivities for the fiber reinforced cement boards, have good agreements to the average value (ε_{ave}') of four samples within 1.0 % for each preparation condition, even for increasing standard deviation σ_{set} as a calculation condition, while the $\Delta|\Gamma|$ from the initial calculation is lower than about 5. Fig.8 also indicates the value of the complex permittivities (both the real part and the imaginary part) are not so variable except the real part of complex permittivities for samples under the C3 condition, while increasing σ_{set}. So, the complex permittivities, which are obtained from the initial calculation when the value of $\Delta|\Gamma|$ is less than 25, can be effective results (Even for samples under the C3 condition, those from initial calculation are better result compared to those from farther calculations).

Same investigations for calsium silicate board samples and mortal board samples are conducted validly estimation of the complex permittivity for building materials, as well.

After above investigation to confirm propriety of the method for estimation of the complex permittivity described in this paper, some calculations for building materials are performed from the four magnitude values of the reflection loss mesurement in the frequency range 1.55 GHz to 6.5 GHz. Fig.9 shows the characteristics of the calculated complex permittivity (the real part marked round, and the imaginary part marked triangle) of fiber reinforced cement boards, calsium silicate boards, and mortal borards in various water content. The fitting curves are also described in Fig.9 with the value of R^2[(15)]. Solid line and break line show the relation of the real part and the imaginaly part of the complex permittivity to water content, resepectively.

Among the calculated complex permittivities, the figures in Fig.9 do not include those when the calculated value of $\Delta|\Gamma|$ is higher than 25, which calculated from samples with very high water content. Increasing water content in samples makes the frequency variation of the complex permittivity larger[(10)], and that cause to exceed the basic calculation condition.

Therefore, the figures in Fig.9 show only up to the certain water content range depending on the samples. However, the calculated complex permittivities with these water content range in Fig.9 are pretty enough to discuss on the materials in interior environment.

These results indicate there are good linier relations of complex permittivity (real and imaginary) to water content in the certain water content range (up to 10 % for calsium silicate boards 7 mm thikness and mortal boards, up to 15 % for fiber reinforced cement boards, and up to 20 % for calsium silicate boards 6 mm thickness) for 1.55 GHz to 6.5 GHz frequency range.

On the other hand, Chiba already conducted an analytical work[(11)] regarding the relation of the complex permittivity to water content for water content range up to 30% at 10.5GHz for concrete, which are agree with above experimental results. However, only few experimental works are done in the microwave frequency range (including wireless LAN frequency) regarding on the characteristic for the complex permittivity besides these results.

4. Conclusion

The boxed type of free space reflection loss measurement system and the iterative calculation by using the magnitude of the reflection loss from four measured data, (samples backed by a metal plate from front side (front-short), samples only from front side (front-open), samples backed by a metal plate from back side (back-short), and samples only from back side (back-open)), are proposed in order to calculate the complex permittivity for the general building materials.

The building materials are generally very inhomogeneous, difficult to control the thickness, rough surface condition, variety of water distribution, water content, and so on. The free space measurements are suitable for these types of materials, but it is necessary to take into account the above diversity or inaccuracy for the focused material. So this paper described the one way to achieve the proper complex permittivities.

Before conducting calculation for building materials, fundamental investigations, such as, the size of the sample and calculation factors, are performed using the acrylic plate, which is common for use and have lots of data obtained under various type of works, to confirm the propriety of the method described above.

The calculated complex permittivities have good agreement within 1.5% of reference value for acrylic plates, and within 1% of averaged value of samples for fiber reinforced cement boards.

This paper also presents the experimental linier relation of the complex permittivity to water content and for three kinds of building materials (fiber reinforced cement boards, calcium silicate boards and mortar boards) for the frequency between 1.55 GHz and 6.5 GHz. The above results have good agreement to the past analytical work.

A useful and necessary extension of this work, such as uncertainty of the complex permittivity, variety of samples in same materials, and farther investigation on the calculation factors $\Delta|\Gamma|$ including imaginary part, should be performed as next works.

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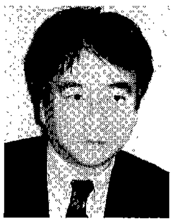
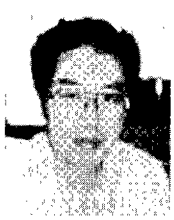


Ken-ichi Kimura (Non-member) received the B.E, and M.E. degree from the Department of Nuclear Engineering, Tohoku University, Miyagi, Japan in 1984 and 1986, respectively. He joined Technical Reserch Institute, Fujita Corporation, Atugi, Kanagawa, Japan, in 1986, where he is researcher of building research department. He has been engaged in research on electromagnetic compatibility for building envirnment. He is a member of IEICE, AIJ, and IEEE.



Osamu Hashimoto (Member) graduated in 1976 from the Dep. Of Applied Electronic Engineering, the Universitu of Electro-Communications, where he subsequently obtained an M.S. in 1978. Later that year, he joined Toshiba Corporation. In 1981, he joined the Defense Agency, Defense Technical Development Laboratories, 2nd Laboratory. He received a Dr.Eng. degree from Tokyo Institute of Technology (1986). Presently, he is Professor in the Dept. of Electrocal and Electronic Engineering, Aoyama Gakuin University. He has been engaged in research on wave absorbers as well as and measurement and analysis of radar cross sections. He is the author/co-author of more than ten books including "Introduction to Wave Absorber" and "Introduction to Finite Difference Time Domain". He is a member of IEEJ, JIEP, AIJ, and IEEE.