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K. Mubarak

Karl Joseph Bois

R. Zoughi
Missouri University of Science and Technology, zoughi@mst.edu

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A Simple, Robust, and On-Site Microwave Technique for Determining Water-to-Cement Ratio (w/c) of Fresh Portland Cement-Based Materials

Khalid Mubarak, Karl J. Bois, *Member, IEEE*, and Reza Zoughi, *Senior Member, IEEE*

***Abstract*—Inspection and evaluation of cement-based materials such as concrete is of great interest to the construction industry. In particular, real-time and on-site evaluation of water-to-cement ratio (w/c) is an important practical issue, since the compressive strength of a concrete structure is significantly influenced by its w/c. Currently, there is no single real-time, on-site, relatively inexpensive, easy-to-implement, and operator friendly technique for evaluating this parameter. Microwave nondestructive testing and evaluation techniques have shown great promise when used for inspection and evaluation of the properties of cement-based materials. In this paper, the optimal design of a monopole antenna probe used to evaluate w/c of fresh cement-based materials in real-time and *in-situ* is presented. This probe, operating at 3 GHz, is used along with a reflectometer whose dc output voltage is shown to be linearly correlated to w/c of fresh cement paste and fresh concrete specimens. This paper presents the optimal probe design procedure, the experimental verification of the results, and the results of using the custom-made reflectometer for quick and robust w/c measurement of fresh cement paste and concrete.**

***Index Terms*—Cement paste, concrete, fresh water-to-cement ratio (w/c), microwave testing, monopole antennas.**

I. Introduction

CONCRETE is one of the most widely used materials in the construction industry. It is primarily composed of cement, water, fine aggregate (e.g., sand), and coarse aggregate (e.g., rocks). The aggregate in the mixture mainly acts as filler material. On the other hand, the cement and water chemically combine to form the cement paste binder portion of the mixture. The proportion of each constituent in the mixture is mainly specified for the desired compressive strength of the resulting structure. Practically, the compressive strength of concrete is almost always the vital parameter in the structural design of concrete structures, and is the parameter specified for building code compliance. When the compressive strength is specified, it is given as the strength after the concrete has cured for 28 days. In practice, the water-to-cement ratio (w/c) is the single most important factor influencing the strength of fully compacted concrete [1]. All other factors being the same, the strength of concrete decreases as the w/c increases as specified by Abram's Law [2]. Additionally, w/c also has an effect on the relative gain of strength of concrete over time; that is, concrete with a lower w/c gains strength quicker than one with a higher w/c [2].

The w/c of a concrete mix is typically given at the batch plant. However, there may exist discrepancies in the intended ratio due to incorrect weighing of the constituents at the batch plant, or deliberate changing of the water content in the field. There are several methods available for testing fresh concrete, but they have serious limitations in the field [1], [3], [4]. One chemical method set by the American Society for Testing and Materials (ASTM), ASTM C 1078-87, gives the value of cement content in fresh concrete. When this information is used in conjunction with the amount of free water in fresh concrete, found from ASTM C 1079–87, an estimate of the w/c may be obtained [5]. These ASTM methods require sophisticated equipment and special operator skills, which are not commonly found in the field [1]. Several other methods are also outlined by Neville; nevertheless there exist no reliable and practical methods and procedures for measuring the w/c of fresh concrete [1].

II. Background

In recent years, emerging near-field microwave nondestructive evaluation (NDE) techniques have demonstrated the potential for inspecting and evaluating various properties of cement-based materials [6]. These techniques are commonly based on the response of the interaction of an electromagnetic wave, at microwave frequencies, and a Portland cement-based structure. This response (usually the reflection coefficient properties of an open-ended rectangular waveguide probe in contact with the cement-based structure) is subsequently correlated to the mechanical and material properties of the structure. More specifically, the magnitude of reflection coefficient $|\Gamma|$ of such microwave probes is correlated to the intended properties of a structure. Some of the many advantages of these near-field microwave techniques are as follows.

- They are applicable in a nondestructive, if needed in a noncontact, real-time, *in-situ* and quick fashion.
- They provide for relatively high sensitivity to local and global changes in the material properties of a structure.

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K. Mubarak is with the Applied Microwave Nondestructive Testing Laboratory (AMNTL), Electrical and Computer Engineering Department, Colorado State University, Fort Collins, CO 80523 USA.

K. J. Bois is with Hewlett-Packard Company, Fort Collins, CO 80528 USA.

R. Zoughi was with the Applied Microwave Nondestructive Testing Laboratory (AMNTL), Electrical and Computer Engineering Department, Colorado State University, Fort Collins, CO 80523 USA. He is now with the University of Missouri-Rolla, Rolla, MO 65409-0040 USA (e-mail: zoughir@umr.edu).

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- They can be implemented using low-cost microwave components, and be designed to be portable and require little or no need for operator expertise in the field of microwave engineering and measurement.

Thus far, near-field microwave NDE techniques have been successfully used to evaluate various properties of cement paste, mortar, concrete, and masonry with different material compositions [6]–[16].

All of the above-mentioned investigations have been conducted on hardened specimens (i.e., moist-cured in the hydration room for three days and subsequently left in ambient temperature with low humidity). However, in certain cases, the material content determination of *fresh* concrete may be required. For example, in batch plants determining the *actual* w/c of Portland cement-based materials, before they are dispatched to a construction site, is always of great interest. This is particularly important since the water content may be altered while in transit from the batch plant to the site. In addition, the desired w/c may be altered due to incorrect constituent weighing during the mixing process. In some cases the moisture present in the aggregate can also modify the desired w/c. Therefore, accurate evaluation of fresh w/c associated with a concrete mixture is very important. Microwave signals are known to be very sensitive to the presence of moisture (or free water) in a material. Therefore, microwave techniques are known as excellent candidates for aquametry in environments in which moisture content determination is sought. Hence, the objective of this investigation has been to design and develop an *optimal* microwave probe capable of evaluating fresh w/c in cement-based materials. This paper presents a simple microwave NDE technique for this purpose.

III. Overall Approach

The first step in this study is to determine the type of microwave probe that would be conducive for this type of application. Monopole antenna probes are excellent candidates for dielectric material characterization of fluids and semi-fluid materials [17], [18]. Given the semi-fluid nature of fresh concrete and the previous success in using these probes for microwave reflection property characterization of hardened (cured) cement paste, this probe was used for this investigation. The technique is similar to that used by Shalaby *et al.* [8] for hardened cement paste w/c evaluation. The electrical properties of a monopole probe are controlled by its length, frequency of operation, the coaxial line geometry used to excite it, and the dielectric properties of the medium surrounding it (e.g., fresh concrete). When this probe is inserted into a fresh batch of concrete, its measured microwave reflection coefficient changes are compared to when it is radiating into free space. This information can be obtained in real-time, and correlated to the properties of the cement paste binder portion of concrete. Cement paste binder portion of a cement-based material predominantly influences the reflection properties of the monopole probe, as will be seen later. In addition, this probe is easily inserted into a fresh batch of concrete, and its sensitivity to changes in w/c can be maximized by the optimal choices of the operating frequency and monopole dimensions. Moreover, due to the relative ease of use, multiple measurements can be conducted at several locations to obtain an average value for w/c resulting in higher measurement robustness. Fig. 1 shows the schematic of a typical monopole probe. Such a probe is an extension of the inner conductor of a coaxial transmission line whose outer conductor is commonly terminated in an infinite ground plane (in theory).

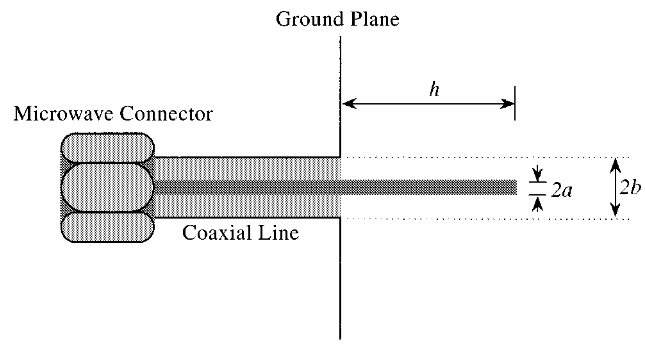

Fig. 1. Schematic of a typical monopole probe/antenna.

The design and development of an optimal monopole probe sensitive to slight variation in the w/c of fresh cement-based materials requires several specific steps to be taken. The following is a brief outline of the steps followed in this investigation.

Step 1) Using the dielectric properties of water and cement powder in conjunction with a dielectric mixing model, the dielectric properties of fresh cement paste were obtained for a wide range of w/c and microwave frequencies.

Step 2) An existing electromagnetic formulation was used to obtain the reflection properties of a monopole probe when inserted into a dielectric material. This formulation was then used in conjunction with the results obtained in Step 1 to arrive at optimal design parameters such as the frequency of operation and monopole probe dimensions.

Step 3) Subsequently, an optimal monopole probe was constructed, and its calibrated reflection properties were measured and compared to those obtained from the theoretical formulation, resulting in excellent agreement.

Step 4) This optimal monopole probe was then incorporated into a custom-design microwave reflectometer whose dc output voltage is proportional to the magnitude of reflection coefficient at the probe.

Step 5) This system was then extensively tested using various fresh cement paste and concrete specimens, showing an excellent correlation between the system output and the specimen w/c.

IV. Determining Dielectric Properties of Fresh Cement Paste

The basic component of any Portland cement-based material is its cement paste portion (binder), which is a mixture of Portland cement powder and water. This is the portion that undergoes a complex chemical process in which water molecules bind to the cement (i.e., curing). However, in the first few minutes following the mixing of these two components, the mixing is physical rather than chemical; that is, the water and Portland cement have not yet had time to significantly interact with each other. Therefore, if the dielectric properties of water and Portland cement powder are known, the dielectric properties of fresh cement paste can be closely calculated. Once the effective dielectric properties of fresh cement paste are determined as a function of w/c and frequency, the optimal measurement parameters such as the operating frequency and the dimensions of the monopole probe can be determined. Optimization would be in the context of obtaining the maximum difference between the reflection properties of the probe as a function of varying w/c (i.e., sensitive to slight variations in w/c). Therefore, the first task is to determine the dielectric properties of fresh cement paste as a function of w/c and frequency.

Dielectric Mixing Model

In the past few decades, many researchers have developed several models predicting the effective behavior of an electromagnetic wave with a mixture consisting of some particles (i.e., cement powder) immersed in a background medium (i.e., water). These models are referred to as *dielectric mixing models*. These models predict the macroscopic behavior of the dielectric properties of a heterogeneous medium composed of several different dielectric constituents. These models give the effective dielectric properties of a mixture, $\varepsilon_{\text{eff}} = \varepsilon'_{\text{eff}} - j\varepsilon''_{\text{eff}}$. The real part, $\varepsilon'_{\text{eff}}$, is known as the permittivity which indicates the ability of the mixture to store electromagnetic energy (i.e., ability to be polarized). The imaginary part, $\varepsilon''_{\text{eff}}$, is known as the loss factor which is an indication of the attenuation (or loss of amplitude) that an electromagnetic signal experiences when travelling through the dielectric mixture.

After studying several potentially viable dielectric mixing models the Maxwell-Garnet dielectric mixing formula was considered [19]

$$\varepsilon_{\text{eff}} = \varepsilon_{host} + 3\varepsilon_{\text{host}} f_{\text{inc}} \frac{\dfrac{\varepsilon_{\text{inc}} - \varepsilon_{\text{host}}}{\varepsilon_{\text{inc}} + 2\varepsilon_{\text{host}}}}{1 - f_{\text{inc}} \dfrac{\varepsilon_{\text{inc}} - \varepsilon_{\text{host}}}{\varepsilon_{\text{inc}} + 2\varepsilon_{\text{host}}}}. \qquad (1)$$

Here, $\varepsilon_{\text{host}}$ and ε_{inc} are the dielectric properties of the host (or background material) and inclusion, respectively, and f_{inc} is the volume fraction occupied by the inclusion in the mixture (i.e., $0 \leq f_{\text{inc}} \leq 1$). In the present case, water is considered to be the host material, and cement powder is considered as the inclusion. Thus, as input to this model, the dielectric properties of water and cement powder are needed at various frequencies.

Dielectric Properties of Water

The dielectric properties of water vary considerably as a function of frequency, salt content (i.e., salinity), and temperature. Empirical equations have been developed to calculate the dielectric properties of water as a function of these parameters [20]. To examine the validity of the empirical relationship given in [20], the dielectric properties of tap water were measured at 3 GHz (as will be explained later and per previous investigations this frequency has been found to be sensitive to w/c measurements in cement-based materials [6]). Moreover, the information at this frequency was later used to determine the dielectric properties of water and fresh cement paste in a wide range of frequencies. To accomplish this, a plug-loaded two-port transmission line dielectric property characterization technique developed recently for the purpose of measuring the dielectric properties of fluids and granular materials was utilized [21]. The temperature and salinity of the water were also measured for close comparison to the empirical results. The results of the measured relative (to free space) dielectric properties are presented in Table I along with the predicted results obtained from the empirical relationships given in [20]. There is an excellent agreement between the empirical and the measured results. Therefore, for the present modeling purposes and to avoid measuring the dielectric properties of water in a wide range of frequencies, the empirical relationships outlined by Ulaby *et al.* [20] were used for this and other frequencies.

TABLE I
COMPARISON BETWEEN THE MEASURED AND CALCULATED DIELECTRIC PROPERTIES OF TAP WATER AT 3 GHz

	Calculated		Measured		Error %	
f	ε'_w	ε''_w	ε'_w	ε''_w	ε'_w	ε''_w
3.0 GHz	78.07	13.09	78.33	12.99	0.32	1.10

Dielectric Properties of Cement Powder

The relative dielectric properties of Portland cement type I/II were also measured at 3 GHz to be $\varepsilon_r = 3.398 - j0.065$, using the same technique. It must be mentioned that since cement powder is a low-permittivity and low-loss dielectric material, its dielectric properties are expected to remain fairly constant as a function of frequency. It is observed that the dielectric properties of Portland cement are much lower, both in the real and imaginary parts, than those of water. Therefore, and as it is shown later, it is expected that the dielectric properties of fresh cement paste will be relatively large since the contribution of free water dominates the effective dielectric properties of fresh cement paste. Now that the dielectric properties of the two main constituents of fresh cement paste are determined as a function of frequency, the effective dielectric properties of fresh cement paste as a function its w/c can be calculated using (1). Subsequently, the theoretical optimization of the monopole probe and the experimental verification of the results may be performed.

Dielectric Properties of Fresh Cement Paste

In this study, two classes of cement-based materials were investigated; namely, fresh cement paste and fresh concrete. Several cement paste specimens were produced with w/c of 0.35–0.60 with 0.05 increments. The dielectric properties of each mixture were measured at 3 GHz using the two-port plug-loaded dielectric property measurement technique mentioned earlier [21]. The measured values were then compared to those obtained from the dielectric mixing model given by (1). This was done to test and verify the validity of the dielectric mixing model results. The results of these measurements are presented in Table II. Except for the loss factor of the specimens with w/c of 0.35 and 0.40, the results predicted by the mixing model and those measured are in good agreement (within 5%). Even though the error for loss factor of these two specimens is slightly higher, these w/c values are not as commonly used in practice

TABLE II
MEASURED AND CALCULATED DIELECTRIC PROPERTIES OF CEMENT PASTE AT 3 GHz

	Mixing Model		Measured		Error %	
w/c	ε'_{wc}	ε''_{wc}	ε'_{wc}	ε''_{wc}	ε'_{wc}	ε''_{wc}
0.60	45.43	14.63	43.85	14.13	3.60	3.56
0.55	43.82	14.07	42.12	13.93	4.03	1.03
0.50	42.05	13.45	41.60	13.14	1.08	2.35
0.45	40.08	12.76	38.84	13.13	3.20	2.79
0.40	37.89	12.00	36.35	13.13	4.25	8.60
0.35	35.43	11.14	35.79	12.25	1.00	9.05

for concrete mixes since the resulting mixtures would be too dry. An interesting feature of the results as a function of w/c is that there is a constant increase both in the permittivity and loss factor as a function of increasing w/c. This is expected, since as the w/c increases, the volumetric fraction of free water increases in the fresh cement paste mixture. As mentioned earlier, water possesses much higher dielectric properties than Portland cement. Thus, an increase in w/c is expected to result in larger overall dielectric properties for the mixture. Since, the dielectric properties of fresh cement paste with varying w/c are now known, these values can be used to optimize the dimensions of the monopole probe.

V. MONOPOLE PROBE DESIGN OPTIMIZATION

The geometry of a monopole probe with an inner conductor of radius a, outer conductor of radius b, and a length of h above an infinite ground plane was shown in Fig. 1. The microwave properties of this probe, namely, its input impedance and subsequently its reflection coefficient are dependent upon the geometry of the monopole, the ground plane, the operating frequency, and the length of the monopole. The thorough formulation for obtaining the reflection coefficient Γ of a monopole probe radiating inside a dielectric medium is presented elsewhere and will not be repeated here [22]. Using this formulation and knowing the dielectric properties of fresh cement paste as a function of frequency and w/c, the reflection coefficient of the probe was calculated for all w/c values and in the frequency range of 1–40 GHz. The results indicated that the best separation among the calculated $|\Gamma|$, as a function of w/c, is obtained at around 3 GHz. This frequency has previously shown to also be optimal for determining w/c in cured cement paste, mortar, and concrete using open-ended rectangular waveguide probes [6], [9], [13]. This frequency also provided a good tradeoff between probe dimension and sensitivity to w/c variation. Therefore, only the results at this frequency are presented here. Fig. 2 shows the calculated effect of monopole length h on the magnitude of reflection coefficient of fresh cement paste as a function of w/c at 3 GHz for a monopole with $a = 0.5$ mm and $b = 1.5$ mm (a commercially available coaxial line). The length of the monopole is changed from 1 mm to 30 mm. The goal of this investigation, as mentioned before, is to select the optimal length of the monopole probe, which yields maximum separation among the calculated values of $|\Gamma|$ as a function of w/c. From Fig. 2, it is clear that a relatively high degree of sensitivity is obtained at any length. However, for h greater than 15 mm, the results are fairly insensitive to any changes in h. This is an attractive feature from a practical point of view since slight variation in this parameter (i.e., due to wear and tear) does not affect the measurement outcome. Thus, for our design, $h = 27$ mm was selected.

It must be mentioned here that the magnitude of reflection coefficient increases as a function of increasing w/c (i.e., more water results in higher dielectric properties of the fresh cement paste), as expected. Moreover, the magnitude of the reflection coefficient for all cases is high, also as expected. However, what is important here is the more than adequate separation among various curves as a function of w/c.

To complete the theoretical study, the magnitude of reflection coefficient for this monopole antenna probe, immersed in a fresh cement paste specimen with known w/c, was measured using a calibrated measurement apparatus. The results were then compared to those calculated from the formulation. In this way, the validity of the theoretical formulation could be examined. To conduct the calibrated measurements of the reflection coefficient of the monopole antenna probe, an HP8510B vector network analyzer was used, as shown in Fig. 3. The measurements were conducted in the S-band (2.6–3.95 GHz) including our frequency of interest (i.e., 3 GHz). Before conducting the experiment, the device was calibrated by conducting reflection property measurements of the monopole antenna probe immersed in three calibration materials (standards) for which the dielectric properties are *a priori* known [8]. The standards (i.e., materials with known dielectric properties) used for this calibration were corn oil, an anti-freeze solution, and a fresh cement paste specimen with 0.45 w/c. Once again, the dielectric properties of these standards were measured using the technique outlined in [21]. Fig. 4 shows the calculated and measured results (calibrated and uncalibrated) of the magnitude of reflection coefficient of the probe for a fresh cement paste specimen with 0.60 w/c in the S-band frequency range. This figure shows that when properly calibrated, the measurements agree well with the theoretical results.

The results are very encouraging, since the entire theoretical study can be accomplished by knowing only the dielectric properties of the Portland cement powder and those of water. Therefore, this study could be repeated for other types of cement (e.g., Portland cement types III and V) and w/c without significant modification to the theoretical protocol. Having determined the validity of the mixing model approach, the optimal dimensions of the monopole probe, and verified the validity of the theoretical modeling via calibrated experimental measurements, the implementation of a low-cost and portable measurement apparatus was subsequently undertaken.

VI. REFLECTOMETER RESULTS

In the previous section, an HP8510B vector network analyzer was used to conduct reflection property measurements. This piece of equipment is expensive, bulky, and is not conducive to on-site measurements. Hence, a relatively inexpensive and simple custom-made device for measuring the magnitude of reflection coefficient is desired. Such a reflectometer system was previously designed and manufactured for the nondestructive

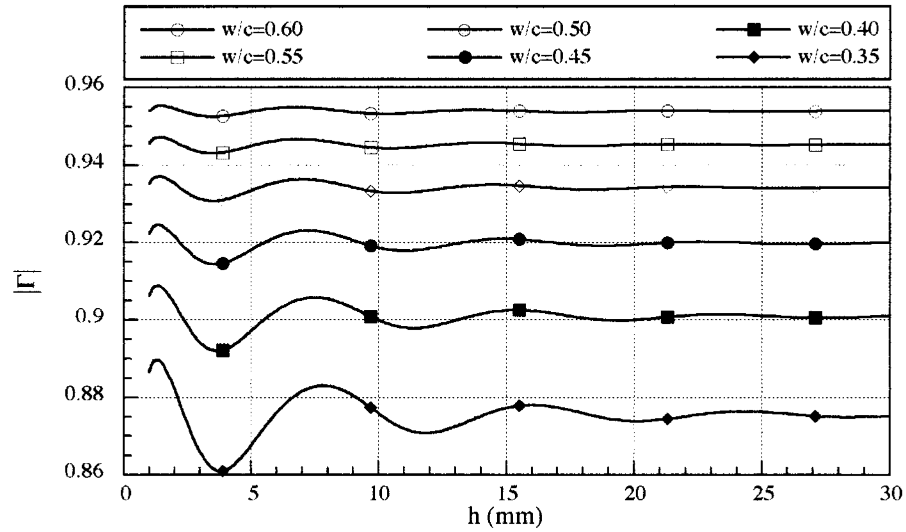

Fig. 2. Calculated magnitude of reflection coefficient $|\Gamma|$ of a monopole probe immersed in cement paste of varying w/c as a function of probe length (h) at 3 GHz.

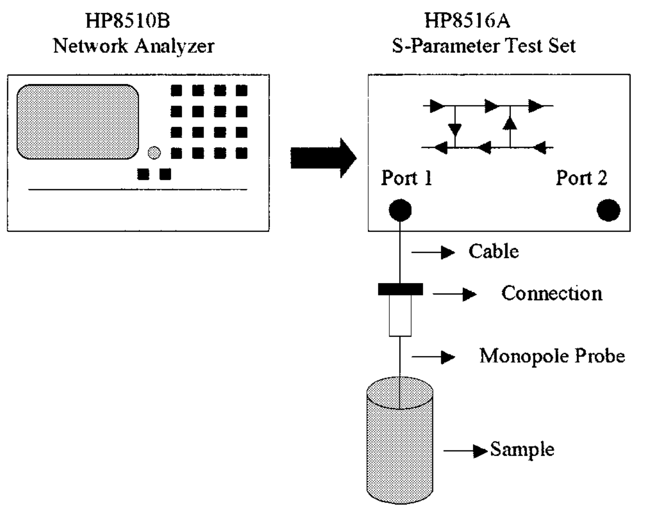

Fig. 3. Measurement setup for the reflection coefficient measurement of the monopole probe.

detection of grout in masonry blocks using open-ended rectangular waveguide probes [6], [16]. A microwave reflectometer is an instrument whose output signal is proportional to a specific reflected signal in a microwave circuit. Although both the magnitude and phase of the reflected signal can be determined using a dual-coupler reflectometer, only the magnitude is needed here. Hence, a single reflectometer is sufficient for this purpose [23]. The output of such a reflectometer is a dc voltage (e.g., output of a detector diode) which is proportional to the magnitude of the reflected signal, and hence the magnitude of reflection coefficient. For our purpose, the behavior of the output voltage of the diode detector must be characterized as a function of w/c. Consequently, six cement paste specimens were produced with w/c of 0.35, 0.4, 0.45, 0.50, 0.55,and 0.60. For each fresh mixture, ten measurements were conducted at 3 GHz using this apparatus. In each measurement, the optimal monopole antenna probe (whose dimensions were determined in the previous section) was immersed in the mixture, the voltage was recorded, and the probe was retrieved and wiped clean. This process took no more than one minute per specimen. The results of the reflectometer output voltage as a function of w/c are shown in Fig. 5. Here, the discrete points indicate the average of the ten measurements accompanied by the error bars representing one standard deviation about the average. The solid line is a linear curve fit through the average points. From Fig. 5 it can be seen that the measurements and the empirical curve fit closely follow each other. The curve fit through the average measured voltages has a regression factor of $R = 0.993$, where $R = 1$ indicates a perfect fit. The expression relating w/c to the diode output voltage from this fit is given by

$$V = -0.342\,82\,(w/c) - 0.192\,48. \tag{2}$$

Subsequently, the following simple relationship gives the value of w/c for these specimens using this apparatus:

$$(w/c) = \frac{-V - 0.192\,48}{0.342\,82}. \tag{3}$$

Therefore, a means for determining w/c of fresh cement-based materials from a simple microwave measurement is now obtained. The advantage of such a simple relationship between w/c and output voltage is that there is practically no need for complex signal processing or data interpretation. Additionally, the hardware required for this type of measurement is simple, and the measurement itself is devoid of complex protocols.

Blind Test

To verify the repeatability of this testing method, a blind test was conducted in which one person prepared fresh cement paste specimens, and another conducted the measurements not knowing the w/c of the specimens. The goal of such a test was to obtain completely impartial results, and examine the repeatability associated with the measurement system. Five specimens were sequentially prepared with w/c of 0.45, 0.475, 0.52, 0.57, and 0.60. For each of these specimens, the custom-made reflectometer apparatus was used to make the measurements. Again, ten measurements were performed for each fresh cement paste specimen. Once the output voltage was measured, (3) was

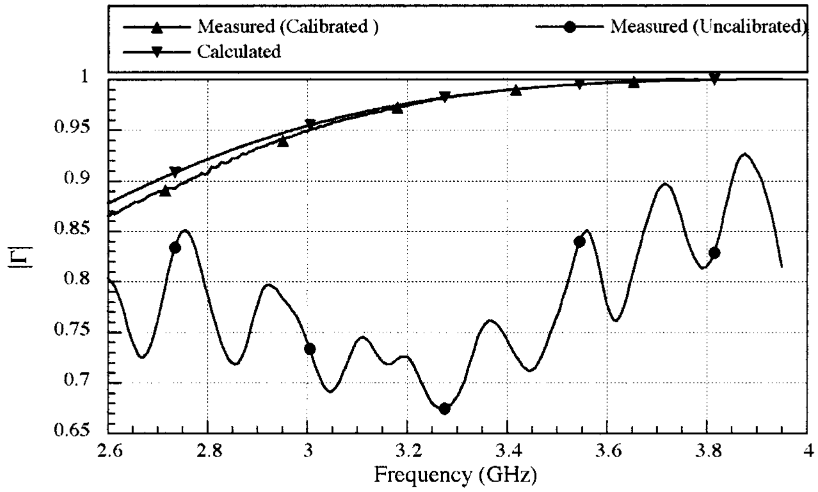

Fig. 4. Measured and calculated magnitude of reflection coefficient for cement paste of 0.6 w/c before and after calibration at S-band (2.6–3.95 GHz).

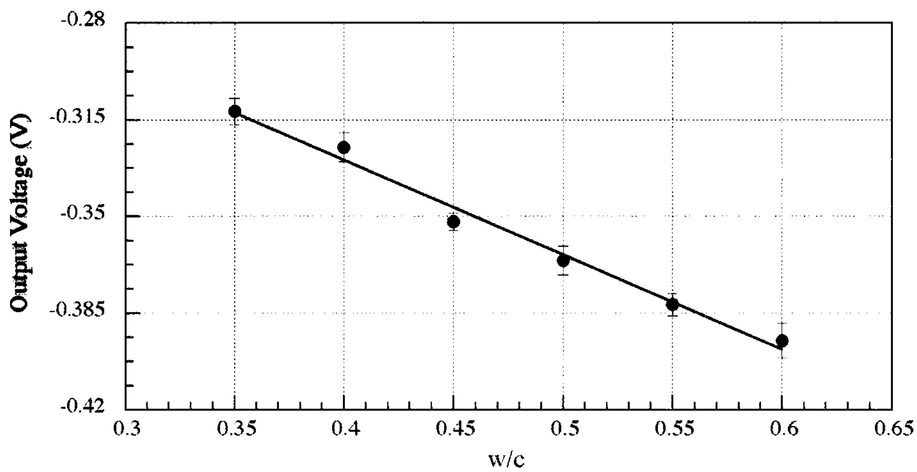

Fig. 5. Reflectometer system voltage output as a function of w/c of fresh cement paste specimens at 3 GHz.

used to determine the w/c of the specimen. Fig. 6 presents the results of these blind measurements. For each specimen, the horizontal axis is the actual w/c, and the vertical axis is the w/c predicted by the reflectometer system. Again, the error bars represent one standard deviation about the measured mean values. The solid line represents a perfect prediction. Therefore, any deviation from this line would represent some degree of error between the predicted and actual w/c of the specimens. From Fig. 6 it is clear that, except for the specimens with 0.475 and 0.52 w/c, the predicted (measured) results agree very well with the expected (actual) results. It is interesting to notice that the measurement variation about the mean is very small. This indicates the robustness of the measurement system. However, to improve the precision of the method a more thorough polynomial expression may be used to refine (3), since the detector diode possesses nonlinear characteristics.

To examine the effect of time and disassembling and assembling of the microwave hardware on the reflectometer system, three fresh cement paste specimens were produced with w/c of 0.4, 0.5, and 0.6 five months after the initial investigation. For each of these fresh cement paste specimens, 20 measurements were conducted using the reflectometer. Fig. 7 shows the results of using (3) and predicting the w/c of these specimens. The solid line represents a perfect prediction with the circles and the error bars showing the mean value of the predicted versus actual w/c and one standard deviation about the mean, respectively.

Thus far, the measurement results indicate that by using this reflectometer and utilizing an optimally designed monopole probe, the w/c determination of fresh cement paste can be accomplished with an accuracy of approximately ± 0.02. However, for a more thorough study we must also determine the influence of aggregates on the measurements.

Concrete

To investigate the influence of aggregate content on the microwave measurements, several fresh concrete specimens were produced with identical w/c of 0.55. Aggregate grade of 3/8 in was added in increments to yield coarse aggregate-to-cement ratios (ca/c) of 0.0, 0.5, 1.0, and 1.5. For each mixture, ten measurements were conducted, and (3) was used to predict the w/c of the mixture. Fig. 8 presents the results of the w/c measurements as a function of ca/c for these fresh concrete specimens. The circles represent the mean of the measured w/c, and the error bars correspond to one standard deviation about the measured mean. Fig. 8 shows that independent of the ca/c, (3)

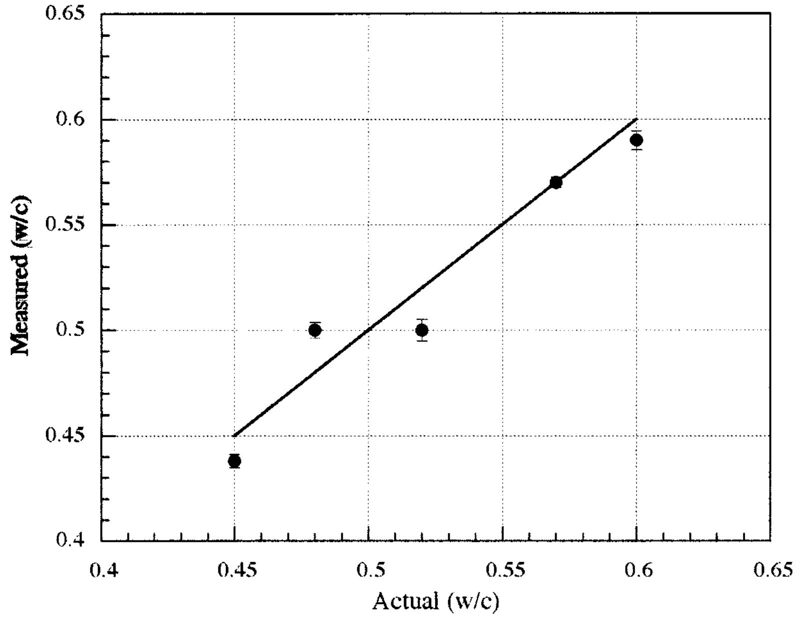

Fig. 6. Blind test average value and the standard deviation for measured specimens with different w/c compared to the actual w/c at 3 GHz.

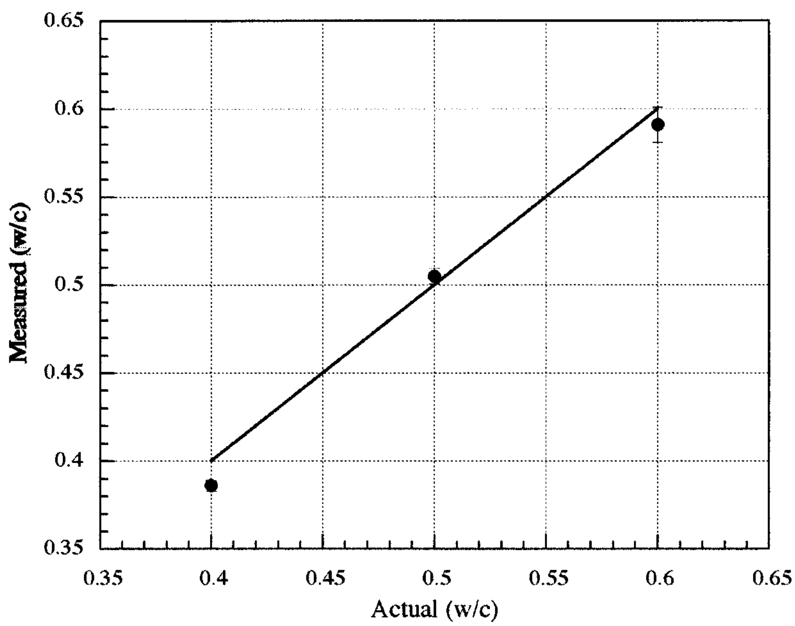

Fig. 7. Measured w/c versus actual w/c for three fresh cement paste specimens at 3 GHz.

very closely predicts the w/c of these fresh concrete specimens. However, an increase in the measurement variation about the mean as a function of ca/c is observed, as expected. This is due to the fact that for increasing aggregate content, the monopole probe might be in contact or very close to the aggregates that influence, to a varying degree, the electromagnetic properties of the probe. Although the maximum variation of the w/c measurement is less than ± 0.01 in the worst case, this measurement variation may still be reduced. By putting a skirt around the monopole probe pushing out the aggregate, the monopole probe would only see the cement paste portion of the concrete. It may also be mentioned, that the standard deviation associated with these measurements may be used as an indicator of the ca/c. The results presented in this section are very encouraging since they indicate that the presence of aggregate on the microwave measurements is not very significant compared to the variation in w/c. This is expected since the dielectric constant of rock is $\varepsilon_r \approx 3$, while the cement paste portion has dielectric properties by an order of magnitude larger. Therefore, the addition of the skirt to the monopole probe may not be necessary if a measurement variation of less than ± 0.01 is acceptable.

In another experiment, two sets of fresh concrete specimens were produced with w/c of 0.4, 0.5, and 0.6 and each set with a ca/c of 1.0 and 1.5, respectively. For each mixture, 20 measurements were conducted, and their average was obtained. Table III shows the actual w/c and the predicted w/c for these fresh concrete specimens. The results show good agreement between the actual and the predicted w/c for the ca/c used.

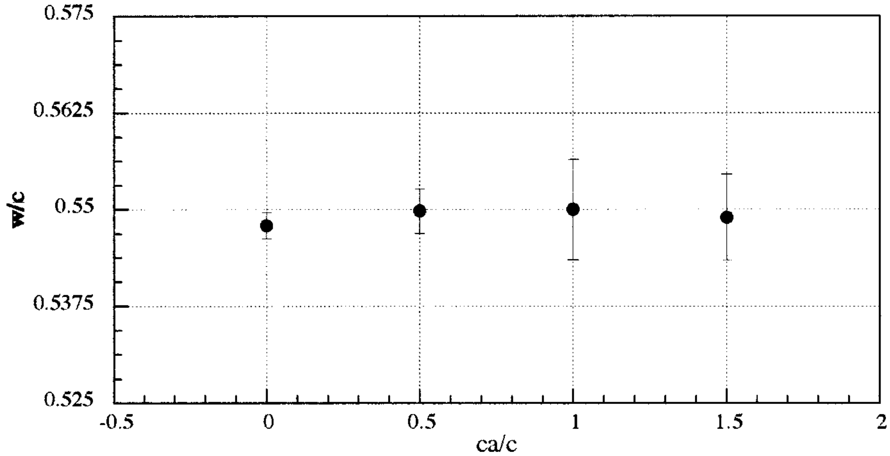

Fig. 8. Average value and the standard deviation of measured w/c versus ca/c for fresh concrete with 0.55 w/c at 3 GHz.

TABLE III
PREDICTED w/c FOR FRESH CONCRETE SPECIMENS WITH ca/c OF 1.0 AND 1.5, RESPECTIVELY

Actual *w/c*	Predicted *w/c* for fresh concrete with *ca/c* = 1.0	Predicted *w/c* for fresh concrete with *ca/c* = 1.5
0.4	0.384	0.384
0.5	0.500	0.502
0.6	0.591	0.585

VII. CONCLUSION

In this paper, the results of a study for the determination of w/c in fresh Portland cement-based materials were presented. This method uses the magnitude of reflection coefficient of a monopole antenna probe immersed in these materials. The measurement apparatus for this purpose uses a simple reflectometer, in which a dc voltage provides for an indication of magnitude of reflection coefficient, and hence the w/c. For probe optimization purposes, the dielectric properties of fresh cement paste, the only component undergoing curing in Portland cement-based materials, were determined using a well-known dielectric mixing model. The dielectric properties obtained using this model were further corroborated by actual dielectric property measurements.

Using an analytical formulation for calculating the magnitude of reflection coefficient of a monopole antenna probe immersed in a medium, the length and cross-sectional dimensions of the probe were optimized. After machining a monopole antenna probe to the specified dimensions, the reflection properties of the probe, while immersed in several fresh cement paste specimens of varying w/c, were measured using the HP8510B vector network analyzer. Once properly calibrated, the experimental results matched the theoretical results well. Subsequently, a custom-made reflectometer was used to determine the relationship between dc output voltage diode readout and the w/c of a specimen under test. This relationship proved to be quite linear which led to a simple expression relating the system output voltage to the w/c of fresh cement paste. Using this relationship, a blind test was conducted to verify the repeatability of the results. Here, five specimens of varying w/c were produced, and the empirical equation was used to determine their w/c. These preliminary results showed that the w/c determination of fresh cement paste could be determined with an accuracy of better than ± 0.02 (worst case) for the specimens tested. The impact of aggregate on the reflection property measurements was also investigated. The results showed that the impact of aggregate on the w/c measurements was less than ± 0.01 in the worst case. Similar measurements were conducted on fresh concrete specimens with varying w/c using different ca/c. The predicted (measured) w/c closely matched the actual w/c.

It must be mentioned that other slightly different sized probes may render satisfactory results, although the results may not be optimal. This fact may be of use in some particular applications in which shorter or thicker monopole antennas may be more desirable to use. Moreover, although an infinite ground plane is assumed in the theoretical derivations, practically the size of this plane varies as a function of probe dimensions, frequency, and the dielectric properties of the material in which it is inserted. High loss and high dielectric materials may not require a very large ground plane. This makes the entire inspection apparatus more user friendly. In all, this study proved to be successful in introducing a very simple nondestructive method for quick and inexpensive determination of w/c in fresh Portland cement-based materials.

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Khalid Mubarak received the B.Sc. degree in electrical engineering from Eitsalat College of Engineering, Sharjha, United Arab Emirates, in 1996, and the M.S.E.E degree from Colorado State University, Fort Collins, in 1999, where he is currently pursuing the Ph.D. degree in the field of satellite communication.

His current area of research is developing the receiver site of satellite by using the pulse compression technique.

Karl J. Bois (M'93) received the B.Sc. and M.Sc. degrees from the Department of Electrical Engineering, Université Laval, Quebec, QC, Canada, in 1993 and 1995, respectively, and the Ph.D. degree from the Department of Electrical and Computer Engineering, Colorado State University (CSU), Fort Collins, in 1999.

From 1995 to 1999, while at the Applied Microwave Nondestructive Testing Laboratory at CSU, his main areas of research involved microwave nondestructive characterization of cement-based materials, developing new techniques for measuring the dielectric properties of materials, and exploring novel theoretical formulas for the near-field characteristics of open-ended rectangular waveguide probes. He is also part of the Electrical Structures and Signals group at Hewlett-Packard, which is associated with the Systems VLSI Technology Operation (SVTO), Fort Collins. His main functions include signal integrity analysis of next-generation computer chip packages and PCB, development of modeling techniques for transmission line structures, and implementation of test benches for experimental verification.

Reza Zoughi (S'85–M'87–SM'93) received the B.S.E.E, M.S.E.E, and Ph.D. degrees in electrical engineering (radar remote sensing, radar systems, and microwaves) from the University of Kansas, Lawrence, in 1982, 1983, and 1987, respectively.

From 1981 to 1987, he was with the Radar Systems and Remote Sensing Laboratory (RSL), the University of Kansas. From 1987 to 2000, he was a Professor in the Department of Electrical and Computer Engineering, Colorado State University (CSU), Fort Collins, where he established the Applied Microwave Nondestructive Testing Laboratory (AMNTL). He served as the Guest Associate Editor for the Special Microwave NDE Issue of *Research in Nondestructive Evaluation* (1995) and Co-Guest Associate Editor for the Special Issue of *Subsurface Sensing Technologies and Applications: An International Journal* on *Advances and Applications in Microwave and Millimeter Wave Nondestructive Evaluation* (2001). He spent a semester of sabbatical leave in 1998 at Département de Recherche en Electromagnétisme, Supélec (Ecole Supérieure d'Electricité), Plateau de Moulon, Gif-sur-Yvette, France. Currently, he is the Schlumberger Distinguished Professor in the Department of Electrical and Computer Engineering, University of Missouri-Rolla. His current areas of research include nondestructive testing of material using microwaves, developing new techniques for microwave- and millimeter-wave inspection and testing of materials, developing new electromagnetic probes to measure characteristic properties of material at microwave frequencies, and embedded modulated scattering techniques for nondestructive testing purposes. He has authored or coauthored over 225 journal publications, conference presentations and proceedings, technical reports, and overview articles. He is the author of a graduate textbook entitled *Microwave Nondestructive Testing and Evaluation Principles* (Norwell, MA: Kluwer, 2000) and the coauthor of a chapter on Microwave Techniques in an undergraduate introductory textbook entitled *Nondestructive Evaluation: Theory, Techniques, and Applications* to be published by Marcel Dekker.

Dr. Zoughi was the recipient of the Dean's Council Award in 1992, and the Abell Faculty Teaching Award in 1995. He was also the 1996 recipient of the Colorado State Board of Agriculture Excellence in Undergraduate Teaching Award.He has been voted "the most outstanding teaching faculty" by the junior and senior students at the Department of Electrical and Computer Engineering at CSU for seven of the past nine years. He has also been recognized as "an honored researcher" for seven of the past ten years by the CSU Research Foundation. He held the Business Challenge Endowment Professorship of Electrical Engineering (1995–1997) at CSU. He is a member of Sigma Xi, Eta Kappa Nu, and the American Society for Nondestructive Testing (ASNT). He is an Associate Technical Editor for the IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT. Along with his students and associates, he has received five patents, all in the field of microwave nondestructive testing and evaluation. He has given numerous invited talks on the subject of Microwave Nondestructive Testing and Evaluation, in addition to organizing and chairing many conference sessions on this topic. He also co-organized (with Professor J. C. Bolomey) the first *Training Workshop on Advanced Microwave NDT/NDE Techniques* which was later held in Paris on September 7–9, 1999.