JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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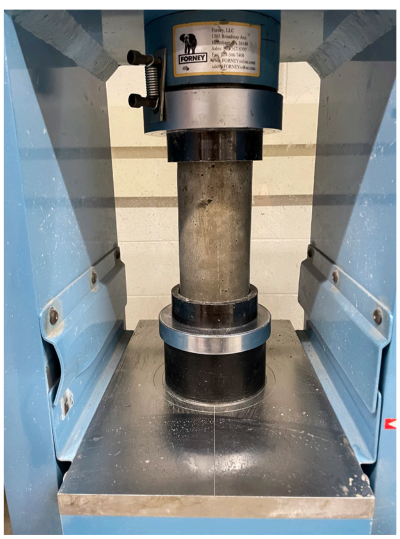
Development of In-Situ Sensing Method for the Monitoring of Water-Cement (W/C) Values and the Effectiveness of Curing Concrete



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SPR-4418 • Report Number: FHWA/IN/JTRP-2022/14 • DOI: 10.5703/1288284317377

RECOMMENDED CITATION

He, R., Lu, N., & Olek, J. (2022). *Development of in-situ sensing method for the monitoring of water-cement (w/c) values and the effectiveness of curing concrete* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2022/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317377

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The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA/IN/JTRP-2022/14</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Development of In-Situ Sensing Method for the Monitoring of Water-Cement (W/C) Values and the Effectiveness of Curing Concrete</td><td colspan="2">5. Report Date
May 2022</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Rui He, Na (Luna) Lu, and Jan Olek</td><td colspan="2">8. Performing Organization Report No.
FHWA/IN/JTRP-2022/14</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Joint Transportation Research Program
1284 Civil Engineering Building
Purdue University
West Lafayette, IN 47907-1284</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
SPR-4418</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Indiana Department of Transportation (SPR)
State Office Building
100 North Senate Avenue
Indianapolis, IN 46204</td><td colspan="2">13. Type of Report and Period Covered
Final Report</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.</td></tr>
<tr><td colspan="4">16. Abstract
As the most widely used construction material, concrete is very durable and can provide long service life without extensive maintenance. The strength and durability of concrete are primarily influenced by the initial water-cement ratio value (w/c), and the curing condition during the hardening process also influences its performance. The w/c value is defined as the total mass of free water that can be consumed by hydration divided by the total mass of cement and any additional pozzolanic material such as fly ash, slag, silica fume. Once placed, field concrete pavements are routinely cured with liquid membrane-forming compounds. For laboratory study, concrete samples are usually cured in saturated lime water or a curing room with a relative humidity (RH) value higher than 95%. Thus, the effectiveness of curing compounds for field concrete needs to be studied.
In this study, the dielectric constant value of plastic concrete was measured by ground penetrating radar (GPR). The w/c value of the plastic concrete was calculated by a mathematical model from the measured dielectric constant value. The calculated w/c value was compared with the microwave oven drying measurement determined result in AASHTO T318. A modified coarse aggregate correction factor was proposed and applied in microwave oven drying measurement to determine the w/c value of plastic concrete in AASHTO T318. The effectiveness of curing compound was evaluated by field concrete slabs by GPR measurement. It was found that GPR can be a promising NDT method for w/c determination of plastic concrete and can be a promising curing effectiveness evaluation method for hardened concrete.</td></tr>
<tr><td colspan="2">17. Key Words
water-cement ratio (w/c), non-destructive testing (NDT), ground penetrating radar (GPR), effectiveness of curing</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
34</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

As the most widely used construction material, concrete is very durable and can provide long service life without extensive maintenance. The strength and durability of concrete are primarily influenced by the initial water-cement ratio value (w/c), and the curing condition during the hardening process also influences its performance. The w/c value is defined as the total mass of free water that can be consumed by hydration divided by the total mass of cement and any additional pozzolanic material such as fly ash, slag, and silica fume. Once placed, field concrete pavements are routinely cured with liquid membrane-forming compounds. For laboratory study, concrete samples are usually cured in saturated lime water or a curing room with a relative humidity (RH) value higher than 95%. Thus, the effectiveness of curing compound for field concrete needs to be studied.

Findings

During the course of the present study, we used ground penetrating radar (GPR) to measure the dielectric constant value of plastic and hardened concrete. The water-cement ratio (w/c) of plastic concrete was calculated by the mathematic model from the measured dielectric constant value. The calculated w/c value from GPR measurement was also verified by the microwave oven drying measurement from AASHTO T318. Moreover, the effectiveness of curing for field concrete slabs was evaluated by the dielectric constant value measurement. The following are the major findings of this study.

1. The dielectric constant value of plastic concrete measured by GPR can be used to calculate the w/c value by a mathematical model. The w/c determination error by GPR measurement is statistically lower than that of the results determined by the microwave oven drying measurement from AASHTO T318.
2. The coarse aggregate correction factor can effectively eliminate the w/c determination deviation caused by sampling error for concrete without fine particles in coarse aggregate. When coarse aggregate has fine particles, the determined w/c results with the application of correction factor (CF) have significant differences with design w/c values. The application of modified correction factor (CF′) determined w/c results have no significant differences with the design w/c values. When the fine particle content in coarse aggregate is less than 4.44%, the calculated w/c with the application of CF will have a 95% confidence to fall within the ± 0.02 error range to target w/c values.
3. The dielectric constant value determined by the two-way travel time method is less influenced by the weather conditions. However, the dielectric constant value obtained by first pulse peak amplitude method is influenced by weather conditions. Weather conditions have greater influences on the amplitude of first reflected pulse peak than the second reflected pulse peak. The second reflected pulse peak amplitude can be used to determine the dielectric constant value of concrete.
4. The dielectric constant value of compound-cured concrete is higher than air-exposed concrete, which indicates a higher water content in compound-cured concrete than in air-exposed concrete.
5. From a practical application objective, the inconsistent relative relationship on the electrical resistivity development of compound-cured and air-exposed concrete might result in inaccurate evaluation of curing effectiveness. The dielectric constant is a good NDT method to evaluate the curing effectiveness of concrete and can be used to indicate further hydration potential.

Implementation

It is recommended that the dielectric constant value be used as a parameter to determine the w/c value of plastic concrete. The modified coarse aggregate correction factor can be used to determine the w/c value by microwave oven drying measurement. The implementation of the dielectric constant determination method and the modified coarse aggregate correction factor can be further verified using trial batches where the target w/c values and the moisture content and specific gravities of aggregates can be well controlled.

The dielectric constant value determined by GPR measurement can be a promising NDT method in the field to evaluate the curing effectiveness of concrete. The dielectric constant determination method can be further simplified.

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1. INTRODUCTION

1.1 Research Background

Concrete is one of the most widely used construction materials with very durable property and long-service life. The mass ratio between free water and the sum masses of cementitious materials (i.e., Portland cement, fly ash, slag, silica fume, and natural pozzolans) in concrete is called water-to-cementitious ratio (w/c).

The use of a w/c value lower than that of design value can result in higher strength but more brittle concrete. Also, the low w/c value concrete may be difficult to place and finish. Similarly, the use of higher w/c value than specified value will result in a decrease in strength and durability. The reason the w/c value has such a crucial influence on concrete's strength and durability performance is that its value directly links to the initial volume ratio of water in concrete, which, further determines the capillary porosity. Since w/c value plays such an important role in controlling concrete quality, there has always been a need for a method to determine the actual w/c value of concrete before placement.

Curing process is particularly important for producing high-quality concrete. Proper curing methods are necessary to maintain satisfactory moisture content for hydration which influences the strength development and durability performance. For pavement concrete, the large surface-to-volume ratio makes it easy to lose water due to evaporation. Thus, the evaluation of curing method effectiveness is of crucial important for its service life prediction.

1.2 Problem Statement

According to ASTM C94 (ASTM, 2021), the batch water used to prepare concrete mixtures "shall be measured by mass or volume to an accuracy of $\pm 1\%$ of the mixing water established by the design mixture proportions." The Indiana Department of Transportation (INDOT) specifications for pavement concrete stipulate that w/c should not vary more than ± 0.03 of the target value (INDOT, 2020). The results of the laboratory research (Dowell & Cramer, 2002; Naik & Ramme, 1989) suggest that a typical tolerance limit for w/c in concrete is 0.02 (or 5%) of the target value. However, the w/c value of any given concrete mixture can be easily altered during the manufacturing, transportation, and placement of concrete. For example, if not properly accounted for, the surface moisture conditions of coarse and fine aggregates can significantly affect the values of w/c. In addition, extra water is often added to concrete mixtures during transportation and/or placement operations to maintain their workability. As a result, the properties of placed concrete can be drastically different than the design specifications.

Once placed, concrete pavements are routinely cured with liquid membrane forming compounds and the application of these types of materials is described in Section 504.04a (INDOT, 2020) of INDOT's specification. These materials are designed to retain moisture in concrete by lowering the rate of evaporation. To be effective, the curing compound needs to meet certain water retention criteria as determined by ASTM C 309 (Subcommittee C09.22, 2019). However, this test has been reported to produce evaporation rate data with inherently high variability. A more accurate method for monitoring the moisture content of concrete will help to minimize the tendency for development of shrinkage cracking.

1.3 Objective

The primary objective of this project is to develop a sensing method that will enable accurate, in-situ determination of w/c value of freshly placed concrete. The secondary objective is to develop a method for in-situ monitoring of hardened values of compressive strength and modulus of elasticity as indicators of the effectiveness of curing.

1.4 Organization of the Report

This report consists of six chapters. The first chapter introduces the research background and objective of this work. The second chapter reviews the previous work on w/c determination methods, curing effectiveness evaluation measurements. The third chapter presents the work in using GPR to determine the dielectric constant value of concrete and further to calculate the w/c value of concrete by dielectric constant value. The fourth chapter reports the work on applying a modified coarse aggregate correction factor in microwave oven drying w/c determination method. The fifth chapter evaluates the curing effectiveness of field concrete slabs. The sixth chapter gives the final conclusions of this work.

2. LITERATURE REVIEW

The water-to-cement ratio (w/c) of concrete is of great importance with respect to the quality of concrete since it influences fresh concrete's properties (i.e., workability (Lavado et al., 2020; Sokhansefat et al., 2019), rheology (Ghafari et al., 2016) to hardened concrete's durability performance (i.e., micropore structure (He et al., 2019), electrical resistivity (He et al., 2018), strength (Su et al., 2019) and chloride resistance (Fu et al., 2022; He et al., 2020, 2022)).

2.1 w/c Value Error Tolerance

For a general concrete mixture with a cement content of 335.0 kg/m^3, the free water content for design w/c=0.40 is 134.0 kg/m^3. A 3.4 kg/m^3 water content error would increase the design w/c to 0.41 while only having a water content relative error of 2.5%. The moisture content variation in aggregate is another important source for w/c error. For general concrete mixture with the design w/c=0.40, the saturated surface dry (SSD) aggregate contents are 857 kg/m^3, and 1,160 kg/m^3, for fine aggregate and coarse aggregate, respectively. The change of 1% in aggregates' moisture content (with respect to the SSD condition) will cause the actual w/c to have about 0.06 deviation from the design w/c.

Numerous literature sources (Allahham & Bordelon, 2016; Lai et al., 2009; Obla et al., 2018; Yohannes & Olek, 2012) have confirmed the critical role of w/c in concrete quality assurance applications. As such, the tolerance limits for w/c values in both laboratory research and job site applications are quite narrow. The results of the laboratory research (Dowell & Cramer, 2002; Naik & Ramme, 1989) suggest that a typical tolerance limit for w/c in concrete is 0.02 (or 5%) of the target value. The Indiana Department of Transportation (INDOT) specifications for pavement concrete stipulate that w/c should not vary more than ±0.03 of the target value (INDOT, 2020). The variation of w/c for concrete can be attributed to a variety of reasons. As an example, the workers may arbitrarily add additional water to increase workability during the concrete placement at the job site.

2.2 Dielectric Constant Measuring Method for w/c Determination

Using the dielectric property to determine the w/c of plastic concrete has been previously described in the literatures (Allahham & Bordelon, 2016; Lai et al., 2009; Yu et al., 2004). It is 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 2.1 that the dielectric constant value of water is much higher than that of solid materials present 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.

As described below, various methods and experimental setups have been tried in the past for the purposes of determining the dielectric constant of hardened concrete. As an example, the transmission line system (Soutsos et al., 2001) has been used to determine the dielectric constant of harden concretes of different compositions. The results showed that both, the cement type and pore solution type, had negligible influence on harden concrete's dielectric constant. A time domain reflectometry (TDR) method has been applied to measure the dielectric constant of harden concrete with different w/c values (Yu et al., 2004). The system consists of three metal electrodes, which were embedded into the concrete at the time of casting. The reported discrepancies between predicted and the target w/c values for two batches of concrete were 0.1 and 0.4, respectively. Previous studies have also utilized a coaxial probe system with a vector network analyzer (VNA) (Chung et al., 2018) to measure the dielectric constant of concrete. The relationship between the mixture proportions (i.e., w/c, aggregate content) and the dielectric constant has been empirically established. An open-ended coaxial probe with a handheld VNA system (Guihard et al., 2020; Klysz & Balayssac, 2007) has also been deployed to evaluate the dielectric constant of harden concrete with different moisture contents. An empirical relationship between the dielectric constant and moisture content has been obtained.

The ground-penetrating radar (GPR) has also been used to assess the dielectric properties of materials. Due to its high accuracy, large detection area, and short setup time, GPR is successfully used as a nondestructive testing (NDT) in various civil engineering applications (Lai & Tsang, 2008; Wai-Lok Lai et al., 2018). The GPR antennas emit electromagnetic impulses, and the response impulses are reflected when the medium they travel through changes. The reflected impulses are analyzed to calculate the dielectric constant of the transport medium based on the wave propagation theory. The GPR has been widely used in underground water pipe mapping (Li et al., 2016), pipe seepage detection (Lai et al., 2017), and steel rebar mapping (Jazayeri et al., 2019). The researchers also explored applicability of GPR to measure the dielectric constant and to characterize the water content change of concrete during the hydration process (Kaplanvural et al., 2018; Lai et al., 2009).

Nevertheless, the relationship between the dielectric constant values of plastic concrete and the water content is still a leftover knowledge gap. Chen et al. (2012) 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

TABLE 2.1
The dielectric constant value of different components of concrete mixtures (Jol, 2009)

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

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 cannot 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 (Schaap et al., 1997; Topp et al., 1980) or hardened concrete (Janoo et al., 1999; Klysz & Balayssac, 2007) 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 (Bruggeman, 1936; Gladstone & Dale, 1863; Looyenga, 1965; Wu et al., 2003). The application of these theoretical models might be a solution to bridge measured dielectric constant values and volumetric water contents of plastic concrete.

2.3 Microwave Oven Drying Method for w/c Determination

Numerous methods have been proposed for w/c determination of fresh concrete (Dowell & Cramer, 2003; Mancio et al., 2010; Popovics, & Popovics, 1998; Yu et al., 2004). Among these methods, microwave oven drying measurement is the most widely used and cost-effective method and has been standardized as AASHTO T318 (AASHTO T318-15, 2019). The microwave oven drying measurement have been adopted by many researchers (Fox et al., 2007; Mardmomen et al., 2019; Nagi & Whiting, 1994; Naik & Ramme, 1987; Nantung, 1998). The principle of this method is well understood. During the microwave oven drying process, the free water in fresh concrete composite will be heated and evaporated out. By measuring the concrete mass change before and after the measurement, the water content of concrete can be determined and then the w/c can be calculated by the measured water content and design cement content.

There are two major concerns regarding the accuracy of microwave oven drying measurement. The first is whether the water can be completely evaporated out of concrete, and the other is the measurement result variation caused by coarse aggregate content deviating from batch concrete in sample, which is also known as sampling error. The deviation of measured w/c results from design values has been reported from -0.052 to +0.067 (Dowell & Cramer, 2002). The National Ready Mixed Concrete Association (NRMCA) specifies the acceptance criteria for microwave oven drying measurement results at ± 0.05 precision of the measured results to target values (Hover et al., 2008). To address the sampling error issues, Fox et al. (2007) proposed to use a 55 μm filter bag to separate the dry cement from the remaining aggregate after drying process to adjust the cement to aggregate ratio in the concrete sample. The measured w/c value after using the filter bag method, for target w/c=0.50, can be expected to fall within the range of 0.48 to 0.52 with 95% confidence. NRMCA (Hover et al., 2008) proposed to use a coarse aggregate correction factor (CF) to adjust the coarse aggregate content in concrete sample. The CF has been applied by several researchers (Mardmomen et al., 2019; Nantung, 1998) and promising w/c determination results in laboratory studies were obtained.

2.4 Curing Effectiveness Evaluation of Hardened Concrete

Curing process is particularly important for producing high-quality concrete. Proper curing methods are necessary to maintain satisfactory moisture content for hydration which influences the strength development and durability performance (ACI Committee 308, 2016). For pavement concrete, the large surface-to-volume ratio makes it easy to lose water due to evaporation. Thus, the evaluation of curing method effectiveness is of crucial importance for its service life prediction.

A variety of curing effectiveness evaluation methods have been proposed in literature and can be divided into two categories, which are, destructive methods and non-destructive methods. Water absorption test is one of the most widely used methods for curing effectiveness evaluation (Abdelaziz, 2006; Poole, 2005; Sun, 2013; Wang et al., 2002), which needs to drill concrete cylinders. The water absorption test is time-consuming and labor-intensive to determine the initial absorption. The hydration degree measurement by thermogravimetric analysis (TGA) is another destructive method to evaluate the curing effectiveness of concrete (Poole, 2005, 2006; Wang et al., 2002, 2006). Nevertheless, TGA analysis needs to be performed in laboratory and requires the high-quality instrument which cannot be used for field practice. The mechanical properties (i.e., compressive strength, tensile strength) have also been widely used to evaluate the curing effectiveness of field concrete (Abdelaziz, 2006; Ibrahim et al., 2013; Wang et al., 2002; Whiting & Snyder, 2003). The labor-intensive mechanical testing method makes it unfavorable for field practice. The abrasion resistance of concrete is another destructive method for curing effectiveness evaluation (Poole, 2005, 2006). Nonetheless, this method can only evaluate the surface properties of concrete. Some other durability properties (i.e., chloride permeability (Ibrahim et al., 2013; Whiting & Snyder, 2003), and micropore structures (Abdelaziz, 2006; Whiting & Snyder, 2003)) have also been used to evaluate concrete performances under different curing methods. Similar to TGA analysis, these methods also need to be performed in laboratory and require special instrument.

Compared to labor-intensive and time-consuming destructive evaluation methods, non-destructive methods are more favorable in field study. The relative humidity sensor measurement is one of the widely used methods to determine the relative humidity of concrete structures (Jeong & Zollinger, 2003; Joshaghani & Zollinger, 2017; Sun, 2013). Nevertheless, the relative humidity is easily influenced by weather conditions which makes it not very reliable for curing effectiveness evaluation. The temperature-based maturity test is another non-destructive method to evaluate the curing effectiveness (Wang et al., 2002, 2006). This method needs to establish a concrete strength database to correlate with collected temperature data prior to perform the field study. The electrical conductivity of concrete can be used to indicate the porosity (He et al., 2018) and chloride diffusivity of concrete (He et al., 2019, 2020). Thus, the electrical resistivity measurement is a widely used method to evaluate the curing effectiveness in fields (Wang et al., 2002, 2006). The dielectric property of concrete can be closely related to the water content of concrete (Klysz & Balayssac, 2007; Leucci, 2012). Thus, in recent years, some researchers have tried to use the dielectric properties of concrete to evaluate the curing effectiveness of concrete structures (Joshaghani & Zollinger, 2017, 2021; Sun, 2013).

2.5 Summary

According to the literature review, the w/c determination error tolerance is relatively narrow (± 0.03 for INDOT). Several techniques are available in existing literature (i.e., microwave oven drying method, electrical resistivity measurement method, etc.). Nevertheless, the w/c determination results by these methods can hardly fulfill the error tolerance. Among those methods, the microwave oven drying method modified by CF and the dielectric constant value determination method are most promising methods which can be used to accurately determine the w/c value of plastic concrete. Thus, in this project, a modified coarse aggregate correction factor (CF′) was proposed to account for the measurement error caused by coarse aggregate in microwave oven drying method. Moreover, the dielectric constant of plastic concrete was determined by a 800 MHz GPR. The relationship between the dielectric constant value of composite and its water content from literature was reviewed and statistically analyzed and applied to calculate the w/c value of plastic concrete in this work.

For curing effectiveness evaluation of hardened concrete, several non-destructive testing (NDT) methods were applied in this project including GPR, electrical resistivity measurement, electrical impedance measurement method to determine the water content, microstructure and compressive strength of hardened concrete under different curing methods. Besides, multiple laboratory testing methods including TGA, MIP and water absorption measurement were adopted to evaluate the hydration degree of concrete under different curing methods.

3. USE OF DIELECTRIC CONSTANT FOR DETERMINATION OF W/C IN PLASTIC CONCRETE

This chapter reports the work of using dielectric constant value determined by a 1.6 GHz GPR to determine the w/c value of plastic concrete. Firstly, several empirical equations and theoretical models in bridging the dielectric constant values and volumetric water contents of plastic concrete were discussed. Then, the dielectric constant values of freshly mixed concrete with various compositions were measured by an 800 MHz GPR and further be used to calculate the w/c values of concrete.

3.1 Models Linking Dielectric Constant Values and Free Water Content

3.1.1 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 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 3.1.

The plots of empirical relationships between the dielectric constant values (ε) and volumetric water contents (θ_w) are illustrated in Figure 3.1. 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. 3.3. When the measured dielectric constant values are higher than 10, the calculated volumetric water contents by Eqs. 3.2 and 3.5 are still very close, while the calculated volumetric water contents from Eqs. 3.1, 3.3, and 3.4 are higher than calculated results by Eqs. 3.2 and 3.5 as presented in Figure 3.1.

3.1.2 Review of the Dielectric Constant Values for Components of Concrete

The dielectric constant of air is 1.0 (Jol, 2009), while the dielectric constant values of cement particle and aggregate particles have been assumed to be 3.365 and 13.215, respectively (Lee & Zollinger, 2012) 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 2.1, the similar research can also be found in Chen et al., 2012. 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

TABLE 3.1
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	$\theta_w = 0.00043\varepsilon^3 - 0.055\varepsilon^2 + 2.92\varepsilon - 5.3$	(Eq. 3.1)	2.5–30	2.5%–50%	Soil
Janoo et al., 1999	$\theta_w = 0.0001928\varepsilon^2 + 1.146\varepsilon - 4.425$	(Eq. 3.2)	7–14	3%–10%	Concrete
Schaap et al., 1997	$\theta_w = 100 \times (0.133\sqrt{\varepsilon} - 0.146)^{0.885}$	(Eq. 3.3)	1–49	0%–70%	Soil
Leucci, 2012	$\theta_w = 0.001\varepsilon^3 + 0.123\varepsilon^2 - 0.043\varepsilon + 3.3035$	(Eq. 3.4)	2–10	4%–14%	Concrete
Klysz & Balayssac, 2007	$\theta_w = 34.85 - 71.60\varepsilon^{-0.5}$	(Eq. 3.5)	4.94–14.06	2%–16%	Concrete

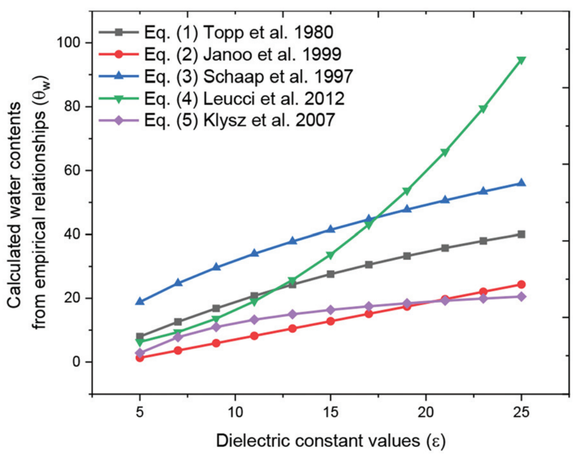


Figure 3.1 Plots of empirical relationships between the values of the dielectric constant (ε) and volumetric water contents (Δw), expressed as percent.

constant of concrete (Soutsos et al., 2001). Therefore, the dielectric constant value of water in freshly mixed concrete can be reasonably considered the same as pure water, 80 (Jol, 2009).

3.1.3 Theoretical Models

In this work, freshly mixed concrete can be considered as composed by four different components, which are, cement, water, air and aggregate. Several theoretical models have been proposed to determine the volumetric water content (θ_w) from dielectric constant value and volumetric fraction as concluded in Table 3.2.

In Eqs. 3.6 to 3.9, 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.

3.2 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 (Chen et al., 2012; Lai et al., 2009; Lee & Zollinger, 2012) were cited and the volumetric water contents were calculated by empirical relationships, which are Eqs. 3.2 and 3.5, and theoretical models, which are Eqs. 3.6 to 3.9. The experimental determined volumetric water content results in terms of measured dielectric constant values of plastic concrete are presented in Figure 3.2. It is obviously that the higher dielectric constant value indicates higher volumetric water content of plastic concrete.

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 the following.

$$\Delta\theta_w = \theta_{cal} - \theta_{exp} \qquad \text{(Eq. 3.10)}$$

The determined $\Delta\theta_w$ results by different models are presented in Figure 3.3. It can be seen that most of calculated results have less than $\pm 10\%$ error to experimental determined water contents except the calculated results from the empirical relationship Eq. 3.4.

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 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 3.3. Only Eq. 3.7 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. 3.7 had no significant difference with 0. Meanwhile, the mean value and variance value of $\Delta\theta_w$ determination results by Eq. 3.7 was the lowest compared with the results calculated by other models. Thus, it is fair to conclude that Eq. 3.7 provides the most accurate water content determination results by the measured dielectric constant values for plastic concrete out of other models in this work.

3.3 Experimental Program

3.3.1 Materials and Mixtures

All tests were carried out on concrete mixtures prepared using ordinary (Subcommittee C01.10, 2020) Type I Portland cement as the only binder. The chemical composition and physical properties of the cement are listed in Table 3.4. The natural sand was used as

TABLE 3.2
Theoretical models for prediction of volumetric water content using empirical values of dielectric constant

References	Theoretical Models	
Gladstone & Dale, 1863	$\theta_w = \frac{\varepsilon - \theta_{cem}\varepsilon_{cem} - \theta_{air}\varepsilon_{air} - \theta_{agg}\varepsilon_{agg}}{\varepsilon_w}$	(Eq. 3.6)
Lichtenecker, 1926 (Lakhtakia, 1996; Wu et al., 2003; Zakri et al., 1998)	$\theta_w = \frac{\ln\varepsilon - \theta_{cem}\ln\varepsilon_{cem} - \theta_{air}\ln\varepsilon_{air} - \theta_{agg}\ln\varepsilon_{agg}}{\ln\varepsilon_w}$	(Eq. 3.7)
Bruggeman, 1936	$\theta_w = \left(\theta_{cem}\frac{\varepsilon - \varepsilon_{cem}}{2\varepsilon + \varepsilon_{cem}} + \theta_{air}\frac{\varepsilon - \varepsilon_{air}}{2\varepsilon + \varepsilon_{air}} + \theta_{agg}\frac{\varepsilon - \varepsilon_{agg}}{2\varepsilon + \varepsilon_{agg}}\right)\frac{2\varepsilon + \varepsilon_w}{\varepsilon_w - \varepsilon}$	(Eq. 3.8)
Looyenga, 1965	$\theta_w = \frac{\varepsilon^{\frac{1}{3}} - \theta_{cem}\varepsilon_{cem}^{\frac{1}{3}} - \theta_{air}\varepsilon_{air}^{\frac{1}{3}} - \theta_{agg}\varepsilon_{agg}^{\frac{1}{3}}}{\varepsilon_w^{\frac{1}{3}}}$	(Eq. 3.9)

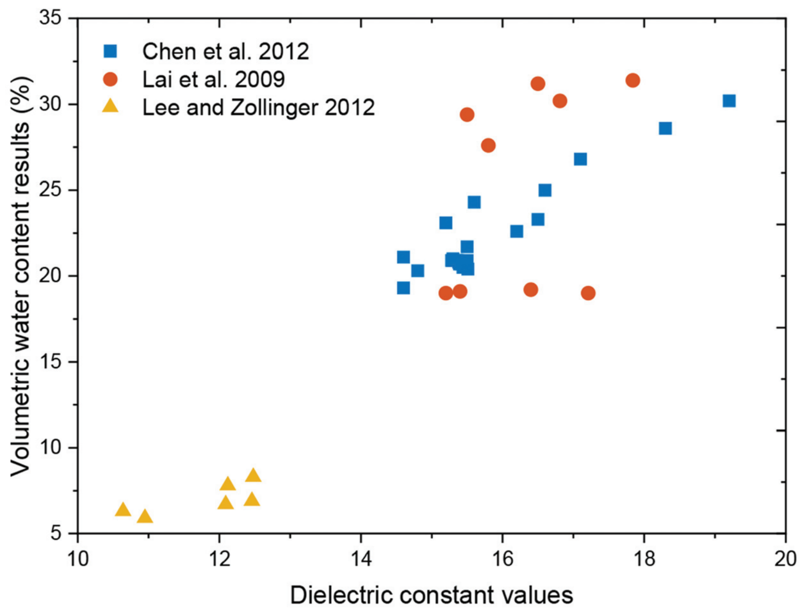


Figure 3.2 Experimental determined volumetric water content results in terms of measured dielectric constant values of plastic concrete from literature (Chen et al., 2012; Lai et al., 2009; Lee & Zollinger, 2012).

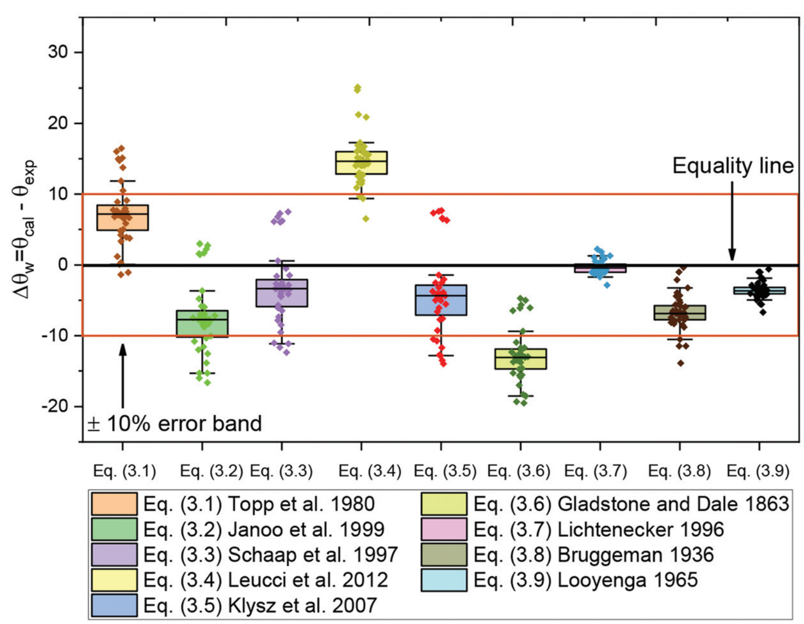


Figure 3.3 Water content determination error results by various models.

TABLE 3.3
T-test results of $\Delta\theta_w$ determination results by different models

References	p-Value	Mean Value (%)	Variance
Eq. 3.1, Topp et al., 1980	7.69E-13	7.29	19.55
Eq. 3.2, Janoo et al., 1999	1.67E-11	-7.48	25.60
Eq. 3.3, Schaap et al., 1997	4.24E-04	-3.13	26.34
Eq. 3.4, Leucci, 2012	2.11E-26	14.87	12.82
Eq. 3.5, Klysz & Balayssac, 2007	4.68E-05	-4.18	33.38
Eq. 3.6, Gladstone & Dale, 1863	2.18E-23	-12.75	13.78
Eq. 3.7, Lakhtakia, 1996; Wu et al., 2003; Zakri et al., 1998	0.07341	-0.29	0.98
Eq. 3.8, Bruggeman, 1936	4.64E-19	-6.73	6.76
Eq. 3.9, Looyenga, 1965	6.49E-21	-3.52	1.44

TABLE 3.4
Chemical composition (% by mass) and fineness of the cement

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	LoI	Fineness (m^2/kg)
62.91	19.55	5.22	2.74	2.94	3.22	2.25	409

fine aggregate with an absorption value of 2.3%, and the saturated surface dry (SSD) specific gravity of the fine aggregate was 2.637. The coarse aggregate used was stone with an absorption value of 1.3% and the SSD specific gravity of coarse aggregate was 2.667. All aggregates were oven dried (OD) before mixing, so the moisture value of aggregates was 0.0%. The details of the mixture proportions are given in Table 3.5, no chemical admixture was used. The initial setting time of these mixtures with the same cement has been reported by companion work (Su et al., 2019), all mixtures' initial setting times were longer than 200 minutes. Each mixture was prepared with three batches and denoted as w/c-1, w/c-2, and w/c-3 (i.e., for w/c=0.39 mixture, three batches were denoted as 0.39-1, 0.39-2, and 0.39-3). GPR measurement, microwave oven drying test, and air content test were conducted for each batch.

3.3.2 GPR Measurement

3.3.2.1 Principles of using electromagnetic wave theory for dielectric constant value determination. The dielectric constant of plastic concrete was determined by analyzing the electromagnetic (EM) waveform. The schematic of the method is shown in Figure 3.4a. A typical GPR signal (EM waveform) is present in Figure 3.4b. The EM wave velocity in the tested concrete sample can be calculated by the arrival time difference (Δt) between the first (t_1) and second (t_2) reflected wave pulse in accordance with Eq. 3.11.

$$v_m = \frac{2h}{\Delta t} \times 10^9 \qquad \text{(Eq. 3.11)}$$

where v_m is the EM wave velocity in concrete sample (m/s), h denotes the thickness of the concrete sample (0.1 m, in this work), Δt denotes the arrival time difference between the first and second reflected wave pulse (ns).

The dielectric constant of concrete can be determined by the EM wave velocity in accordance with Eq. 3.12 (Subcommittee D18.01, 2020).

$$\varepsilon = \left(\frac{c}{v_m}\right)^2 \qquad \text{(Eq. 3.12)}$$

where ε denotes the dielectric constant value of the plastic concrete, c is the speed of light (3×10^8 m/s) and v_m is the EM wave velocity in tested concrete sample (m/s).

3.3.2.2 GPR measurement method. The GPR unit used in this work was a MALA X3M system (manufactured by MALÅ Geoscience USA, Inc.) with 800 MHz antenna. The data acquisition and processing units of the system were controlled by the MALA GroundVision 2.0 software. After the concrete was placed in the mold, the GPR unit was attached into the front face of the mold and powered-up. The measurements were initiated 10 minute after combining cement with water and were conducted at constant temperature of 23°C. Once the measurements were initiated, the data were recorded automatically at intervals of 5 minute. The total duration of the test was 1 hour (i.e., the test was terminated 70 minute after combining cement with water).

3.3.3 Microwave Oven Drying Measurement

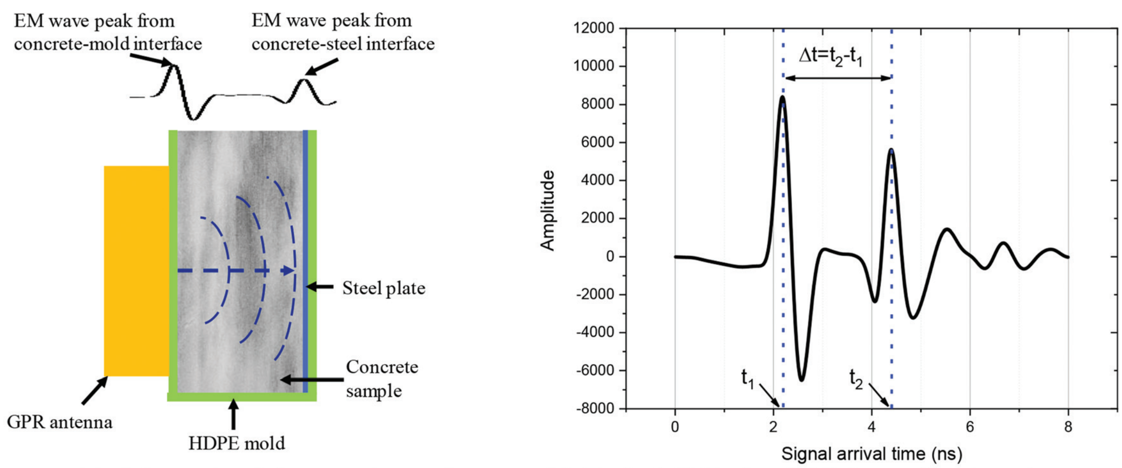
Gravimetric water content of plastic concrete was determined by evaporation method in accordance with AASHTO T318-15 (2019) as shown in Figure 3.5.

3.3.4 Air Content Measurement

The air content (θ_{air}, %) of plastic concrete was determined by an air meter (Figure 3.6) in accordance with ASTM C 231 (ASTM, 2017).

TABLE 3.5
SSD mixture proportions of concrete (kg/m^3)

Design w/c	Cement	Mixing Water	Fine Aggregate	Coarse Aggregate	Design Density (D_{design})
0.39	335	130	860	1,165	2,490
0.42	335	141	849	1,150	2,474
0.45	335	151	838	1,135	2,457
0.48	335	161	826	1,119	2,441
0.51	335	171	815	1,104	2,424



(a) Schematic of the experimental setup for GPR measurement (side view).

(b) Typical GPR signal (EM waveform): t_1 denotes the time of arrival of the first reflected wave pulse, t_2 denotes the time of the arrival of the second reflected wave pulse, $\Delta t = t_2 - t_1$.

Figure 3.4 Schematic of the experimental setup and the example of a typical EM waveform.

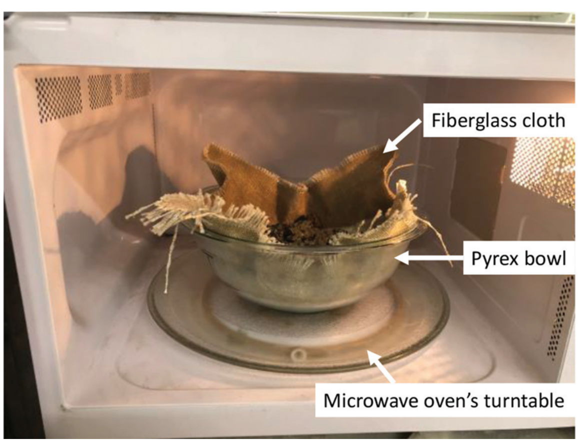


Figure 3.5 Concrete sample in microwave oven.

3.4 w/c Calculation

3.4.1 w/c Calculation from Microwave Oven Drying Measurement Results

3.4.1.1 Gravimetric water content of concrete. The gravimetric water content of concrete (α) can be determined by microwave oven drying measurement in according with AASTO T318-15 (2019) as the following equation.

$$\alpha = \frac{WF - WD}{WF - WS} \times 100\% \qquad \text{(Eq. 3.13)}$$

where WF denotes the combined mass of the Pyrex bowl, cloth, and plastic concrete test specimen together (g), WS represents the mass of the bowl and cloth together (g), and WD is the combined mass of the bowl, cloth, and dry specimen (g).

So, the total water mass in unit volume of plastic concrete can be calculated as Eq. 3.14.

$$M_{water} = \alpha \times D_{design} \qquad \text{(Eq. 3.14)}$$

where D_{design} is the design density of plastic concrete (kg/m^3), which can be found in concrete mixture recipe.

3.4.1.2 Aggregate absorbed moisture adjustment. In microwave oven drying measurement, all water from the concrete sample is removed including the absorbed moisture in aggregates. Concrete mixtures are adjusted and batched by assuming that aggregates are in saturated surface dry (SSD) condition. So, the aggregate absorption must be accounted for in the calculations. The moisture of aggregate (ϕ_{moi}) can be calculated in

Figure 3.6 Air meter used in this work.

accordance with ASTM C127 (2015 edition) (Subcommittee C09.20, 2015) as follows.

$$\phi_{moi} = \frac{M_{dry} - M_{wet}}{M_{dry}} \quad \text{(Eq. 3.15)}$$

where M_{dry} denotes the mass of dry aggregates (g), in microwave oven drying measurement, which is the mass of aggregates after the drying test. M_{wet} denotes the mass of wet aggregates (g), in microwave oven drying measurement, which is the mass of aggregates before mixing. When aggregates are in SSD condition, the absorption of aggregate (ϕ_{moi}) can be calculated as Eq. 3.16.

$$\phi_{abs} = \frac{M_{dry} - M_{SSD}}{M_{dry}} \quad \text{(Eq. 3.16)}$$

where M_{dry} denotes the mass represents the mass of aggregates in SSD condition (g).

Thus, the aggregate absorbed water mass (kg) in unit volume plastic concrete can be calculated as Eq. 3.17.

$$M_{abs} = \frac{\phi_{abs}}{1 + \phi_{moi}} M_{wet} \quad \text{(Eq. 3.17)}$$

where M_{abs} denotes the aggregate absorbed water mass in unit volume of concrete (kg), M_{wet} represents the added aggregate mass in unit volume of concrete (kg), which can be found in concrete mixture recipe.

After the gravimetric water content (α) and the aggregate absorbed moisture content are obtained, the characterized w/c of plastic concrete by microwave oven drying measurement can be calculated as Eq. 3.18.

$$\frac{W}{C} = \frac{M_{water} - M_{CA,abs} - M_{FA,abs}}{M_{cem}} = \frac{\alpha \times D_{design} - \left[\left(\frac{\varnothing_{CA,abs}}{1 - \varnothing_{CA,moi}}\right) M_{CA} + \left(\frac{\varnothing_{FA,abs}}{1 - \varnothing_{FA,moi}}\right)\right]}{M_{cem}} \quad \text{(Eq. 3.18)}$$

where M_{CA} and M_{FA} denote the added coarse aggregate and fine aggregate masses in unit volume concrete, respectively (kg), which can be found in concrete mixture recipe. M_{cem} denotes the added cement mass in unit volume of concrete (kg), which can be found in concrete mixture recipe.

The Eq. 3.18 can also be written as the well-known calculation equation as reported by (Nantung, 1998; NHDOT, 2016; Yohannes & Olek, 2012).

$$\frac{w}{c} = [(N+1) \times MD] - N \times [ACA \times (1 - FA) + AFA \times FA] \quad \text{(Eq. 3.19)}$$

where N denotes the ratio of the total weight of dry aggregates to the cement weight in unit volume of plastic concrete, MD denotes the ratio of the wet weight of the concrete sample minus the dry weight of the concrete sample to the dry weight of the concrete sample in unit volume of concrete, FA represents the ratio of the weight of dry fine aggregate in unit volume of concrete to the total weight of dry aggregates of the same volume of concrete, ACA and AFA represent the absorption value of coarse aggregate and fine aggregate, respectively.

3.4.2 w/c Calculation from GPR Measurement Results

The volumetric water content of plastic concrete (θ_w) can be determined by the dielectric constant result which is obtained from the GPR measurement. In Section 3.2 of this report, a logarithmic rule proposed by Lichtenecker (Lakhtakia, 1996; Wu et al., 2003; Zakri et al., 1998) was found to provide the most accurate volumetric water content calculation results from the measured dielectric constant values. The model can be expressed as Eq. 3.20.

$$\theta_w = \frac{\ln \varepsilon - \theta_{cem} \ln \varepsilon_{cem} - \theta_{air} \ln \varepsilon_{air} - \theta_{agg} \ln \varepsilon_{agg}}{\ln \varepsilon_w} \quad \text{(Eq. 3.20)}$$

where the parameter θ_w denotes the volumetric water content of plastic concrete (%); the parameters θ_{cem}, θ_{air}, θ_{agg}, denote the volumetric contents of, cement particle, air, and aggregate, respectively (%). The parameters ε_{cem}, ε_{agg}, ε_w, ε_{air}, denote, respectively, the dielectric constant values of cement particle, aggregate, water, and air. The parameter ε denotes the total dielectric constant value of plastic concrete (determined by GPR measurement).

The volumetric contents of air (θ_{air}, %) can be determined by the air meter. The volumetric contents of cement particle (θ_{cem}) and aggregates (θ_{agg}) can be determined by the concrete mixture recipe by the following equation.

$$\theta = \frac{M}{1{,}000\rho(1 - \theta_{air})} \quad \text{(Eq. 3.21)}$$

where M is the mass of cement or aggregates in unit volume of concrete, which can be found in concrete mixture recipe (kg). ρ denotes the specific gravity of cement particle (i.e., 3.15 in this work) or aggregate (i.e., 2.637 for fine aggregate, 2.667 for coarse aggregate in this work).

After the volumetric water content (θ_w) has been determined, the w/c of plastic concrete can be calculated in Eq. 3.22.

$$\frac{w}{c} = \frac{1{,}000\theta_w}{M_{cem}(1-\theta_{air})} \qquad \text{(Eq. 3.22)}$$

where M_{cem} denotes the added cement mass in in unit volume plastic concrete (kg), which can be found in concrete mixture recipe.

3.5 Results and Discussion

3.5.1 GPR, Microwave Oven, and Air Content Measurement Results

A summary of GPR, microwave oven and air content measurement results of all batches were concluded in Table 3.6. The arrival time difference (i.e., Δt) resulted from each batch is the average measurement result for the time interval between 10 minutes and 70 minutes after combining cement with water. The arrival time difference of plastic concrete varied from 2.5104 ns to 2.6171 ns, the standard deviation for arrival time difference results is very small which indicates the water content of each batches' concrete remains stable in GPR measurement duration. The microwave oven test duration varied from 18 minutes to 24 minutes. The air content of plastic concrete in this study varied from 2.06% to 2.85%.

3.5.2 w/c Determination from Microwave Oven Drying Measurement Results

The calculated w/c results from the microwave oven drying measurement results in this work are presented in Figure 3.7, the calculated w/c from the measured gravimetric water content in this work shows good correlation with the design w/c. There are only two batches' calculated results which are out of ± 0.03 range.

The coefficient of variation (COV, or also known as relative standard deviation, RSD) was used to evaluate the calculated w/c value's dispersion for each mixture. It shows the extent of variability in relation to the mean of the population. The COV is defined as the ratio of the standard deviation ($sd_{w/c}$) of three batches' calculated w/c values to the mean value ($\bar{x}_{w/c}$) of three batches' calculated w/c values as shown in Eq. 3.23.

$$COV = \frac{sd_{w/c}}{\bar{x}_{w/c}} \times 100\% \qquad \text{(Eq. 3.23)}$$

The COV value of every mixture is presented in Figure 3.7. The average COV value of all mixtures is 4.34%.

3.5.3 w/c Determination from GPR Measurement Results

The calculated w/c of plastic concrete determined by measured dielectric constant values of all mixtures are shown in Figure 3.8. Only three batches' calculated w/c values fall outside the ± 0.03 range which indicates that the calculated w/c results by the measured dielectric constant values in this work shows a strong correlation with the design w/c.

The calculated COV values of all mixtures from GPR measurement results are presented in Figure 3.8. The average COV for all mixtures is 1.28%, which is lower than the microwave oven drying measurement results as presented in Figure 3.7.

TABLE 3.6
GPR, microwave oven drying and air content measurement results of all mixtures

	GPR Measurement		Microwave Oven Measurement				Air Content Measurement
Sample ID	**Δt (ns)**	**Standard Deviation**	**WS (g)**	**WF (g)**	**WD (g)**	**Test Duration (min)**	**θ_{air} (%)**
0.51-1	2.5956	0.0085	1,078	2,627	2,499	24	2.74
0.51-2	2.6171	0.0026	1,083	2,623	2,488	24	2.85
0.51-3	2.6042	0.0094	1,081	2,604	2,475	22	2.62
0.48-1	2.574	0.0058	1,081	2,658	2,531	22	2.55
0.48-2	2.5614	0.0025	1,082	2,582	2,461	22	2.38
0.48-3	2.537	0.0031	1,075	2,595	2,480	20	2.46
0.45-1	2.5527	0.0088	1,080	2,591	2,481	20	2.09
0.45-2	2.5496	0.0037	1,081	2,589	2,470	24	2.06
0.45-3	2.5337	0.0058	1,080	2,656	2,543	18	2.17
0.42-1	2.5217	0.002	1,084	2,597	2,494	20	2.18
0.42-2	2.5389	0.0056	1,079	2,601	2,490	22	2.49
0.42-3	2.5329	0.0024	1,079	2,622	2,513	20	2.73
0.39-1	2.5104	0.0016	1,081	2,603	2,505	20	2.25
0.39-2	2.5263	0.0017	1,081	2,606	2,498	20	2.80
0.39-3	2.5246	0.0028	1,082	2,624	2,517	20	2.34

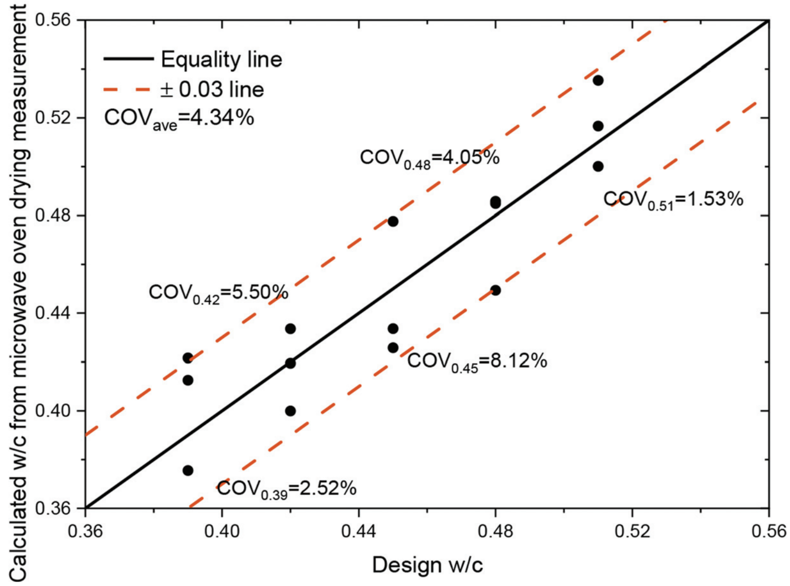


Figure 3.7 Calculated w/c from microwave oven drying measurement results.

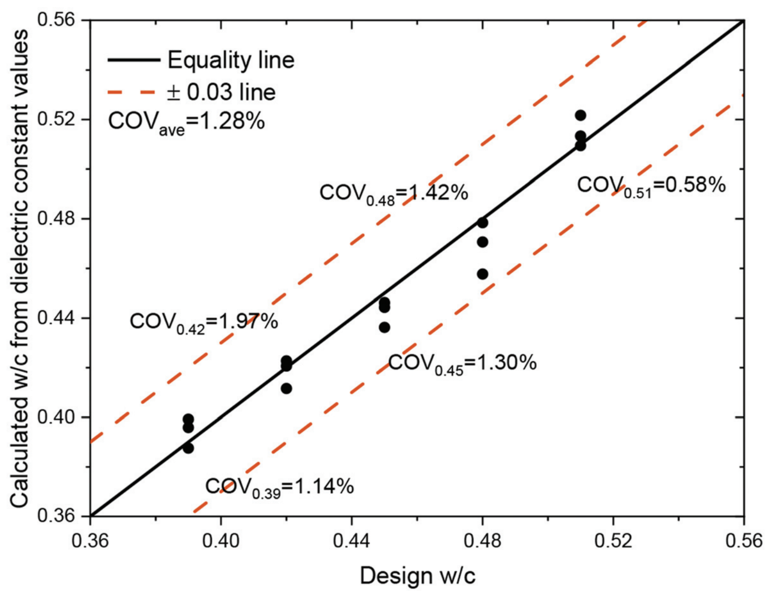


Figure 3.8 Calculated w/c from GPR measurement results.

3.5.4 Statistical Comparison w/c Determination Results by Two Methods

The error of calculated w/c ($\Delta w/c$) by two methods in this work is calculated in Eq. 3.24.

$$\Delta {}^{w}/_{c} = {}^{w}/_{c_{cal}} - {}^{w}/_{c_{des}} \qquad \text{(Eq. 3.24)}$$

where w/c_{cal} denotes the calculated w/c determined by microwave oven drying measurement results (i.e., presented in Figure 3.7) or GPR measurement results (i.e., presented in Figure 3.8), and w/c_{des} denotes the design w/c of the concrete.

The $\Delta w/c$ results from two measurements were evaluated by t-test with the null hypothesis that the mean values of $\Delta w/c$ results by GPR measurement or microwave oven drying measurement have no significant difference with 0. A summary of statistical parameters including the p-value of t-test, mean value and variance value of $\Delta w/c$ results and the COV value for two measurements are presented in Table 3.7. The p-values for both measurements are higher than 0.05 which indicate that the mean value of $\Delta w/c$ results from GPR measurement and microwave oven drying measurement have no significant difference with 0. In other word, the calculated w/c values by GPR and microwave oven drying measurements have no significant different with the design w/c values, the null hypothesis cannot be rejected. The p-value of microwave oven drying

TABLE 3.7
Summary of statistical parameters

Measurements	p-Value	Mean Value	Variance	COV Value
GPR	0.3353	-0.0023	8E-5	1.28%
Microwave	0.7833	0.0015	4E-4	4.34%

measurement is higher than GPR measurement. The mean value of $\Delta w/c$ results for both of the measurements are very close to 0, the absolute value of the mean value for GPR measurement (i.e., 0.0023) is slightly higher than microwave oven drying measurement (i.e., 0.0015), while the variance of GPR measurement is much lower than microwave oven drying measurement. The results of mean value and variance value indicate that although the GPR measurement might slightly provide a larger error in w/c determination results than microwave oven drying measurement, the result from GPR measurement would be more stable than microwave oven drying measurement.

3.6 Summary

In this section, five empirical equations and four theoretical models for determining volumetric water content of plastic concrete by its dielectric constant value were firstly discussed. Then, water-to-cement ratios of plastic concrete were determined by dielectric constant values through an 800 MHz ground penetrating radar (GPR) measurement and gravimetric water content values through a microwave oven drying measurement in accordance with AASHTO T318. Based on the experimental results, the w/c obtained from GPR measurement is comparable with the microwave oven drying measurement in AASHTO T318. The dielectric constant measurement of plastic concrete might be a potential method to determine the w/c.

4. THE APPLICATION OF MODIFIED COARSE AGGREGATE CORRECTION FACTOR TO MICROWAVE OVEN DRYING METHOD

There are two major concerns regarding the accuracy of microwave oven drying measurement. The first is whether the water can be completely evaporated out of concrete, and the other is the measurement result variation caused by coarse aggregate content deviating from batch concrete in sample, which is also known as sampling error. The deviation of measured w/c results from design values has been reported from -0.052 to +0.067 (Dowell & Cramer, 2002). The National Ready Mixed Concrete Association (NRMCA) specifies the acceptance criteria for microwave oven drying measurement results at ± 0.05 precision of the measured results to target values (Hover et al., 2008). To address the sampling error issues, NRMCA (Hover et al., 2008) proposed to use a coarse aggregate correction factor (*CF*) to adjust the coarse aggregate content in concrete sample. The *CF* has been applied by several researchers (Mardmomen et al., 2019; Nantung, 1998) and promising w/c determination results in laboratory studies were obtained.

To address the aforementioned concerns in applying microwave oven drying measurement, a modified coarse aggregate correction factor (CF'), which is based on the correction factor as introduced by NRMCA, was proposed and applied in concrete w/c calculation. The obtained w/c results were statistically verified with the design w/c values.

4.1 Theoretical Background of Modified Coarse Aggregate Correction Factor

AASHTO T318 (2019) provides a microwave oven drying method to test the gravimetric water content (α) of freshly mixed concrete. The w/c of the freshly mixed concrete can be calculated by the tested gravimetric water content and other components' contents from mixture recipe. The details of w/c calculation from microwave oven drying measurement can be found in Section 3.4.1 of this report.

AASHTO T318 proposes to use 1.5 kg freshly mixed concrete as sample for microwave oven drying test. This sample size is small in proportion to the whole batch, which might result in the sample being unable to represent the content of each component due to the deviation of coarse aggregate within the sample from the concrete batch. This deviation of coarse aggregate content is named as sampling error which will influence the calculated w/c result as reported in Dowell & Cramer (2002).

A larger sample size might eliminate sampling error, but the experiment duration would have taken longer and would have been less practical for field use. To address the sampling error issue in associated with small size sample, National Ready Mixed Concrete Association (NRMCA) (Hover et al., 2008) proposed to use a coarse aggregate correction factor (CF) to correct the w/c calculation equation. The coarse aggregate correction factor is expressed as in Eq. 4.1.

$$CF = \frac{1 - CA_{batch}}{1 - CA_{sample}} \quad \text{(Eq. 4.1)}$$

where CA_{batch} represents ratio of the weight of dry coarse aggregate in unit volume of concrete to the total weight of the same volume of fresh concrete, which can be found in mix recipe, CA_{sample} denotes the ratio of the weight of dry aggregate extracted from concrete sample to the weight of wet concrete sample.

Then, the modified w/c calculation equation expression is given below as follows.

$$\frac{w}{c} = \frac{\alpha \times D_{design} \times CF - \left(\frac{\phi_{CA,abs}}{1-\phi_{CA,moi}}\right) M_{CA} - \left(\frac{\phi_{FA,abs}}{1-\phi_{FA,moi}}\right) M_{FA}}{M_{cem}} \quad \text{(Eq. 4.2)}$$

In this work, a modified CF expression is given as Eq. 4.3.

$$CF' = \frac{1-(1-GF_{CA})CA_{batch}}{1-CA_{sample}} \quad \text{(Eq. 4.3)}$$

where GF_{CA} is coarse aggregate grading factor which denotes No. 4 sieve percent passing value of coarse aggregate.

Finally, the w/c of freshly mixed concrete can be calculated by applying the modified coarse aggregate correction factor (CF') as follows.

$$\frac{w}{c} = \frac{\alpha \times D_{design} \times CF' - \left(\frac{\phi_{CA,abs}}{1-\phi_{CA,moi}}\right)M_{CA} - \left(\frac{\phi_{FA,abs}}{1-\phi_{FA,moi}}\right)M_{FA}}{M_{cem}} \quad \text{(Eq. 4.4)}$$

It is worth noting that the coarse particles in fine aggregate (which cannot pass No. 4 sieve) is not considered in Eq. 4.4 since in most cases, the coarse particle content in fine aggregate is negligible. For example, the No. 4 sieve passing percent requirements for INDOT #23, #24 (INDOT, 2019) and ASTM C33 (ASTM, 2018) fine aggregates are both 95%–100%.

4.2 Experimental Program

Ordinary Portland cement Type I (Subcommittee C01.10, 2020) with the specific gravity of 3.150 was used as the only binder for all concrete mixtures. The chemical composition and physical properties of the cement are listed in Table 3.4. Four types of aggregates were used in this work, which are, normal weight coarse aggregate (NWCA), normal weight fine aggregate (NWFA), lightweight coarse aggregate (LWCA), and lightweight fine aggregate (LWFA). The aggregate size grading curves for NWFA, LWCA and LWFA are presented in Figure 4.1. The lightweight coarse aggregate grading factor (GF_{LWCA}) was 11.72%. Due to the variation of NWCA grading curve, the normal weight coarse aggregate grading factor (GF_{NWCA}) for each mixture design was determined by sieving the NWCA through a No. 4 sieve before every mixing.

4.3 Mixture Design

4.3.1 Cement Paste and Mortar Mixture Design

In this work, different cementitious composites were mixed and dried by the microwave oven drying measurement. For a fresh concrete composite, water is primarily in mortar. Thus, several cement paste and cement mortar samples with different fine aggregate moisture contents were prepared for microwave oven drying measurement. The mixture design for cement paste (CP) and mortar samples are concluded in Table 4.1.

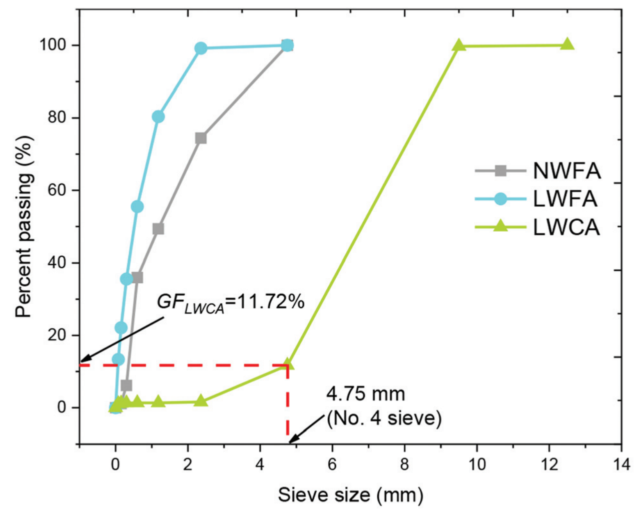


Figure 4.1 Aggregate grading curves.

4.3.2 Concrete Mixture Design

Concrete was also prepared with dry aggregate and wet aggregate for each w/c mixture. Four different composite types were prepared, which are, normal weight concrete (NWC), lightweight concrete (LWC), normal weight concrete without fine aggregate (NWC-no NWFA), and lightweight concrete without fine aggregate (LWC-no LWFA). The details of concrete mixture design are presented in Table 4.2.

4.3.3 Coarse Aggregate Grading Factor Study Mixture Design

In order to study the influence of fine particle content on w/c calculation results with the application of unmodified correction factor (Eq. 4.2), several concrete mixtures with different pre-design coarse aggregate grading factor values were prepared. Three NWC mixtures of w/c 0.42, 0.45, and 0.48, respectively, were prepared. All mixtures were mixed with dry NWCA and NWFA (i.e., $\phi_{NWCA,moi}=\phi_{NWFA,moi}=0.00\%$). For each w/c concrete, nine mixtures with different GF_{NWCA} values were prepared. The GF_{NWCA} values were designed from 0.00% to 16.00% with 2.00% interval.

4.3.4 Measurement Time Delay Study Mixture Design

In this study, three NWC mixtures with the w/c of 0.42, 0.45, and 0.48, respectively, were prepared. After mixing, each mixture was prepared with six samples in concrete cylinder molds with a diameter of 76.2 mm (3 inches) and a height of 152.4 mm (6 inches). All cylinder samples were stored in an environmental room with a temperature of 23°C and a relative humidity of 75% without lid. The first cylinder sample was tested right after the mixing process was done and then in 30 minutes intervals up to 150 minutes measure the mass of all remaining samples and take one cylinder sample out for microwave oven drying measurement.

TABLE 4.1
Mixture design of cement paste and cement mortar (kg/m^3)

Composite Types	Design w/c	Cement	Water	FA	$\phi_{FA,moi}$	Design α (%)
CP	0.38	1,434	545	/	/	27.54
	0.35	1,498	524	/	/	25.93
	0.32	1,569	502	/	/	24.24
	0.29	1,646	477	/	/	22.48
	0.26	1,732	450	/	/	20.63
NWM	0.43	664	286	1,328	0.00% for dry NWFA	13.85
	0.40	678	271	1,355	2.86% for wet NWFA	13.09
	0.37	692	256	1,383		12.31
	0.34	706	240	1,413		11.53
	0.31	722	224	1,443		10.73
	0.28	738	207	1,475		9.91
	0.25	754	189	1,508		9.08
LWM	0.43	552	237	1,105	0.00% for dry LWFA	18.09
	0.40	562	225	1,123	6.57% for wet LWFA	17.35
	0.37	571	211	1,142		16.62
	0.34	581	198	1,162		15.87
	0.31	591	183	1,183		15.11
	0.28	602	169	1,204		14.33
	0.25	613	153	1,226		13.54

TABLE 4.2
Mixture design of concrete

Composite Types	Design w/c	Cement	Water	FA	CA	GF_{CA} (%)	$\phi_{FA,moi}$	$\phi_{CA,moi}$	Design α (%)
NWC-dry aggregates	0.57	335	191	793	1,073	8.04	0.00%	0.00%	9.31
	0.54	335	181	804	1,089	4.01			8.84
	0.51	335	171	815	1,104	3.57			8.38
	0.48	335	161	826	1,119	4.00			7.93
	0.45	335	151	838	1,135	2.57			7.48
	0.42	335	141	849	1,150	1.04			7.04
	0.39	335	130	860	1,165	0.89			6.61
NWC-wet aggregates	0.57	335	191	793	1,073	12.41	2.85%	0.20%	9.31
	0.54	335	181	804	1,089	5.84			8.84
	0.51	335	171	815	1,104	10.40			8.38
	0.48	335	161	826	1,119	8.71			7.93
	0.45	335	151	838	1,135	8.06			7.48
	0.42	335	141	849	1,150	9.37			7.04
	0.39	335	130	860	1,165	5.57			6.61
LWC	0.52	335	174	579	643	11.72	0.00% for dry	0.00% for dry	15.65
	0.49	335	164	587	652		LWFA	LWCA	15.09
	0.46	335	154	595	661		10.53% for wet	3.11% for wet	14.55
	0.43	335	144	603	670		LWFA	LWCA	14.00
	0.40	335	134	611	679				13.45
	0.37	335	124	619	688				12.90
	0.34	335	114	627	697				12.36
NWC-no NWFA	0.44	883	389	/	883	0.00	/	0.00% for dry	18.55
	0.41	907	372	/	907			NWCA	17.45
	0.38	932	354	/	932			1.34% for wet	16.51
	0.35	959	336	/	959			NWCA	15.44
	0.32	988	316	/	988				14.34
	0.29	1018	295	/	1018				13.23
LWC-no LWFA	0.41	731	300	/	731	0.00	/	0.00% for dry	19.72
	0.38	747	284	/	747			LWCA	18.72
	0.35	764	268	/	764			3.36% for wet	17.68
	0.32	782	250	/	782			LWCA	16.61
	0.29	801	232	/	801				15.52
	0.26	821	213	/	821				14.40

4.4 Coarse Aggregate Correction Factor Determination Procedures

In this work, the gravimetric water content of freshly mixed concrete is determined in accordance with AASHTO T318 (AASHTO T318-15, 2019) while the CA_{sample} value is obtained by the method proposed in *Determination of Water-To-Cement Ratio in Fresh Concrete Using Microwave Oven* (Nantung, 1998). The CA_{sample} value determination procedures are concluded to be the following.

1. After the mixing process was done, prepare two cylinders with a diameter of 76.2 mm (3 inches) and a height of 152.4 mm (6 inches) (the volume of the cylinder is 6.93 L, concrete mass with this volume is 1.6 kg $\pm$0.1 kg), record the mass of two empty cylinders as C_1 and C_2. Filling two cylinders with freshly mixed concrete and then determine the masses of two cylinders together with concrete. If the mass difference between two cylinders is higher than 10 g, dump concrete and refill two cylinders until the mass difference is lower than 10 g.
2. Take the first cylinder and pour the concrete into a No. 4 sieve with the bottom. Carefully scrape off the concrete on the inner wall of the cylinder. Determine the mass of the emptied cylinder as CC_1, the mass difference between C_1 and CC_1 should be less than 10 g. Then record the mass of concrete in the sieve as M_1 (g).
3. Wet sieve the concrete and then put all coarse aggregated left in No. 4 sieve into a heat-resistant glass tray. Put the glass tray into an oven and set the temperature of the oven to 105°C. Dry the coarse aggregate for at least 5 hours or put the glass tray into a microwave oven and turn the microwave on for at least 30 minutes to completely dry the coarse aggregate. Record the mass of dried coarse aggregate as M_2 (g).
4. The value of CA_{sample} can be calculated as Eq. 4.5.

$$CA_{sample} = \frac{M_2}{M_1} \qquad \text{(Eq. 4.5)}$$

4.5 Results and Discussion

4.5.1 Cement Paste and Mortar Measurement Results

In this work, all cement paste and mortar tests were stopped when the mass change was less than 1.0 g, and then kept continuing to dry the samples until the mass change was less than 0.5 g. Eq. 3.13 can calculate the results of measured gravimetric water content. The results of measured gravimetric water content results of cement paste and mortar samples are presented in Table 4.3. The measured gravimetric water content

TABLE 4.3
Measured gravimetric water content results of cement paste and mortar samples

Mixture Type	Design α_{des} (%)	Measured $\alpha_{mes0.5}$ (%)	Relative Error ($RE_{\alpha0.5}$, %)	Measured $\alpha_{mes1.0}$ (%)	Relative Error ($RE_{\alpha1.0}$, %)
CP	27.54	27.58	0.15	27.21	-1.17
	25.93	25.45	-1.84	25.39	-2.08
	24.24	24.31	0.27	23.73	-2.10
	22.48	22.12	-1.61	22.06	-1.86
	20.99	20.41	-2.76	20.41	-2.76
	20.63	20.78	0.70	20.56	-0.38
NWM 2.86% moisture for wet NWFA	13.09	13.05	-0.32	12.82	-2.03
	12.31	12.42	0.84	11.65	-5.38
	11.53	11.44	-0.75	11.42	-0.97
	10.73	10.55	-1.68	10.27	-4.28
	9.91	9.93	0.24	9.58	-3.31
	9.08	9.12	0.38	8.74	-3.74
NWM 0.00% moisture for dry NWFA	13.85	13.5	-2.50	13.4	-3.27
	13.09	13.18	0.69	12.71	-2.90
	12.31	12.51	1.55	12.16	-1.29
	11.53	11.69	1.40	11.54	0.12
	10.72	10.8	0.78	10.64	-0.75
	9.9	9.94	0.36	9.63	-2.78
	9.08	9.64	6.14	9.38	3.37
LWFA 0.00% moisture for dry LWFA	18.08	18.48	2.19	18.21	0.74
	17.36	17.23	-0.76	17.09	-1.57
	16.62	16.69	0.41	16.59	-0.20
	15.87	15.92	0.31	15.85	-0.10
	15.12	15.62	3.31	15.17	0.32
	14.33	14.59	1.84	14.46	0.90
	13.55	14.06	3.77	14.06	3.77
LWFA 6.57% moisture for wet LWFA	18.09	18.1	0.08	17.83	-1.42
	17.35	17.26	-0.53	16.95	-2.31
	16.62	16.36	-1.54	15.86	-4.58
	15.87	15.85	-0.15	15.53	-2.17
	15.11	15.42	2.03	14.88	-1.53
	14.33	14.78	3.09	14.55	1.51
	13.54	13.5	-0.34	13.48	-0.47

Note: Measured $\alpha_{mes0.5}$ and $\alpha_{mes1.0}$ denote the measured gravimetric water contents when the measurements were stopped when the mass change was less than 0.5 g and 1.0 g, respectively. Relative error (RE_α) = (α_{mes} - α_{des}) / α_{des} $\times$100%.

results are very close to the design gravimetric water content. When measurements were stopped when mass changes were less than 1.0 g, the calculated gravimetric water content result relative errors fall within the range of -5.38% to 3.77%. When samples were continuously dried when mass changes were less than 0.5 g, the calculated gravimetric water content result relative errors fall within the range of -2.76% to 6.14%.

The calculated w/c error ($\Delta w/c$) is expressed as Eq. 4.6.

$$\Delta \frac{w}{c} = \frac{w}{c}_{cal} - \frac{w}{c}_{des} \qquad \text{(Eq. 4.6)}$$

where w/c_{cal} denotes the calculated w/c value and w/c_{des} represents the design w/c value.

The $\Delta w/c$ results obtained from two experiment termination criteria methods were evaluated by t-test with the null hypothesis that the mean value of the difference between the calculated w/c results and design w/c is 0. The p-values of the t-test, mean values, and variance values of $\Delta w/c$ results from these two termination criteria methods are summarized in Table 4.4. The p-value of t-test for the 1.0 g termination method was 7.08E-4, which is lower than 0.05 while for 0.5 g termination method was 0.1187, which is higher than 0.05. Thus, it is suggested to terminate the microwave oven drying test when the mass change is less than 0.5 g. The following tests in this study, all tests were stopped when concrete mass change was less than 0.5 g.

4.5.2 Concrete Measurement Results

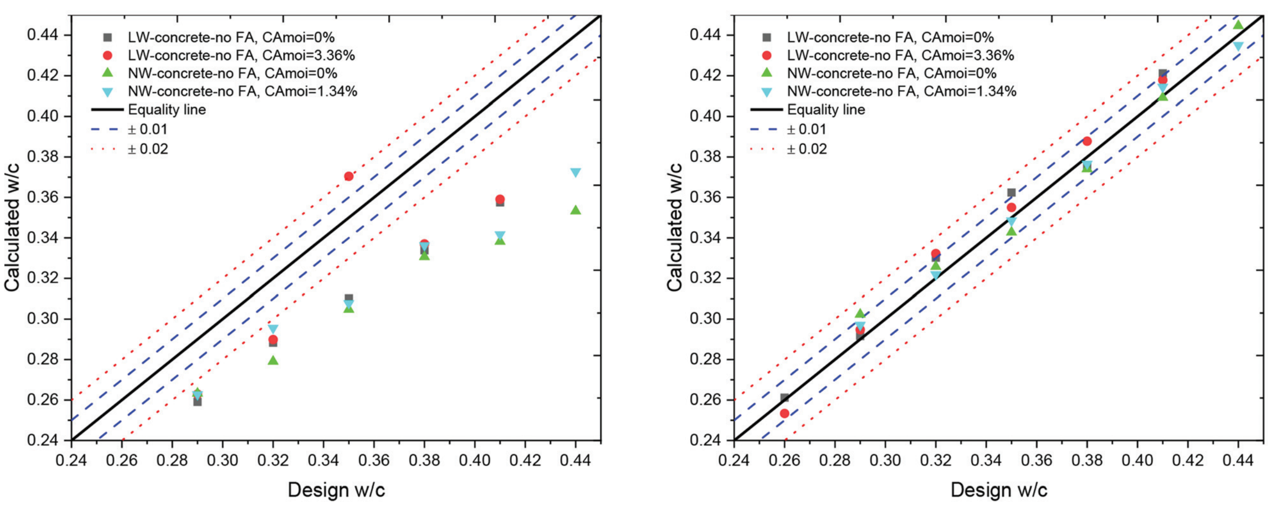
4.5.2.1 Concrete without fine particles. The calculated w/c results of concrete without fine particles are presented in Figure 4.2. It is obvious that the calculated w/c results without the application of *CF* have a large departure from the target values. When the coarse aggregate correction factor (*CF*) was applied in the calculation, the calculated w/c results were close to design values. All of the calculated results fall within ±0.02 w/c error range.

The water in cement mortar can be evaporated out as described in Section 4.5.1. In Figure 4.2a, concrete samples mixed with dry and wet coarse aggregates showed similar error and all concrete samples mixed with dry and wet coarse aggregates had very close calculated w/c results with the application of CF as presented in Figure 4.2b. Thus, it is reasonable to attribute the departure in Figure 4.2a into coarse aggregate sampling error.

4.5.2.2 Concrete with fine particles. The w/c of concrete with fine aggregates and fine particles in coarse aggregates can be calculated in accordance with

TABLE 4.4
Summary of statistical parameters for cement paste and mortar test results

Measurement Termination Criteria	p-Value	Mean Value	Variance
Mass change was less than 1.0 g	7.08e-4	0.00207	5.67e-5
Mass change was less than 0.5 g	0.1187	-0.00549	7.35e-5



(a) w/c calculation results in terms of design w/c without the application of *CF*

(b) w/c calculation results in terms of design w/c with the application of *CF*

Figure 4.2 Calculated w/c results in terms of design w/c for concrete without fine particles.

Eqs. 3.13, 4.2, and 4.4 for the results without coarse aggregate correction factor, the application of coarse aggregate correction factor and the application of modified correction factor. The calculated w/c results in terms of design w/c are presented in Figure 4.3. The calculated w/c results without coarse aggregate correction factor show deviation from target w/c values (Figure 4.3a). With the application of coarse aggregate correction factor, the calculated results still deviate from the design w/c values (Figure 4.3b). The calculated results with the application of modified coarse aggregate correction factor are close to the design w/c (Figure 4.3c).

The t-test results for the Δw/c results in Figure 4.3 are summarized in Table 4.5. The p-value of applying *CF′* method was higher than 0.05 while the other two methods had p-values lower than 0.05. The results of p-value in t-test indicated that the calculated *w/c* results in applying *CF′* had no significant difference with the design w/c values.

4.5.3 Coarse Aggregate Grading Factor Influence Study

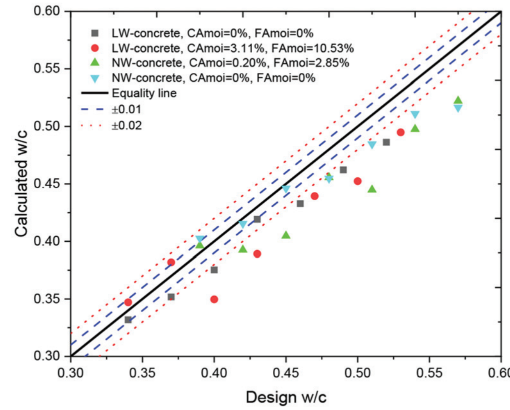
The calculated w/c errors in terms of the measured grading factor of concrete samples are plotted in Figure 4.4. When w/c calculation without coarse aggregate correction factor, the *Δw/c* distributed in negative side as described in Section 4.5.2.2. A linear regression analysis was applied into the relation between grading factor and *Δw/c* results obtained from the application of *CF* with the fitting parameter R^2=0.8374. It can be concluded from the linear regression results that when the fine particle content in coarse aggregate is less than 4.44%, the calculated w/c with the application of *CF* will have a 95% confidence to fall within the ±0.02 error range to target w/c values.

4.5.4 Aggregate Moisture Content Influence Study

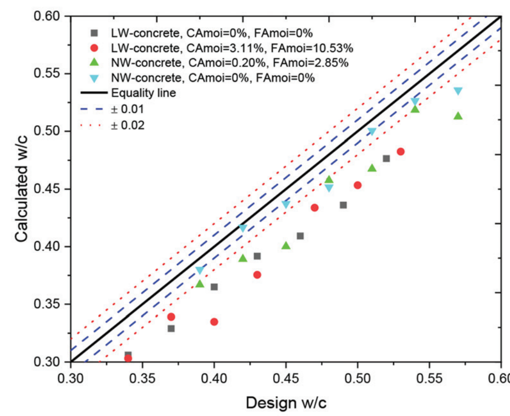
The boxplot of *Δw/c* results in terms of coarse aggregate moisture contents are presented in Figure 4.5. The w/c results were determined with the application of modified coarse aggregate correction factor (*CF′*). The summary of t-test results is presented in Table 4.6. The p-value of all groups were higher than 0.05 which indicated that the determined w/c results with different coarse aggregate moisture contents had no significant differences with design w/c. The t-test results implied that the coarse aggregate moisture contents have no influence in w/c determination with the application of *CF′*.

4.5.5 Measurement Delay Time Study

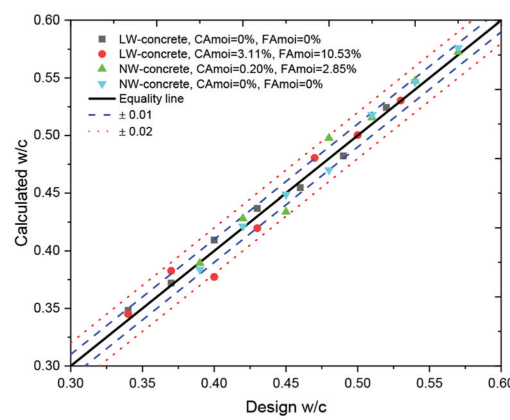
The calculated *Δw/c* results in terms of evaporation duration are presented in Figure 4.6. The microwave oven drying measurement determined w/c results in first 60 minutes after combining water with cement are acceptable if the accepted *Δw/c* is ±0.02. After 90 minutes of cement combining with water, the calculated



(a) w/c calculation results without the application of *CF*



(b) w/c calculation results with the application of *CF*



(c) w/c calculation results with the application of *CF′*

Figure 4.3 w/c calculation results in terms of design w/c for concrete with fine particles.

TABLE 4.5
Summary of t-test results of *Δw/c* results for different *w/c* determination methods

w/c Determination Methods	p-Value	Mean Value	Variance
Without CF	5.44E-7	-0.0254	0.0004
Applied CF	6.36E-12	-0.0347	0.0003
Applied CF′	0.3661	0.0016	8E-5

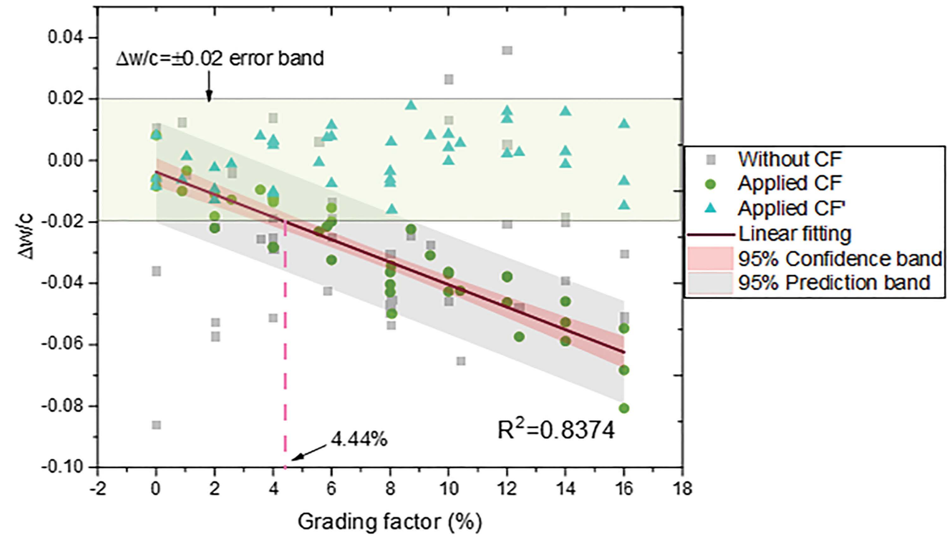


Figure 4.4 *Δw/c* in terms of grading factor.

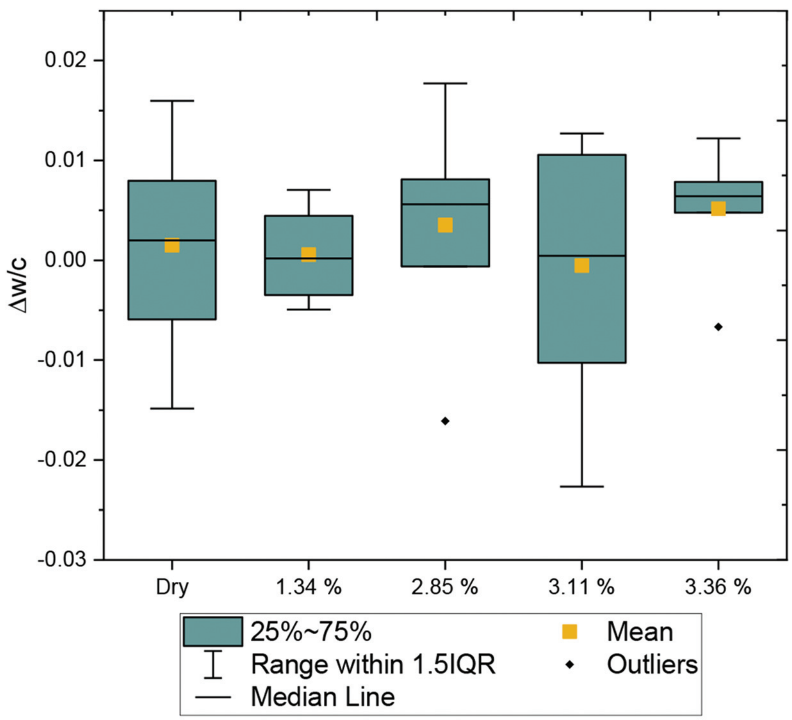


Figure 4.5 *Δ*w/c in terms of coarse aggregate moisture contents.

w/c results for design w/c=0.45 and 0.48 fall out of ±0.02 error range while the result of design w/c=0.42 still in ±0.02 error range. After 90 minutes, all of calculated w/c results have an error larger than 0.02 to target values. The average mass loss of concrete in this study at 90 minutes after combining water with cement is only 0.17% as shown in Figure 4.6.

4.6 Summary

In this section, a modified coarse aggregate correction factor (*CF'*) was proposed to consider the influence of fine particles within coarse aggregate in determining the w/c of concrete samples. The following conclusions can be drawn.

TABLE 4.6
Summary of t-test results of w/c determination results with different moisture contents aggregate

Aggregate Moisture Content (%)	p-Value	Mean Value	Variance
0.00 (Dry)	0.1733	0.0015	6.42E-5
1.34	0.7715	5.87E-4	2.20E-5
2.85	0.4010	0.0035	0.0001
3.11	0.9153	-5.18E-4	0.0002
3.36	0.1046	0.0052	4.08E-5

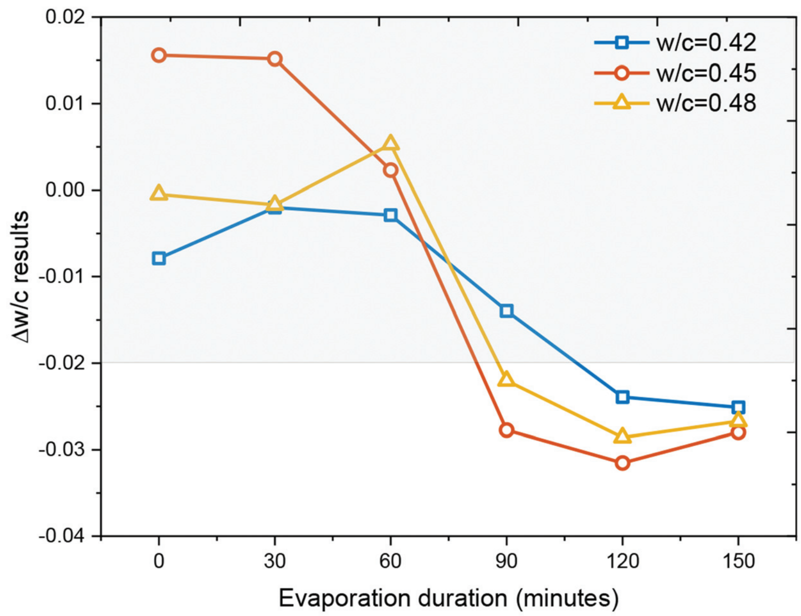


Figure 4.6 *Δw/c* results in terms of evaporation duration.

1. The *CF* can effectively eliminate the w/c determination deviation caused by sampling error for concrete without fine particles in coarse aggregate. When coarse aggregate has fine particles, the determined w/c results with the application of *CF* have significant difference with design w/c values. The application of *CF′* determined w/c results have no significant difference with the design w/c values.
2. When the fine particle content in coarse aggregate is less than 4.44%, the calculated w/c with the application of *CF* will have a 95% confidence to fall within the ±0.02 error range to target w/c values.
3. Under the evaporation conditions in this study (i.e., environmental temperature was 23°C, relative humidity was 75%, and the evaporation area was a circle with a 3-inch diameter), the determined w/c results in 60 minutes after combining water with cement fall within ±0.02 error from target values.

5. FIELD STUDY ON CONCRETE CURING EFFECTIVENESS EVALUATION BY GPR AND ELECTRICAL RESISTIVITY MEASUREMENTS

In this work, a field study was conducted to evaluate the curing effectiveness of concrete slabs cured by air and compound. Two non-destructive testing methods including ground penetrating radar (GPR) and electrical resistivity measurement were used.

5.1 Experimental Program

5.1.1 Materials and Mixtures

In this work, ordinary Type I Portland cement (Subcommittee C01.10, 2020) was used as the only binder for concrete. The natural sand with an absorption value of 2.3% and the saturated surface dry (SSD) specific gravity of 2.637 was used as fine aggregate. The coarse aggregate was stone with an absorption value of 1.3% and SSD specific gravity of 2.667. The design w/c value of the concrete was 0.50. The mixture composition of the concrete is shown in Table 5.1. No chemical admixture was used in concrete mixture. The curing compound used in this study was produced by W.R. MEADOWS 1600-white series, water-emulsion, wax-based concrete curing pound.

5.1.2 Concrete Slab Casting, Curing, and Testing

A large concrete slab with the dimensions of 12 feet × 8 feet and a thickness of 8 inches was cast in Purdue CAI center (located in West Lafayette, IN, USA). The slab was divided into two sections by a plywood separator as shown in Figure 5.1. In addition to the concrete slab, 32 concrete cylinders, with the diameter of 4 inches and length of 8 inches, were cast simultaneously to test the compressive strength development of concrete. One section of concrete slab and 16 concrete cylinders were cured by compound (CP) and the other section of slab, and the left 16 cylinders were exposed in natural air (AC).

The slab and cylinders were tested using the ground penetrating radar (GPR) instrument. Additional tests included measurements of the electrical resistivity, thermogravimetric analysis (TGA), mercury intrusion porosimetry (MIP) and compressive strength tests at 1, 3, 7, 14, and 28 days of age.

The concrete was poured on August 30, 2021, at 8 am. After 4 hours of pouring, the surface of one section slab and 16 cylinders' surfaces were sprayed with a layer of curing compound (CP). The other section of the slab and the left 16 cylinders were exposed in air (AC). The weather history of West Lafayette area from 1 day to 30 days is shown in Figure 5.2 (Weather Underground, 2021).

5.2 Results and Discussion

5.2.1 GPR Measurement Results

5.2.1.1 Dielectric constant value determination by travel time method. The travel time difference (Δt) between the first and second reflected electromagnetic (EM) pulse can be used to calculate the dielectric constant value (ε) of concrete as demonstrated by the previous research (Chen et al., 2012; Chen & Shen, 2013; Lai et al., 2009; Shen et al., 2016).

TABLE 5.1
Mix proportions of concrete (kg/m^3)

Design w/c	Cement	Mixing Water	Fine Aggregate	Coarse Aggegate
0.50	335	167	819	1,109

$$\varepsilon = \left(\frac{c\Delta t}{2h} \times 10^{-9}\right)^2 \qquad \text{(Eq. 5.1)}$$

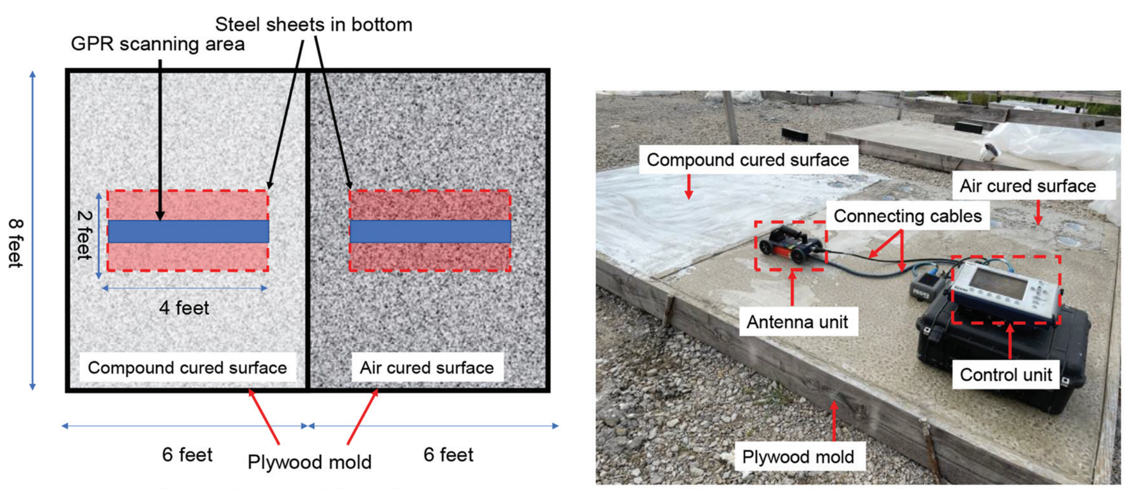
where c denotes the speed of light (3×10^8 m/s), h represents the thickness of concrete slab (0.2 m), and Δt is the travel time difference between the first and second reflected EM wave pulse, $\Delta t = t_1 - t_2$ (ns).

5.2.1.2 Dielectric constant value determination by first pulse amplitude. The amplitude of the first pulse amplitude (A_{p1}) can also be used to calculate the dielectric constant of concrete (Bourdi et al., 2012; Harris, 2006; Lahouar, 2003; Wimsatt et al., 1998).

$$\varepsilon = \left(\frac{A_0 + A_{p1}}{A_0 - A_{p1}}\right)^2 \qquad \text{(Eq. 5.2)}$$

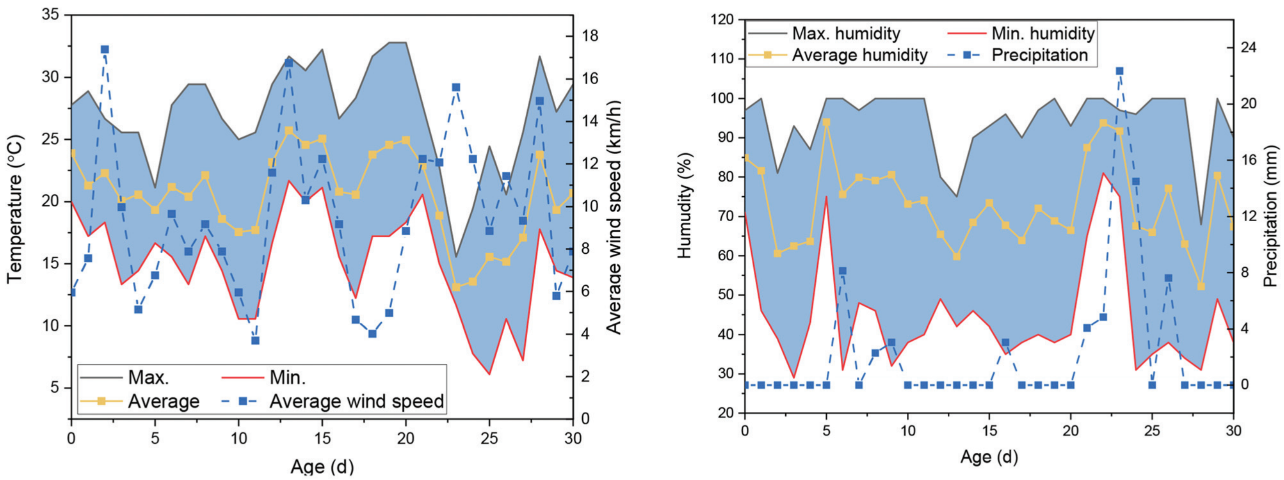
where A_0 denotes the reflected wave pulse amplitude by directly testing the steel sheet with GPR; in this work, A_0 was pre-determined as 7,000.

5.2.1.3 Dielectric constant determination results. The results of calculated dielectric constant values are shown in Figure 5.3. The dielectric constant values determined by two-way travel time method (i.e., Eq. 5.2) decreased with the increase of the curing age, which is reasonable, since the hydration process consumes water. Thus, the water content in concrete slabs decreased with the increase in the curing age. However, the dielectric constant values determined by the amplitude of first pulse peak method (i.e., Eq. 5.2) showed unreasonable increase at 7 days and 28 days. The reason for this abnormal increase of dielectric constant values can be explained by the wet surface of the specimen, which influenced the measured first pulse amplitude.



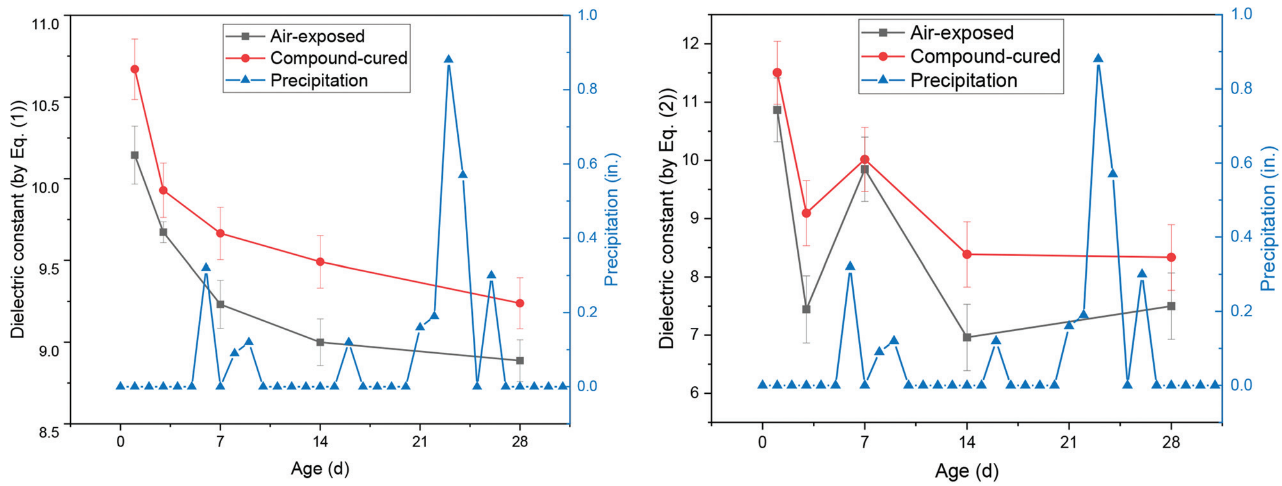
(a) Configuration of slab and steel sheets (b) Photo of the slab in GPR testing

Figure 5.1 Schematic of concrete slabs.



(a) Temperature and wind speed history (b) Relative humidity and precipitation history

Figure 5.2 Weather history of West Lafayette, IN, USA, from 8/30/2021 to 9/30/2021.



(a) Determined by Eq. 5.1 (b) Determined by Eq. 5.2

Figure 5.3 Dielectric constant value development with curing age determined by two methods.

5.2.2 Compressive Strength Development

The compressive strength measurement results of compound-cured (CP) and air-cured (AC) cylinders are illustrated in Figure 5.4. Each data point was the average value of three cylinders. The compound-cured cylinders presented higher compressive strength than air-cured cylinders which is reasonable since the curing compound resisted the water evaporation from concrete cylinders. Thus, there was more water available in CP cylinders for hydration, which has been proved by the dielectric constant measurement results.

5.2.3 Electrical Resistivity Measurement Results

The electrical resistivity measurement results are illustrated in Figure 5.5. The electrical resistivity values for air-cured concrete slab were higher than compound-cured slab at 1- and 3-days age. Then, starting from a 7-day age, the compound-cured concrete slab presented higher electrical resistivity than air-cured slab.

5.2.4 TGA Results

Figure 5.6 presents the CH content development of AC and CP slab sections. The compound-cured slab had higher CH content than air-cured concrete slab at any age since more water was available in compound-cured slab for hydration. Thus, at the same age, the hydration degree of compound-cured concrete was higher than air-cured concrete.

5.2.5 Mercury Intrusion Porosimetry Results

The porosity and average pore diameter results from mercury intrusion porosimetry (MIP) tests are presented

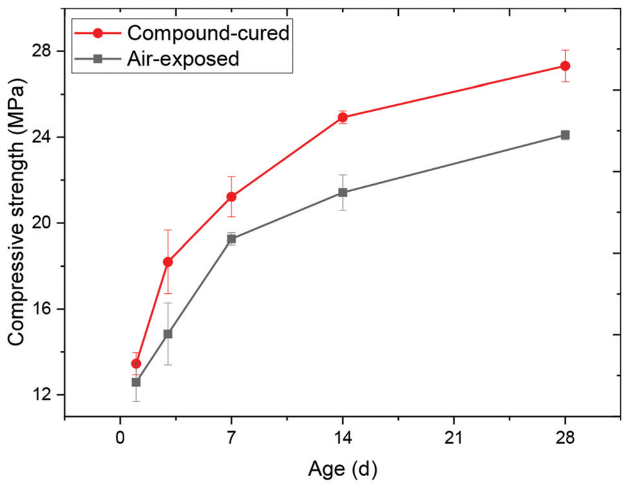


Figure 5.4 Compressive strength development.

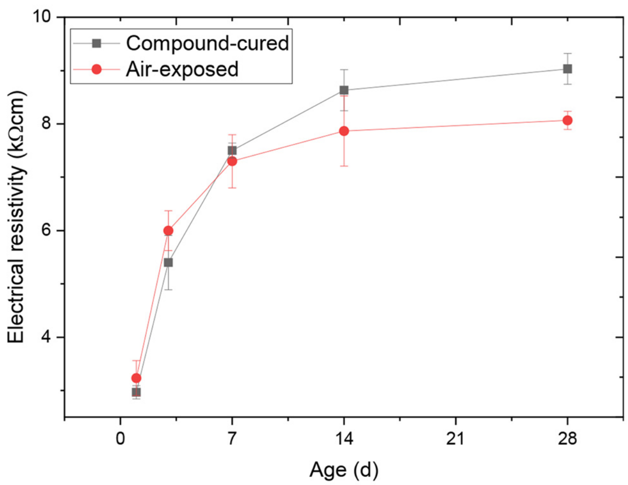


Figure 5.5 The electrical resistivity development with curing age.

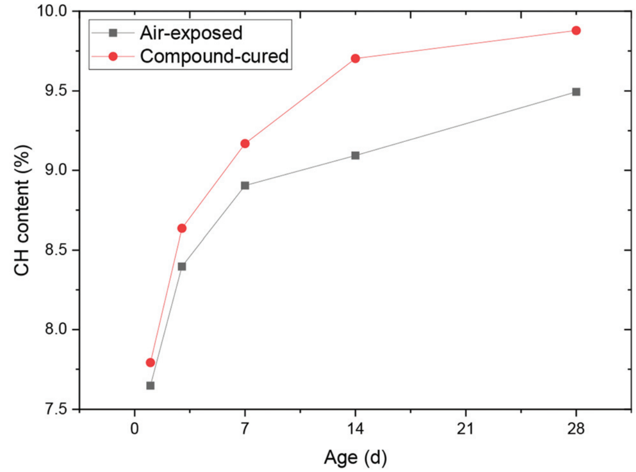


Figure 5.6 $Ca(OH)_2$ (CH) content development of AC and CP concrete slabs.

TABLE 5.2
Porosity and average pore diameter results from MIP tests

	Porosity (%)		Average Pore Diameter (nm)	
Age (days)	**Compound Cured**	**Air Cured**	**Compound Cured**	**Air Cured**
1	25.65	26.60	56.50	68.90
3	23.21	24.79	40.30	42.00
7	20.08	23.31	32.50	33.40
14	17.62	21.95	29.10	30.90
28	16.64	20.64	26.10	27.90

in Table 5.2. It can be seen that the AC concrete samples presented more porous microstructures than CP samples as the porosity and average pore diameter of AC concrete samples were higher than CP concrete samples. The pore size distribution curves are presented in Figure 5.7. Two major peaks at around 100 nm and 1,000 nm were observed for AC samples while one major peak at around 100 nm for CP samples was obtained.

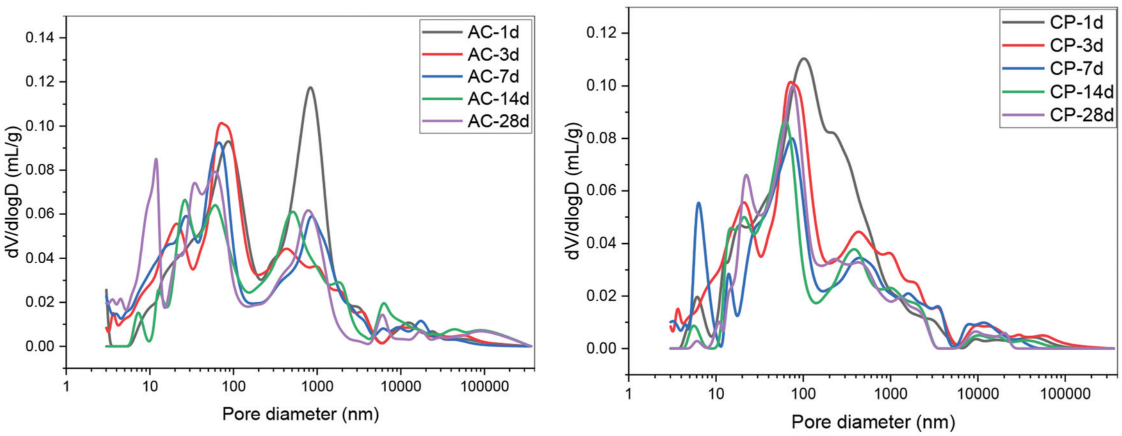
5.2.6 Comments on Practical Application of Curing Effectiveness Evaluation Methods

In this work, two practical methods (i.e., dielectric constant value and electrical resistivity measurements) were adopted to evaluate the curing effectiveness of air-cured concrete and compound-cured concrete. The relative relationship of dielectric constant value development between AC and CP concrete was consistent with compressive strength, TGA results and MIP results while the electrical resistivity for AC concrete was higher than CP concrete before 3 days, but lower than CP concrete starting from 7-days age. The relative relationship of electrical resistivity development between AC concrete and CP concrete was not consistent with compressive strength, TGA and microstructure measurement results.

In addition, it has been found that the dielectric constant value of hardened concrete can be directly correlated with water content (Janoo et al., 2009; Klysz & Balayssa, 2007; Lee & Zollinger, 2012; Leucci, 2012). Thus, from a development perspective, the higher dielectric constant value of CP concrete than AC concrete also indicates that CP concrete could provide more water for further hydration. In other words, the "hydration potential" for CP concrete is higher than AC concrete.

5.3 Summary

In this part of work, a concrete slab was cast in West Lafayette, IN, USA, and divided into two sections. These two concrete slab sections were cured in natural environment while one section was exposed in air (AC)



(a) Pore size distributions of AC sample. (b) Pore size distributions of CP sample.

Figure 5.7 Pore size distribution curves.

and the other section was cured by compound (CP). The dielectric properties of two sections were measured by a GSSI 1.6 GHz ground penetrating radar (GPR) system. The electrical resistivity developments for both concrete slab sections were determined by 4-point method. The compressive strength developments were determined by testing the concrete cylinders and the hydration degrees of AC and CP concrete sections were obtained by determining the $Ca(OH)_2$ (CH) content through thermogravimetric analysis (TGA) with a modified method. The microstructure developments of AC and CP concrete were characterized by mercury intrusion porosimetry (MIP) measurements. The main conclusions of this work can be drawn as follows.

The dielectric constant value determined by two-way travel time method is less influenced by the weather conditions while the dielectric constant value obtained by first pulse peak amplitude method is influenced by the weather conditions.

1. The dielectric constant value of CP concrete is higher than AC concrete which indicates a higher water content in CP concrete than in AC concrete.
2. The electrical resistivity of AC concrete was higher than CP concrete before a 3-day age and then lower than CP concrete starting from a 7-day age.
3. For a practical application objective, the inconsistent relative relationship on electrical resistivity development of CP and AC concrete might result in inaccurate evaluation on curing effectiveness. The dielectric constant is a good NDT method to evaluate the curing effectiveness of concrete and can be used to indicate the further hydration potential.

6. FINAL CONCLUSIONS AND RECOMMENDATIONS

This final chapter contains the final conclusions of the current study, and the recommendations for the future research.

6.1 Conclusions

In this work, the w/c value of plastic concrete is determined by the measured dielectric constant value and the microwave oven drying measurement. A modified coarse aggregate correction factor is further proposed to consider the influence of fine particles within coarse aggregate in determining the w/c of concrete samples. Additionally, the effectiveness of curing compound is evaluated by GPR and electrical resistivity measurements for field concrete slabs.

Based on the results of laboratory and field studies, the following conclusions can be drawn.

1. The volumetric water contents of plastic concrete calculated from the measured dielectric constant values from the logarithmic rule proposed by Lichtenecker provides the most accurate results out of other models.
2. The dielectric constant values and gravimetric water contents have linear relationship with the design w/c, the fitting parameters (R^2) are 0.7687 and 0.8340, respectively. The dielectric constant values and gravimetric water contents showed a better linear relationship with the fitting parameters (R^2) of 0.9235. The COV for calculated w/c values by GPR measurement is 1.28% while for the microwave oven drying measurement is 4.34%.
3. The p-values of t-test for the w/c determination error ($\Delta w/c$) of GPR measurement and microwave oven drying measurements are 0.3353 and 0.7833, respectively, which indicate the mean values of $\Delta w/c$ determined by GPR and microwave oven drying measurements have no significant difference with 0. The mean value of $\Delta w/c$ results by GPR and microwave oven drying measurements are -0.0023 and 0.0015, respectively, while the variances are 8E-5 and 4E-4, respectively.
4. When the microwave oven drying test was terminated when mass change was less than 1.0 g, the determined *w/c* results of cement paste, and mortar samples had significant difference with the design w/c values. When the test was terminated when the sample mass change was less than 0.5 g, the determined w/c results had no statistical difference with designed w/c.

5. When coarse aggregate has fine particles, the determined *w/c* results with the application of *CF* have significant difference with design *w/c* values. The application of *CF'* determined *w/c* results have no significant difference with the design *w/c* values.
6. When the fine particle content in coarse aggregate is less than 4.44%, the calculated w/c with the application of *CF* will have a 95% confidence to fall within the ± 0.02 error range to target w/c values.
7. Under the evaporation conditions in this study (i.e., environmental temperature was 23°C, relative humidity was 75%, and the evaporation area was a circle with a 3-inch diameter), the determined w/c results in 60 minutes after combining water with cement fall within ± 0.02 error from target values. The aggregate moisture content has no influence in *w/c* determination with the application of *CF'*.
8. The dielectric constant value determined by two-way travel time method is less influenced by the weather conditions while the dielectric constant value obtained by first pulse peak amplitude method is influenced by the weather conditions.
9. The dielectric constant value of compound-cured concrete is higher than air-exposed concrete which indicates a higher water content in compound-cured concrete than in air-exposed concrete.
10. The electrical resistivity of air-exposed concrete is higher than compound-cured concrete before a 3-day age and then lower than compound-cured concrete starting from a 7-day age.
11. The compressive strength and CH content of compound-cured concrete are higher than air-exposed concrete while the porosity is lower than air-exposed concrete, and the pore structure of compound-cured concrete is finer than air-exposed concrete.
12. For a practical application objective, the inconsistent relative relationship on electrical resistivity development of compound-cured and air-exposed concrete might result in inaccurate evaluation on curing effectiveness. The dielectric constant is a good NDT method to evaluate the curing effectiveness of concrete and can be used to indicate the further hydration potential.

6.2 Recommendations for Future Research

It is recommended that the dielectric constant value can be used as a parameter to determine the w/c value of plastic concrete. The modified coarse aggregate correction factor can be used to determine the w/c value by microwave oven drying measurement. The implementation of dielectric constant determination method and modified coarse aggregate correction factor can be further verified using trial batches where the target w/c values along with the moisture content and specific gravities of aggregates can be well controlled.

The dielectric constant value determined by GPR measurement can be a promising NDT method in field to evaluate the curing effectiveness of concrete. The dielectric constant determination method can be further simplified.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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About This Report

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He, R., Lu, N., & Olek, J. (2022). *Development of in-situ sensing method for the monitoring of water-cement (w/c) values and the effectiveness of curing concrete* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2022/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317377