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Use of Dielectric Constant for Determination of Water-To-Cement Ratio (W/C) In Plastic Concrete: Part 1. Volumetric Water Content Modeling

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Abstract

This paper series includes two parts: (1) volumetric water content modeling, and (2) comparison determined w/c values by ground penetrations radar (GPR) and microwave oven drying measurements. In part (1), the several empirical equations and theoretical models for determining volumetric water content of plastic concrete by dielectric constant value were reviewed. The applicability of these models in determining volumetric water content of plastic concrete was statistically evaluated by the experimental data in literature. It was found that the logarithmic rule proposed by Lichtenecker for plastic concrete's volumetric water content calculation from its constituents' volumetric fractions and dielectric constant values provides the most accurate volumetric water content determination results when compared with other models discussed in this work. The p-value of the t-test of difference ($\Delta\theta_w$) between the calculated volumetric water contents and the determined volumetric water contents for the logarithmic rule was 0.07341, the mean value and variance value of $\Delta\theta_w$ results from the logarithmic rule was -0.29% and 0.98, respectively. The investigation results from this work indicate that dielectric constant value of concrete might be used as an indicator of water content of freshly mixed concrete, which will be further used to calculate the water to cement ratio of concrete in part 2 of this work.

Keywords: Water-to-cement ratio (w/c); Ground penetrating radar (GPR); Microwave oven drying method; Dielectric constant; Water content.

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1. Introduction

The water-to-cement ratio (w/c) is of great importance with respect to the quality of concrete since it influences numerous properties of this material, including: workability,[1–3] porosity,[4,5] resistivity,[6] strength[7,8] and other durability properties.[9–13] As reported by Robertson and Ley,[14] for typical concrete mixture the increase of w/c by 0.01 would cause the decrease of expected service life for the structure by about one year.

Many methods have been proposed to characterize the w/c of plastic concrete. These methods fall into two categories, indirect methods, and direct methods. The indirect methods utilized some measured parameters (*i.e.*, ultrasonic wave velocity,[15] electrical resistivity[16]) to empirically connect the measured parameters with the w/c. The AASHTO T-318[17] suggested to use a microwave oven to directly dry out the water of plastic concrete and determine the w/c.

Using the dielectric property to determine the w/c of plastic concrete has been previously described in the literature.[18–20] It has well-known that different materials have different polarization potential (or the energy storing ability) under the electromagnetic field, which is referred to as the dielectric constant (also called relative dielectric permittivity). It can be seen from Table 1 that the dielectric constant value of water is much higher than that of solid materials presented in concrete. This significant difference in the value of the dielectric constant between water and solid components of concrete makes it sensitive to the changes of water content of concrete mixes and further to the changes of w/c. It is worth noting that the dielectric constant value of water in Table 1 is based on pure water. It is undeniable that the concrete mixing water is

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usually tap water or the water from natural river, which may contain "ppm" level of salt ions. According to previous studies,[21,22] ion type and concentration do have influence on dielectric constant value of its aqueous solution. However, this influence only be significant when the concentration is in percentage level. For example, the dielectric constant value of NaCl solution with the concentration of 0.5M is 74.6,[21] which is 4.4% lower than that of the pure water, and the concentration of 0.5M NaCl equals 29.22 g/L of concentration, or 29220 ppm. Thus, for tap water with the ion (*i.e.*, calcium, magnesium) concentration in the range of 0-500 ppm,[23] the dielectric constant variation is negligible in terms of its influence on concrete bulk's dielectric constant value.

Table 1. The dielectric constant value of different components of concrete mixtures.[24]

Materials	Dielectric constant	Materials	Dielectric constant
Fresh water	78-80.1	Sandstone-dry	4-7
Granite-dry	5-8	Sandstone-wet	5-15
Granite-wet	5-15	Sand-dry	3-6
Limestone-dry	4-8	Sand-wet	10-15
Limestone-wet	6-15	Cement	1.5-2.1

Nevertheless, the relationship between the dielectric constant values of plastic concrete and the water content is still a leftover knowledge gap. Ref. [25] proposed a hybrid capacitor model to describe the relationship between the measured dielectric constant values and the volumetric water contents of plastic concrete. The hybrid capacitor model was based on the equivalent electrical circuit method which assumed the air, water, cement, and aggregates can be equivalent to capacitors, the dielectric constant value of each capacitor is proportional to the volumetric content of each component. By connecting these capacitors in series or in parallel, the volumetric water content of plastic concrete can be calculated by the measured dielectric constant values. However, the arbitrary selected equivalent electrical circuit can't be used as a universal method to determine the water content of plastic concrete with various mixtures. Several empirical equations have been proposed to correlate the measured dielectric constant values of soil[26,27] or hardened concrete[28,29] and the volumetric water contents. The empirically fitted equations might be valid for specific bulk material in exact water content range. For plastic concrete with various mixtures, the applicability of empirical equations needs to be evaluated. Some physicists also proposed theoretical models to determine the dielectric constant values of composites with various components.[30–33] The application of these theoretical models might be a solution to bridge measured dielectric constant values and volumetric water contents of plastic concrete. There are several methods based on different physical principles that have been adopted to measure the dielectric constant value of concrete. The transmission line system[34] was used to determine the dielectric constant value of hardened concrete with various composition. In addition, a time domain reflectometry (TDR) system with three metal electrodes was applied to monitor the[18] hydration process of concrete. Vector network analyzer (VNA) is another method which has been used to determine the dielectric constant value of hardened concrete.[29,35] Ground penetrating radar (GPR) is another method which has been widely used in civil engineering study for different purposes such as underground water pipe mapping,[36] pipe seepage detection,[37] and steel rebar mapping[38] by utilizing the dielectric property of different materials. In the part 2 of this paper series, the dielectric constant value of plastic concrete is determined by a GPR system.

To fill the aforementioned knowledge gaps, this work describes the use of GPR to measure the dielectric constant values of plastic concretes with different compositions in order to establish their sensitivity to changes in w/c values, the results were compared with microwave oven drying method determined results. This paper series includes two parts: (1) volumetric water content modeling, and (2) comparison w/c characterization results by two methods.

In part (1), several empirical equations and theoretical models in bridging the dielectric constant values and volumetric water contents of plastic concrete were discussed. The applicability of these empirical equations and theoretical models in plastic concrete were evaluated by the experimental data in literature. The validity of the volumetric water content results determined by these models were assessed by statistical analysis and the most applicable model for plastic concrete volumetric water content calculation from dielectric constant value was selected.

2. Models linking dielectric constant values and free water content

2.1 Empirical relationships

Modeling the dielectric constant of freshly mixed concrete can reveal the quantitative relationship between the composition of concrete mix and its dielectric constant. Several empirical relationships (Eqs. (1) to (5)) between civil engineering materials' (*i.e.*, concrete and soil) dielectric constant values (ε) and volumetric water contents (free water) (θ_w) have been established by previous researchers as concluded in Table 2.

The plots of empirical relationships between the dielectric constant values (ε) and volumetric water contents (θ_w) are illustrated in Fig. 1. It can be seen that when the measured dielectric constant values are lower than 10, the calculated volumetric water contents from empirical relationships are close, with the range from around 0% to 10%, except Eq (3). When the measured dielectric constant values are higher than 10, the calculated volumetric water contents by Eqs. (2) and (5) are still very close while the calculated volumetric water contents from Eqs. (2), (3) and (4) are higher than calculated results by by Eqs. (2) and (5) as presented in Fig. 1. The Eq. (2) was fitted from the measurement of wet soil,[26] the measured volumetric water content range was 2.5% to 50% and the measured dielectric constant value range was 2.5 to 30.

Table 2. Empirical relationships between measured dielectric constant values (ε) and measured volumetric water contents (θ_w) reported in the literature.

References	Equations		ε value range for fitting	θ_w range for fitting	Bulk material
Topp *et al*. 1980[26]	$\theta_w = 0.00043\varepsilon^3 - 0.055\varepsilon^2 + 2.92\varepsilon - 5.3$	(1)	2.5-30	2.5%-50%	Soil
Janoo *et al*. 1999[28]	$\theta_w = 0.0001928\varepsilon^2 + 1.146\varepsilon - 4.425$	(2)	7-14	3%-10%	Concrete
Schaap *et al*. 1997[27]	$\theta_w = 100 \times (0.133\sqrt{\varepsilon} - 0.146)^{0.885}$	(3)	1-49	0%-70%	Soil
Leucci *et al*. 2012[39]	$\theta_w = 0.001\varepsilon^3 + 0.123\varepsilon^2 - 0.043\varepsilon + 3.3035$	(4)	2-10	4%-14%	Concrete
Klysz *et al*. 2007[29]	$\theta_w = 34.85 - 71.60\varepsilon^{-0.5}$	(5)	4.94-14.06	2%-16%	Concrete

Eq. (2) was fitted from the experimental results of hardened concrete[28] with the measured dielectric constant range of 7 to 14 and the volumetric water content range of 3% to 10%. Eq. (3) was also fitted from the wet soil[27] with the measured dielectric constant range of 1 to 49 and the volumetric water content from 0% to 70%. Eq. (4) was fitted from hardened concrete[39] over a period of one year with repeated cycles of humidification and drying, the measured volumetric water content range was 4% to 14% and the measured dielectric constant value range was 2 to 10. A similar research on hardened concrete measurement over a period of 150 days was reported in[40] at 2018 with the measured volumetric water content range of 3.91% to 7.20% and the measured dielectric constant value range from 2.38 to 5.67, and a fitting relationship that was exactly the same as Eq. (4) was obtained. Eq. (5) was also obtained from the fitting results of hardened concrete with the measured volumetric water contents from 2% to 16% and the dielectric constant values from 4.94 to 14.06.[29]

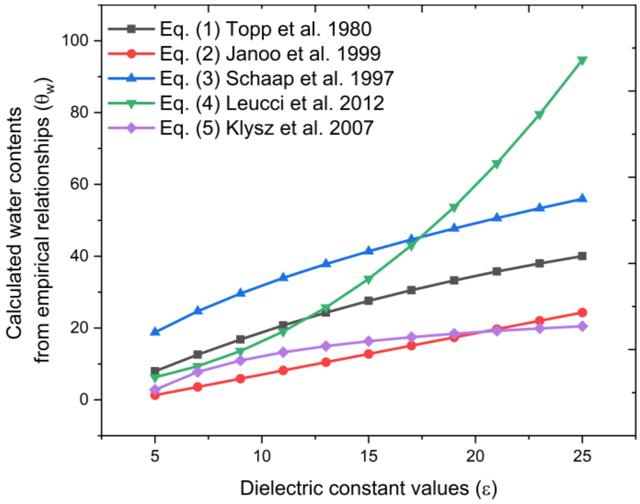

Fig. 1 Plots of empirical relationships between the values of the dielectric constant (ε) and volumetric water contents (θ_w), expressed as percent.

The fitting relationships between dielectric constant values and volumetric water contents are dependent on the experimental results and the selected mathematical equations. The dielectric constant value of a bulk material is also dependent on the composition of the matrix material. Due to the low moisture content in hardened concrete, the contribution of the dielectric constant from other components, such as cement and aggregate, is not negligible, despite the low dielectric constant value of those components. As a result, the same dielectric constant value from different samples of hardened concrete may not represent the same moisture content.

2.2 Review of the dielectric constant values for components of concrete

The dielectric constant of air is 1.0,[24] while the dielectric constant values of cement particle and aggregate particles have been assumed to be 3.365 and 13.215, respectively[41] by simulation method. It is worth noting that the dielectric constant values of fine aggregate and coarse aggregate might be slightly different. In this work, it is reasonable to take these two values as the same since the dielectric constant value of different saturated aggregates usually has a similar range as shown in Table 1, the similar research also can be found in Ref. [25]. The water in the freshly mixed concrete is a liquid solution composed of water and some other ions (*i.e.*, K^+ Na^+ SO_4^-). However, the ion concentration in water has a negligible impact on the calculation for the dielectric constant of concrete.[34] Therefore, the dielectric constant value of water in freshly mixed concrete can be reasonably considered the same as pure water, 80.[24]

2.3 Theoretical models

If the contents of the different components of a mixture are known, the overall dielectric constant value (ε) of the bulk can be determined through each component's (i) dielectric constant value (ε_i) and the volumetric content (θ_i). Several theoretical models have been proposed to calculate the composite's dielectric constant value consistent with sizeable number of heterogeneous mixtures.

Gladstone and Dale[30] expressed a model for the dielectric constant calculation of mixtures which was proportional and linear to the volumetric contents and dielectric constant values of constituents. The model was based on liquid mixtures and has been reported by other researchers[42,43] as Eq. (6):

$$\varepsilon = \sum_{i=1}^{n} \theta_i \varepsilon_i \tag{6}$$

A logarithmic rule for composite's dielectric constant value calculation from its constituents' volumetric fractions and dielectric constant values was firstly proposed by Lichtenecker and reported by[33,42,44,45] and be expressed as Eq. (7):

$$ln\, \varepsilon = \sum_{i=1}^{n} \theta_i \, ln\, \varepsilon_i \tag{7}$$

Another theoretical mathematical model was proposed by

Bruggeman[31] and have been reported by some researchers.[41,43] The model was based on self-consistent effective medium theory as described in[33] and[44] and can be expressed as Eq. (8):

$$\sum_{i=1}^{n}\theta_i\left(\frac{\varepsilon_i-\varepsilon}{\varepsilon_i+2\varepsilon}\right)=0 \tag{8}$$

Looyenga[32] proposed a calculation model for heterogeneous mixtures' dielectric constant calculation based on Bottcher's work[46] as Eq. (9):

$$\varepsilon=\left(\sum_{i=1}^{n}\theta_i\varepsilon_i^{\frac{1}{3}}\right)^3 \tag{9}$$

In Eqs. (6) to (9), ε denotes the overall dielectric constant value of the composite, θ_i represents the volumetric content of constituent i, ε_i denotes the dielectric constant value of constituent i, n is the total components number.

In this work, freshly mixed concrete can be considered as composed by 4 different components, which are, cement, water, air and aggregate. Thus, Eqs. (6) to (9) can be expanded and written as determining volumetric water content (θ_w) from dielectric constant value and volumetric fraction as concluded in Table 3:

In Eqs. (10) to (13), the parameters θ_{cem}, θ_{air}, θ_{agg}, denote the volumetric contents of, respectively, cement particle, air and aggregate; the parameters ε_{cem}, ε_{air}, ε_{agg}, and ε_w denote, respectively, the dielectric constant values of cement particle, air, aggregate and water.

2.4 Evaluation of the applicability of the empirical relationships and theoretical models for prediction of the fraction of water in plastic concrete

In this study, several experimental results from previous published works[20,25,41] were cited and the volumetric water contents were calculated by empirical relationships, which are Eqs. (2) to (5) and theoretical models, which are Eqs. (10) to (13). The experimental determined volumetric water content results in terms of measured dielectric constant values of plastic concrete are presented in Fig. 2. It is obviously that the higher dielectric constant value indicates higher volumetric water content of plastic concrete. Data from Chen *et al.*[25] has the w/c varies from 0.40 to 0.65, with cement mortar and concrete materials. Results from Lai *et al.*[20] used normal weight aggregate and light weight aggregate concrete with the w/c value varies from 0.28 to 0.65. Data from Lee and Zollinger[41] contains the concrete with the w/c value from 0.32 to 0.40.

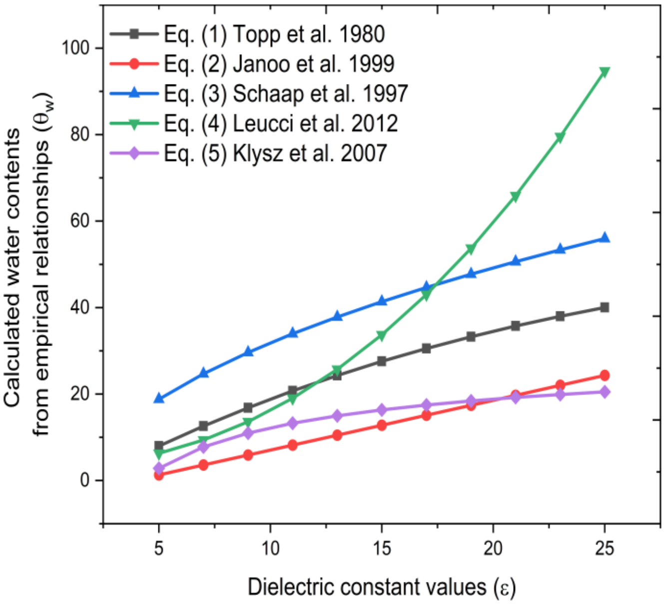

Fig. 2 Experimental determined volumetric water content results in terms of measured dielectric constant values of plastic concrete from literature.[20,25,41]

The volumetric water contents can be calculated by empirical relationships by Eqs. (2) to (5) and theoretical models by Eqs. (10) to (13) and the mixture recipes in literature.[20,25,41] The calculated volumetric water contents (θ_{cal}) in terms of the experimental determined volumetric water contents (θ_{exp}) are concluded in Fig. 3.

The water content determination error ($\Delta\theta_w$) between the calculated volumetric water contents (θ_{cal}) by different models and experimental determined volumetric water contents (θ_{exp}) can be expressed as Eq. (14):

$$\Delta\theta_w=\theta_{cal}-\theta_{exp} \tag{14}$$

The determined $\Delta\theta_w$ results by different models are presented in Fig. 4. It can be seen that most of calculated results have less than ± 10% error to experimental determined water contents except the calculated results from the empirical relationship Eq. (4). The water content determination error ($\Delta\theta_w$) results by empirical relationships and theoretical models were evaluated by t-test with the null hypothesis that the mean value of $\Delta\,\theta_w$ determination results had no significant

Table 3. Theoretical models for prediction of volumetric water content using empirical values of dielectric constant.

References	Theoretical models	
Gladstone and Dale 1863[30]	$\theta_w=\dfrac{\varepsilon-\theta_{cem}\varepsilon_{cem}-\theta_{air}\varepsilon_{air}-\theta_{agg}\varepsilon_{agg}}{\varepsilon_w}$	(10)
Lichtenecker 1926[33,42,44]	$\theta_w=\dfrac{ln\,\varepsilon-\theta_{cem}\,ln\,\varepsilon_{cem}-\theta_{air}\,ln\,\varepsilon_{air}-\theta_{agg}\,ln\,\varepsilon_{agg}}{ln\,\varepsilon_w}$	(11)
Bruggeman 1936[31]	$\theta_w=\left(\theta_{cem}\dfrac{\varepsilon-\varepsilon_{cem}}{2\varepsilon+\varepsilon_{cem}}+\theta_{air}\dfrac{\varepsilon-\varepsilon_{air}}{2\varepsilon+\varepsilon_{air}}+\theta_{agg}\dfrac{\varepsilon-\varepsilon_{agg}}{2\varepsilon+\varepsilon_{agg}}\right)\dfrac{2\varepsilon+\varepsilon_w}{\varepsilon_w-\varepsilon}$	(12)
Looyenga 1965[32]	$\theta_w=\dfrac{\varepsilon^{\frac{1}{3}}-\theta_{cem}\varepsilon_{cem}^{\frac{1}{3}}-\theta_{air}\varepsilon_{air}^{\frac{1}{3}}-\theta_{agg}\varepsilon_{agg}^{\frac{1}{3}}}{\varepsilon_w^{\frac{1}{3}}}$	(13)

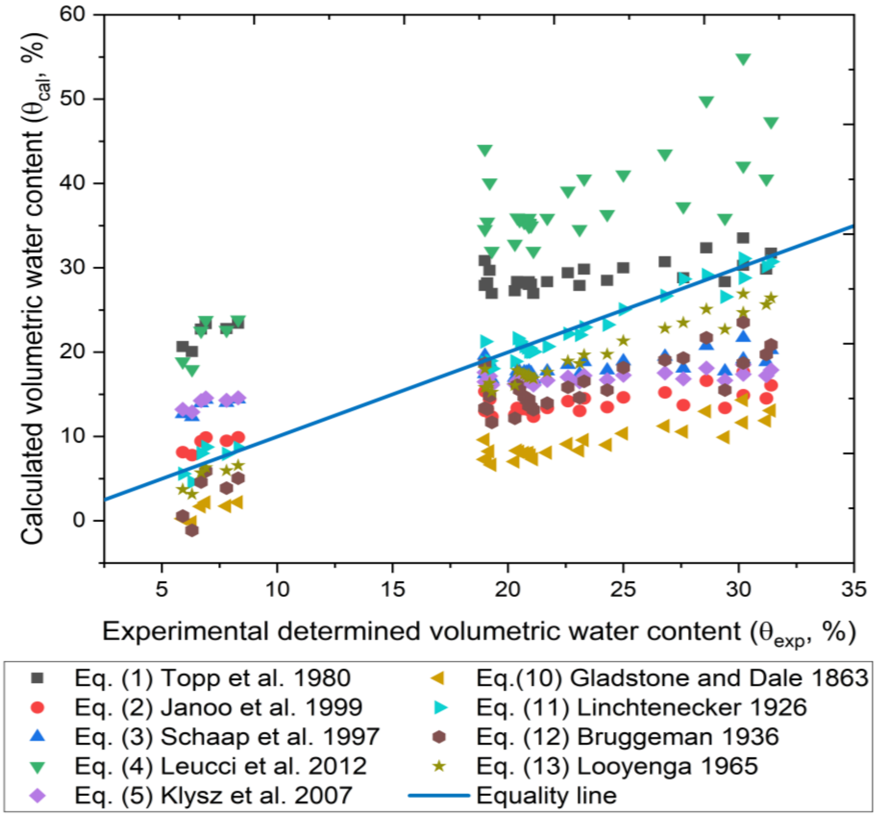

Fig. 3 Calculated volumetric water contents (θ_{cal}) in terms of experimental determined volumetric water contents (θ_{exp}).

difference with 0. The p-value of the t-test, mean value, and the variance results of $\Delta\theta_w$ determination results by each model were concluded in Table 4. Only Eq. (11) determined $\Delta\theta_w$ results had a p-value higher than 0.05 which indicated the mean value of $\Delta\theta_w$ determination results by Eq. (11) had no significant difference with 0. Meanwhile, the mean value and variance value of $\Delta\theta_w$ determination results by Eq. (11) was the lowest compared with the results calculated by other models. Thus, it is fair to conclude that Eq. (11) provides the most accurate water content determination results by the measured dielectric constant values for plastic concrete out of other models in this work.

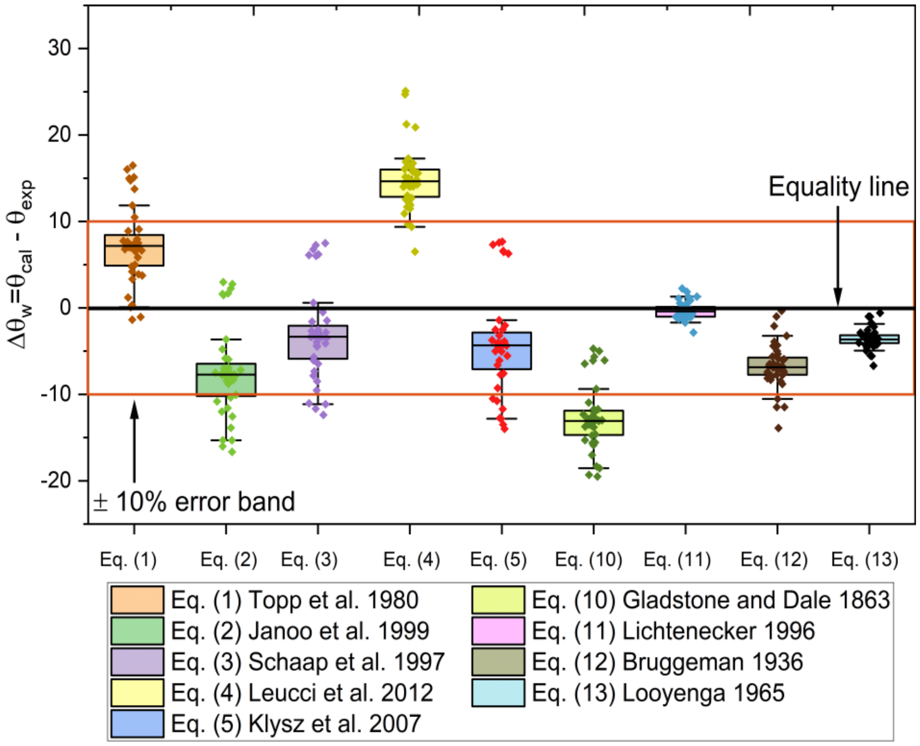

Fig. 4 Water contents determination error results by various models.

Table 4. t-test results of $\Delta\theta_w$ determination results by different models.

References	p-value	Mean value (%)	Variance
Eq. (1), Topp *et al*. 1980[26]	7.69E-13	7.29	19.55
Eq. (2), Janoo *et al*. 1999[28]	1.67E-11	-7.48	25.60
Eq. (3), Schaap *et al*. 1997[27]	4.24E-04	-3.13	26.34
Eq. (4), Leucci *et al*. 2012[39]	2.11E-26	14.87	12.82
Eq. (5), Klysz *et al*. 2007[29]	4.68E-05	-4.18	33.38
Eq. (10), Gladstone and Dale 1863[30]	2.18E-23	-12.75	13.78
Eq. (11), Lichtenecker 1926[33,42,44]	0.07341	-0.29	0.98
Eq. (12), Bruggeman 1936[31]	4.64E-19	-6.73	6.76
Eq. (13), Looyenga 1965[32]	6.49E-21	-3.52	1.44

4. Conclusions

In this work, 5 empirical equations and 4 theoretical models for determining volumetric water content of plastic concrete by its dielectric constant value were discussed. Empirical equations and theoretical models were applied to calculate the volumetric water contents of plastic concrete by experimentally determined dielectric constant values in literature. The water content determination results by different equations and models were statistically analyzed and compared. The conclusions of this work can be drawn as:

1. From the literature review, it was found that dielectric constant value is a good indicator of moisture content in composite. The high moisture content results in high dielectric constant value of the composite.
2. The results of t-test indicate that the water content calculation results from the empirical equations used in this work show statistical deviation from the determined values in literature.
3. The t-test results suggest that the logarithmic rule calculated water content of plastic concrete has no significant different with the determined value in literature. The mean value and the variance value by the logarithmic rule are the lowest compared with other empirical equations and theoretical model calculation results.
4. The statistical calculation results indicate that the logarithmic rule might be appropriate to calculate the water content of freshly mixed concrete from the dielectric constant value of the bulk concrete, which will be used in part 2 of this paper series.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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