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Evaluation of the Dielectric Constants and Air Voids of Asphalt Concrete Using a Parallel Plate Method

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Abstract: The density of a hot-mix asphalt (HMA) pavement is one of the most important factors influencing the pavement quality. In Korea, pavement density is generally determined by measuring the bulk density of core samples. The more convenient way measuring pavement density in the field is to use the non-destructive pavement density testing devices. Recently, the dielectric properties of pavements have been used in these devices. The dielectric-type pavement density testing devices have an inherent advantage over core measurements and nuclear density gauges in that coring and extra security precautions are not required. The literatures show that dielectric constants are varied with the density and air void of materials. However, the dielectric constants of asphalt materials have not been tested and evaluated until recent in Korea. In this study, the dielectric constants and air voids of asphalt concrete were evaluated. Two types of asphalt concrete specimens were prepared with one type of aggregate and two types of asphalt binder; PG 64-16 and PG 82-22. Asphalt mixtures were compacted using a gyratory compactor at 0 to 20% of air voids, and then cut to the size of 150*mm* in diameter and 25*mm* in thickness. Parallel plate methods using low frequency (100*KHz* to 50*MHz*) impedance analyzer were used to measure the dielectric constants of asphalt concrete specimens. Test results showed that dielectric constants of asphalt concrete specimens were linearly decreased as frequency increased. The change rate of dielectric constants of PG 82-22 specimen was higher that that of PG 64-16. The dielectric constants were rapidly increased at 20*MHz* of frequency due to the resonance nature of test. Test results also showed that dielectric constants of asphalt concrete specimens were linearly decreased as air void increased. The correlation models between dielectric constants and air voids of asphalt concrete were suggested by linear regression.

Key words*: Air voids; Asphalt concrete; Dielectric constants; Parallel plate method.*

Introduction

Proper compaction is the key to achieve a better performance of asphalt pavement [1, 2], and the amount of compaction is controlled by the air voids of asphalt concrete. As an assessment tool for the degree of compaction, nondestructive density gauges are widely used. Currently, the most common methods for nondestructive pavement density measurement are in two folds: the use of nuclear density gauges and the use of dielectric constants measuring technique (non-nuclear density gauges).

Currently, the two most common methods of nondestructive pavement density test are through the use of nuclear density gauges and nonnuclear density gauges that use the dielectric constants of the asphalt mixtures. Unfortunately, the use of nuclear density gauges is very limited in Korea since they contain radioactive materials hence the operators must be certified by law due to the safety issues regarding the radioactive material. This restriction makes the dielectric constant measuring technique more promising method in Korea for the pavement density assessment.

Dielectric constant measuring device sends an electrical sensing field into the pavement. The reading is influenced by the overall dielectric constant of the asphalt mixtures, which is a combination of the dielectric constant of the components in the pavement multiplied by their volumes [3]. Dielectric constants can be varied with the density and air voids of the materials [4, 5]. Although these aspects of the dielectric constant provide an alternative way to assess the asphalt density as a nondestructive technique, it has not been used to date in Korea since the measuring devices are not well implemented or calibrated to the local material in Korea.

This study was focused on the development of the low frequency dielectric measuring devices, and the relationship between the dielectric constant and air void of asphalt concrete using local materials. Standard specimens that have air voids of various ranges (0 to 20%) were used to measure the dielectric constant using parallel plate (PP) method that measures low frequency dielectric constant. Then, the effect of temperature and moisture content on dielectric constants of asphalt concrete was evaluated to develop the standard curve between dielectric constant and air void of asphalt concrete.

Relationship between Dielectric Constant and Air Void

Dielectric Constant of Material

Generally, the dielectric constant is a measure of polarization or capacity of storing energy when an electric field is applied into a material, in which the polarization means rearrangement of electric charges. A material can store energy and electric charges through

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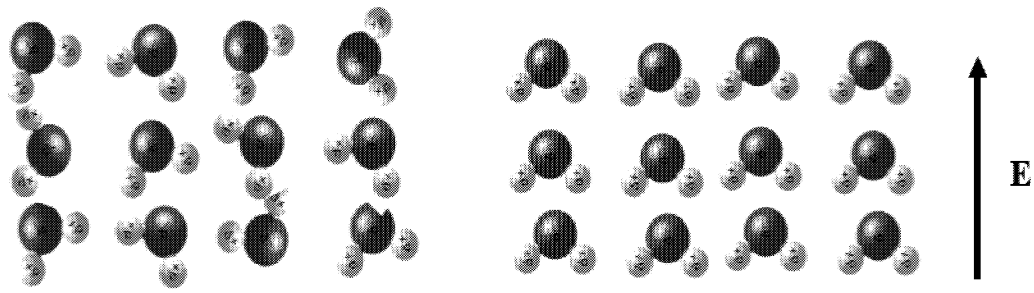


Fig. 1. Polarization Mechanism of H_2O Molecules.

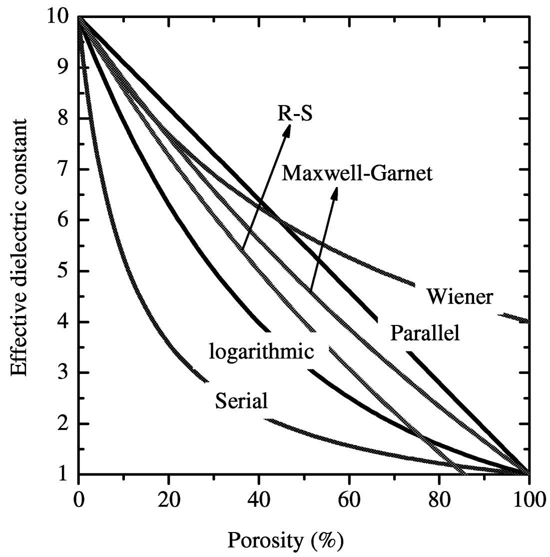


Fig. 2. Model Curves of Dielectric Constant as a Function of Air Void.

Table 1. Model Equations of Dielectric Constant as a Function of Air Void.

1.	Serial Model	$1/\varepsilon' = P + (1-P)/\varepsilon_1$
2.	Parallel Model	$\varepsilon' = P + (1-P) \times \varepsilon_1$
3.	Logarithmic Model	$\log\varepsilon' = (1-P) \times \log\varepsilon_1$
4.	Wiener Model	$\varepsilon' = \varepsilon_1/(1+1.5P)$
5.	M-G Model	$\varepsilon_1(1-[(3P(\varepsilon_1-1)/(2\varepsilon_1+1-P+P\times\varepsilon_1)])$
6.	R-S Model	$\varepsilon' = \varepsilon_1 * (2-2P)/(2+P)$

(ε': effective dielectric constant, P: porosity, ε_1 : dielectric constant when porosity is 0)

these polarization mechanisms. Fig. 1 shows the polarization mechanism of water (H_2O) molecules when an electric field was applied to upper direction. It can be seen that the water molecules was arranged to upper direction.

When an electric field is applied to materials, the materials can store electric energy (or charges). In the case of air molecules, the stored total charge is $8.854 \times 10^{-12} F/m$. A material with dielectric constant of ‘k’ can store 'k' times higher charges than air. For example, a dielectric constant of water is 80 because water can store eighty times higher total charge than air.

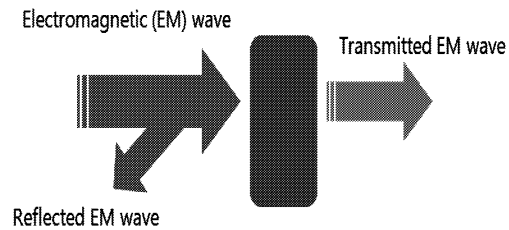


Fig. 3. Theory of High-Frequency Measurement Method.

For a long time, the relationship between air void and dielectric constants of material has been studied. Fig. 2 shows an example that contains various air voids ratio in a single phase material, in which the dielectric constant of the single phase material is 10 when there is no air void. In the figure, the total dielectric constant is decreased as increasing the ratio of air void. The representative model equations were summarized in Table 1 [6].

Measurements of Dielectric Constant

The dielectric constants of materials vary with the measured frequency. Therefore, the measurement methods of dielectric constant were classified according to frequency, i.e., low-frequency (< 300*MHz*) method and high-frequency (300*MHz* to 300*GHz*). In addition, various sub-methods exist according to the characteristics or properties of materials.

High-Frequency Methods

In the case of high-frequency methods as shown in Fig. 3 the reflection and transmission of the incident electromagnetic (EM) wave is taken place when the EM wave is applied to materials. Therefore, it is possible to measure the dielectric constant of a material through comparison and analysis of relative contents between the incident and reflected (or transmitted) EM wave [7]. The high-frequency dielectric constant is usually measured at the frequency range of 300*MHz* to 300*GHz* and four kinds of sub-methods are used according to purpose of measurement and properties of materials as shown in Table 2.

Low-frequency Methods

In low-frequency methods, the measurement is performed at the

Table 2. Types and Characteristics of the High-Frequency Methods.

Methods	Characteristics
Coaxial Probe Method	- Measure of the reflected electromagnetic wave (EM) - Wide frequency range (0.200 - 50*GHz*) - Simple and easy - Non-destructive method
Transmission Line Method	- Measure of the reflected or transmitted EM wave - Wide frequency range (0.1-110*GHz*) - Possible to measure magnetic properties - Limitation of high dielectric loss materials
Free Space Method	- Measurement using antenna - Non-destructive and non-contact methods - Possible to 325*GHz* - Possible to control and measure of temperature
Resonant Cavity Method	- Measurement using the resonant frequency of EM wave - Limitations of sample dimensions - Relatively precise measurement

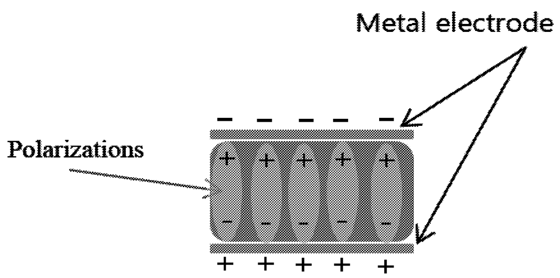


Fig. 4. Principle of Parallel-Plate (PP) Method.

frequency below 300*MHz* mainly using PP. The PP method has the advantage for the measurement at wide range of frequency and precise evaluation. However, it is necessary to coating or contact of metal electrode such as copper (Cu) or silver (Ag) at the upper and down side of sample.

The dielectric constant is evaluated by using the dimensions of the sample (height and radius) and the measured capacitance (C). The capacitance is measured by the impedance analyzer or LCR (Inductance (L), Capacitance (C), and Resistance (R)) meter. Although the PP method has some disadvantage such as coating of metal electrode, the PP method is widely used because the measured dielectric constants are precise and the equipments are simple.

Fig. 4 shows the principle of low-frequency method. When an electric field was applied to the sample, additional charges according to the sample's polarizations are created at the metal electrode and these additional charges affect the total capacitance of the sample. Therefore, the evaluation of the dielectric constant of the sample makes it possible to measure the total capacitance [8].

Laboratory Test

Asphalt Concrete Standard Specimen

The standard specimens were made using different PG binders (PG 64-16 and PG 82-22) without changing aggregate gradation. The aggregate gradation and the asphalt binders selected in this study are most typically used in Korea asphalt pavement. They were compacted

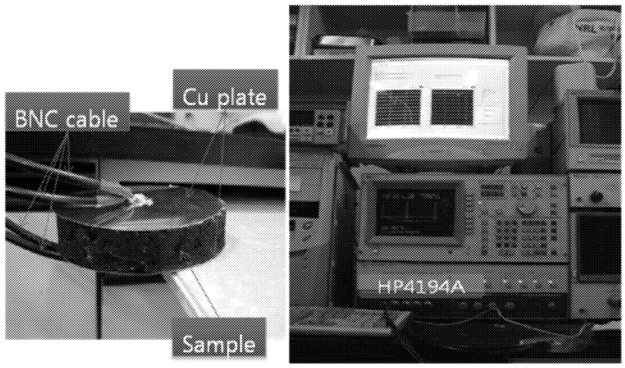


Fig. 5. Apparatus and Impedance Analyzer.

to 150*mm* in diameter and 170*mm* in height using Servopac SGC (Superpave Gyratory Compactor) by controlling air voids from 0 to 20%. They were dried for 7 days in the oven after cutting them in a height of 25*mm*. The density of each specimen was measured and results are shown in Table 3. The surface of each specimen was grinded to secure good contact area between copper electrode and specimen.

Instruments and Measurements of the Dielectric Constants

The dielectric constants of asphalt concrete standard specimens were measured at 100*kHz* to 50*MHz* using the PP method. The measurement and evaluation of the dielectric constants were conducted as follows;

- Equipments: Impedance analyzer (HP 4194A) equipped with Z-probe (~100*MHz*)
- Apparatus: Copper plate with thickness of 1*mm* was cut in a circle, which had the same radius with the test specimen. BNC cables (50*ohm* matched) were connected at the center of the copper plates (Fig. 5). For a secure contact, aluminum foil was inserted between copper plate and the specimen.
- Q (Charge quantity) = C × V, (C: capacitance, V: applied voltage).
- $C = \varepsilon_r \times (A/d)$, ($\varepsilon_r$: dielectric constant, A: specimen area (*mm*), d: specimen height (*mm*).

Table 3. Air Voids of Asphalt Concrete Standard Specimens.

PG 64-16				PG 82-22			
No.	MTD	Volume	Air-Voids (%)	No.	MTD	Volume	Air-Voids (%)
1-1	2.543	164.38	2.3	2-1	2.503	203.78	1.7
1-2	2.543	158.89	1.8	2-2	2.503	192.35	0.8
1-3	2.543	166.57	0.8	2-3	2.503	195.87	2.2
1-4	2.543	162.29	3.8	2-4	2.503	198.41	1.3
1-5	2.543	163.80	5	2-5	2.503	197.73	4.4
1-6	2.543	168.88	4.8	2-6	2.503	199.01	6
1-7	2.543	152.33	7.2	2-7	2.503	195.02	6.5
1-8	2.543	151.23	5.9	2-8	2.503	197.5	8.2
1-9	2.543	152.03	8.5	2-9	2.503	195.78	8.6
1-10	2.543	161.12	9.9	2-10	2.503	201.69	8.7
1-11	2.543	148.24	9.3	2-11	2.503	194.61	9.9
1-12	2.543	177.49	10.7	2-12	2.503	200.61	11.5
1-13	2.543	161.13	12.6	2-13	2.503	203.76	13.7
1-14	2.543	151.25	13.4	2-14	2.503	195.99	11.7
1-15	2.543	159.03	13	2-15	2.503	200.66	12.3
1-16	2.543	225.71	14.2	2-16	2.503	193.01	13.6
1-17	2.543	181.29	13.8	2-17	2.503	196.81	15.3
1-18	2.543	200.57	15.8	2-18	2.503	196.33	9.1
1-19	2.543	198.07	14.9	2-19	2.503	200.02	8.6
1-20	2.543	194.68	16.7	2-20	2.503	193.26	9.8
1-21	2.543	157.64	15.2	2-21	2.503	199.84	13.7
1-22	2.543	161.13	14.2	2-22	2.503	196.25	13.9
1-23	2.543	159.85	17	2-23	2.503	199.06	17.1

※MTD(Maximum Theoretical Density)

Measurements of Temperature-Dependant Dielectric Constant

For evaluation of temperature-dependant dielectric constants, the apparatus was positioned on the temperature controllable (25 to 100 ^{o}C) hot plate and waited until the temperature was saturated (about 10*min*). The temperature was checked at the bottom, middle, and upper sides of the specimens for the reproducible experiments. The temperature has an average error range of ±5^{o}C.

Measurements of Moisture-Dependant Dielectric Constants

For evaluation of moisture-dependant dielectric constants, a thermo-hydrostat chamber was used and the specimens were saturated with moisture contents of 0, 50, and 100%. After the saturation, the dielectric constants were measured immediately.

Calculation and Evaluation of the Measured Dielectric Constants

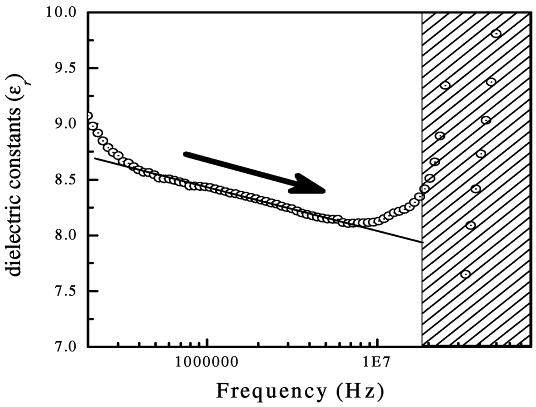
Three standard specimens with same air voids were prepared for the facilitation of statistical analysis. For each specimen, the dielectric constant was measured three times repeatedly to decrease of the errors.

Results and Discussion

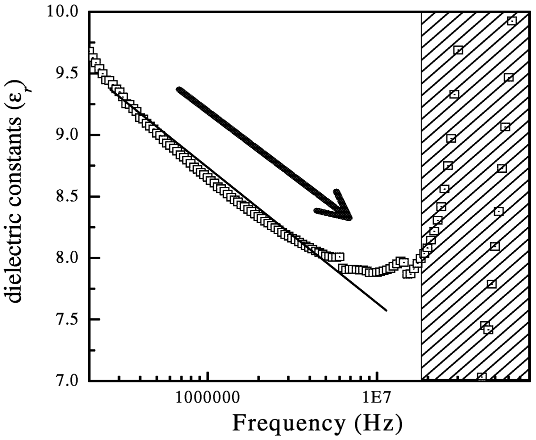
Frequency Dependence on Dielectric Constants in Asphalt Concrete Standard Specimens

Fig. 6 shows the frequency dependence of dielectric constant in the standard specimens (#1-9 and #2-9), which have air void value of 8%. The dielectric constants of both specimens were linearly decreased as the frequency increased. It is well known that the dielectric constant of materials decrease because the amount of the polarization decrease as the frequency increased due to stagnation of polarization formation. However, the two specimens show different slope of decrease, i.e., the #2-9 specimen using PG 82-22 binder exhibited higher slope. The difference in slope may be caused by the effects of the binder property. Note that the abrupt increase at frequency above 20*MHz* was attributed to the dimensions which used for measurement, and thus some improvements of the measurement apparatus are necessary for measuring at frequency above 20*MHz*.

The dielectric constants of both specimens are fixed at frequency

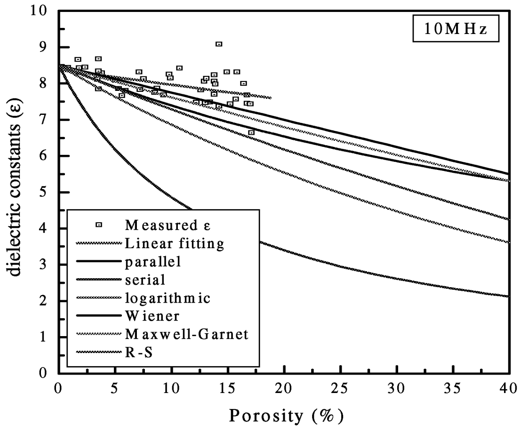


(a)

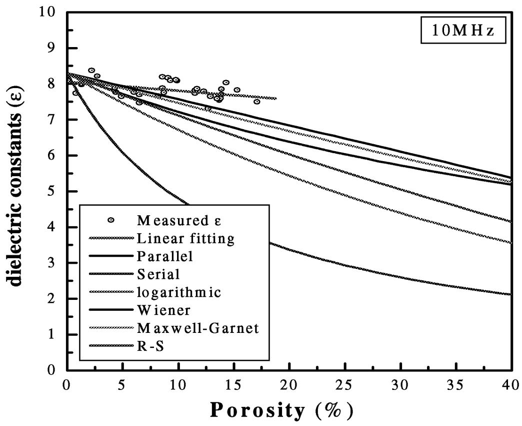


(b)

Fig. 6. Frequency Dependence of Dielectric Constant for Specimens (a) #1-9 and (b) #2-9.



(a)



(b)

Fig. 7. Air Void Dependence of Dielectric Constant for Specimens Using (a) PG 64-16 and (b) PG 82-22 Binders.

of 10*MHz*. Therefore, all the following tests were performed at 10*MHz* to reduce the frequency influence.

Relationship between Dielectric Constant of Asphalt Concrete Standard Specimens and Air Voids

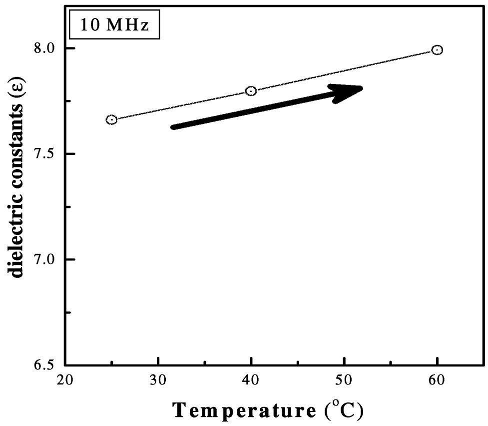
Fig. 7 shows the relationship between the dielectric constant of standard specimens and air voids. In the figure, the well-known model equations shown in Table 1 were also plotted. It was found that dielectric constants of standard specimens were linearly decreased as an increase of air voids and discrepancy with model equations were observed. This discrepancy may be due to the difference of polarization mechanism, i.e., the model equations was derived only from single phase material and air voids, whereas the measured dielectric constant of the standard specimens was from the combination of the aggregate, binder, and air void. As can be seen in the figure, however, linear decrease behavior in the model curves were observed in the air void range below 20%. During the construction of the asphalt concrete pavement, the change over air voids is within 20%. Therefore, it is reasonable to evaluate the measured dielectric constant of asphalt concrete standard specimens as linear fitting method. Consequently, the measured dielectric constants were fitted as first order linear functions and plotted in the figure [9]. The first order linear functions derived from the measured values are shown as follows;

- $\varepsilon_1 = 8.3804-(0.04124\times P)$ (@ 10*MHz*, 25°C, moisture 0%, PG 64-16)
- $\varepsilon_1 = 8.0.567-(0.02476\times P)$ (@ 10*MHz*, 25°C, moisture 0%, PG 82-22)

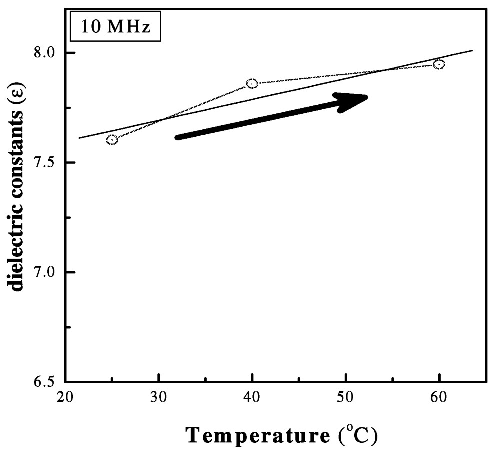
Where P is air voids in %.

Temperature Dependence on the Dielectric Constants

In order to evaluate the effect of the temperature on the dielectric constants of asphalt pavement specimens, the temperature of the specimens was changed from 25°C (room temperature) to 60°C. Fig. 8 shows two representative examples of the temperature-dependant dielectric constant. A material with low dielectric constant below 10 usually shows a increasing of the dielectric constant as the temperature increased.

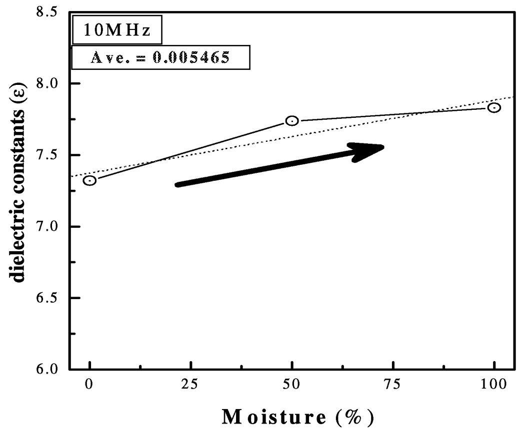


(a)

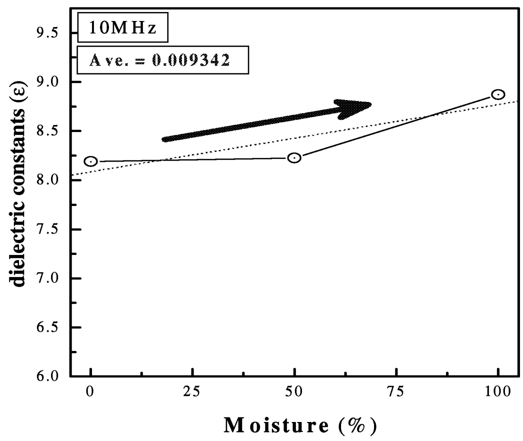


(b)

Fig. 8. Temperature Dependence on Dielectric Constant for (a) PG 64-16 and (b) PG 82-22.



(a)



(b)

Fig. 9. Moisture Dependence on Dielectric Constant for (a) PG 64-16 and (b) PG 82-22.

The measured dielectric constants of the asphalt pavement specimens also increased as the temperature increased. Moreover, the increase of slope in the specimens with two different binders was different, which was similar to other various experiments. Based on the temperature experiments, two equations based on the specimens with different binders were derived as follows;

- $\varepsilon(T) = \varepsilon o+(0.0148\times T)$ (@ 10*MHz*, moisture 0%, PG 64-16)
- $\varepsilon(T) = \varepsilon o+(0.0129\times T)$ (@ 10*MHz*, moisture 0%, PG 82-22)

Where, T is temperature in °C and εo is the dielectric constant at room temperature.

Moisture Content Dependence on the Dielectric Constants

The moisture content dependence on the dielectric constants of the asphalt concrete standard specimens was evaluated by using a thermo-hydrostat chamber. The moisture contents were adjusted to 0, 50, and 100%. Fig. 9 shows the moisture-dependant dielectric constants of the standard specimens. The dielectric constant of water is about 80. Therefore, the dielectric constants of material increased as the moisture contents increased. The standard specimens exhibited similar behavior, i.e., the dielectric constants were increased as the increasing of the moisture contents. The slope of increase in the specimen with PG 82-22 was higher than that with PG 64-16. Generally, it was expected that the specimens with more air voids (higher porosity) could contain more water molecules, and thus exhibited higher dielectric constant. Despite of air void, however, the slopes of increase were almost constant. This behavior was caused by that most air voids in the standard specimens were closed voids, and thus the moisture which supplied at the thermo-hydrostat chamber was adsorbed at the open voids near the surface of the specimens.

The slopes in the specimens using PG 64-16 and PG 82-22 are 0.00547 and 0.0093, respectively. Interestingly, the dielectric constant in the specimen with PG 82-22 exhibited slight decreased at the moisture contents 50%. Although detailed analysis is needed, this decrease appears to be attributed to chemical reactions between water and the binder. The following equations were derived from the moisture experiments. Other variables such as temperature and air void were fixed, except for the moisture contents.

- $\varepsilon(\varphi)=\varepsilon_o+0.00547\times\varphi$ (@ 10*MHz*, 25°C, PG 64-16)
- $\varepsilon(\varphi)=\varepsilon_o+0.00934\times\varphi$ (@ 10*MHz*, 25°C, PG 82-22)

where, ε_o is a dielectric constant at 25°C, φ is moisture content (%).

Model Equations Based on the Experiment Results

From the above experiments, new model equations were proposed as follows;

- $P(\%) = (\varepsilon_o - 0.37 - \varepsilon mea + (0.0148\times T) + (0.00547\times\varphi))/0.04124$ (@10*MHz*, PG 64-16)
- $P(\%) = (\varepsilon_o - 0.32 - \varepsilon mea + (0.0129\times T) + (0.00934\times\varphi))/0.02476$ (@10*MHz*, PG 82-22)

where, ε_o is a dielectric constant at 25 °C, moisture content 0%, air void 0%, and εmea is measured dielectric constant at 10*MHz*, T is temperature (°C), φ is moisture content (%).

ε_o was 8.38 for the specimen with PG 64-16 and 8.06 for the specimen with PG 82-22. It should be noted that ε_o value is constant for the specific asphalt mixture, so that additional experiments and statistical analysis are necessary to obtain more exact model equations. Nevertheless, the results obtained in this study serves useful and fundamental aspects of the measurements of the air void in the asphalt concrete.

Conclusions

This study has presented a relationship between dielectric constants and air void of asphalt concrete through the development of the low frequency dielectric constants measuring system. The effect of temperature and moisture content on dielectric constants of asphalt concrete was evaluated, and the standard curve between dielectric constant and air void was suggested. The results of this study provide a basis for the design and development of the nonnuclear type density measuring device. The conclusions drawn from this study are as follows;

- The dielectric constants of the asphalt pavement specimens were decreased linearly as the frequency increased. The decreased dielectric constants are due to the decreased polarization as the frequency increased. The slope of decrease was different with the type of asphalt binder, which was caused by the effects of binder properties.
- The correlation models between dielectric constants and air voids of asphalt concrete by considering the temperature and moisture contents were suggested by applying linear regression as follows;
  - $P(\%) = (\varepsilon o - 0.37 - \varepsilon mea + (0.0148\times T) + (0.00547\times\varphi))/0.04124$ (@10*MHz*, PG 64-16)
  - $P(\%) = (\varepsilon o - 0.32 - \varepsilon mea + (0.0129\times T) + (0.00934\times\varphi))/0.02476$ (@10*MHz*, PG 82-22)

where, εo is a dielectric constant at 25°C, moisture content 0%, air void 0%, and εmea is measured dielectric constant at 10*MHz*, T is temperature (°C), φ is moisture content (%).

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