

Development and Demonstration of NDT for Evaluating the Curing Effectiveness of Concrete Pavement Construction

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ABSTRACT

Early-age concrete surface moisture evaporation can be a factor during paving of concrete pavement resulting in plastic shrinkage cracking and spalling related delamination. The use of liquid membrane-forming curing compounds is one of the most prevalent methods to protect hydrating concrete surfaces. However, success in the application of curing compounds is not always assured under field conditions; lacking a tool to evaluate the curing effectiveness in terms of the uniformity and the rate of application are main issues. Previous research focused on the measurement of the surface dielectric constant (DC) of concrete as an indicator of the moisture retention capability of a given method of curing; however, the inherent limitations associated with the previous handheld technology prevents the method from being extensively utilized under field conditions. To employ better curing practices and the qualification of the application of different methods of curing, this research considers the use of ground penetrating radar (GPR) technology to measure DC at the surface of a concrete pavement. Analyses of the DC measurements indicated that the GPR system provided a very useful means to rapidly and extensively evaluate the curing effectiveness over a broad extent of a paved surface with great data repeatability; visual observations and statistical analyses validated that the system was able to suggest the uniformity of curing applications and differentiate the effectiveness of various curing applications due to varied rates of application. The research also reinforces the notion that the moisture retention capability of a given method of curing increases with the increase of the rate of application and improvement of curing uniformity.

KEYWORDS: Concrete pavement, concrete curing, curing compounds, ground penetrating radar (GPR), dielectric constant (DC)

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INTRODUCTION

A variety of combinations of field environmental conditions (such as high temperature, wind and solar radiation) can cause excessive moisture evaporation at the surface of newly placed concrete pavement. As a result, high porosity and inadequate hydration may occur at the surface concrete which lead to a series of problems, such as low surface abrasion strength leading to durability issues and significant amount of shrinkage which induces even more detrimental effects, such as concrete delamination and spalling. These can be very severe problems that will eventually affect the long-term performance of a concrete pavement [1].

Spraying liquid membrane-forming curing compounds at the surface of pavements is the most widely used approach to moderate moisture evaporation at early ages [2]. However, the key to achieving successful curing effectiveness, proper application of a curing compound is not always accomplished during placement [1-4]. Non-uniform curing and inappropriate curing rates (for a given environmental condition) can often result in negative performance consequences. However, there are few tools available to prevent such problems during paving operations. Since the curing effectiveness is tied to the performance of a concrete pavement in a number of ways, development of new technologies for evaluating the effectiveness of a given curing practice would be indispensable.

Research on curing effectiveness has considered relating dielectric constant (DC) to the moisture retention capability of a curing membrane. Choi and Won (2008) [5] developed a ground-coupled ground penetrating radar (GPR) to detect DC measurements at the surface of concrete; however, the results were neither consistent nor accurate. Sun and Zollinger (2015) [6] investigated the use of a handheld percometer to obtain DC measurements at the surface of curing concrete; the DC measurements were fitted to a modified Weibull distribution function to characterize the observed reduction rate of the DC measurements as a means to assess the moisture retention capability of a curing membrane. Although the measurements and the associated trends were relatively consistent and indicated potential with respect to a relationship with the moisture retentivity of a given method of curing, its application under field conditions was limited due to the nature of the handheld technology (which prevents extensive data collection in a short period of time).

In the same research, Sun and Zollinger (2015) [6] suggested an index parameter referred to as the effectiveness index (EI) to qualify the effectiveness of curing; in addition, the paper demonstrated a relationship between EI and DC measurements which can be used to facilitate the evaluation of curing effectiveness under field conditions. It was expected that with the assistance of advanced GPR technology, the relationship could be improved with greater utility.

This paper advances a novel approach to assess the curing effectiveness by using a specially designed GPR system as is subsequently elaborated.

OBJECTIVES

The primary objectives of this paper are:

- Briefly review the theoretical basis for using DC measurement to evaluate both the

moisture content and the effectiveness of curing,

- Briefly explain the significance of EI, how its relationship with DC measurements can be used to facilitate the evaluation of curing effectiveness under field conditions,
- Demonstrate and validate a method of using the GPR system to determine the uniformity and effectiveness of curing in concrete pavement construction, and
- Evaluate the main factors that contribute to the successful curing by analyzing the DC measurements.

THEORETICAL BASIS FOR THE RESEARCH INVESTIGATION

A key aspect of this research was the DC measurements collected by using a GPR system at the surface layer of concrete pavements. This section provides the theoretical basis for the use of DC to evaluate curing effectiveness.

Dielectric constant of concrete constituents

Dielectric constant (DC) is a value that explains the ability of a material to change or store electric energy due to an electric field with a given intensity [7]. Typical DC values are given in Table 1 [8, 9]:

Table 1 Typical dielectric constant range for materials [8, 9]

Materials	Dielectric constant ranges
Air	1.0
Water	80 - 82
Sand	3.0 – 6.0
Gravel	5.8 - 6.5
Cement	3.6 - 4.0
Hydrated cement paste products	4.0 - 5.0

As shown in the table, water has the largest DC among the typical materials. Researchers found that DC is an indicator of the amount of unbound free moisture content for aggregate-constituted materials [7]. Furthermore, DC could also have a certain relationship with the unbound free moisture within concrete mixtures.

Because concrete is a mixture of constituents that have different properties, the DC would be considered as a composite measurement [10]. Theoretically, the distinctive characteristics of each constitute in the composite should be identifiable; however, concrete is a complex composite because of the chemical reactions that place between cement and water during the cement hydration process [1, 10]. As a result of the chemical reactions, the amount of each portion of the composite change, i.e., the amount of capillary water inside the concrete diminish with time due to the processes associated with the hydration inside concrete as well as evaporation potential as dictated by the ambient environment [11]. Figure 1 shows diagrams of volumetric changes of different portions of concrete due to hydration.

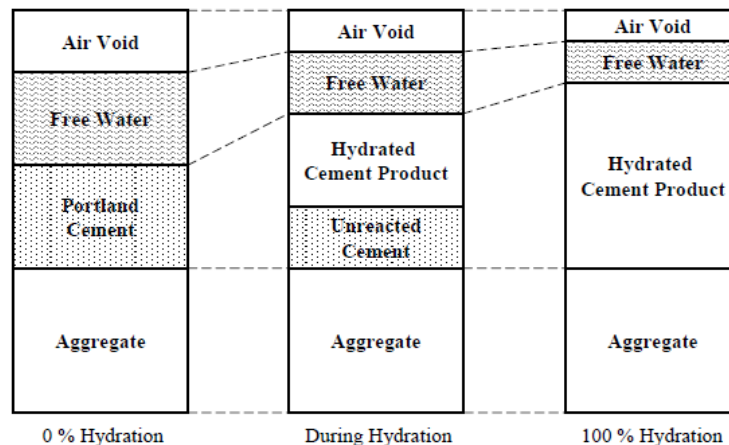


Figure 1 Changes of different portions of concrete due to hydration [12]

Previous research [12, 13] indicated that DC measurements are highly sensitive to free moisture (the amount of water that is available to react with the cement) in hydrating concrete. A model proposed by Lee [12] was used to estimate the volumetric free moisture content in concrete at an early age based on DC measurements. In general, high DC measurements in early-age concrete correspond to high volumetric surface moisture content. Due to moisture evaporation and hydration, the free moisture inside a concrete decreases with time; accordingly, the measured DC showed decreasing trends with time. It was also indicated by Lezama [13] that the decreasing trends of DC measurements were influenced by the curing environment, where well sealed specimens exhibited lower decreasing rates of DC measurements compared to uncured specimens. Based on this research, there seems to be a potential of using DC measurements to differentiate curing effectiveness.

Expectedly, a measure of the moisture retention capability provided by a given method of curing is suggested by the rate of the change in the free moisture content in concrete; a method of curing with better moisture retention capability should yield a lower reduction rate of free moisture in concrete, which should be reflected by DC measurements. Therefore, this research considers further the use of DC measurements to assess curing effectiveness.

RESEARCH SIGNIFICANCE AND MOTIVATION

As elaborated in the previous research by Sun and Zollinger [6], both EI and DC measurements have been found to be capable of evaluating the curing effectiveness of concrete, where the concept of EI utilizes the moisture-based maturity of concrete, DC measurements are used to reflect the rate of moisture evaporation and the moisture retention capability of the curing. Although the two methods can be used separately, a coupled relationship developed based on the EI and DC measurements is a more powerful tool to not only evaluate the curing effectiveness, but also for pavement design. Fortunately, the advancement of GPR technology allows for the collection of surface DC measurements much faster, accurately and extensively over a wide surface area of a concrete pavement.

EI, its significance

In short, EI is a ratio that represents the effectiveness of curing at the surface of concrete by comparing the maturity of the surface concrete (which is affected by the concrete surface curing effectiveness) to the maturity of the concrete few inches below the top surface (where the curing condition is almost perfect and not affected by the surface curing condition). The detailed definition of EI and the procedure of measuring EI under both laboratory and field conditions are elaborated in the previous research [6].

The significance of EI is that this parameter can not only be used to characterize the curing effectiveness, more importantly, it can also be incorporated into a design procedure to determine the set gradient of concrete pavement considering the effect of curing effectiveness, which has not been done until recently by Sun and Zollinger [6]. Set gradient is a factor that affects the fatigue cracking behavior of a concrete pavement which is often influenced by the curing regime [14-16]. Therefore, to include the curing effectiveness (EI) in the calculation of set gradient is a very significant advancement for designing concrete pavement.

However, the determination of EI under field conditions is limited to a single location due to the nature of the measuring device itself according to the literature (only a small area is being monitored by the measuring device) [6]. To further facilitate the evaluation under field conditions, DC measurements are employed as a means to extend the curing effectiveness assessment over a wider area of paving rather than a single position.

Coupled EI and DC relationship

As aforementioned, DC measurements are made to extend the utility of the EI parameter as determined at the ACMM base location. The previous research [6] focused on using a handheld percometer to take DC measurements at the surface of concrete pavements; the DC measurements vs. time data were fitted to a modified Weibull distribution function to determine the reduction rate of the DC measurements over time for assessing the moisture retention capability of a given curing method. One of the regression parameters, α in the modified Weibull distribution function essentially represents the reduction rate of the DC over time. Through a series of laboratory experiments, a relationship was found between EI and α [6]. Applying this relationship, one can determine EI over a much wider area at the surface of a concrete pavement based on a series of DC measurements over time and calculating the associated α value.

However, the percometer is not well suited for taking DC measurements over a large area due to the nature of the data collection procedure (the probe of a percometer must be in contact with the surface of concrete). The size of the probe in comparison to a wide paved surface is a significant limitation to obtaining a measure of the quality of curing over a broad area.

Research motivation

Due to the aforementioned limitations of a percometer, the motivation of this research is to explore the utility of GPR technology to take DC measurements at the surface of concrete pavement as well as taking advantage of the greater efficiency that a GPR system offers. The

following provides the detailed results of the investigation.

FIELD INVESTIGATION SCHEME

A field investigation was conducted in a series of test sections established during placement of a concrete paving project in Victoria, Texas. GPR was used to measure the surface DC of the freshly placed concrete surface where the curing application rates were varied and monitored at different test sections which created differences in the curing quality for the research investigation purposes. The application rates were validated by using the two methods elaborated below.

GPR System Setup

The GPR system used in the study was developed by Texas Transportation Institute. As shown in Figure 2, the system is equipped with of a 2.5 GHz air-coupled antenna in the front of the specially designed cart and a portable computer embedded near the cart handle for data collection. With this data collection configuration and the software pre-installed in the computer mounted on the cart (Figure 2), it was possible to calculate the DC for the surface concrete instantly and spatially while moving the cart over the pavement surface. This configuration allowed for an extensive evaluation of the curing conditions over a large area of a concrete paving within a short period of time. The DC measurements were recorded every 1/3 in. as the wheels rolled. Results collected at such area density are of great value particularly for the assessment of variability and uniformity.

Prior to the data collection, the GPR was routinely calibrated with respect to open air space and a metal plate to ensure good data quality. To maintain good data repeatability, as shown in Figure 2 (b), the wheels on one side of the cart were aligned with the longitudinal joint at the centerline of the concrete pavement. The collected DC measurements were only relevant to the linear path (e.g. 1/3 in.²/in.) over which the antenna was passed.



(a)



(b)

Figure 2 GRP used in this study (a) front view and (b) side view

Application Rate Assessment

One of the major steps in this research was to validate the rate of application of the curing compound sprayed on the pavement surface. To achieve this purpose, two approaches were adopted in this field study. The first one was to prepare small round plates with various diameters (different surface areas), then place them at different locations on the surface of concrete pavement before curing was applied; immediately after the application of curing, the plates were weighed using a high accuracy scale; knowing the area and the initial weight of the

plate, it was possible to determine the curing application rate for a specific section. The second method was to measure the level differences in the curing compound storage container by inserting a tape measure before and after the application of curing as well as measuring the diameter of the cylindrical container; knowing the sprayed area, the application rate could be determined easily. An average of the application rates obtained by the two methods was calculated for different test areas.

RESULTS AND DISCUSSIONS

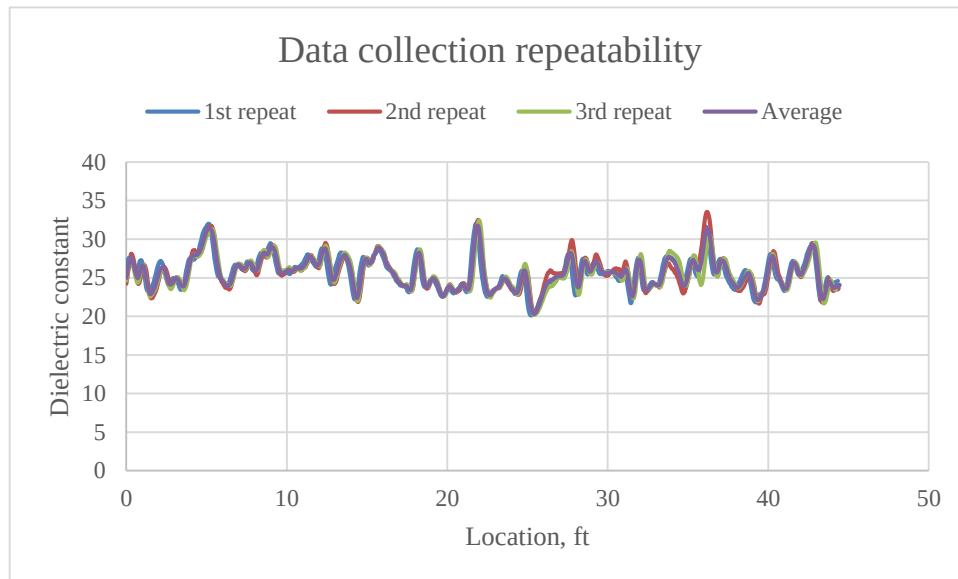
In order to validate the efficacy of using GPR to evaluate the curing quality, the application rate were varied at different sections, whereas the type of the curing compound remained the same for all the sections (as specified by the contractor). The following discussions address the test results.

Results Interpretation

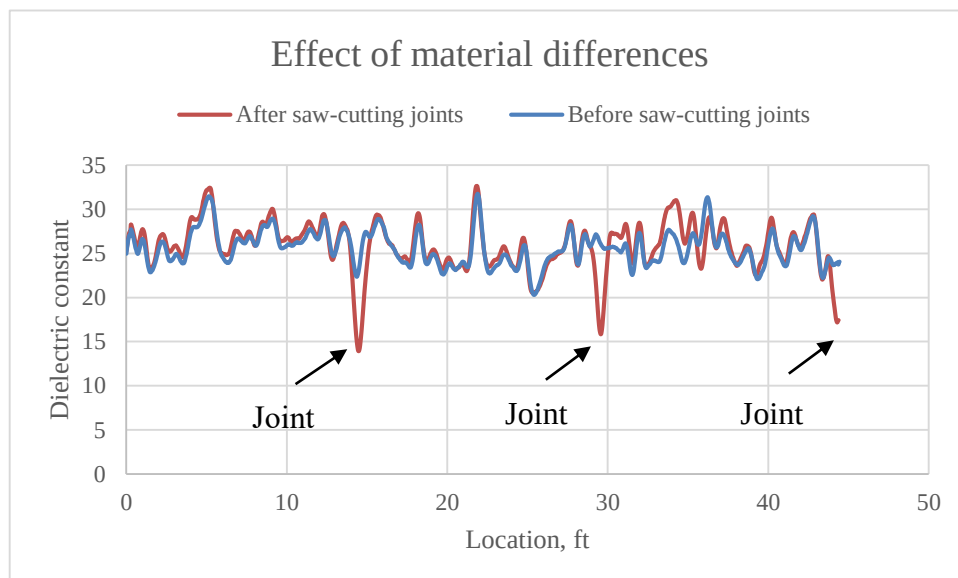
Figure 3 shows typical data sample taken over a 45 ft. long section (where joints were spaced at 15-ft intervals). The degree of variability and the repeatability can be observed in this figure.

The repeatability of the data collection is shown in Figure 3 (a). The data was collected after curing compounds dried for a period of time to avoid disturbance to the sampling area as the collection was repeated three times. During the data collection, aligning the wheels on one side of the cart with the longitudinal joint seemed to improve repeatability of the data. The data in Figure 3 (a) shows that the variance of the three repetitions at each location was very small; for all the positions in this section, the average of the standard deviation and the average of the coefficient of variation for three repetitions was only 0.68 and 0.026, respectively, which indicated that the variance of the data collection procedure was very low and the repeatability of the testing procedure was very good.

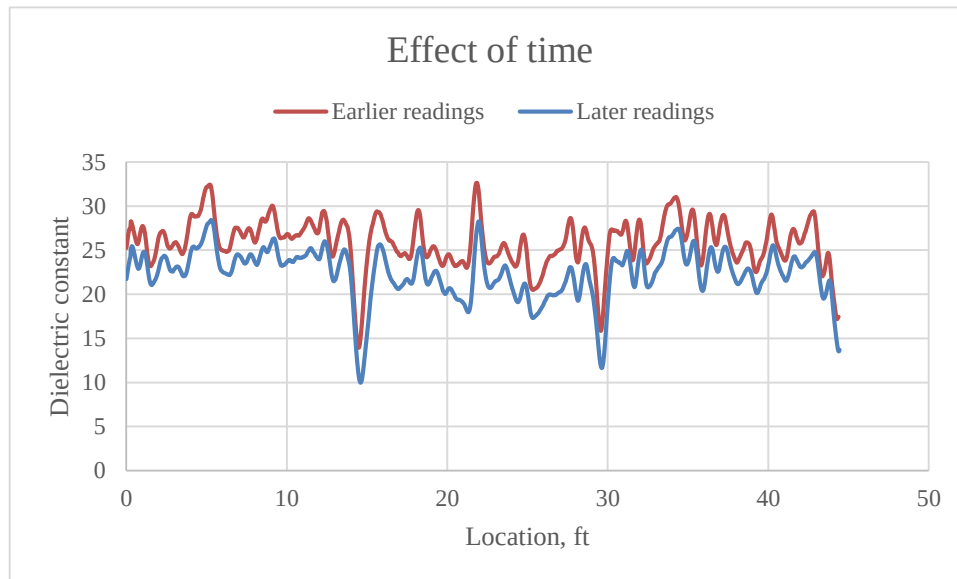
As shown in Figure 3 (b), before the sawcut joints were made, some variations in the DC at specific locations along the collection path were evident, but major variation (other than that due to variability in the curing quality) occurred where sawcuts were made in the surface of the pavement. The sawcuts were essentially a gap of continuous air in the surface of the concrete; consequently, the DC at those joints was significant lower than the DC of other locations.



(a)



(b)



(c)

Figure 3 GPR data interpretation (a) the data collection repeatability (b) the effect of material differences and (c) the effect of time

Figure 3 (c) shows the effect of time on the DC measurements along the collection path. The “later readings” were taken 3 hours later than the “earlier readings” at the same locations. The shapes of the amplitude of the two data sets were almost the same, whereas the magnitudes of the “earlier readings” were greater comparing to those of the “later readings”. This sensitivity is the key to evaluate curing effectiveness.

When a curing compound is sprayed over the surface of a concrete pavement, the protecting layer provided by the compound should hinder the evaporation of free moisture, creating favorable moist conditions at the near surface to facilitate strength gain of the surface concrete. Since free moisture is held at the surface, the DC measurements are expected to stay at higher level for a longer period of time compared with those of uncured concrete. Supposedly, the better the curing practice is, the longer it takes for DC to drop to lower levels.

Curing Effectiveness Evaluation and GPR Efficacy Validation

Achieving better curing practices is likely the result of many factors, including the type of the curing compound, the curing application rate, the uniformity of the curing application, the timing of the application given the ambient weather conditions.

In a previous research, Sun [17] performed laboratory evaluation of curing effectiveness by making DC measurements at the surface of concrete specimens using a handheld percometer. Results indicated that the DC measurements were very sensitive to the type and the application rate of curing compounds; it was found that specimens sprayed with a better quality or a greater application rate of curing compound were associated with lower rates of reduction in DC measurements (under controlled laboratory environment and uniform application of curing compounds), which indicated that a percometer was effective to detect the difference in the

free moisture content at surface of concrete due to varying quality and application rate of the applied curing compounds.

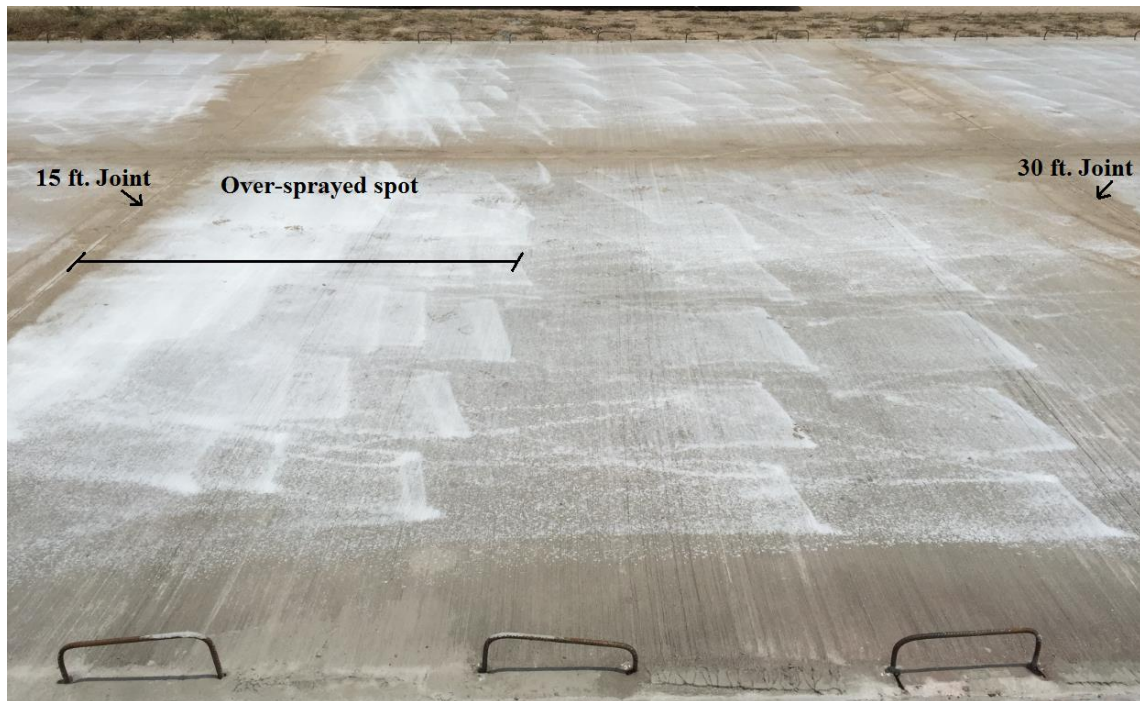
This research focuses on validating the efficacy of using GPR to assess the curing effectiveness in terms of the uniformity and the rate of curing applications since these are two highly varied factors under field conditions. Besides, the type of the curing compound remained the same for the field test sections and the ambient environmental condition was considered a constant factor since all the test sections were placed at the same time.

Application uniformity

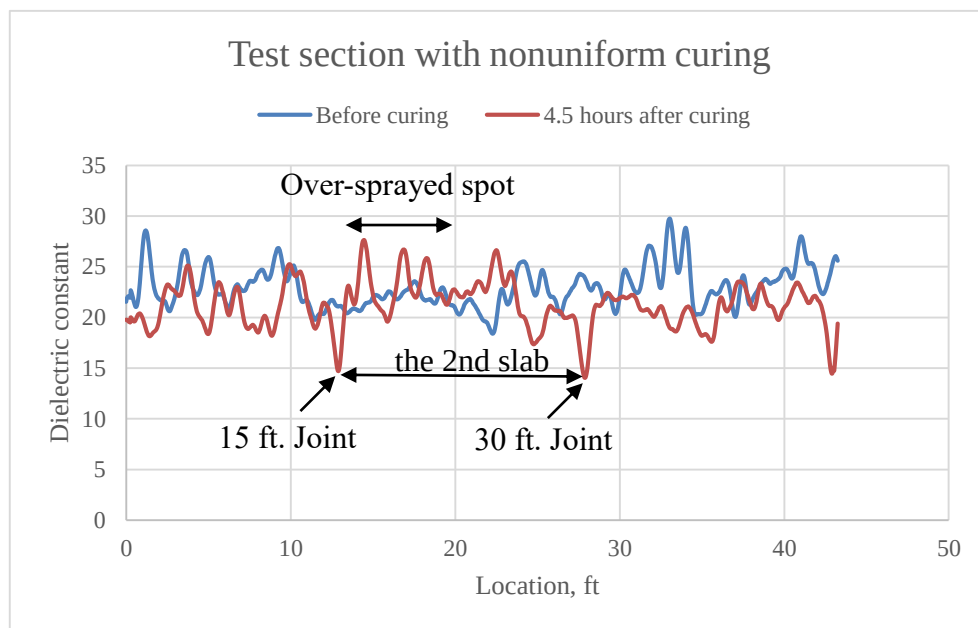
The uniformity of the curing application is one of the most important factors that affect the curing effectiveness. To achieve better application uniformity, many construction operations utilize curing machines that bridge over the paved roadway to provide access and a more consistent spray pattern. However, the curing compound was manually hand sprayed in this field application, which created many nonuniform areas.

Figure 4 (a) shows a picture of the 2nd slab of a 45-ft test section (between 15 ft. joints). As shown in the picture, curing compound was over-sprayed at this slab for about 21 ft. of the section, creating a thicker white banded area comparing to the other locations. DC measurements of this section were taken prior to the curing application and 4.5 hours after the application as shown in Figure 4 (b).

As explained early, the application of curing can create areas of extra bleed moisture at the surface of the concrete, therefore, temporarily increase the DC of the cured area depending on the application rate of the sprayed curing. As the bleed moisture evaporates and time elapses, the DC will slowly drop to a lower level in a fashion similar to what Figure 3 (c) shows if the curing application is relatively uniform. However, if the curing was sprayed at a high application rate at one spot, it may take more time before the DC starts to decrease at that specific location. The DC measurements shown in Figure 4 (b) are a representation of this phenomenon. As shown in Figure 4 (b), the DC at the over-sprayed spot maintained at a higher level 4.5 hours after the curing compound was applied, whereas the DC at other locations already decreased to a level slightly lower than the uncured condition since the thin curing layer did not provide enough protection to slow moisture evaporation.



(a)



(b)

Figure 4 (a) the 2nd slab of a 45-foot pavement section with nonuniform curing spots and (b) the DC results of this section before and after curing compound was applied

The efficacy of using GPR to evaluate the uniformity of curing applications was also checked based on statistical analysis of the DC measurements. In order to evaluate how curing uniformity can affect DC measurements, the percentage reduction in the DC measurements from “before curing” to “4.5 hours after curing” (shown in Figure 4 (b)) was calculated for each point of the 2nd slab of the 45-ft test section. Second, the percentage reduction values were divided into two groups; the first group consisted of values for the first 6-ft area based on the

observation that approximate 40% of the 15-ft slab was over-sprayed as shown in Figure 4 (a); the second group consisted of values for the other 9-ft under-sprayed area. Third, a two-sample *t*-test was performed for the two groups considering unequal variances. Results showed that the mean percentage reductions of the first and second groups were -5.08% and 2.44%, respectively; the *p*-value was 6.8E-9 (far smaller than 0.05) which indicated that there were significant differences in the percentage reductions between the two groups. The statistical analyses showed that the average percentage reduction of the first group was actually negative whereas the second group was positive; this again is likely due to the first group exhibiting a higher level of surface moisture content (DC measurements) due to the greater rate of curing application which formed a thicker protecting layer and slowed moisture evaporation.

Furthermore, the first group (covers the 6-ft linear area) was divided into two 3-ft groups and a two-sample *t*-test was also conducted for the percentage reduction values. Results showed that the mean percentage reductions of the first and second 3-ft groups were -4.13% and -6.02%, respectively; the *p*-value was 0.267 (greater than 0.05) which indicated that there were no significant differences in the percentage reductions between the two groups. These results were in accordance with the observations that the curing application was generally uniform for the first 6 ft. within the over-sprayed area and the spray pattern was repeated every 3-ft (the width of the spray pattern). It should be noted that a different spray pattern may result in different statistical results, future research is expected to investigate the effects of spray pattern on DC measurements.

The aforementioned visual observations and statistical analyses validated that GPR could potentially be very useful and sensitive to detection of placement uniformity of a curing compound; it also reinforces the importance of having a proper amount of curing compound in terms of maintaining a favorable humid curing environment at the surface of a concrete pavement.

Application rate

Increasing the application rate of a curing compound is another way to achieve a greater moisture retention capability for a given curing compound. Previously, Figure 4 (b) not only indicated the importance of achieving a uniform application of curing, but also revealed that a greater rate of curing application could help to maintain a higher level of moisture condition at the surface of concrete within 4.5 hours after curing was applied. Subsequent discussion addresses the effects of varying rates of curing application on the changes in DC measurements monitored over a period of 60 hours.

Two 45-ft test sections were uniformly sprayed with the same curing compound about 2.5 hours after placement of the concrete but with different rates of application. The test section named as “L250” shown in Figure 5 (a) was sprayed with a lower application rate (250 ft²/gallon) and the test section named as “H150” shown in Figure 5 (b) was sprayed with a higher application rate (150 ft²/gallon). The curing application was relatively uniform for these two sections judging by the whiteness of the curing compound layer at the pavement surfaces as shown in Figure 5, therefore the application rates determined using the aforementioned methods were considered representative.



(a)



(b)

Figure 5 Photos of (a) test section L250 with a 250 ft²/gallon curing application rate and (b) test section H150 with a 150 ft²/gallon curing application rate

DC measurements were taken at the two test sections over a period of about 60 hours. Comparisons of DC measurements for the two sections were made at both 2 hours and 63 hours after the application of curing. As shown in Figure 6 (a), the DC measurements for section H150 were generally higher than those of section L250 almost over the entire collection path. This was due to the fact that the higher curing application rate introduced greater amount of moisture to the pavement surface at section H150, leading to the higher DC values. As shown in Figure 6 (b) when comparison was made for the DC of the two sections taken 60 hours after, it was found that the differences in DC at the same locations were larger nearly everywhere along the collection path; it appears that the reduction in the DC measurements at section L250

were much greater than those of section H150.

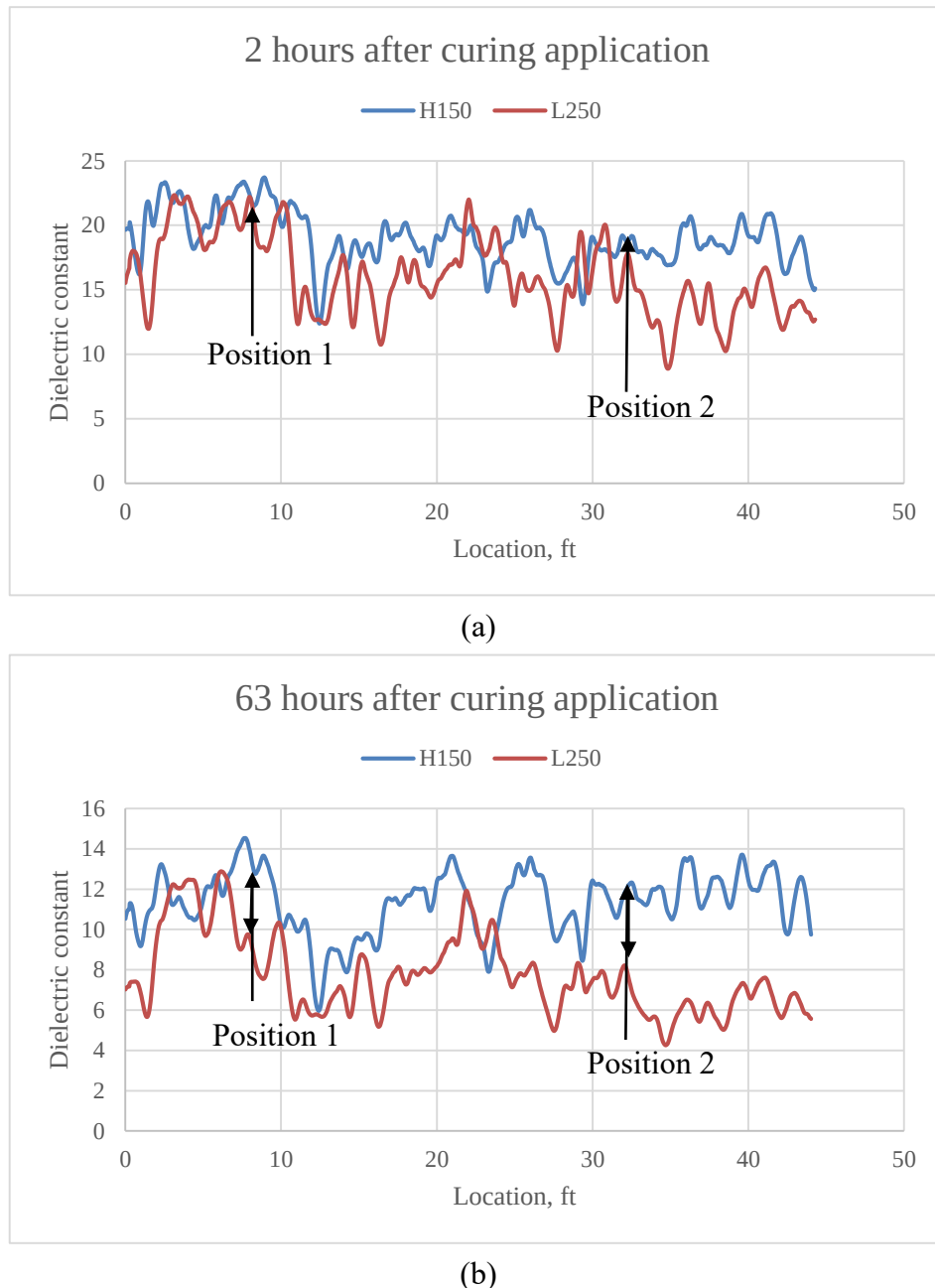
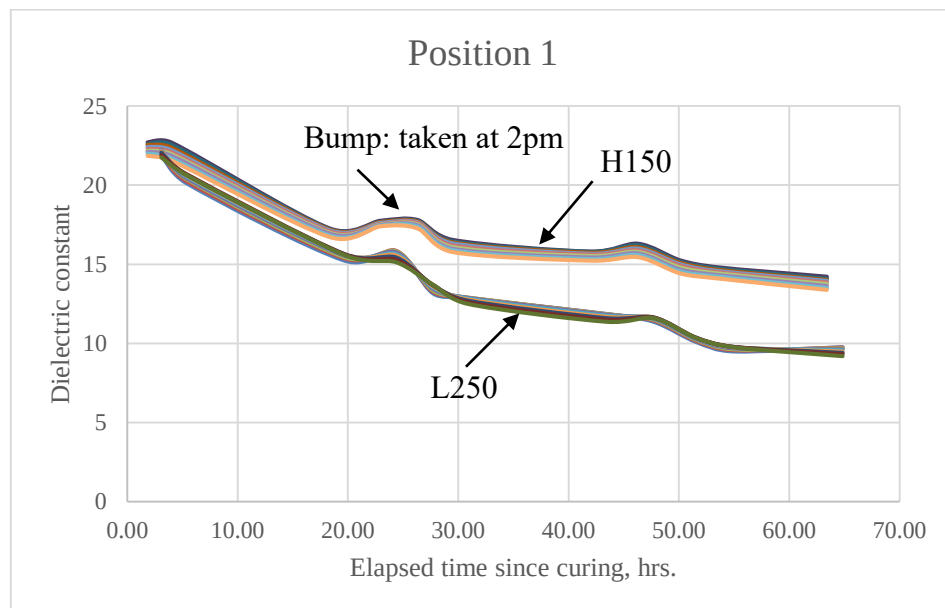


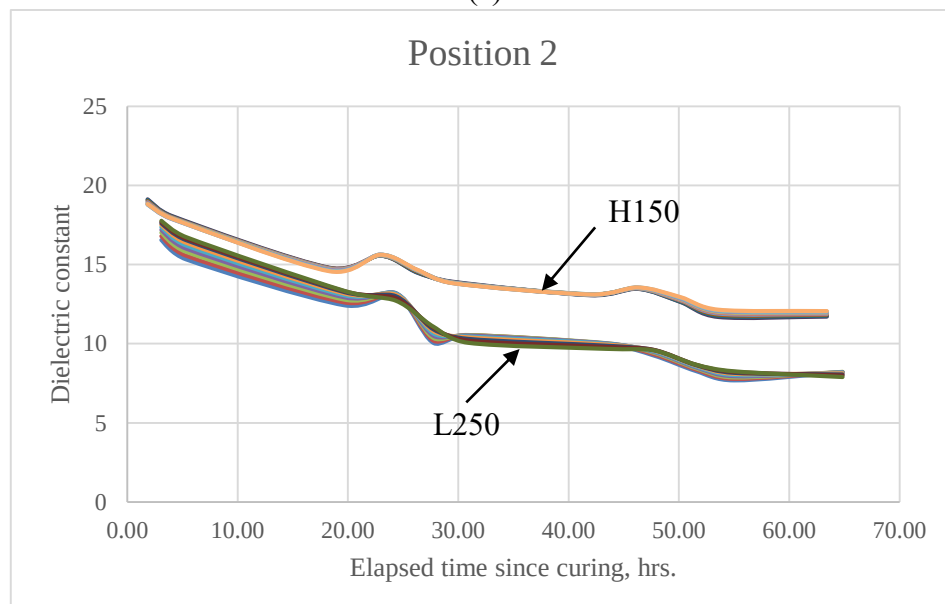
Figure 6 Comparisons of DC for the two test sections at (a) 2 hours after curing application and (b) 63 hours after curing application

Two locations (shown in Figure 6) where substantial DC separations occurs were selected to demonstrate the long-term effects of varying curing application rates. The two spots were at about 8 ft. and 32 ft. from the beginning of the trace, respectively. 9 DC data points (which cover a linear area of 3-in²/in) were selected at each spot in each section and the results are shown in Figure 7 (a) for position 1 and (b) for position 2. Note that some jumps were observed in all the DC measurements and this phenomenon was not occurring coincidentally since they were recorded in the afternoon around 2pm during the hottest time of the day which was perhaps when the effects of bleeding were magnified.

As shown in Figure 7, DC dropped rapidly within the first 20 hours after curing was applied; after which the decreasing trends for the two test sections started to separate from each other where section H150 had a lower decreasing rate and section L250 had a higher decreasing rate. This was very likely due to the fact that the high application rate of curing made at section H150 created a better protecting layer which led to a better moisture retention capability to keep moisture from evaporating. Consequently, at the end of 63 hours after the curing application, concrete in section H150 still had greater amount of free moisture which was the reason to account for the greater DC observed at this section comparing to section L250.



(a)



(b)

Figure 7 Comparisons of DC vs. Time for the two sections at (a) Spot 1 – 8 ft. from the beginning of the section and (b) Spot 2 – 32 ft. from the beginning of the section

A statistical analysis was also performed for the DC measurements of the two sections.

Again, the percentage reduction in the DC measurements from “2 hours after curing application” to “63 hours after curing application” was calculated for each point of the two 45-ft test sections – H150 and L250. A two-sample *t*-test was conducted for the percentage reduction values of the two sections; results indicated that the mean percentage reductions of section H150 and L250 were 40.4% and 52.0%, respectively; the *p*-value was very close to zero (far smaller than 0.05) which suggested that there were significant differences in the percentage reductions between the two sections and section H150 generally exhibited much lower percentage reductions comparing to section L250. This analysis further validated the efficacy of using GPR to evaluate curing effectiveness of concrete pavements regarding the effect of varying rates of application and again reinforced the notion that a greater rate of curing application provides a better curing condition that slows moisture evaporation.

CONCLUSION

- The configuration of the GPR system used in this study allows for an extensive evaluation of the curing effectiveness over a broad area of a concrete slab within a short-period of time;
- The GPR system provided great data repeatability;
- Through visual observations and statistical analyses, the efficacy of using the GPR system to suggest the uniformity of curing applications based on the DC measurements was validated;
- Results suggested that the GPR system was capable of detecting the differences in the curing effectiveness based on the comparisons made between two test sections with varied rates of curing application;
- Results reinforced the notion that the moisture retention capability of a curing practice increases with the increase of application rate and the improvement of curing application uniformity.

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